CONSEQUENCES OF NUCLEAR TESTING IN THE MARSHALL ISLANDS

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On the cover: A reproduction of a classic photograph printed in newspapers around the world from the second nuclear test at Bikini Atoll in July 1946. There were about 42,000 observers of the test including 40,000 U.S. servicemen. Photograph courtesy of the National Archives.

A MESSAGE TO OUR SUBSCRIBERS

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EDITORS' REMARKS

IT is with great pleasure that we, along with Editor-in-Chief Ken Miller and the Health Physics editorial staff, bring you this special issue, *Consequences of Nuclear Testing in the Marshall Islands*. Many readers undoubtedly are thinking: Why report on the Marshall Islands now? There are several answers to that question, but certainly an important one is that the issues of radiation protection made necessary by the nuclear testing program, are still relevant today, and the assessments of health, social and ecological impacts, are still going on. Furthermore, radiation protection issues in the Marshall Islands have similarity to issues in other countries that have experienced similar events.

The genesis of this issue was in 1993 at the mid-year Health Physics Society meeting in Coeur d'Alene, ID. We began a dialogue then to discuss the possibility and the relevance of an issue devoted entirely to the Marshall Islands. It was particularly fitting at that time to plan for such a publication since two commemorative dates were approaching: (1) 1994 would mark 40 years since the infamous BRAVO test that seriously exposed Marshallese on Rongelap and neighboring atolls, and (2) 1995 would mark 50 years that the Bikini people had been gone from their traditional home, originally displaced by the nuclear testing program. Though it was not possible to publish the issue in 1994 or 1995, this issue serves to commemorate those events.

We agreed that the papers presented here needed to be scientifically based but we felt that it was also important to go beyond the hard facts of radioactivity measurements and dose assessments to provide some information on the impact that nuclear weapons testing had on the culture and society of the island country as well as the context of the events in the history of the time. Thus, you will observe a slight departure from the usual content of this Journal though all papers have undergone the customary level of anonymous peer review.

The papers presented here were authored by scientists ranging in age from those well into mature careers at the time of nuclear testing program to those who were just youngsters, too young to understand the events taking place. It is impressive just how many scientists over the decades have applied themselves to studying and solving the problems brought about by nuclear testing in the Marshall Islands, and a cross-section of those are represented by the authors of these papers.

The response of the scientific community to a formal Call-For-Papers was enthusiastic; consequently, this issue is one of the largest ever published by *Health Physics*. The papers have been arranged into what we feel to be a logical sequence: (a) History, (b) Radiological Monitoring, (c) Dose Assessment, (d) Health Effects, (5) Environmental Studies, and (6) Additional Papers. The only topic that seemed essential for completeness but that could not be included was a description of the programs and the criteria for the radiological cleanup of Enewetak Atoll which took place from 1978 to 1980.

We are indebted to the authors, reviewers, editors and our publisher for the efforts they extended to assist in producing this special issue. In particular, we would like to acknowledge the financial support of this publication by the Office of International Health Programs of the U.S. Department of Energy. Publication cost for authors working within DOE supported programs as well as for independent authors without institutional affiliation or provisions was supported. We sincerely appreciate the assistance of the Department of Energy for making this issue possible.

We, as well as many other scientists, believe that it is worthwhile and imperative to publish these papers today. Other countries on several different continents are grappling with the same issues as in the Marshall Islands: environmental damages, health consequences, societal fear of radiation and cancer and financial issues, including costs of remediation, community rebuilding and compensation. Thus, information from the Marshall Islands should be useful in a global sense, and that fact increases the value of the information presented here.

Finally, we should all be aware of a problem that is rather difficult for us to accept: that the zealousness with which the scientific community approaches studies of radiation effects sometimes leads to a misunderstanding by those who have been exposed or believe themselves to have been exposed. The opportunity to learn from our mistakes is invaluable, but the tendency of scientists to poke and prod and sample *ad infinitum* can sometimes be misunderstood as evidence of having purposefully created the injury. We understand that the opportunity to conduct research that may be of far-reaching value has no relation to the circumstances that led to the injury. This conclusion was reached by President Clinton's investigative panel on Human Radiation Experiments in relation to the Marshall Islands exposures. As specialists in radiation protection, we owe our attention and our best efforts to the Marshallese, and in that spirit we present this issue on *Consequences of Nuclear Testing in the Marshall Islands*.

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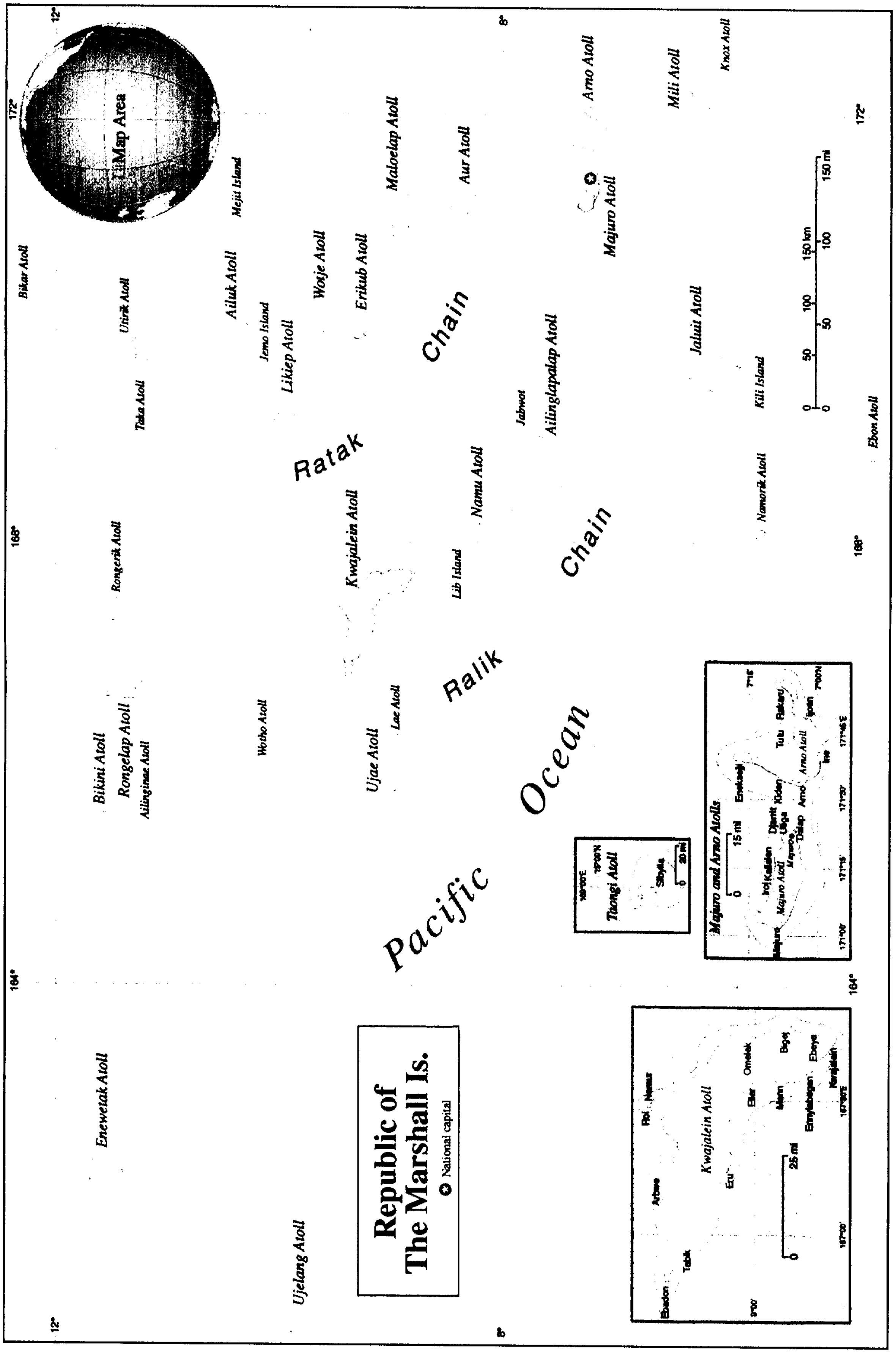
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A BRIEF HISTORY OF PEOPLE AND EVENTS RELATED TO ATOMIC WEAPONS TESTING IN THE MARSHALL ISLANDS

Steven L. Simon*

Abstract—**The events related to nuclear testing in the Marshall Islands began at the end of WWII when the U.S. began an initiative to determine the effect of nuclear weapons on naval vessels and on the performance of military personnel. The first tests took place in 1946 even though the area known as Micronesia was not entrusted to the U.S. by the United Nations until 1947. Beginning with the first relocation of the Bikini people to Rongerik Atoll in 1946, the saga of the Marshall Islands involvement in the atomic age began. Although the testing program was limited to the years 1946 through 1958, many of the consequences and events related to the testing program continued over the decades since. That story is still ongoing with programs currently underway to attempt to resettle previously displaced communities, remediate contaminated islands, and to settle claims of damages to individuals and communities. The history of the years subsequent to 1958 are a mixed chronicle of a few original scientific investigations aimed at understanding the coral atoll environment, continued surveillance of the acutely exposed Marshallese, some efforts at cleanup and remediation, numerous monitoring programs and many studies repeated either for credibility purposes, to satisfy international demands or because the changing state of knowledge of radiation protection has necessitated us to rethink earlier beliefs and conclusions about late health effects and social consequences. The objective of this paper is to briefly note many of the historical and political events, scientific studies, persons and publications from 1946 to the present that relate to atomic weapons testing in the Marshall Islands.**

Health Phys. 73(1):5–20; 1997

Key words: Marshall Islands; fallout; weapons; exposure, radiation

INTRODUCTION

THE MELDING of the history of the Marshall Islands and the United States began at the end of WWII when the U.S. Navy began an initiative to determine the effect of atomic weapons on naval vessels and the performance of military personnel. Beginning under the Truman administration and continuing under Eisenhower, the enthusiasm of the U.S. government for testing new and larger atomic weapons was apparently a sign of post-war uneasiness, partially a result of advances in nuclear technology by our Soviet counterparts. The 1950's was the period of Mutual Assured Destruction (MAD[1]), when the East and West manufactured 50,000 nuclear and thermonuclear weapons. During those years, children in the U.S. were taught to plunge under school desks at the sound of an air-raid siren, and their parents were encouraged to build fallout shelters. The nuclear rivalry during those years and the anxiety that accompanied it ultimately led the U.S. to involve the remote mid-Pacific islands (Marshall Islands, Johnston Atoll, and Christmas Island) in the blossoming nuclear age.

The technical programs as well as the administration of the U.S. atomic weapons testing program in the Marshall Islands is recorded in many thousands of historical military and government documents, but little historical narrative of the events related to the testing program has been written. MSC (1978) and Deines et al. (1991) provide substantial summary information in chronological order and may be consulted by interested readers. At least one early book (Hines 1962) concentrated on discussing scientific studies in the Pacific that were conducted during the testing years. Schultz and Schultz (1991) provided a bibliography of government related documents to atomic testing in the Marshall Islands while Stannard (1988) reviewed in general the era of testing and the exposure of the Marshallese from BRAVO. Eisenbud (1990) gave a fascinating account of events, mainly during the 1954 CASTLE series, from the point of view of the director of the AEC Health and Safety Laboratory. Several of the above publications are not easily obtainable and none include developments over the last 5 y.

The objective of this paper is to provide a short overall synthesis of events and medical and environmental consequences and to note some of the people involved and important publications related to the atomic weapons testing program in the Marshall Islands. The literature sources mentioned above were drawn upon as were numerous scientific reports from past and present U.S. agencies, historical memoranda from archives, as well as events witnessed by the author during the last 7 y. No attempt is made to list all available publications, rather a cross-section of important documents is given. Some

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[1] See Table 1 for a list of all acronyms used in text.

emphasis is given to the BRAVO incident because of its notable importance to later day consequences. This chronology covers the history to the present date.

HISTORY OF THE MARSHALL ISLANDS: PRE-ATOMIC TESTING ERA

2000 B.C. to 1500's

The small islands of the mid-Pacific, later to be known as Micronesia, were discovered by canoe-traveling seafarers from western Melanesia or southeast Asia. Parent communities spawned other communities at distances that could be covered by canoe, sometimes up to hundreds of km distance. This prehistoric movement across the Pacific resulted in the eventual migration and colonization of Oceania (Bellwood 1979), including the area now known as the Marshall Islands.

1600's–1900

The small islands, later to be known as the Marshalls, were discovered by Spanish, Dutch, and English explorers and later Germans. The southern islands of the Marshalls were put to use for gathering coconuts for production of copra oil.

Early 1900's

Japan began an administration of the islands; their domination afforded them the opportunity for military buildup in anticipation of WWII.

THE ATOMIC WEAPONS TESTING ERA

1944

The Marshall Islands, which had been administered by Japan since the end of WWI, fell to the U.S. military forces in bloody battles at Kwajalein and Enewetak and other atolls during the war in the Pacific. There were about 3,000 U.S. casualties and about 11,000 Japanese casualties in these battles.

1946

In February following the end of WWII, Commodore Ben H. Wyatt, the appointed military governor of the Marshall Islands, asked the people of Bikini if they would leave their atoll temporarily so that the United States could begin testing atomic bombs "for the benefit of all mankind" (Weisgall 1994). In March, the 166 Bikini people were relocated by the U.S. Navy to Rongerik Atoll, about 125 miles east, to make way for preparations for the atomic testing program on Bikini beginning with Operation CROSSROADS. Residents of Enewetak, Rongelap, and Wotho Atolls were also temporarily relocated during CROSSROADS. The Enewetak community was moved to Meck Island (Kwajalein), and the communities on Rongelap and Wotho were moved to Lae Atoll.

The spectacle of Operation CROSSROADS, which included the world's third and fourth atomic explosions (ABLE and BAKER), was displayed at Bikini Atoll in June and July under the watchful eye of some 42,000 soldiers, press, politicians, and official spectators. Nearly 100 vessels were used as targets for the tests of CROSSROADS including the US aircraft carrier *Saratoga*, the US battleship *Arkansas*, the Japanese battleship *Nagato*, the German cruiser *Prinz Eugen*, and the Japanese cruiser *Sakawa*.

The Atomic Energy Commission (AEC) was born under the Truman administration by the signing of the Atomic Energy Act in August.

1947

The entire area of Micronesia was designated by the United Nations Security Council as the United Nations Strategic Trust Territory (TT) to be administered by the United States. Truman delegated the administration of the TT temporarily to the U.S. Navy.

The Applied Fisheries Laboratory[‡](AFL) of the University of Washington issued a report on a resurvey of Bikini Atoll conducted in the summer (Donaldson 1947). The studies reported on were a continuation of studies they began immediately following CROSSROADS in 1946.

An investigating board recommended removal of the Bikini people from Rongerik because of insufficient food and water (Deines et al. 1991).

The 145 Enewetak inhabitants were relocated to Ujelang Atoll to ready Enewetak Atoll for nuclear testing upon a recommendation of AEC Chairman, D. Lilienthal.

1948

The Bikini people were relocated to Kwajalein Atoll for about 6 mo because of near starvation on Rongerik Atoll. After a lengthy search for a new home, the Bikini people agreed to relocate to Kili Island because of the absence of alternative residence sites, and they were again moved (see Niedenthal, 1997). Kili was viewed as only a temporary home[§] because it lacks a lagoon and protected anchorage, both important for fishing as a means of feeding the community.

Operation SANDSTONE was conducted in April and May at Eniwetak Atoll and included 5 tests. In May, the AFL collected aquatic specimens for study. A second collection was made at Eniwetak in July after the completion of a survey of Bikini.

1949

A report on the Bikini "resurvey," i.e., a second collection of aquatic organisms, was issued by AFL (Donaldson 1949).

1951

Operation GREENHOUSE was conducted in April and May at Eniwetak Atoll and included 4 tests.

[‡] The Applied Fisheries Laboratory had begun in 1944 as part of the Manhattan District program; its name was deliberately made misleading to hide its connection. The name was changed in January 1958 to the Laboratory of Radiation Biology (Hines 1962).

[§] The Bikini people are still resident on Kili Island today.

1952

The Health and Safety Laboratory (HASL, now the DOE Environmental Measurements Laboratory) located within the AEC New York Operations Office was originally assigned to monitor the area in the Marshall Islands beyond 500 miles, leaving the closer islands the responsibility of Joint Task Force 132. In September, however, "the NYOO assignment was extended to include all of the islands of the Trust Territory except Enewetak itself" (Eisenbud 1953a). The monitoring programs that were subsequently developed included 111 gummed film stations worldwide as well as a system for aerial monitoring of the islands in the western Pacific.

In early October, before Operation IVY, the Navy transported 169 Ujelang people 100 miles further away from Enewetak as a precautionary measure.

Operation IVY (2 tests) was conducted in October and November at Eniwetak Atoll; the first test MIKE was the first U.S. thermonuclear weapon detonated. MIKE vaporized the island of Elugelab, which housed the cryogenic plants for maintaining liquid tritium and deuterium. Left in its place was a one-half mile deep crater. In the nuclear debris from MIKE, two new isotopes of plutonium were discovered (^{244}Pu and ^{246}Pu) as well as two new elements, einsteinium and fermium (Seaborg and Loveland 1990). Fortunately, the main fallout debris from MIKE fell onto the open Pacific Ocean as planned (Eisenbud 1990).

1953

Maj. Gen. P. W. Clarkson was appointed military commander for Joint Task Force 7 (JTF7), which had responsibility for the conduct of the CASTLE series.

HASL issued a report on radiological surveys following Operation IVY (Eisenbud 1953b) and began preparations for monitoring Operation CASTLE. It was decided that automatic continuous reading radiation monitors would be installed at Truk, Ponape, and Kusaie (all three in the TT; now the Federated States of Micronesia) and Majuro, Rongerik, and Ujelang (three atolls of the Marshall Islands). The equipment as designed was automatically triggered into operation by an increase in the radiation level from the passing of a radioactive fallout cloud. Power provisions would keep the instrument running from 8 to 10 d, after which it was intended that they would be retrieved. Also planned was the placement of gummed paper on naval vessels in the Pacific (Eisenbud 1953a) to supplement the limited data that could be obtained from island monitoring.

In October, the AEC Weather Bureau office issued a "Meteorological Analysis of the Transport of Debris from Operation IVY" (Hubert et al. 1953).

A report (Lulejian 1953) was issued by the Air Research and Development Command in November to evaluate the long range hazards of radioactive fallout. The report was immediately classified and recalled soon after distribution (statement of M. Eisenbud, Congress 1994).[||] The report predicted for the first time that lethal concentrations of radioactivity may extend 30–50 miles downwind of the detonation site of 10 megaton weapons. Furthermore, it predicted high concentrations of radioactivity over an elliptical area of 1,000–5,000 square miles.

Maj. Gen. Clarkson determined that pre-shot evacuation of inhabited atolls would not be necessary for CASTLE because wind conditions prior to the test would be used to judge the safety of the pending tests. HASL recommended a standby evacuation plan for Marshallese in case of unexpected fallout on inhabited atolls but the suggestion was not accepted by JTF7 (Eisenbud 1990).

The AFL reported on tumors on *Ipomoea tuba* plants (a ground vine) at Enjebi Island, Eniwetak, sampled during July and August 1949, 17 mo after a test (Biddulph and Biddulph 1953).

1954

BRAVO, the first test of Operation CASTLE, was detonated at 6:45 AM on 1 March (local Pacific date, time) at Bikini Atoll. The explosive yield of BRAVO was "three times the most probable predicted value and twice the predicted upper limit. . . " (DNA 1954a).

The winds above 17,000 feet were blowing ENE at the time of detonation (DNA 1979); consequently heavy radioactive fallout was received at Rongelap, Rongerik, and Utrik Atolls, exposing inhabitants there as well as the fishing vessel, the *Lucky Dragon*, which was NE of Bikini. Much lower levels of radioactivity reached various locations in the Marshall Islands including Kwajalein Atoll (Harley et al. 1960) and Majuro Atoll (Breslin and Cassidy 1955[¶]).

Twenty-eight American military personnel were stationed as weather observers on Rongerik Atoll. The onset of visible fallout at Rongerik was approximately 1400–1430 h (Sharp and Chapman 1957). A stationary measurement instrument with strip-chart output that had been placed at the Rongerik Atoll weather station (Eniwetak Island) by HASL (Eisenbud 1990) went off scale at 100 mr h^{-1} at H + 6 h, 48 min (Sharp and Chapman 1957). Following the radio transmission from Rongerik to the JTF flagship *Estes*, there was an unexplained delay in confirming the reported fallout (Eisenbud 1990; Eisenbud 1997).

The weather observers were evacuated from Rongerik in two different groups: the first eight men were removed about 22.5 h following the onset of fallout (1245, 2 March), the remaining twenty men at about 28 h (1800, 2 March).

Sixteen Marshallese were evacuated by plane from Rongelap at 1000, 3 March (H + 51 h). Forty-eight Marshallese were evacuated from Rongelap on the USS *Philip* at the same time (total of 64 persons). Eighteen Rongelapese temporarily staying on Sifo Island, Ailinginae, were evacuated on the USS *Philip* at H + 54 h. Survey measurements on Rongelap Island made by the evacuation team reported readings of 7.2×10^{-8} C

[||] The Lelujian report was declassified in 1996.

[¶] Both unclassified and classified versions of this report seemed to have existed simultaneously. The unclassified version was available since 1955; the SECRET version was declassified in May 1994.

$\text{kg}^{-1}\text{s}^{-1}$ (1.0 r h^{-1}) to 1.7×10^{-7} C $\text{kg}^{-1}\text{s}^{-1}$ (2.3 r hr^{-1}) in the main village (Sharp and Chapman 1957).[#]

The Rongelap people were taken to Kwajalein for decontamination, examinations, and health care provided by a medical team formed from personnel from the Naval Medical Research Institute (NMRI) and the Naval Radiological Defense Laboratory (NRDL). The team was headed by Dr. Eugene Cronkite. Within the first 24 to 38 h after exposure, about two-thirds of the Rongelap people experienced anorexia and nausea including diarrhea. Many experienced itching and burning of the skin. About 2 wk after exposure, cutaneous lesions and loss of hair was experienced by many. Following a short stay on Kwajalein, the Rongelap people were relocated to Ejit Island (Majuro Atoll).

On 4 March, 159 people were evacuated from Utrik to Kwajalein on the USS *Renshaw*. The Utrik population was not examined by the Brookhaven medical team until March 1957 (Lessard et al. 1980).

Also exposed were three persons *in-utero* on Rongelap, one on Ailinginae, and eight on Utrik.[**]

Twenty-three Japanese fishermen on board the fishing boat *Fukuru Maru No. 5* (*Lucky Dragon*) were about 90 miles NE of Bikini at the time of the BRAVO detonation. They reported seeing a reddish-white flash and hearing an explosion 7 or 8 min later. Dust began coating the boat about 3 h following the explosion. It was reported that the dust coating was about 0.5 g m^{-2} with an areal activity concentration of 26 GBq m^{-2} (JSPS 1956).

Within a few days, the fisherman were nauseous, and in 7 or 8 d evidence of burns appeared on exposed areas of skin. The fishermen voyaged for approximately 2 wk on the contaminated boat until 14 March when they arrived at Yaizu Harbor, Shizuoka Prefecture, Japan (BICRKU 1954).

On 10 March, the AEC first announced the exposure of the Marshallese (see Associated Press 1954) with the misleading statements that an evacuation was carried out according to plan as a precautionary measure. The *New York Times* also reported that the AEC announced that although some individuals were unexpectedly exposed to radiation, there were no burns and that after the tests were completed, the Marshallese natives would be returned to their homes.

After the return of the *Fukuru Maru* to Japan, a public panic occurred there over the notion of radioactively contaminated tuna (*New York Times* 1954b; Eisenbud 1990; Parrot 1954), which resulted in significant economic damage to the commercial tuna market.

In May, the 154 people evacuated from Utrik in March were returned to their atoll.

On 1 April, the *New York Times* (1954) reported on the press conference presented by AEC Chairman, Lewis Strauss, in which he misled the American public by stating that the skin lesions on the fisherman of the Lucky Dragon "are believed to be due the chemical activity of the converted coral material, rather than to radioactivity. . . ".

Joint Task Force Seven (JTF7) reported by memorandum the exposure-rate readings made by radsafe surveys in the first 5 d following the BRAVO detonation (House 1954). JTF7 also reported on external radiation exposures to military personnel during Operation CASTLE (Servis 1954). The highest reported exposures[††] were 40 R by weather station personnel on Rongerik and 17 R by one weather reconnaissance pilot. The bulk of Task Force exposures between 1.6×10^{3} C kg^{-1} (6R) and 3.1×10^{-3} C kg^{-1} (12 R) were reported for Navy ship decontamination and Air Force cloud sampling teams. Reported were 8,101 individuals exposed from 0 $-$ 5.2×10^{-4} C kg^{-1} (0 $-$ 2 R), 1,440 exposed to $5.2 \times 10^{-4} - 1.0 \times 10^{-3}$ C kg^{-1} (2 $-$ 4 R), 549 exposed $1.0 \times 10^{-3} - 1.6 \times 10^{-3}$ C kg^{-1} (4 $-$ 6 R) 161 exposed $1.6 \times 10^{-3} - 3.1 \times 10^{-3}$ C kg^{-1} (6 $-$ 12 R), and 37 exposed to over 3.1×10^{-3} C kg^{-1} (12 R).

The CASTLE series continued with four more tests at Bikini Atoll during the 9-wk period following BRAVO and with a single test at Enewetak 1 wk after the Bikini series.

In the spring, JTF7 issued a two-volume radiological safety report of Operation CASTLE. It appears that the original report was classified (an extract for public distribution was later issued by Defense Nuclear Agency in 1985).

During the summer, relationships with Japan improved and a joint U.S./Japan radiobiological conference was held in Tokyo. Research findings from the vessel *Shinkotsu Maru* showed that the radioactivity from Bikini lagoon flowed into the Equatorial and Kurishio Currents which would eventually reach Japan and Asia. HASL prepared a research team headed by John Harley to track the radioactive plume under Operation TROLL; the 3-mo mission began in San Francisco in February 1955. Although the Operation confirmed that concentrations of radioactivity in seafood were below health concerns, it did provide new data on mixing rates in Pacific waters (Eisenbud 1990).

Extensive radiological monitoring throughout the 1954 Castle series was conducted by HASL using continuous reading gamma radiation monitors placed at eleven locations in the Marshall, Caroline, and Mariana Islands and by aerial surveys (Breslin and Cassidy 1955). The instrument located at the main population center, Majuro, documented that fallout from BRAVO resulted in an increase from 4.7×10^{-15} C kg^{-1} s^{-1} (0.065 μR h^{-1}) to 7.9×10^{-14} C kg^{-1} s^{-1} (1.1 μR h^{-1}) for about 14 d following the test. Possibly the first successful aerial radiation surveys were conducted over the Marshall Islands as part of the HASL program. Twelve lengthy flights were conducted, some missions surveying as many as sixteen atolls. During this series of aerial monitoring missions, measurement data were collected on all 28 atolls of the Marshall Islands, in addition to

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[#] The abbreviation of "r" in Sharp and Chapman (1957) refers to roengten, now usually abbreviated as "R."

[**] Confirmed in 1982 (Adams et al. 1982).

[††] This early report did not have information on internal exposures to the weather observers stationed at Rongerik. See 1986 entry for additional information.

many more distant locations such as the Hawaiian Islands, Midway, Guam, and Palau.

A number of field missions to Rongelap with various sampling objectives were held in 1954: (1) March 26, the Applied Fisheries Laboratory (AFL) visited Rongelap to make radiation readings and capture animals for study; (2) April 13 by U.S. Naval Radiological Defense Laboratory (NRDL) and Naval Medical Research Institute (NMRI); (3) July 16 by the AFL; and (4) December 18 by AFL.

1955

Additional U.S. agency sampling missions to Rongelap were conducted in 1955: (1) January 25 to 30 by NRDL; (2) October 21 to 23 by AFL; and (3) November 7 by AFL.

In January, the AEC Health and Safety Laboratory (HASL) reported on radioactive debris from Operation CASTLE in the Pacific (Breslin and Cassidy 1955) and in worldwide fallout (Lynch 1955). The latter report estimated that the world wide fallout of beta-activity, excluding the test site, was 5.6×10^{16} Bq (1.5 MCi) per month in March, April, and May of 1954, decreasing to 2.8×10^{16} Bq (0.75 MCi) in June and July and 4.4×10^{16} Bq (1.2 MCi) in August.

In February, AEC Chairman Lewis Strauss released an article to the public, "The Truth About Radioactive Fall-Out" (Strauss 1955). In this article he confirmed the then classified predictions of Lulejian (1953) in his reference to the March 1 test at Bikini[‡‡]: "Thus, about 7,000 square miles of territory downwind from the point of burst was so contaminated that survival might have depended upon prompt evacuation of the area or upon taking shelter and other protective measures." The notion of an "unexpected shift in the winds" as the main cause of the exposure of the Marshallese can be traced to this article despite the evidence that the wind was blowing ENE, dangerously close to the direction of the inhabited atolls, at the time of the detonation.

In March, AFL issued a report (Donaldson et al. 1955) on radioactivity in fish collected at Ponape in late 1954 (then the Trust Territory, now Federated States of Micronesia). Although the analysis as described was limited to gross count-rates, attention was brought to the fact that islanders prefer to consume the liver of fish, thereby resulting in a possible tenfold increase in the radioactivity consumed as compared to consuming equal amounts of fish flesh.

In April, the NMRI and NRDL issued an addendum report on Project 4.1A of Operation Castle: "Medical Examination of Rongelap People Six Months After Exposure to Fallout" (Bond et al. 1955).

In early May, the Navy Foreign Claims Commission settled claims for the damages to Marshallese related to the BRAVO test. A total of \$5,162.53 was paid to Rongelap residents and \$1,719.27 was paid to Utrik inhabitants (Deines et al. 1991).

A single Pacific Ocean test was detonated as part of Operation WIGWAM in mid-May. The test was located about 640 km SW of San Diego; the 30 kT device was suspended by a cable from a barge at a depth of 600 m.

Possibly the first open literature publication describing the acute health effects among the Rongelapese was published in the Journal of the American Medical Association in 1955 (Cronkite et al. 1955).

The Applied Fisheries Laboratory reported on their various surveys of Rongelap during 1954 and 1955 (Donaldson 1955). From March 1954 to January 1955, the radioactivity in coconut meat and milk declined to about 4% of its initial value though measurements were limited to the gross beta-decay rate.

1956

Operation REDWING was conducted May through July at both Bikini and Eniwetak Atolls and included 17 tests, several of which were hydrogen bombs.

Additional sampling missions to Rongelap were conducted: (1) February 7 to 14 by NRDL and (2) July 23 to 24 by AFL. The survey at the end of July found external dose-rates on Rongelap Island to be about 1.4×10^{-11} C kg^{-1} s^{-1} (0.2 mR h^{-1}) – 3.6×10^{-11} C kg^{-1} s^{-1} (0.5 mR h^{-1}) with an average of 2.9×10^{-11} C kg^{-1} s^{-1} (0.4 mR h^{-1})(AEC 1957). The exposure rate was noted to be higher than anticipated by considering the theoretical decay rate of BRAVO fallout and was attributed to additional radioactive fallout received on Rongelap from Operation REDWING.

In November, The U.S. Government completed an agreement with the Enewetak chiefs through the TT High Commissioner, allowing the Enewetak people full use of Ujelang Atoll until they could return to Enewetak; the sum of \$175,000 was provided for assistance.

In the same month, a similar agreement was settled with Bikini and the sum of \$325,000 was provided.

1957

In March an addendum report of Project 4.1 of Operation Castle was issued on "Exposure of Marshall Islanders and American Military Personnel to Fallout" (Sharp and Chapman 1957). The report detailed the homes, water catchments, etc., of the Rongelap community as well as the movements of the service personnel in the hours after fallout and before evacuation. The report also included film-badge readings from the service personnel.

In February, the AEC approved the return of the Rongelapese to their atoll based on the projection of an exposure of 1.3×10^{-4} C kg^{-1} (0.5 R) in the first year, declining thereafter. In mid-June, measurements showed the external exposure-rate to be about 2.1×10^{-12} C kg^{-1} s^{-1} (0.26 R y^{-1}). On 29 June, about 250 people were returned to Rongelap Island, including those originally evacuated and some additional people added by marriage and birth.

Brookhaven National Laboratory (BNL) developed a whole-body gamma scintillation spectrometer for the purpose of measuring the internal radioactivity of

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[‡‡] Strauss was referring to the BRAVO test but the publication did not give its code name.

Rongelap people. Members of the Rongelap community were transported by air to the U.S. for whole-body counting. Dr. Robert Conard of BNL took over directing the medical surveillance program of the exposed Marshallese.

In August, the AEC issued a report entitled "Radioactive Contamination of Certain Areas in the Pacific Ocean From Nuclear Tests" (AEC 1957). Despite the elusive title, the document summarized data from the radiological surveys of Rongelap and the medical examinations of the evacuated populations.

1958

The last series of Marshall Islands tests was conducted as Operation HARDTACK I. Both Bikini and Enewetak Atolls were used for the 35 detonations.

A "portable" 21-ton steel whole body counting facility was developed by BNL to take to Rongelap aboard a landing craft for whole-body counting of the Rongelap community members.

The United States, Great Britain, and USSR suspended nuclear weapons testing as part of a nuclear testing moratorium on 31 October.

POST-TESTING ERA

1960

The University of Washington Laboratory of Radiation Biology (LRB, previously AFL) issued a report (Palumbo 1960) on the recovery of land plants at Enewetak following the testing. LRB also issued a report (Chakravarti and Held 1960) on ^{137}Cs in the coconut crab (*Birgus Latro*) collected from Rongelap Atoll during 1958. The coconut crab, recognized to be a delicacy to Marshallese, was found to contain high levels of ^{137}Cs due to its diet of fresh coconut.

1962

A book was published describing the radiobiological studies in the Pacific during the years 1946–1961 (Hines 1962).

The Federal Radiation Council issued the first report on the pathological effects of thyroid irradiation, summarizing the experience of the Rongelapese to date (FRC 1962).

1963

Nine years after exposure to BRAVO fallout, the first thyroid nodule in the heavily exposed Rongelapese was detected (diagnosed in a 12-y-old girl, i.e., 3 y of age at exposure).

The first paper was published on the chemical and radiochemical composition of the Rongelapese diet (Chakravarti and Held 1963). High dietary intake levels of ^{137}Cs and ^{90}Sr were noted where local fruit was consumed, and ^{60}Cs and ^{65}Zn were associated with diets of local fish.

1964

The University of Washington's Laboratory of Radiation Biology resurveyed Bikini. Compensation for exposed Rongelapese as a result of BRAVO fallout was appropriated by P.L. 88-485 in the amount of $950,000. The compensation was considered as a full settlement of all claims against the U.S. (U.S. 1964; Deines et al. 1991).

1965

Held (1965) reported on gamma dose rates on Rongelap during the years 1954 to 1963 and concluded that the exposure rate had decreased faster in the environment than predicted by the theoretical decay of ^{235}U. The reason given was due to the downward movement of ^{137}Cs in the soil. Their data also showed that the dose rate on Rongelap Island at $D + 1$ (time of detonation plus one day) was 9.8×10^{-6} Gy s^{-1} (3.5 r h^{-1}) and 9.8×10^{-5} Gy s^{-1} (35 r h^{-1}) on Lomuilal Island in the northern part of the atoll.[§§]

Held et al. (1965) also reported on redistribution of radionuclides in soils following fallout contamination. Some basic tenets of radioecology resulted from those studies, including the observations that soil algae, found as a surface crust in undisturbed areas, had the highest levels of radioactivity and that vegetation litter redeposits ^{137}Cs and ^{90}Sr back to the surface layer of soil.

1966

The National Academy of Sciences issued an updated version (FRC 1966) of its 1962 report on pathological effects of thyroid irradiation, further summarizing the experience to date of the exposed Rongelapese.[‖‖] By this date, 79% of children less than 10 y of age at time of exposure had developed thyroid abnormalities as compared to no thyroid pathology in non- or lesser-exposed populations.

In 1966, an open literature publication summarized the induction of thyroid nodular disease among the exposed Rongelapese (Conard et al. 1966).

Secretary of the Interior, Stewart Udall, advised AEC Chairman Seaborg that the Department of the Interior was anxious to determine whether the Bikini people could be returned to the homeland and requested the AEC to make that determination as soon as possible.

1967

Following a request in 1966 from the High Commissioner of the Trust Territories of the Pacific to the AEC to rehabilitate Bikini, the atoll was resurveyed in April and May by personnel from HASL, the Division of Biology and Medicine (DBM), NRDL, the Trust Territory (TT), and University of Washington (UW). A report by HASL was issued on the external radiation levels determined by the survey (Beck et al. 1967).

[§§] The abbreviation of "r" refers to roengten, now usually abbreviated as "R."

[‖‖] The reader should take note that two of the four conclusions of the 1966 report are still topics of research and, although not yet fully resolved, some of these questions may be answered by studies of the effects of the Chernobyl accident: (1) The shape of the response cure below 1 Gy (100 rad) is unknown. (2) X rays are probably as effective if not more so than ^{131}I in producing thyroid lesions for equal, average absorbed doses delivered to the gland at similar rates.

In October, 300 Enewetak people living on Ujelang were moved to Majuro for better food and improved living conditions.

1968

In April, the AEC DBM appointed an *Ad Hoc* committee of eight experts to consider the question of return of the Bikini population (McCraw n.d.).

In August, President Johnson publicly announced the decision to resettle the Bikini people on their home atoll (AEC 1968).

1969

In February, a clean-up phase as part of the rehabilitation of Bikini was begun by the AEC and Department of Defense (AEC 1971) and was completed by October. The *Ad Hoc* committee reviewing the 1967 survey concluded that the Bikini-Eneu complex of islands could be used for continuous occupancy and agricultural development to support the returning population. The committee stated that, on the basis of information provided, the exposures to radiation resulting from the repatriation of Bikini people would not offer a significant threat to their health and safety (McCraw n.d.; AEC 1968). The committee further recommended that test-related debris should be removed to eliminate physical hazards. The concentrations of ^{90}Sr in the food chain were believed at that time to be the primary hazard with respect to internal dose. The committee's recommendations were made to the Chairman of the AEC who informed the Secretary of the Interior, the Administrator for the Trust Territory of the Pacific.

About 40 people began living on Eneu Island, Bikini Atoll. A general cleanup of debris and buildings was begun. An agricultural reclamation program was initiated with the planting of coconut trees on Eneu and Bikini Islands. Pandanus, papaya and banana were planted on Bikini Island (Robison et al. 1977). Construction of 43 houses was begun (continuing until 1974).

1971

The AEC issued a summary report of the 1969 and 1970 surveys of Bikini Atoll (AEC 1971).

1972

In January during the Congress of Micronesia, a Marshall Islands representative accused the U.S. of intentionally exposing the inhabitants of Rongelap and Utrik to develop medical capabilities for treating radiation exposure during wartime. In response to the accusations, the Rongelapese boycotted the BNL medical survey charging them with using the Rongelap people as guinea pigs.

The 40 people living on Eneu Island (Bikini Atoll) and an additional 20 women and children moved to Bikini Island. Additional monitoring was conducted by AEC Division of Operational Safety with support of the AEC Nevada Operations Office, UW and the Western Environmental Research Laboratory of the Environmental Protection Agency.

Plans continued for a cleanup of Enewetak Atoll. An interagency meeting delegated responsibilities for funding the pre-cleanup survey to AEC, the radiological and nonradiological cleanup to DOD and the rehabilitation costs to DOI. In October, the pre-cleanup radiological survey of Enewetak began.

The only documented death from radiation-induced leukemia among the exposed Rongelapese occurred in a 19-y-old male, exposed at age 1 y (Conard 1975). He died at the National Institutes of Health, where he was being treated.

1973

Field operations of a survey of Enewetak (pre-cleanup survey) were completed in February.

Testimony provided during House Appropriations Committee hearings disclosed that urine bioassays of people intermittently resident on Bikini showed ^{137}Cs higher than in 1970 by about 10× and ^{90}Sr higher by about 4×. The increase in body burdens was attributed to the consumption of fruits grown on Bikini Island.

1974

Compensation was paid by the AEC to the TT in the amount of $18,212, to be dispersed in equal payments of $116 to the exposed Rongelapese or their heirs.

The AEC task group recommended cleanup levels for plutonium contaminated soil at Enewetak Atoll: 1.48 Bq g^{-1} (40 pCi g^{-1} original units)—no action required; 1.48 to 14.8 Bq g^{-1} (40 to 400 pCi g^{-1})—corrective action determined on a case-by case basis (related to projected land use); and greater than 14.8 Bq g^{-1} (400 pCi g^{-1})—corrective action required.

President Ford created the Energy Research and Development Administration (ERDA).

1975

A survey of Bikini and Eneu Islands was conducted by Lawrence Livermore National Laboratory (LLNL) under contract with ERDA to determine low-exposure sites for additional housing.

In June, P.L. 94-34 authorized an *ex gratia* payment of $3 million to the people of Bikini in recognition of the hardship they endured (U.S. 1968).

In September, the DOD discussed the postponement of the resettlement of Bikini, implying that a radiological survey of Bikini, similar to the pre-cleanup survey of Enewetak, might be necessary. The Bikinians brought a lawsuit in U.S. District Court in Hawaii to force the U.S. to stop the resettlement until a comprehensive radiological survey of the atoll was conducted.

1976

Brookhaven National Laboratory (BNL) conducted an external radiation survey program of five northern atolls and, in April, surveyed some of Bikini Atoll.

1977

In March, 56 Enewetak community members returned to Japtan Island in Enewetak Atoll.

In August, President Carter created the Department of Energy (DOE) by Public Law 95-91.

P.L. 95-134 mandated a continuous medical care program for the Marshallese exposed to BRAVO fallout.

A report was issued by LLNL to assess dose to returning Bikini residents (Robison et al. 1977).

1978

In April, urine was sampled from the Bikini residents by BNL; those data and ^{137}Cs body burdens determined by whole-body counting were reported to the DOE in July. Body burdens of several individuals exceeded the maximum permissible body burden (MPBB) of 1.1×10^5 Bq (3.0 μCi), and values for a dozen individuals ranged between 2.2×10^4 Bq (0.6 μCi) and 2.2×10^5 (5.9 μCi) (Greenhouse 1978). In September, as a result of the increases in body burdens, the Bikini residents were again relocated to Kili Island.

The Northern Marshall Islands Radiological Survey began in September under a contract issued by the DOE to EG&G for aerial monitoring of eleven atolls. A helicopter mounted NaI detector array was used for gamma spectrometry measurements. LLNL also acquired plant and soil samples as part of the monitoring program.

A $75M settlement with Bikini for damages resolved claims against the U.S. for taking and using Bikini as a testing grounds (Weisgall 1994).

1979

DNA (1979) issued a "Compilation of Local Fallout Data" for oceanic tests. This volume gave the H hour, H + 3 hour, and H + 6 hour hodographs for the BRAVO test clearly showing the winds above 17,500 feet to have been blowing ENE.

In March and April, the DOE through LLNL conducted a survey of Enjebi Island (Enewetak). In September, a concrete dome was completed over a radioactive waste repository made from the CACTUS (shot) crater on Runit Island (Enewetak). Over 100,000 m^3 of soil contaminated with transuranic radionuclides, principally isotopes of plutonium and americium, were mixed with cement and imbedded in the crater.

Twelve of the twenty-eight military personnel exposed on Rongerik to BRAVO fallout were medically examined in possibly the only medical follow-up of this exposed group (Bailey 1995).

1980

In March, the cleanup of Enewetak Atoll was completed at an estimated cost of $218 million (Deines et al. 1991). Over 4,000 U.S. servicemen assisted in the cleanup effort and six lives were lost in accidents. In May, the Enewetak people returned to their atoll.

In the fall, DOE issued the "Meaning of Radiation at Bikini Atoll" (DOE 1982a). The report stated that the Bikini people would be within U.S. radiation standards if they returned to Eneu Island, that they ate no more than 50% locally grown food and spent no more than 10% of their time on Bikini Island. (In the 2 y following, 14 petitions on behalf of approximately 5,000 Marshallese were filed in U.S. Court of Claims. The alleged damages in these suits totaled $5.75 billion.)

BNL published a reconstruction of chronic dose equivalent to Rongelap and Utrik residents for the years 1954 through 1980 (Lessard et al. 1980). Doses were relatively high for Utrik residents because the Rongelapese had been relocated from their atoll following the BRAVO test until late June of 1957. Estimated doses to adults were 0.17 Sv (17 rem) and 0.039 Sv (3.9 rem) to whole-body (Rongelap and Utrik, respectively), 0.16 Sv (16 rem) and 0.045 Sv (4.5 rem) to thyroid (Rongelap and Utrik, respectively), 0.23 Sv (23 rem) and 0.049 Sv (4.9 rem) to red bone marrow (Rongelap and Utrik, respectively).

1981

Following the Enewetak cleanup, 100 Enewetak people returned to Ujelang from Enewetak because of insufficient locally grown food.

Calculations were performed for DNA (Gminder 1981) to estimate the radiation dose to a representative individual on Kwajalein Atoll from 1 May to 18 September 1948 during the rainout of radioactive fallout from Shot YOKE of Operation SANDSTONE. The external exposure (maximum value, no building shielding) was estimated to have been 7.7 mSv (770 mrem).

Findings of the EG&G aerial survey were released in a report (Tipton and Meibuam 1981) that gave exposure-rate values and estimated soil concentrations of selected fission products on 11 atolls and two separate reef islands.

1982

The U.S. Congress created a $20 million Resettlement Trust Fund to be used for upgrading and improving living conditions for the Bikini people on Kili Island.

Congress created the Bikini Atoll Rehabilitation Committee (BARC) to investigate the feasibility and costs of rehabitating Bikini. The committee was chaired by Dr. Henry Kohn.

LLNL updated its dose assessment for Bikini (Robison et al. 1982b) and published the results of the ground sampling from the 1978 survey of the northern Marshall Islands (Robison et al. 1982a).

The Department of Energy issued a bilingual report (English/Marshallese) in 1982 (DOE 1982b) explaining the meaning of radiation and giving information on the radiological conditions on the northern atolls as obtained by the 1978 aerial survey. For the first time in this report, Marshallese were given information that showed that islands of northern Rongelap Atoll were as contaminated as Bikini Island.

The 28-y follow-up medical report from Brookhaven National Laboratory (Adams et al. 1982) confirmed two additional individuals *in-utero* on Utrik at the time of the BRAVO fallout. The report also listed the previous 64 BNL publications concerning follow-up of exposed Marshallese. Updated dose assessments for the Marshallese known to have been exposed to BRAVO fallout were also provided in an appendix.

1983

In May, the Bikini people filed a class action suit against the executive branch of the U.S. Government seeking compensation for damages to Bikini.

The DOE Marshall Islands dose assessment programs were transferred from Emergency Preparedness to Defense Programs within the DOE.

The Compact of Free Association was approved by the electorate of the Marshall Islands.

The Rongelap community decided that, due to the startling evidence of contamination of their atoll brought to light in DOE (1982b), they must abandon their atoll (King 1986) and began to solicit internationally for evacuation assistance.

1984

In February, LLNL published results of calculations (Hicks 1984) for a limited number of Marshall Islands tests giving the relationship between external gamma exposure rates for local fallout and the related radionuclide composition.

In November, BARC submitted its first report to Congress stating that Bikini Island may be resettled if no locally grown food or ground water is consumed for 80 y. The Bikini council rejected that option.

The Bikinians, disappointed with the Compact of Free Association, an agreement under negotiation between the U.S. and the Marshall Islands, brought a suit in U.S. Federal Court in Honolulu to attempt to force the U.S. to conduct a cleanup and to hastily resettle the Bikini people to their atoll.

1985

The lawsuit of the Bikinians was settled on March 15 with the U.S. agreeing to conduct a cleanup upon completion of the findings of BARC.

In May, 327 Rongelap people went into self-imposed exile as a result of their fear of the radioactive contamination of Rongelap brought to light by the 1982b DOE report of the northern Marshall Islands radiological survey.[¶¶] After an international plea for evacuation assistance that lasted several years, the Rongelapese left Rongelap Atoll for Mejatto Island (Kwajalein Atoll) with the assistance of the Greenpeace organization. Taking four trips of the *Rainbow Warrior* (King 1986) to move the community and their belongings, the Rongelap people settled on Mejatto.[##]

Lessard et al. (1985) reported results of calculations to estimate acute thyroid exposure to residents of Rongelap, Ailinginae, and Utrik Atolls from the BRAVO test. They concluded that ingestion was the main route of internal exposure. Whole body exposure was estimated at Rongelap to be about 1.75 Sv (175 rem). Thyroid doses (internal dose + external exposure) at Rongelap from BRAVO were estimated for the age categories of adult, 9 y, 1 y, newborn and *in utero*: 12 Sv (1200 rem), 22 Sv (2200 rem), 52 Sv (5200 rem), 44 Sv (4400 rem) and 8.7 Sv (870 rem), respectively. Maximum estimates were about 4× greater. Dose estimates at Ailinginae and Utrik were about 30% and 15%, respectively, of the Rongelap estimates.

The Compact of Free Association (COFA) was passed by the U.S. Congress (as part of P.L. 99-239) and enacted a $150 million compensation program to the Marshall Islands. Under Section 177 of the COFA, the people of Bikini, Enewetak, Rongelap, and Utrik were awarded $75 million, $48.75 million, $37.5 million, and $22.5 million, respectively, to be paid in quarterly installments over a 15-y period. The COFA also made available $3 million to conduct medical surveillance and radiological monitoring.

In September, the Defense Nuclear Agency (DNA) issued an extracted version (DNA 1954a, b) of the JTF7 Final Report on Radiological Safety written in 1954.

1986

In January, President Reagan signed P.L. 99-239, which enacted the Compact of Free Association (COFA); it became effective in October.

A report (Klemm et al. 1986) was issued by Science Applications International Corporation for the DNA on the analysis of radiation exposure to service personnel on Rongerik Atoll at the time of shot BRAVO. External doses for the first and second evacuation group were estimated at 0.33 Sv (33 rem) and 0.38 Sv (38 rem) to 0.43 Sv (43 rem), respectively. Internal doses varied by organ: representative estimates were 2.3 Sv (230 rem) to the thyroid, 1.15 Sv (115 rem) to lower large intestinal wall, 0.85 Sv (85 rem) to upper large intestinal wall, and 0.4 Sv (40 rem) to 0.5 Sv (50 rem) to other organs (Klemm et al. 1986; Goetz et al. 1987).

1987

In August, the Republic of the Marshall Islands (RMI) contracted Dr. Henry Kohn, previous chairman of BARC, to chair a review of the 1982 DOE report on the findings of the 1978 radiological survey of the northern Marshall Islands. The purpose of the review was "to determine whether or not DOE's 1982 Report proved that the Rongelap Island is safe for habitation" (Kohn 1989a, b). The Rongelap Reassessment Project was formed as a result, and a panel of consultants was selected to provide expertise on various scientific and technical issues.

Also in August, Hamilton et al. (1987) published results of a thyroid screening program conducted during the previous 4 y in the RMI. This paper concluded that there is an excess of thyroid nodular disease in the southern Marshall Islands as well as the northern atolls, with the prevalence decreasing with increasing distance from Bikini. The paper hypothesized that radioactive contamination from the nuclear tests in the Marshall Islands was more widespread than previously known.

[¶¶] The creation of fear among Rongelap community members as a result of the 1982 report is difficult to document. The Mayor and Senator of Rongelap wrote in a letter to H. I. Kohn in 1988: "The 1982 DOE report and revelations contained in it terrified our people. . . The disclosure in 1982 made it evident that DOE was not truthful with the Rongelap people from to 1957 to 1982 regarding the level of atoll contamination. . . We have become Pacific nomads, not out of choice, but of fear. . . " (Mwekto and Anjain 1988).

[##] The Rongelap people are still resident on Mejatto today though part of the community has split off to Majuro and Ebeye (the two main population centers of the Marshall Islands).

In July, LLNL published a dose assessment for Enjebi Island (Enewetak) (Robison et al. 1987). The average whole-body effective dose-equivalent was estimated as 1.69 mSv y^{-1} (169 mrem y^{-1}) in 1990.

In November, the U.S. Claims Courts dismissed several billion dollars of suits filed in 1980, contending that the COFA withdrew the consent of the U.S. to be sued for claims arising from the atomic weapons testing program in the Marshall Islands.

The Nuclear Claims Tribunal Act was enacted in the RMI creating a judicial body for administering the compensation funds made available by the COFA (RMI 1987).

The first compensation payments were made in 1987 to the people of Bikini, Enewetak, Rongelap and Utrik as outlined in Section 177 of the COFA.

1988

In June, the Mayor and Senator of Rongelap wrote to the Chairman of the Rongelap Reassessment Project stating that it was to their understanding that their study was now controlled by the Department of Energy, and that information concerning contamination and health of Rongelapese was being withheld.

In July, the Rongelap Reassessment Project (Kohn 1988) issued a report stating that Rongelap Island is safe for habitation provided that the diet is equivalent to that formerly used. Among other conclusions stated in the abstract were the following: "the dose to infants and small children is another potential cause of concern. . . " and "In the course of planning for Atoll resettlement, the fact that Rongelap Island appears safe for resettlement now should not be lost site of." Kohn addressed the concerns of the Mayor and Senator as a number of misunderstandings.

In December, the U.S. Courts of Appeals sustained the Claims Courts decision to dismiss Marshallese lawsuits.

The final BARC report was issued, suggesting potassium treatment of the soil to be an effective mitigation technique to prevent the uptake of ^{137}Cs into food crops and estimating costs of $66 to $100 million for rehabilitation of Bikini and Eneu Islands.

The U.S. Congress appropriated $90 million to be paid during 1988 through 1992 to the Bikini Resettlement Trust Fund so that a radiological cleanup of Bikini and Eneu Islands could be conducted.

1989

In February, the Nuclear Claims Tribunal and the RMI Government solicited internationally for independent scientific advisors and a resident scientist to direct a nationwide monitoring program which would use funds from Section 177 of the COFA.

The Rongelap Reassessment Project issued its 2nd report in March (Kohn 1989a). In April, a $6.6 M "Phase 2" study of Rongelap was proposed from a U.S. engineering firm (P&D 1989) including testing the plutonium mining cleanup technology developed by the DNA for Johnston Atoll (Bramlitt 1988). The project was not funded by Congress.

Also in April, the Department of Energy issued a summary of information in the Marshallese language concerning Enjebi island (Enewetak Atoll) (DOE 1989). The report recommended that future Enjebi inhabitants maintain a source of imported foods to prevent individual exposures from exceeding 1.7 mSv y^{-1} (170 mrem y^{-1}).

LLNL published an analysis of doses received by adults as compared to children in the northern Marshall Islands (Robison and Phillips 1989). The report concluded that adult estimates could be treated as conservative estimates for children.

A detailed survey of soils found in the Marshall Islands was issued (USDA 1989) by the U.S. Department of Agriculture to assist the Marshall Islands in agronomy, construction and conservation.

The Marshall Islands Government recruited a resident scientist in October (S. L. Simon) to direct the first nationwide radiological monitoring program of the Marshall Islands. As part of that initiative, a five-member Scientific Advisory Panel was appointed without any American participation.

In November, Senator Jeton Anjain of Rongelap testified to the House Appropriations Committee that the independent study of Rongelap promised in P.L. 99-239 should be initiated as soon as possible. In December, Senator Anjain testified before the DOE Secretarial Panel for the Evaluation of Epidemiological Research Activities (SPEERA) that the DOE Defense Programs could not be objective in the management of the Marshall Islands dose assessment programs.

1990

A revised edition of the report of the Rongelap Reassessment Project was issued in March (Kohn 1989b) following Congressional hearings in November 1989 and May 1990.

In March, the Secretary of Energy directed the consolidation of medical surveillance, epidemiology, and other health matters into the new office of Environmental Safety and Health. Marshall Islands programs were transferred from Weapons to the new division.

The Rongelapese representatives continued to lobby Congress for an independent evaluation of the radiological conditions of Rongelap.

1991

The Marshall Islands Nationwide Radiological Study, a study supported by the Marshall Islands Government, finished the construction of a dedicated radiological laboratory in Majuro (capital city of the Marshall Islands) for the purpose of supporting their monitoring program.

The first individual claims were paid to Marshallese by the Nuclear Claims Tribunal under the process enacted by the COFA.

A report was issued by the U.S. National Parks Service (Delgado et al. 1991) describing the unique archeological artifacts in the lagoon of Bikini Atoll: ships sunk by Operation CROSSROADS in 1946.

1992

In February, a four-way Memorandum of Understanding was signed between the DOE, DOI, RMI Government, and Rongelap Local Government. Though the document provided few binding responsibilities, it called for two independent studies (by Rongelap and DOE) to determine (1) if the maximally exposed person while living on Rongelap Island and eating only locally produced food would exceed 1 mSv y^{-1}, and (2) whether soil concentrations of transuranics on Rongelap Island exceeded a 7.4×10^3 Bq m^{-2} (0.2 μCi m^{-2}) guideline of the EPA (EPA 1990a, b). Compliance with both conditions would imply that resettlement could begin without consideration for mitigative actions (see Simon et al. 1997).

The Rongelap Resettlement Project came into being with the signing of the four-way MOU and the appropriation of $1.6 million from DOI. The project fulfilled the independent assessment promised under P.L. 99-239. The project was administered by the Rongelap Local Government, and oversight was provided by a six-person panel representing five countries. Scientific investigation was contracted to a Scientific Management Team (K. F. Baverstock, B. Franke, S. L. Simon) appointed by Rongelap leaders.

Gessell and Walker (1992) published findings on soils and plants of the Northern Marshall Islands from studies conducted by the authors from 1958 to 1964.

S. L. Simon requested through the Ministry of Foreign Affairs of the Republic of the Marshall Islands data on the explosive yields on the nuclear tests conducted at Bikini and Enewetak. Prior to that date, explosive yields for 45 of 66 tests were still classified.

1993

Late in 1993, the U.S. Secretary of Energy released the explosive yields of the tests conducted in the Marshall Islands to the RMI Government and the U.S. public as part of an "Openness Initiative" (DOE 1993).

The Marshall Islands Nationwide Radiological Study began the first phase of a thyroid disease screening program intended to re-examine the findings and hypothesis of Hamilton et al. (1987). During 1993, thyroid examinations were provided to 1,367 Marshallese who live on Kwajalein Atoll (Takahashi et al. 1997).

1994

On 24 February, the House of Representatives Subcommittee on Oversight and Investigations of the Committee on Natural Resources held a hearing on "Radiation Exposure From Nuclear Tests in the Pacific" with an emphasis to disclose the circumstances leading to the exposure of Marshallese from the BRAVO test. Written and oral testimony (Congress 1994) was provided by a number of witnesses including M. Eisenbud, S. L. Simon, T. Hamilton, E. Radford and numerous Marshallese delegates. Few conclusions were reached as a result of the hearing though it was a landmark as it was the first public hearing on the BRAVO incident.

In April, the Scientific Management Team of the RRP issued an Executive Summary of its findings (SMT 1994) and on May 5 presented it to the House Appropriations Committee. A slightly revised version was issued in November. The findings of the RRP included that the compliance limit of 1 mSv y^{-1} would likely be exceeded by 25% to 75% of the population, depending on dietary assumptions. The compliance limit for transuranic concentration in soil was found to be only exceeded by about 1% of the samples, thus it was not seen as an impediment to resettlement. Recommendations were made to minimize the contribution of ^{137}Cs to the diet so as to reduce the expected dose and enable a resettlement of Rongelap Island to take place.

In mid-year, the Marshall Islands Government began serious consideration of a proposal talked about for numerous years—commercial storage of high-level nuclear waste. Reporting of their interest appeared in various Pacific press (e.g., Davis 1994), and strong opposition was voiced by Greenpeace and many of the South Pacific nations (North 1994). Bikini was the main site of consideration for the storage although Bikini Local Government were affronted with the passage of a bill by the Marshall Islands Nitijela (Legislature) that the President of the Marshall Islands and other traditional chiefs would receive a third of any income Bikini derived from nuclear storage (North 1994).

In December, the Marshall Islands Nationwide Radiological Study issued its summary report to the Cabinet of the Government of the Republic of the Marshall Islands on the radiological conditions of all the atolls (Simon and Graham 1994). Endorsement of the report by the Scientific Advisory Panel was provided in a letter to the Cabinet and in a formal presentation to the Cabinet. Findings showed that soil ^{137}Cs was elevated above the value expected in the mid-Pacific at atolls further north than 9° (see Simon and Graham 1997); measurements confirmed minimal amounts of fallout contamination as far south as Kwajalein Atoll though only four atolls (Enewetak, Bikini, Rongerik and Ailinginae) had islands where habitation might result in doses in 1995 in excess of 1 mSv y^{-1}.

The National Academy of Sciences, National Research Council (NRC 1994) issued its report evaluating the DOE Marshall Islands programs with emphasis given to an assessment of Rongelap. The environmental measurement programs of DOE through LLNL were found to be credible although some recommendations were given to improve the assessment for a returning population to Rongelap. The estimated doses by NRC were nearly identical to those produced by the Rongelap Resettlement Project (i.e., SMT 1994; SMT 1995; also see Simon et al., 1997)

A publication discussing the intake of natural ^{210}Pb and ^{210}Po from a seafood based diet (Noshkin et al. 1994) showed that the background radiation dose to Marshallese was comparable to that received in continental locations because the intake of seafood compensated for the lower terrestrial exposure on the coral atolls.

The most comprehensive list to date of U.S. atomic tests was issued by the Department of Energy (DOE 1994).

The Marshall Islands Nuclear Claims Tribunal reported that, at the end of the year, $32,440,750 had been awarded to 830 individuals in compensation for damages assumed to have been brought about by the nuclear testing program.

1995

The complete report of the RRP with technical appendices of all scientific work undertaken was issued in May (SMT 1995).

The Marshall Islands Nationwide Radiological Study began the second phase of a thyroid disease screening program intended to re-examine the findings and hypothesis of Hamilton (1987). In this phase of work, 5,265 Marshallese were examined who lived mainly on Majuro Atoll.

The Marshall Islands Government continued soliciting for funding for feasibility studies to store high level nuclear waste on one of the atolls, and further opposition was voiced in Pacific news media (e.g., Rashid 1995). In March, the Bikini Local Government Council seriously considered the option of storing high-level nuclear waste on one of the islands of Bikini Atoll as a commercial venture; after a 2-mo emotionally debilitating debate, the Council decided against the idea (Neidenthal 1997).

The most recent report (sixteenth in a series) to disseminate information concerning the 253 Marshallese exposed to BRAVO fallout was published by Brookhaven National Laboratory (Howard et al. 1995).

In October, the Marshall Islands Nitijela (Parliament) passed Bill No. 151 which rejected the findings of the Nationwide Radiological Study which they had financed, stating that the Republic had not accepted the findings as valid or accurate.

In October, the Marshall Islands Nitijela (Parliament) also passed Bill No. 232 which amended the Marshall Islands Nuclear Claims Tribunal Act to extend rights to compensation to any Marshallese who were physically present (including *in utero*) at any time after 30 June 1946, or who is the biological child of a mother who was physically present (including *in utero*) in the Marshall Islands any time after 30 June 1946. The law states: "a casual relationship between a presumed medical condition and the United States Nuclear Testing Program will be presumed, and the presumed medical condition shall be treated equally in all respects, including compensation" (Nitijela 1995).

President Clinton's Advisory Committee on Human Radiation Experiments (ACHRE) heard testimony that Marshallese had been purposefully exposed as "guinea pigs"; the committee also reviewed historical documents of studies conducted soon after the BRAVO exposure. The ACHRE concluded that they found no evidence to indicate that the exposures were motivated by research purposes (ACHRE 1995).

SUMMARY AND CONCLUSION

This chronology illuminates a 50-y saga and several important points. First, there is no doubt that unsuspecting Marshallese were irradiated as a consequence of the nuclear testing program and that several communities were displaced without their full consent. Likewise, it is indisputable that there has been land and crop damage, land contamination, and some induction of radiogenic disease. The extent of those damages will always be a matter of contention and disagreement.

The significance of the environmental and social consequences following the testing however, has been fully appreciated by the international community of scientists. The many monitoring and ecological studies, medical programs, and compensation programs attest to this. For example, seven agencies of the United States Government played major to minor roles at one time or another in a effort to remediate the damages to the Marshall Islands. These are named in the text. At least six major U.S. laboratories and university organizations have taken part in the evaluation of contamination, the course of the exposures, establishment of doses, health care, and logistic support. Several agencies and universities in Japan took part in the matter of the *Lucky Dragon*. At least as many separate and distinct advisory committees were formed as there were agencies involved in the studies. Even so, each committee reported and disbanded only to be replaced by a similar group with a different composition and a slightly different charge. Recommendations have come and gone with still no complete solution at hand. There have been at least four formal surveys of environmental radioactivity levels and contamination of food and human beings, each taking several years to complete with two long term U.S. sponsored programs still in effect.

Over $300 million dollars has been awarded directly to groups of Marshallese people to compensate them for social and physical damages. Many more millions have been spent in support of the many surveys, committees, U.S. national laboratory programs, the Marshall Islands own radiological monitoring program, care of the exposed individuals, and attempts to make the islands again basically inhabitable by cleanup and community rebuilding. Yet, with all of this travail, the lives of numerous Marshallese are still affected today by the long since completed atomic weapons testing program. In short, all the displaced Marshallese are not home yet and others who are not displaced continue to fear ill health. Many are still unhappy for one reason or another including the feeling that they have been made into "guinea pigs." It is a tragic dilemma for all concerned. Whether or not the future will see a complete solution is unclear. It is clear, however, the whole episode can serve a larger purpose: The public health must always be given primary consideration in light of what we have learned about widespread radioactive fallout, the consequences of which can extend over many decades.

It is hoped that this written history has served to illuminate the record of science as well as the human story. Neither is separate from the other just as the lives of Marshallese are not really separate anymore from the lives of Americans. The cold war brought the two together in a way that must be recognized and dealt with fairly, regardless of the difficulties.

POSTSCRIPT

Certain developments from 1995 to the present (1997) are worth noting.

Endorsement of the Nationwide Radiological Study (NWRS) as well as interpretations of the scientific findings of that study were given to the RMI Government in December 1994 by the Scientific Advisory Panel they had selected. The Summary Report (Simon and Graham 1994) of the Nationwide Radiological Study to the Cabinet of the RMI included their letter of approval. Some highlights of their letter are as follows.

"In 1989, you appointed us as members of the Scientific Advisory Panel to the Nationwide Radiological Study. . .We have reviewed this report in detail and we endorse it and commend it to you. . .We believe that the current levels of radioactive contamination of the territory of the Marshall Islands pose no risk of adverse health effects to the present generation. . .Four atolls have been identified where exposure rates are elevated to the extent that remedial actions are indicated for some islands."

Additional support for the scientific findings and interpretation of the Nationwide Radiological Study came from two other sources: the Technical Oversight Group of the Rongelap Resettlement Project (including scientists from Germany, UK, New Zealand and Japan) and the report of National Research Council (NRC 1995). The assessment for Rongelap made by the NWRS was very close to that reported by the NRC.

Despite these various expressions of support for the findings of the NWRS, the RMI Nitijela (Parliament) in its 16th session (August 1995) adopted Resolution No. 151 which rejected the findings of the radiological study. Major points of the lengthy resolution are summarized here.

". . .Whereas, the Nitijela has recently learned that at least two members of the scientific advisory panel were originally recommended to the Marshall Islands in 1989 by a DOE scientist. . .Whereas the conclusions contained in the NWRS Summary Report are based to a large extent on interpretation, evaluation and adjustments of various factors by its authors;. . . Whereas, the Nitijela strongly disagrees with the conclusion of the Summary Report that "radiation illness is. . .very rare, even among Marshallese. . .", Recognizing that the Nationwide Radiological Study does provide some practical and useful information, such as an indication of which atolls are presently dangerous for human habitation. . .Be it resolved by the people of the Republic of the Marshal Islands,. . . that the findings of the Nationwide Radiological Study as contained in the Summary Report. . .have not been accepted by the Republic as valid or accurate."

In a written response to the Nitijela, the Scientific Advisory Panel wrote: ". . .The scientists selected by the RMI Government to form the Scientific Advisory Panel are independent scientists chosen for their expertise in fields of health physics, radiation biology and radiation genetics. . .Rejection of the study's findings and the Summary Report is therefore a rejection of expert scientific knowledge on these matters. . .The Nationwide Radiological Study has provided the Government of the Republic of the Marshall Islands and the Marshallese people with a comprehensive, soundly based survey of the radiological status of their islands. It would be deplorable if through ignorance and prejudice the results of the study were to be set aside. To do so would be to demonstrate that the RMI Government has no interest in seeking truth on these matters."

Nearly one year after the delivery of the Summary Report, the RMI Government requested the International Atomic Energy Agency (IAEA) to convene an international advisory group to review the radiological conditions of Bikini Atoll. In response, the IAEA appointed an advisory group that included scientists from Australia, France, Japan, New Zealand, Russia, UK, USA as well as from the WHO and IAEA. The advisory group met in December 1995 and following their review, they concluded: ". . .several in-depth studies on the radiological situation on and around the former [Marshall Islands] test sites were made. The US Government sponsored long term studies, and the Marshall Islands themselves financed a completely independent nationwide survey. . .This truly international scientific panel came, for one thing, to the conclusion that the existing data on the radiological situation were certainly correct. The studies, carried out independently of each other, had come to practically the same results."***

Despite these independent endorsements, the Nitijela to date has made no changes in its stand with respect to the findings of the NWRS.

In 1996, the people of Bikini memorialized 50 years of exile from their homeland. A dedicated effort was begun by the Bikini community to rehabilitate their atoll for community residence and a commercial dive operation was started to attract tourist trade income.

In September 1996, the Clinton Administration announced a $45 million settlement with the Rongelap community to enable a resettlement of their atoll; the agreement provides for radiation mitigation and construction of homes, schools and other infrastructure.

On 19 December 1996, President Amata Kabua died. He was first elected president of the RMI and had been in office since 1979.

The Marshall Islands Nuclear Claims Tribunal reported that at the end of 1996, it had approved 1,297 compensation awards for personal injury claims. The awards totaled $50.9 million, $5 million more than the $45 million it is to receive for distribution from the COFA. The Nuclear Claims Tribunal projected a liability of $100 million in personal injury claims by the year 2001 when the COFA expires (Johnson 1997).

In early 1997, the Enewetak community filed a claim with the Nuclear Claims Tribunal for close to $300 million for losses on the use of their atoll since 1947 when they were relocated to make way for the nuclear testing program (Johnson 1997).

*** unpublished letter of Advisory Committee to the IAEA Director General, January 1996.

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Author's note: Any inaccuracy in the events or documents related here are my own responsibility and are a likely result of my attempt to piece together the history from a variety of sources and sometimes confusing or barely legible documents. Similarly, any omission of significant persons, publications or events are my responsibility but have occurred only out of my ignorance and not of deliberate disregard.

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Paper

MONITORING DISTANT FALLOUT: THE ROLE OF THE ATOMIC ENERGY COMMISSION HEALTH AND SAFETY LABORATORY DURING THE PACIFIC TESTS, WITH SPECIAL ATTENTION TO THE EVENTS FOLLOWING BRAVO

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***Abstract*—The fallout from test BRAVO in March 1954 has had scientific, political, and social implications that have continued for more than 40 years. The test resulted in serious injury to the people of the Marshall Islands and 23 men on a nearby Japanese fishing boat. Prior to BRAVO there was insufficient appreciation of the dangers of fallout to people living downwind from surface or near-surface explosions of megaton weapons. In the absence of sufficient preplanning for fallout monitoring beyond the test-sites of earlier smaller yield tests, and as a result of the concern of the photographic film manufacturers, the Atomic Energy Commission Health and Safety Laboratory, now the Department of Energy Environmental Measurements Laboratory, was requested to develop a program of fallout surveillance. Beginning with Operation IVY in 1952, these surveys included aerial monitoring of the islands of the mid and western Pacific, as well as establishment of fallout monitoring stations in the United States and abroad. The first evidence of the post-BRAVO fallout was detected by a Atomic Energy Commission Health and Safety Laboratory instrument installed on the atoll of Rongerik, where 28 military personnel were stationed. The results of radiation surveys conducted immediately after BRAVO, as well as the reports of medical investigations, radioecological studies, and dose reconstruction that have been conducted by many laboratories over the years have been available from the beginning in unclassified form. However, from the time of the fallout, and continuing to the present, there have been many unanswered questions about what happened during the hours immediately after the fallout was reported. No formal investigation of the circumstances of the fallout was ever conducted, and there were serious misrepresentations of the facts in the official statements made at the time.**

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Key words: Marshall Islands; atomic bomb; fallout; nuclear war

INTRODUCTION

Origin of the Health and Safety Laboratory

When the Atomic Energy Commission was formed in 1947, operating responsibilities for procuring needed materials such as beryllium, uranium, and thorium was assigned to the New York Operations Office (NYOO). The plants that had produced these products during the war years had many industrial hygiene, health physics, and industrial safety problems that required attention, but the facilities were relatively small, compared to the those at Hanford, Oak Ridge, and Los Alamos, and could not be expected to develop the in-house expertise with which to deal with their health problems. The Commission therefore established within NYOO a Medical Division directed by Bernard Wolf, with a mandate to provide the contractors with the consulting and laboratory services that would be required. I was hired to develop the special laboratory and field capabilities that would be required. When Wolf retired after two years, I was named Director. The name of the unit was changed to the Health and Safety Laboratory with the acronym HASL (Eisenbud 1994a). Thirty years later the name was changed again, to the Environmental Measurements Laboratory, by which it is known to this day, almost fifty years after its formation.

The laboratory was unique for the time, in that it contained all the specialties required to administer a health and safety program including physicians, industrial hygienists, radiological safety specialists, instrument designers, and sanitary and safety engineers. When it was established, and for many years afterwards, it was the only laboratory operated directly by the AEC and not under contract with industry or universities. This was done because the Commission wanted the laboratory to be fully responsive to its immediate programmatic needs.

HASL would not have been involved in fallout monitoring but for an unexpected development shortly after the testing program began in January 1951. No national system of radiation monitoring had been established despite knowledge that after the first test explosion at Alamogordo in July 1945, fallout many hundreds of miles away caused damage to film produced by Eastman Kodak Company (EK). Based on that experience (Webb 1949), the company had installed radiation monitors in the air supplies for its production facilities. An increase in radioactivity was detected at the Rochester plant thirty-six hours after a test air burst in Nevada.

The AEC Division of Military Applications requested that HASL investigate the report, and that was

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the beginning of HASL's involvement in the fallout studies of our nation's nuclear weapons testing program (Eisenbud 1990). It was Friday, it had been snowing throughout the area and temperatures were well below freezing. We decided to obtain snow samples to help us determine the extent and the amount of fallout. We knew many people to whom we could turn to help collect snow in quart sized ice-cream containers for hand-delivery to our laboratory in Manhattan. The HASL staff worked around the clock to collect the equipment needed to evaporate and beta-count the water samples. (There would be better ways of doing it today!). In this way we succeeded in demonstrating that surprising amounts of fallout could occur over large areas thousands of miles from a relatively small air burst. The incident attracted attention, not only within the Commission, but among the officials of EK who put AEC on notice that they would hold it responsible for any damage caused by the tests unless they were provided with information that would make it possible for the industry to protect its processes. HASL was requested by headquarters to do whatever was necessary to learn about long-range fallout. What I didn't know until much later was that there were intelligence organizations within the government that were well equipped to monitor fallout and were, in fact, doing it for other reasons. One advantage in our being assigned to monitor overtly was that our work could be unclassified. In all the time we were monitoring fallout from the tests we had essentially no contact with the "other monitors."

OPERATION JANGLE

By the spring of 1951, preparations were underway for tests of two surface and underground devices in Nevada (Operation JANGLE). Although relatively small, the tests were expected to result in much higher levels of fallout than the previous ones, which were exploded high in the air or on towers. I was briefed on the plans for the tests and learned that monitoring would be conducted only within 320 km (200 miles) from the explosion. I was of the opinion that intensive monitoring should extend to 800 km (500 miles), and HASL was accordingly assigned responsibility for the 200–500 mile (320–800 km) annulus around the test-site. HASL also decided to develop a worldwide monitoring program that could at least provide semi-quantitative information about where and when fallout would occur. This led to deployment of the gummed films that made it possible for the many participating stations to mail a daily collection sheet to HASL. It is now many years since the gummed film collectors were used but the data we collected continue to be useful in dose reconstruction efforts that have become necessary in recent years (Beck et al. 1990). The monitoring plans for JANGLE included mobile monitoring teams, staffed by military personnel assigned to HASL for that purpose. The teams were equipped with aircraft that transported the personnel to stations picked because they lay across the expected path of the fallout. These teams measured airborne dust and gamma radiation, and particulate deposition. The results of our monitoring activities in the 320–800 mile annulus confirmed our concern about possible high levels of fallout. Salt Lake City, about 640 km away, received exceptionally high levels of fallout from the small-yield Nevada tests, with the dose through 1955 estimated at 1.60 mGy (Eisenbud and Harley 1956).

My late colleague John Harley and I assembled the data we were collecting into articles that were published periodically in Science (e.g., Eisenbud and Harley 1953, 1956). At that time there was little public interest in the levels of fallout to which the public was being exposed, and our reports received little attention in the media. The media seemed more interested in the drama of the Nevada tests themselves. Although the data we were collecting could be published in the open literature, there were many things about the tests that remained classified. In advance of the tests this included the time of detonation, much to the frustration of the media photographers. However, the tests took place at about weekly intervals, approximately at daybreak. Many of the reporters assigned to the test program would still be at the Las Vegas gambling tables when members of the test organization would come through the lobby in field clothes. That a shot was imminent could no longer be kept a secret and the reporters would leave for the various vantage points atop hills from which they could see and photograph the explosions. Classification rules were often puzzling to me.

The results of the Jangle fallout studies resulted in HASL being drawn further into plans for Operation IVY to be conducted in the Marshall Islands by Joint Task Force 132 (JTF 132), beginning on 1 November 1952. The HASL group continued to believe that tests with yields equivalent to millions of tons of TNT had the potential to produce dangerous levels of fallout at great distances. It was a simple matter to scale the results of the fractional kiloton Jangle tests to tests in the range of ten megatons, but there was surprisingly little concern about the subject. Some even said the blast would project the debris into outer space from which it would not return. I never understood the process of psychological denial that led the weapons group to be so cavalier about the potential danger from the many petabecquerals of fission products and induced radionuclides that would be released by the test explosions. There was, however, at least one noteworthy exception within the military organizations: LCL N.M. Lulegian, an Air Force meteorologist. We had had several conversations about the possibility of lethal long-range fallout, and in November 1953 he wrote a meteorological analysis in which he confirmed that lethal levels of fallout could occur over an area of 5,000 square miles (1,953 km^2) a few hours after a 10 megaton thermonuclear explosion (Lulegian 1953). A copy of his classified report, which essentially confirmed what we believed, was sent to me at the time but a few days later was mysteriously ordered to be returned to the originating office. The report was not declassified for more than forty years.

OPERATION IVY

By the summer of 1952, our gummed film network had been extended worldwide, thanks to the cooperation of the Air Weather Service and other government overseas organizations that cooperated by manning the stations. The U.S. Weather Bureau was particularly helpful in making these arrangements. However, we found little interest on the part of the Task Force in monitoring beyond the atoll of Eniwetok where Operation IVY was to be conducted. However, the officers on the staff of the Commander-in-Chief-Pacific (CINCPAC) learned of our concerns through John Bugher, who had recently joined the staff of the AEC Division of Biology and Medicine. The Marshall Islands were then a United Nations Trust Territory assigned to the United States for administration, and CINCPAC was responsible for the security of the people of the Marshall Islands. CINCPAC took the position that all atolls in the Marshall Islands and other island groups should be monitored after each test. At HASL, we too believed that the atolls should be surveyed, but how could it be done? By the early summer of 1952 we decided that it would be feasible to monitor each island by low level (62 to 156 m) overflights, using a HASL designed and built portable scintillation detector (Cassidy 1954; Cassidy et al. 1957). The instrument had a rapid response time and a logarithmic range from 2.5×10^{-9} to 2.5×10^{-4} C kg^{-1} (0.01 to 1,000 mR h^{-1}). After several conferences it was decided that CINCPAC would relieve JTF132 of the burden of supporting our mission, which would require a fleet of long-range aircraft. Calibration of our monitoring system took place first at the Nevada Test Site and later at Eniwetak where there were many "hot spots" at the sites of previous tests (U.S. AEC 1953). The system designed for IVY was the first major use of aerial surveillance methods.

In addition to the aerial monitoring instruments, we also designed and built one dozen continuously recording gamma radiation monitors to be placed on key atolls. These also had a logarithmic response and a range of $2.5 \times {}^{-9}$ to 2.5×10^{-5} C kg^{-1} (0.01 to 100 mR h^{-1}). We reasoned that the land based monitors would help us to vector the aerial sweeps. By early October we were fully prepared and John Harley, Al Breslin, Mel Cassidy and myself, all from HASL, proceeded to the Marshall Islands. On the way, I stopped for another conference at Pearl Harbor and was requested by the CINCPAC staff to make every effort to survey all the Pacific island groups. I promised to do our best but emphasized the importance of giving the highest priority to the islands downwind of the tests. We then moved to our base on Kwajalein where we would be housed close to the aircraft assigned to us. I made my headquarters on the U.S.S. Estes, a Command and Control vessel that was the Task-Force flagship. During the last days of October, the HASL staff continued to test our aerial survey instruments by flying over the bomb craters of Eniwetok atoll. We confirmed that we had stable and reproducible calibration factors to relate the aerial measurements to measurements made on the ground. An interesting feature of the "scintililogs," which was what we called the aerial survey instruments, was that they employed two-channel tape recorders, one for a frequency modulated radiation detection system and the other for voice-recording of our position.

At daybreak on 1 November 1952, MIKE, the first multi-megaton thermonuclear explosion, took place. Our plan called for me to leave the Estes by helicopter within 1 h post-detonation, proceed to a task-force carrier, and leave immediately from there for a 2-h flight to Kwajalein. Mel Cassidy and myself were scheduled to begin the surveys at first-light the following morning using two PBM's, sturdy long-range flying boats. We were each to sweep about 1,000 miles in the downwind direction, descending to about 60 m for surveillance of the low coral islands. When we departed just before dawn the radiation background on Kwajalein was about 10 times normal, indicating that a part of the cloud had passed our way.

During my first flight I made measurements above fifteen exquisite atolls with Polynesian names like Taongi, Utirik, Wotho, and Bikini, but there was no way to avoid frequent squalls that interfered with our visibility and made the flight uncomfortable. We repeatedly passed through minor parts of the bomb-test cloud and particles of radioactive dust would impact on the leading edges of the aircraft, which caused an increase in the radiation levels within the cabin. We soon found that most of the particles would wash away when we flew through a rain-squall. I recorded only minor elevations of the radiation levels on the atolls despite the fact that I had chosen the sector that I thought would have the heaviest fallout. After six days of searching for the MIKE fallout we concluded that it had probably deposited in the vast spaces between the atolls. CINCPAC was delighted with the negative results. However, there would be other multimegaton explosions in the Pacific and the good fortune might not always prevail. Because the islands were so small and so widely separated, we needed new ways to study the intensity of fallout from such tests.

During the months after IVY there was much speculation about the whereabouts of the MIKE debris. There was very much less world-wide fallout than expected, and we had found very little fallout in the immediate downwind area of Eniwetak. Could the debris have been blown into outer space? It was far more likely that the MIKE dust particles had been injected into the stratosphere. If so, at what rate would the dust enter the troposphere where it would mix rapidly and be readily detectable before it deposited on the surface of the earth? At that time we did not know the rates of exchange between stratospheric and tropospheric air.

One way to obtain information would be to sample the stratospheric air at an altitude of at least 30,000 m. I favored sampling by electrostatic precipitation, a method that had long interested me. Our group had no experience with high altitude balloons, but the Weather Bureau came to our assistance, as they frequently had done in the past. Although it was already October 1953, and the first test of the CASTLE series was scheduled for 1 March 1954, we did succeed in designing and building an electrostatic precipitator system and completing a series of about twelve flights into the stratosphere at the desired altitude (Holland 1959). We did identify ^{90}Sr in the dust samples we recovered but the samples were too few to permit an inventory of the stratospheric radioactive dust burden. However, that venture did lead HASL to later conduct a more elaborate stratospheric sampling program that was highly successful for many years (Feely 1960).

OPERATION CASTLE

Late in the Fall of 1953 I returned to Pearl Harbor to discuss our participation in CASTLE, which would involve tests of several multimegaton yield thermonuclear devices, beginning on 1 March 1954. This time the tests would take place on the atoll of Bikini, where Operation CROSSROADS, the first post-war series of tests took place in 1946. I was warmly received by the CINCPAC staff, who I knew were both pleased and reassured by our work during IVY. We had developed a symbiotic relationship with CINCPAC even though our interests and objectives were very different. CINCPAC had the obligation to assure that the inhabitants of the Pacific Islands were safeguarded. The HASL objective was to develop a better quantitative understanding of the fallout phenomenon, the severity of which we believed was being greatly underestimated by the AEC and the Department Defense.

The HASL plan for CASTLE was to use the same general methods developed for IVY except that the ground instrumentation would be improved and would be located on islands on which military weather stations would be located. As before, a HASL representative would be stationed aboard the Estes to obtain the data needed to plan the aerial sweeps. John Bugher, after conversations with us, wrote to General Clarkson, the Commander of the joint task force (JTF7) assembled to conduct the tests, recommending that an evacuation capability be provided for the atolls nearest the tests, but he replied that this would not be necessary because they would not fire any devices unless the safety of the islands was assured. This proved to be a serious mistake.

At HASL we recognized that it was probable that the fallout would again deposit on the vast expanses of ocean water between the atolls. We conceived the idea of laying slicks of oil that could catch and retain fallout long enough to permit measurement from the air. We even went so far as to use the Brookhaven reactor to irradiate dust that could be dropped on the oil slicks in tests undertaken by Al Breslin off the New Jersey coast. The winter weather did not cooperate with us and we started to transfer the tests to Pearl Harbor. This proved not to be necessary because on 1 March 1954, shot BRAVO was fired from a position at the northern end of Bikini atoll and within a few hours there was no longer any doubt about the fact that fallout from megaton weapons can produce lethal or near-lethal levels of exposure at great distances from an explosion.

About 6 h after the burst the Air Weather Service personnel on Rongerik, an atoll about 160 km east of Bikini, noticed that the recording gamma monitor had pegged at its limit of 2.5×10^{-3} C kg^{-1} (100 mrem h^{-1}). The information was immediately sent to Al Breslin the HASL representative aboard the Estes who then passed the information to me at the New York laboratory. The procedure we adopted, which had been approved by both JTF 7 and CINCPAC called for immediate aerial confirmation by aerial surveillance using the aircraft assigned to our team. When Breslin attempted to send the necessary instructions to Kwajalein where the aircraft were based he was denied use of the radio facilities aboard the Estes. This resulted in a blackout of information for a critical period of time. After 24 h, during which I received no additional information, I called John Bugher at AEC headquarters and learned that he had no knowledge of what had transpired. I then flew to Washington to confer with him, and by the time I arrived he had learned that there had been some sort of fallout in the forward area but had no details. On the Estes, confirmation of the high radiation levels on Rongerik was obtained the following day independently of Breslin. The 28 Air Weather Service personnel were evacuated by air about 24 h after the fallout occurred. They had received an external whole body dose estimated to be 0.78 Gy.

More alarming was the fact that the surveillance aircraft detected much higher radiation levels on the populated atoll of Rongelap about 210 km west of Bikini. An evacuation by boat was ordered and 258 people were removed from the atoll about 50 h after the fallout occurred. It was later estimated that 67 people on Rongelap had received whole body doses of about 1.75 Sv. The thyroid doses among children less than 10 y old averaged about 20 Sv (Lessard 1984). The thyroid dose estimates must be regarded as uncertain because they were based on radiochemical analysis of urine samples that were not collected until at least 2 wk after exposure (Conard 1992). Those were days before gamma spectrometry was available for radioiodine analysis and little has been published about the chemical separations procedures used at the time. There could have been no measurements of the short-lived radioiodines, since these would have already decayed.

There were several more tests in the CASTLE series, but these were uneventful. HASL completed the assignment given it by CINCPAC and was able to document the fallout on 40 atolls and Islands (Breslin and Cassidy 1955). It was a surprise to many of those associated with a 1994 Congressional hearing on BRAVO that all the information developed by HASL had been published in an unclassified report only a few months after the tests were concluded (Committee on Natural Resources 1994).

THE JAPANESE FISHING BOAT

Unknown at the time of the Bravo explosion was the fact that a Japanese fishing boat, the *Fukyru Maru* (Lucky Dragon) was on its way to its home port of Yaizu in Japan after being subjected to fallout about 180 km East of Bikini. Unobserved by the precautionary sweeps conducted by the Task Force before the test explosion, 23 men aboard the 100-ton vessel were fishing for tuna when they saw the BRAVO flash. Fallout began to deposit on the ship about 4 h later. The men knew they were in proximity to the restricted zone announced by the Task Force but there is no evidence that they were within it. After encountering the fallout they decided to return home, which they reached on 16 March. By that time the men were showing signs of radiation sickness, but they had no understanding of what was happening. During the trip home they maintained radio silence which they later explained was because the crew had been poaching in Indonesian waters the year before and had been apprehended and jailed. They said they were afraid that if their whereabouts became known they would once again be arrested and detained. By the time they reached Yaizu all were suffering from severe symptoms of acute radiation sickness. The tuna they caught were found to be heavily contaminated and were disposed of by land burial. Thus began the first post World War II crisis between the U.S. and Japan, known locally known as the Great Tuna Panic.

At the Atomic Energy Commission the staff learned about the Lucky Dragon in the same way as the rest of the world—from the news broadcasts. John Morton, a thoracic surgeon from the University of Rochester was then Director of the Atom Bomb Casualty Commission in Hiroshima (now the Radiation Effects Research Foundation). He was instructed to assess the situation and shortly afterwards placed a conference call to John Bugher and myself in which he asked for help in dealing with the radiological aspects of the problem. I left for Tokyo immediately, totally unprepared for what I found on arrival after 40 h (air travel was at that time quite a bit slower than today). The Japanese nation was very angry about the incident. They were the only people to have been hurt by American atom bombs, first during the war and now again. Many of the Japanese scientists were making sensational statements to the media. No one in Japan understood the technical implications of the event, and it didn't take long for me to realize that I had a difficult educational mission ahead of me. Morton was in an especially difficult position. He knew nothing about radiation medicine but was invited to Japan because he had developed a reputation as an effective scientific administrator. He was in no position to answer the kinds of questions that were being asked. How should the doses to the fishermen be calculated? What radioactive substances were in the fallout? What was the allowable level of radioactivity in tuna fish? How is radiation sickness treated?

The incident was the first major interruption in the otherwise smooth relationships that had existed between the U.S. and Japan since the end of World War II. The problem was made worse by statements made by some Americans that the fishermen were spying, despite good evidence to the contrary. The fishermen were very sick and getting sicker by the day. Yet some Washington officials made statements that minimized the effects. Some U.S. officials wanted U.S. physicians to treat the fishermen, but the Japanese physicians refused assistance because they were offended by the suggestion that they could not provide the men with the best of medical care. It was certainly true that the Japanese had unique experience with the acute radiation syndrome among the people of Hiroshima and Nagasaki. In this post-war period the Japanese were offended by the suggestion that they could not assume responsibility for the care of their citizens.

The dispute between the Japanese physicians and John Morton persisted for several days. The public clamor increased. The Japanese Foreign Office established a committee of physicians and scientists to deal with the scientific aspects of the problem and requested that Morton and myself deal only with them. This proved to be a very wise move. I soon found that, despite the problems that existed between the Japanese and American physicians, I was quickly developing rapport with the physicists and chemists, most of whom were highly qualified but had not had any association with U.S. science since before the war.

I soon was able to define the three major problems with which we were confronted:

1. The clinical management of the 23 fishermen. In my opinion there was very little help to be offered. The U.S. had no methods of treating radiation sickness that were not already known to the Japanese;
2. Determining the dose received by the fishermen. This included the dose delivered by external radiation during the fourteen days on the contaminated ship and the dose from absorbed internal emitters. The Japanese scientists indicated that they were willing to allow us to collaborate in estimating the internal dosimetry; and
3. The concerns of the Japanese that the Pacific tuna were becoming dangerously contaminated.

By the time of my arrival, the Japanese physicists had already estimated the external radiation dose received by the fishermen using pre-war electrometers that nevertheless gave quite reliable results in their expert hands. However, they did not know how to calculate the dose from the internal emitters. In 1954, even the composition of bomb fallout was still secret, but by the time of my arrival considerable progress had been made by Japanese radiochemists in determining the principal radionuclides present in the particles recovered from the fishing boat. Much of this was done by Kenjiro Kimura, a distinguished chemist who had attracted attention after the nuclear bombings of Japan by concluding correctly that the Nagasaki bomb was built with plutonium because he found traces of that element in soil samples obtained from an area where rainout had occurred. In my first meeting with him he told me that his radiochemical analysis of the "Bikini ashes" led him to conclude, also correctly, that BRAVO involved fast neutrons acting on ^{238}U, a fact that was classified at the time.

I had requested that urine samples be collected from the fishermen and these were sent to HASL for analysis. Much to the surprise of all of us it was found that only minimal amounts of ^{90}Sr was deposited in their bodies even though they had spent 14 d living in such a highly contaminated environment. Several months later one of the fishermen died of serum hepatitis and Kimura was able to confirm our estimates of only minimal exposure to internal emitters (Kimura 1956). The serum hepatitis was believed to have resulted from infection in the course of many blood transfusions. Thus, although the death did not result directly from the effects of radiation, it certainly should be considered an indirect effect.

The Lucky Dragon incident had implications beyond concern about the health of the fishermen. When reports of the incident were received in the U.S., The Food and Drug Administration decided to monitor all incoming tuna from Japan. This was a reasonable decision under the circumstances and would have created no problems because there was no general contamination of the Pacific tuna. However, in response to this the tuna fish companies gave notice that they would not pay for shipments of fish from the Japanese tuna fleet unless the fish were certified as non-radioactive before they left Japan. There was no mechanism for providing certification at the time. Consumption of tuna in both Japan and the U.S. dropped precipitously as a result of the extensive publicity. The Japanese tuna fleet of 1,000 vessels, with an annual catch worth 26 million dollars, suffered grievously as a result.

SOME UNANSWERED QUESTIONS

The events surrounding the BRAVO fallout remain obscure in many respects. This is particularly true with respect to many details at the time of the test, some of which I have mentioned in this article. A more lengthy account appears elsewhere in more detail (Eisenbud 1990). I am unaware of any official investigations of the facts surrounding the fallout. Did an unexpected wind shift occur, as has been commonly said, or was the meteorological "window" that existed too narrow for safety? Why wasn't an evacuation capability provided for the atolls most likely to be in the path of the fallout? AEC had in fact requested the task force to provide such a capability. Why were Breslin's communications with Kwajalein and New York interrupted?

Evacuations of the military personnel and the residents of Rongelap were not announced until ten days after they took place and were stated to be "according to plan as a precautionary measure" (U.S. AEC 1954a). Since no mention was made of the severity of the fallout, this was a clear understatement of the facts. No further announcements were made until March 24 when it was announced that the restricted area around the testing area was being expanded to provide greater assurance against unauthorized entry into the restricted zone (U.S. AEC 1954b). The big shock to Morton and myself came on 1 April, when we learned that President Eisenhower and Admiral Strauss, AEC Chairman, had held a televised news conference on the subject. It was said that the fishermen "must have been well within the danger area," although there was no evidence that this was so (U.S. AEC 1954c). By the time of the press conference the men were suffering from severe beta burns of the skin, in addition to the fact that their blood counts were still dropping and their lives were in danger. At the 31 March (1 April in Japan) press conference and in the accompanying public announcement it was said the "skin lesions are believed to be due to the chemical activity of the converted material in the coral rather than radioactivity. . . " In other words, the burns were attributed to the action of the calcium oxide produced by the intense heating of coral in the fireball!

This last statement had a devastating effect on the relationships Morton and I had developed with the Japanese scientists and physicians. It was only natural that they should assume we were the sources of these statements. To the credit of Ambassador Allison who was capably representing the U.S. during this difficult period, he was angered by what was said in Washington.

Morton and I had ceased to be useful in Japan and we left for Eniwetak to report on what we had learned and to become informed about developments in the Marshall Islands. Although I was bitter about the course of recent events, I could take comfort in the fact that the fallout was detected by an instrument that HASL believed was necessary for the safety of the Marshallese people. If the instrument had not been installed, the fallout might not have been detected for several days and the radiation injuries to the servicemen and the people of Rongelap would have been far more severe, perhaps fatal. And, had the evacuation capability recommend by HASL been provided by the Task Force, the doses received would have been greatly reduced. Moreover, HASL had surveyed and recorded the radiation levels on more than 100 atolls and islands after the IVY and CASTLE tests.

One of the remaining mysteries of the BRAVO affair was that no official inquiry was conducted. It was not until 40 y later that I was requested to testify before a congressional committee at the request of representatives of the Republic of the Marshall Islands. When I reported that to my knowledge there had been no formal inquiry of the circumstances of the BRAVO fallout, the committee Chairman, Representative George Miller stated "If the Navy runs a tugboat aground, we have a board of inquiry !" (Committee on Natural Resources 1994). That is in fact a poignant statement. Forty-two years later, without the benefit of a timely inquiry, when so many of the participants have passed from the scene, and with memories becoming increasingly fallible, a detailed explanation of what happened on the morning of 1 March 1954 is likely to remain a gap in history.

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A HISTORY OF THE PEOPLE OF BIKINI FOLLOWING NUCLEAR WEAPONS TESTING IN THE MARSHALL ISLANDS: WITH RECOLLECTIONS AND VIEWS OF ELDERS OF BIKINI ATOLL

Jack Niedenthal*

Abstract—**The people of Bikini Atoll were moved from their homeland in 1946 to make way for the testing of 23 nuclear weapons by the United States government, beginning with the world's fourth atomic detonation. The subsequent half-century exodus of the Bikini people included a 2-y stay on Rongerik Atoll, where near starvation resulted, and a 6-mo sojourn on Kwajalein Atoll, where they lived in tents beside a runway used by the U.S. military. In 1948, they were finally relocated to Kili, a small, isolated, 200-acre island owned by the U.S. Trust Territory government. Numerous hardships have been faced there, not the least of which was the loss of skills required for self-sustenance. Located 425 miles south of Bikini, Kili Island is without a sheltered lagoon. Thus for six months of the year, fishing and sailing become futile endeavors. Because of the residual radioactive contamination from the nuclear testing, the majority of the Bikinian population still resides on Kili today. One attempt was made to resettle Bikini in the late 1960's when President Lyndon B. Johnson, on recommendations from the Atomic Energy Commission, declared Bikini Atoll safe for habitation. In 1978, however, it was discovered by the U.S. Department of Energy that in the span of only one year, some of the returned islanders were showing a 75% increase in their body burdens of ^{137}Cs. In 1978, the people residing on Bikini were moved again, this time to a small island in Majuro Atoll. In the early 1980's, the Bikinians filed a class action lawsuit against the U.S. government for damages arising out of the nuclear testing program. Although the claim was dismissed, eventually a $90 million trust fund was established for their local government. Since then the leaders of the people of Bikini residing on Kili Island and Majuro Atoll have been confronted with the immense responsibility of determining how to clean their atoll while at the same time maintaining the health and welfare of their displaced population. For the community and their leaders, grappling with these technical decisions has created a life of strife, debate and conflict—and an uncertain future. Now, a radiological cleanup of Bikini is expected to begin sometime within 1997. The objective of this paper, with the support of the views and the recollections of elder Bikinians, is to recount the history and discuss issues facing the first displaced people of the nuclear age.**

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Key words: Marshall Islands; atomic bomb; ^{137}Cs; radioactivity, removal of

INTRODUCTION

Bikini is 1 atoll among the 29 atolls and 5 islands that compose the Marshall Islands. These atolls of the Marshalls are scattered over 357,000 square miles of a lonely part of the world located north of the equator in the Pacific Ocean. They help define a geographic area referred to as Micronesia.

Once the Marshalls were discovered by the outside world, first by the Spanish in the 1600's and then later by the Germans, they were used primarily as a source for producing copra oil from coconuts. The Bikini islanders maintained no substantial contacts with these early visitors because of Bikini Atoll's remote location in the very dry, northern Marshalls. The fertile atolls in the southern Marshalls were attractive to the traders because they could produce a much larger quantity of copra. This isolation created for the Bikinians a well integrated society bound together by close extended family association and tradition, where the amount of land they owned was a measure of their wealth.

In the early 1900's, the Japanese began to administer the Marshall Islands, and this domination later resulted in a military build up in anticipation of World War II. Bikini and the rest of these peaceful, low lying coral atolls in the Marshalls suddenly became strategic. The islanders' life of harmony drew to an abrupt close as the Japanese prepared for the American invasion of Bikini. The Japanese built and maintained a watchtower on Bikini Island. Throughout the conflict the Bikini station served as an outpost for the Japanese military headquarters in the Marshall Islands, Kwajalein Atoll.

After the war, in December of 1945, President Harry S. Truman issued a directive to Army and Navy officials that joint testing of nuclear weapons would be necessary "to determine the effect of atomic bombs on American warships." Bikini, because of its location away from regular air and sea routes, was chosen to be the new nuclear proving ground for the United States government.

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In February of 1946, Commodore Ben H. Wyatt, the military governor of the Marshalls, traveled to Bikini and, on a Sunday after church, assembled the Bikinians to ask if they would be willing to leave their atoll temporarily so that the United States could begin testing atomic bombs for "the good of mankind and to end all world wars." King Juda, then the leader of the Bikinian people, stood up after much confused and sorrowful deliberation among his people, and announced, "If the United States government and the scientists of the world want to use our island and atoll for furthering development, which with God's blessing will result in kindness and benefit to all mankind, my people will be pleased to go elsewhere" (Mason 1954).

While the 167 Bikinians were preparing for their exodus, preparations for the U.S. nuclear testing program advanced rapidly. Some 242 naval ships, 156 aircraft, 25,000 radiation recording devices and the Navy's 5,400 experimental rats, goats, and pigs began to arrive for the tests. Over 42,000 U.S. military and civilian personnel were involved in the testing program at Bikini (Shurcliff 1947).

The nuclear legacy of the Bikinians began in March of 1946, when they were first removed from their islands for the preparations of Operation Crossroads. The history of the Bikini people from that day has been a story of the struggle to understand scientific concepts outside of their realm as well as to deal with day-to-day problems of finding food, raising families, and maintaining their culture amidst the progression of events set in motion by the Cold War that were, for the most part, out of their control. The objective of this paper, with the inclusion of the recollections of elder Bikinians, is to recount the history and discuss issues facing the first displaced people of the nuclear age.

MOVEMENT OF THE BIKINI PEOPLE

In preparation for Operation Crossroads, the Bikinians were sent 125 miles eastward across the ocean on a U.S. Navy LST landing craft to Rongerik Atoll. Rongerik Atoll was uninhabited because traditionally the Marshallese people thought the islands were unlivable due to their size (Rongerik is 1/6 the size of Bikini Atoll) and due to an inadequate water and food supply. There was also a deep rooted traditional belief that the atoll was inhabited by evil spirits. The Administration left the Bikinians food stores sufficient only for several weeks. The islanders soon discovered that the coconut trees and other local food crops produced very few fruits when compared to the yield of the trees on Bikini. As the food supply on Rongerik quickly ran out, the Bikinians began to suffer from starvation and fish poisoning due to the lack of edible fish in the lagoon. Within 2 mo after their arrival they began to request that U.S. officials move them back to Bikini (Mason 1948).

Emso Leviticus, a young woman at the time of the exodus, recalls the transition from being under the Japanese rule to the American takeover, to their journey to Rongerik:[†]

> How our lives began to change... I remember when we women used to wear clothes made out of woven pandanus leaves with our tops sometimes going bare until one day the Japanese brought us dresses to wear. I eventually had about five dresses or so like most of the other girls and that seemed to be plenty for us to wear. All the girls loved the change of style, especially because the clothes felt comfortable to us, and so we were wearing dresses when the Americans finally arrived on our islands.
>
> We were elated when we discovered that the Americans weren't going to hurt us, in fact, the Navy men were very kind and gave us big bins filled with all kinds of food that we had never seen or eaten before like C-rations, chocolates, corned beef and other wonderful things. They took some of us to the ship to get medical attention. One woman named Tamar was very sick, and when she returned, she was all better again. The Americans stayed awhile and I befriended one of the men. He often visited with me and built a cement water catchment for my house.
>
> I can still recall the day when the more important looking Americans came to ask us to move from our islands. All of these new men were wearing beautiful uniforms. After church one day, they asked us to come together on Rosie's and Dretin's land called Loto, near Lokiar's land, to have a community meeting.
>
> We were all there—men, women and children—and we tried to listen carefully to what they were asking our leaders. All of the women became surprised when we found out that they were requesting that we move to Rongerik Atoll or Ujae Atoll. I remember that our leaders answered: If we have to leave, we would rather go to Rongerik because we don't want to be under the leadership of another king or *iroij* on Ujae.
>
> No one dissented in front of the Americans when they asked us if we would be willing to go to another island so they could test their bombs. We had had a meeting beforehand. It had been decided that we would all stand behind Juda when he gave our answer to the man with the stars on his hat and clothes.
>
> We were a very close-knit group of people back then. We were like one big family. We loved each other accordingly. After we made the final decision, no one made any problems about it. We agreed to go along with whatever was decided by our leaders.
>
> Eventually, they sent a group of our men ahead to begin getting Rongerik ready, and, in the meantime, we had a church service at the cemetery of our elders. We put flowers on their graves and cleaned up the area. I remember being very sad at that time because of the strange feeling of having to leave behind the bones of my ancestors while strangers would be walking around on our island.
>
> We left our island after loading everything we owned including our canoes, various kinds of food, bibles, dishes, tools and even some pieces of our church and Council house. We loaded it all onto one of those big ships that open in the front [Navy landing craft], and then, after finding our places on the ship, we waved good-by to our islands and sailed to Rongerik.
>
> Being a curious young girl, never having seen anything like this before, I had fun on the ship. We finally arrived at Rongerik Atoll, and after we unloaded all of our belongings

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[†] Personal communication, Leviticus, E. 1990.

> onto the beach, the Council immediately began to decide on which families would live in the various houses that had been prepared for us. We started dividing up the food that the Navy men had given us, and we tried to fall back into the daily routines of our lives.
>
> Routine was difficult now though because there were many newsmen on Rongerik taking pictures of us. I guess it was all exciting in a way, but it was also a little scary. Those people who were looking at us were strange. The island itself looked so different from Bikini. It was smaller. And, from the beginning, we had reason to lack confidence in our abilities to provide for our future on that small place. We could only remain hopeful and keep thinking that one day soon we would be returned to Bikini.

In July, the Bikinian leader, Juda, traveled with a U.S. government delegation back to Bikini to view the results of the second atom bomb test of Operation Crossroads, code named Baker. Juda returned to Rongerik and told his people that the island was still intact, that the trees were still there, that Bikini looked the same (Mason 1954).

The two atomic bomb blasts of Crossroads were both about the size of the nuclear bomb dropped on Nagasaki, Japan. Eighteen tons of cinematography equipment and more than half of the world's supply of motion picture film was on hand to record the movement of the Bikinians from their atoll and also the opening minutes of each of the two explosions.

Later that year, from December of 1946 through January of 1947, the food shortages worsened on Rongerik and the Bikinians had to continue to struggle with near starvation. During the same period of time, the area of Micronesia was designated as a United Nations Strategic Trust Territory (TT) to be administered by the United States. Indeed, it was the only strategic trust ever created by the United Nations. The trusteeship agreement for the trust territory of the Pacific Islands, the U.S. committed itself to the United Nations directive to "promote the economic advancement and self-sufficiency of the inhabitants, and to this end shall. . . protect the inhabitants against the loss of their lands and resources. . . (Trusteeship agreement 1947)" The Bikini people have long seen the irony in the conduct of the TT agreement that allowed the bombing of their homeland and that forced them into starvation on Rongerik Atoll.

In May of 1947, to make the Bikinians' situation on Rongerik even more serious, a huge fire damaged many of the coconut trees, and by July, when a medical officer from the U.S. visited the island, the Bikinian people were found to be suffering severely from malnutrition. A team of U.S. investigators determined in the fall, after a visit to Rongerik, that the island had inadequate supplies of food and water and that the Bikini people should be moved from Rongerik without delay. The U.S. Navy was harshly criticized in the world press for neglecting the Bikini people on Rongerik. Harold Ickes, a reporter, stated in his 1947 syndicated column *Man to Man* that, "The natives are actually and literally starving to death" (Ickes 1947).

Immediate preparations began for the transfer of the Bikinians to Ujelang Atoll in the western Marshalls. In November, a handful of young Bikinian men went there, and with the help of Navy Seabees, they began to arrange a community area and to construct housing. At the end of the year, however, the U.S. selected Enewetak Atoll as a second nuclear weapons test site. The Navy then decided that it would be easier to move the Enewetak people to Ujelang despite the fact that the Bikinians had built all the housing and held high hopes that they would be moved there quickly.

In January of 1948, anthropologist Leonard Mason, from the University of Hawaii, traveled to Rongerik at the request of the Trust Territory High Commissioner to report on the status of the Bikinians living there. Horrified at the sight of the withering islanders, Mason immediately requested a medical officer along with food supplies to be flown in to Rongerik.

The torment and grief experienced during the two years that the Bikini people spent suffering on Rongerik Atoll has been best expressed by Lore Kessibuki, considered the poet laureate by the Bikinians. Rarely did the bitterness of his people's trials and tribulations show through his smile and the sweetness of his personality. However, whenever he was called upon by the media to do an occasional brief review of the Bikinians exodus, he always described the stay on Rongerik with an enormous amount of remorse and hatred. The situation on those islands was obviously a dreadful situation for the people. But it was felt deeper by Lore, for he was one of the leaders of a forgotten and starving community:[‡]

> While on Rongerik there were of course many problems for us to deal with as leaders. But the crisis in particular that stands out in my mind, even today after the many years have gone by, is the illness that many of us came down with as starvation became prolonged and excruciatingly painful.
>
> The first symptom was that we all suddenly had a very hard time sleeping. When we would finally manage to doze for a short time late at night, and afterwards, wake in the morning, we would find ourselves feeling weak and dizzy and shockingly unable to stand. We could see that the sun had already risen above the trees. This gave us the urge to start working for our families. I used to lay on my mat in the mornings just wondering what was wrong with me until finally I would manage to find the strength to get up and move around enough to get a drink of water. It was then that we would be confronted with the strangest of feelings. By simply touching the water our limbs would be shot with pain as if thousands of needles were running up and down our hands and legs. These sensations, coupled with the awkwardness of adjusting to our new found environment, left us feeling very perplexed.
>
> I remember that sometimes I would have no feeling in my hands, and in addition to this personal dilemma, I had to watch helplessly as we all became so very thin and sick. We had no meat on our legs and arms, and our muscles were worn thin from the lack of activity.
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> In Rongerik you just shouldn't eat the fish. The fish have a history of being poisoned by the food that they ate from the reef—even though they were the exact same kind of fish that

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[‡] Personal communication, Kessibuki, L. 1987, 1988, 1990, 1991.

> we used to eat on Bikini. One reason we knew that the island was uninhabitable, even before we arrived there, was because our elders had taught us that Rongerik was inhabited by a demon named Litobora.
>
> Even through all of these hardships it was unfathomable that we still held high hopes that the Americans would help us. . . Bikini is like a relative to us: like a father or a mother or a sister or a brother, perhaps most like a child conceived from our own flesh and blood. And then, to us, that child was gone. . . Buried and dead.
>
> In the old days we lived and worked together in harmony and treated each other with a great amount of respect. That is how we respect the Americans now. But back then we would get upset with each other for believing in the Americans and in the promises that they made when they asked us to move. We would shout at each other that the promises weren't true because surely this wasn't "the best of their ability"—as they had promised—being shown towards us. After all, it was certainly clear that they had forgotten about us. Even as the problems began to mount, it was still extremely hard to let go of the belief that the Americans would someday come through.

In March of 1948, after two unpleasant years on Rongerik, the Bikinians were transported to Kwajalein Atoll and housed there in tents on a strip of grass beside the airport. The Bikinians fell into yet another debate among themselves about alternative locations soon after they settled on Kwajalein. Kilon Bauno, who while alive was the *iroij* of the Bikinians, and earlier in his life, during the time of exodus, a councilman, gives his firsthand account of life on Kwajalein and the decisions that had to be made by the islanders, which include their transition to Kili Island:[§]

> We lived a strange life on Kwajalein. From day to day we were frightened by all the airplanes that continuously landed very close to our homes. We were also frustrated by the small amount of space in which we were permitted to move around. We had to depend on the U.S. military for everything. We were always asking them to help us in one way or another. We were afraid of this alien environment and almost from the day we got there we began thinking about other places to live.
>
> We talked about moving to many places, like Wotho, Lae and Ujae Atolls. But we encountered the same types of problems with all of these islands. One major factor was that these islands already had people living on them and therefore we thought that we would have social conflicts with the inhabitants because they recognized the *iroij* of those atolls. We Bikinians did not. We were afraid that they wouldn't let us live by our own rules and so we began asking the Americans to find somewhere else for us. Then, Dr. Mason asked us about Kili Island. We debated among ourselves about where we should go. Finally it came to a vote. We chose Kili by a large majority over Wotho and Ujae as the sight of our third temporary home.
>
> They sent some Navy men along with some of us Bikinians to help set up our community there. I remember that time well because we were so tired of all this moving around, building new communities and then having to adjust to new places—always adjusting, adjusting, adjusting. Now, once again, we had to start thinking of how to move all of our people to this next island. It was terrible. We were so weary and exhausted, not only by the labor we were going through to get these places ready, but also by these thoughts in our minds: What was happening to Bikini? How long would we be in this new place? Sometimes we wouldn't eat for an entire day because of the combination of hard work and all the worry that we were experiencing. We were always asking ourselves, What are we doing here? What are we going to eat when we get our people to this new place? How will our lives be there? Questions like this were a great burden for the leaders at that time.

So it was in June of 1948, that the Bikinians chose Kili Island in the southern Marshalls. This choice ultimately doomed the Bikinians' traditional diet and lifestyle, both based on fishing.

In September of 1948, two dozen Bikinian men were chosen from among themselves to accompany eight Seabees to Kili in order to begin the clearing of land and the construction of a housing area for the rest of the people who remained on Kwajalein.

In November of 1948, after 6 mo on Kwajalein Atoll, the 184 Bikinians set sail once again. This time the destination was Kili Island, their third community relocation in 2 y.

Starvation also troubled the Bikinians on Kili; this situation lead the Trust Territory administration to donate a 40-foot ship to be used for copra transportation between Kili and Jaluit. Later, in 1951, the boat was washed into the Kili reef by heavy surf and sunk while carrying a full-load of copra. In the following years rough seas and infrequent visits by the field trip ships caused food supplies to run critically low many times on the island and once even required an airdrop of emergency food rations.

Later, in January of 1955, the Trust Territory ships continued to have problems unloading food in the rough seas around Kili, and the people once again suffered from starvation. The following year the food shortage problems grew even worse. Consequently, the United States decided to give the Bikinians a satellite community located on public land on Jaluit Atoll, thirty miles to the north. Three families moved to Jaluit. During 1957, other families rotated to Jaluit to take over the responsibilities of producing copra for sale.

During this period the Bikinians signed an agreement with the U.S. government turning over full use rights to Bikini Atoll. According to the agreement, any future claims by the Bikinians based on the use of Bikini by the government of the United States, or on the moving of the Bikinian people from Bikini Atoll to Kili Island, would have to be made against the Bikinian leaders and not against the U.S government. In return for this agreement, the Bikinians were given full use rights to Kili and several islands in Jaluit Atoll which were Trust Territory public lands. In addition, the agreement included $25,000 in cash and an additional $300,000 trust fund which yielded a semi-annual interest payment of approximately $5,000 (about $15 per person a year). This agreement was made by the Bikinians without the benefit of legal representation (Juda et al. 1984).

[§] Personal communication, Bauno, K. 1988, 1990.

Typhoon Lola struck Kili late in 1957, causing extensive damage to crops and sinking the Bikinians' supply ship. Shortly afterwards in 1958, Typhoon Ophelia caused widespread destruction on Jaluit and all the other southern atolls. The Bikinians living on Jaluit moved back to Kili because the satellite community became uninhabitable due to the typhoon damage. The Bikinians continued to fight the problems associated with inadequate food supplies throughout 1960.

The difficulty in inhabiting Kili is due in part to the small amount of food which can be grown there, but more so because it has no lagoon. Kili differs substantially from Bikini because it is only a single island of one-third of a square mile in land area with no lagoon, compared to the Bikinians' homeland of 23 islands that forms a calm lagoon and that has a land area of 3.4 square miles. Most of the year Kili is surrounded by 10 to 20 foot waves, which deny the islanders of the opportunity to fish and sail their canoes. After a short time on Kili—an island that some of the older people believe was once an ancient burial ground for kings and therefore overwrought with spiritual influence—they began to refer to it as a "prison." Because the island does not produce enough local food for the Bikinians to eat, the importation of USDA canned goods, and also food bought with their supplemental income, has become an absolute necessity for their survival.

Meanwhile, back on Bikini, on 1 March 1954, as part of the Castle series, a 15 megaton hydrogen bomb code named Bravo was detonated in the northwest corner of the atoll. The explosion turned three islands into a fine gritty mist, heavily irradiated Bikini Atoll and most of the northern Marshalls—including the people still inhabiting those atolls—and left a hole in Bikini's reef 1 mile wide and 400 feet deep.

In 1967, U.S. government agencies began considering the possibility of returning the Bikinian people to their homelands based on data on radiation levels on Bikini Atoll from the U.S. scientific community. This scientific optimism stemmed directly from an AEC study (AEC 1969) that stated, "Well water could be used safely by the natives upon their return to Bikini. It appears that radioactivity in the drinking water may be ignored from a radiological safety standpoint... The exposures of radiation that would result from the repatriation of the Bikini people do not offer a significant threat to their health and safety." Accordingly, in June of 1968, President Lyndon B. Johnson publicly promised the 540 Bikinians living on Kili and other islands that they would now be able to return to their homeland. The President also stated that "It is our goal to assist the people of Bikini to build, on these once desolated islands, a new and model community." He then ordered Bikini to be resettled "with all possible dispatch" (New York Times 1968).

In August of 1969, an 8-y plan was prepared by the U.S. government for the resettlement of Bikini Atoll in order to give the crops planted on the islands a chance to mature. The first section of the plan involved the clearing of the radioactive debris on Bikini Island. This segment of the work was designed by the AEC and the U.S. Department of Defense. Responsibility for the second phase of the reclamation, which included the replanting of the atoll, construction of a housing development, and the relocation of the community, was assumed by the Trust Territory government.

By late in the year of 1969, the first cleanup phase was completed. The AEC, in an effort to assure the islanders that their cleanup efforts were successful, issued a statement that said: "There's virtually no radiation left and we can find no discernible effect on either plant or animal life" (AEC 1969).

All that was theoretically left now in order for the people to return was for the atoll to be rehabilitated, but during the year of 1971 this effort proceeded slowly. The second phase of the rehabilitation encountered serious problems because the U.S. government withdrew their military personnel and equipment. They also brought to an end the weekly air service that had been operating between Kwajalein Atoll and Bikini Atoll (Mic. Supp. Com. 1984). The construction and agricultural projects suffered because of the sporadic shipping schedules and the lack of air service.

In late 1972, the planting of the coconut trees was finally completed. During this period it was discovered that as the coconut crabs grew older on Bikini Island they ate their sloughed-off shells. Those shells contained high levels of radioactivity, hence, the AEC announced that the crabs were still radioactive and could be eaten only in limited numbers. The conflicting information on the radiological contamination of Bikini supplied by the AEC caused the Bikinian Council to vote not to return to Bikini at the time previously scheduled by American officials. The Council, however, stated that it would not prevent individuals from making independent decisions to return.

Three Bikinian families, their desire to return to Bikini being great enough to outweigh the alleged radiological dangers, moved back to Bikini Island and into the newly constructed cement houses. They were accompanied by approximately 50 Marshallese workers who were involved in the construction and maintenance of the buildings.

The population of islanders on Bikini slowly increased over the years until in June of 1975, during regular monitoring of Bikini, radiological tests discovered "higher levels of radioactivity than originally thought." U.S. Department of Interior officials stated that "Bikini appears to be hotter or questionable as to safety" and an additional report pointed out that some water wells on Bikini Island were also too contaminated with radioactivity for drinking. A couple of months later the AEC, on review of the scientists data, decided that the local foods grown on Bikini Island, i.e., pandanus, breadfruit and coconut crabs, were also too radioactive for human consumption. During medical tests, urine samples from the 100 people then living on Bikini detected the presence of low levels of ^{239}Pu and ^{240}Pu. Robert Conard of Brookhaven Laboratories commented that these readings "are probably not radiologically significant."

In October of 1975, after the contemplation of these new, terrifying and confusing reports on the radiological condition of their atoll, the Bikinians filed a lawsuit in U.S. federal court demanding that a complete scientific survey of Bikini and the northern Marshalls be conducted. The lawsuit stated that the U.S. had used highly sophisticated and technical radiation detection equipment at Enewetak Atoll, but had refused to employ it at Bikini. The effect of the lawsuit was to convince the U.S. to agree to conduct an aerial radiological survey of the northern Marshalls in December of 1975. Unfortunately, more than 3 y of bureaucratic squabbles between the U.S. Departments of State, Interior and Energy over costs and responsibility for the survey, delayed any action on its implementation. The Bikinians, unaware of the severity of the radiological danger, remained on their contaminated islands.

While waiting for the radiological survey to be conducted, further discoveries of these radiological dangers were made. In May of 1977, the level of radioactive ^{90}Sr in the well water on Bikini Island was found to exceed the U.S. maximum allowed limits. A month later a Department of Energy (DOE) document stated that "All living patterns involving Bikini Island exceed Federal [radiation] guidelines for thirty year population doses." Later in the same year, a group of U.S. scientists, while on Bikini, recorded an 11-fold increase in the ^{137}Cs body burdens of the more than 100 people residing on the island. Alarmed by these numbers, the DOE told the people living on Bikini to eat only one coconut per day and began to ship in food for consumption.

In April of 1978, medical examinations performed by U.S. physicians revealed radiation levels in many of the now 139 people on Bikini to be well above the U.S. maximum permissible level. The very next month U.S. Interior Department officials described the 75% increase in radioactive cesium as "incredible." The Interior Department then announced plans to move the people from Bikini "within 75 to 90 days," and so in September of 1978, Trust Territory officials arrived on Bikini to once again evacuate the people who were living on the atoll. An ironic footnote to the situation is that the long awaited northern Marshalls radiological survey, forced by the 1975 lawsuit brought by the Bikinians against the U.S. government, finally began only after the people were again relocated from Bikini.

Pero Joel, a Bikinian elder involved in the aborted move back to Bikini in the 1970's, describes his experience of living on his traditional, though radioactive, homeland for the first time in 25 years. Pero uses the word all Marshallese people use for radiation: "poison." As a person often employed in the translation of the Marshallese language, I believe this phenomena was a result of amateurish translation attempts by Americans trying to describe the dangerous attributes of radioactivity:[‖]

> Once I had heard that the U.S. government was proclaiming that Bikini was safe and free from poison, I began to have overwhelming thoughts of joy. I immediately began requesting that they send a ship to pick up me and my family from Rongelap, where we were living at the time, so that we, too, could go to Bikini and get involved in the restoration. The ship finally did arrive and took us to Bikini where we began living in a house on the southern end of the island in a town we called Lokwerkan, which the U.S. government had built for us.
>
> I worked on Eneu and Bikini planting crops, pulling weeds, and, in general, refurbishing the islands. I felt so happy, peaceful and proud, and why not? It was our land, our islands, and we were content to be there working and living there. We felt that we belonged on Bikini because it is the place that God had given us.
>
> During the cleanup, life on Bikini was not like these days where we worry about everything and find ourselves always bickering with each other. The only problems we encountered were due mainly to the fact that we had no reverend with us. But we really didn't have any worries until those scientists started talking about the island being poisoned again. You see, right before they began warning us about the coconuts, pandanus and the crabs being unsafe, the ships had started coming much more infrequently, and so we had to rely heavily on our local food.
>
> On Eneu we had gardens and on Bikini we drank coconuts and ate pandanus all the time. I was one of the people helping to make those gardens. We were told in the beginning of our stay on Bikini that it was safe to eat anything that we wanted, so we did. We had many kinds of foods, bananas and things like that. The scientists would come and explain a little about the radiation, but we were always under the impression that everything was safe and that we could go about our everyday business and not worry. I used to ask them a lot of questions like, "How deep into the soil did the poison go?" When they would answer me they would say that it was about one foot deep into the ground, but that it wasn't anything for us to worry about.
>
> Then the Americans started changing the rules on us. Before they had said that we shouldn't worry about the poison. Then they started saying that they weren't sure and that we shouldn't be drinking as many coconuts or eating coconut crabs, nor anything else that lived off the land, because maybe there was more poison in the soil than they had originally thought. I didn't understand this. It was if we were being told two totally conflicting rules that we had to follow at the exact same time: You know, "Well, it is safe for you people to live on Bikini, but there still is enough poison on the island that you shouldn't eat more than one coconut per day. . . " These statements confused us. Earlier they told us to eat what we want, and then they told us to go easy on the local food. I couldn't explain this even to myself, how was I supposed to make sense of it when I told these things to my family when they began to ask me questions?
>
> Finally, the Americans and their scientists came back a few years later saying that we had to leave Bikini. They said we had ingested too much poison and that it wasn't safe to live on Bikini anymore. We didn't care at this point because we had already started to get that hopeless feeling again; though

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[‖] Personal communication, Joel, P. 1989.

> because we all wanted to stay on Bikini we did explore all possibilities in an attempt to find a way out of this problem. We kept thinking, the Americans first told us that it was safe to live here. Then they changed their minds and made some rules for us to follow. Now they are telling us to leave. Should we go?
>
> We kept having meetings among ourselves that would last from sunup until sundown. We were so heartbroken that we didn't know what to do. But our islands were now again being declared poison. The Americans were telling us that we had to leave. We had to follow what they were saying because we really felt that we had no choice. If they say it is not safe to live there, we have to go, even though we hated departing from the islands where we had come to know peace and quiet for the first time in many years. We even asked them if we could stay on Eneu Island and we formulated a plan among ourselves where we were going to try to live by the airport, but they said we would have to wait until they knew more about the poison before we could remain anywhere on Bikini Atoll. And so we followed their wishes because we knew we shouldn't go against what the Americans say. We were sad, but we didn't want to make a problem for the Americans. If they say move, we move. . . The ship was in the lagoon the night before our departure. . . While leaning on the railing of the ship I drifted back in my mind to when I was still on Rongelap and first heard they were going to allow us to return to Bikini. I could have swam the whole way from Rongelap to Bikini [100 miles] I was so happy. Now we were going away from our homeland again. . . "

Another member of the aborted return to Bikini was Jukwa Jakeo, an outspoken elder who died in October of 1988. To get ready for a future cleanup of their atoll, a delegation of Bikinians went back to Bikini in April of 1987 to reestablish the traditional land boundaries that run in a vertical fashion across the island from the lagoon to the ocean side. While on Bikini, Jukwa had this to say about being back on his homeland for the first time since the second exodus:[¶]

> The thoughts that I have now, as I stand again on Bikini, are very similar to the thoughts I had back when we were moved here in the 1970's: Happiness. I have another feeling, however. It enters my mind as I stand here, and it confuses me very much. That is: Why did they move us off our islands back then, telling us that they were poison, but we are able to return and visit here today?
>
> I know we have come here to try to figure out the old boundary lines that divided our pieces of land. But when I stop to think about this task it is extremely difficult for me because I keep remembering all those conflicting statements and ideas that have been expressed about Bikini over the years since we were sent away by the Americans. Why are we setting boundaries on land that has already been declared unsafe?
>
> The technical difficulties that we experienced in our attempts to reestablish the boundaries stem from the fact that all the natural surroundings and markers that we used to delineate the land partitions are now gone. They were destroyed by the U.S. government and all of their atomic bomb testing. Today, when we draw the lines, we are using estimations only. We are guessing. This inability to be accurate makes it impossible for us to mark the boundaries as they were before the testing period. Age has robbed me of my ability to think. These other old men here are simply making guesses. . . We are old men and our bodies are now tired and sore from all this work. We have argued with each other now our thoughts are all mixed up. We are so exhausted. The difficulties make me feel the happiness of our return less. It has been a long time from 1946 until now, more than 40 y that some of us have been gone from our homeland.
>
> I want now to speak about land and the reason we Marshallese treasure it so highly. The land we sit on now as we talk is like gold. The ground that you walk on, from time to time and from day to day, no matter where you are in the Marshall Islands, is also like gold. If you were Marshallese and you didn't have any land you would be considered a bum, a drifter or a beggar. But if you were an owner of vast amounts of land you would be considered a very rich and wealthy man. Land is the Marshallese form of gold. To all Marshallese land is gold. If you were an owner of land you would be held up as a very important figure in our society. Without land you would be viewed as a person of no consequence. . . But land here on Bikini is now poison land. When I think of that as a consequence for my family members, it frustrates me. I apologize to them because I don't quite understand the depth of the situation here on Bikini. I am an uneducated man. I am Marshallese and I can't quite understand or tell what is safe and what is unsafe here. I can only have faith in the U.S. government. They have the responsibility for telling us what is good for us and what is dangerous. But for myself, my foresight and my knowledge concerning these radiation issues ends right here in front of my face. As I said this morning to those newsmen: I can't tell if these Americans who are working on this island are doing a poor job, or performing miracles of science. I am uneducated in these matters. I am unintelligent because I didn't go to school to study radiation science. So, I can only hope that the U.S. government will tell us the truth about Bikini, whether it is safe for us to live here now or in the future.

REPARATIONS FOR DAMAGES

In 1978, after the people of Bikini were removed from their atoll for a second time, the U.S. government funded a $6 million trust fund titled The Hawaiian Trust Fund for the People of Bikini (U.S. Public Law 94-34). This trust fund currently produces $31,000.00 of income per month, which is used as a per capita distribution (approximately $14 per person per month). Because of a devaluation in the bond market over the past several years, and because expenditures were often more than the revenue of the trust, the fund today is worth approximately $5.3 million. Steps have been taken internally to correct the downward trend of this fund. This trust fund will exist until the year 2006.

In 1982, the people of Bikini received a second trust fund from the U.S. government totaling $20 million, titled The Resettlement Trust Fund for the People of Bikini (U.S. Public Law 97-257). This trust fund was later supplemented (U.S. Public Law 100-446) with $90 million in additional funds to provide for a cleanup of Bikini and Eneu islands of Bikini Atoll. These funds are also used for construction and resettlement activities for Bikinians living on Kili Island and Majuro Atoll. The usual fiscal year budget ranges from between $7 million

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[¶] Personal communication, Jakeo, J. 1987.

and $10 million. These funds pay for local government operations (Council employees, scholarships and a medical plan for Bikinian students living and going to school abroad, travel for meetings, attorneys fees, etc.) The total value of the fund as of 1 March 1996 is approximately $109 million.

In 1986, an agreement with the U.S. government, the Compact of Free Association (COFA), became effective. Section 177 of the COFA pledged reparations for damages to the Bikinians as well as to other northern atolls in the Marshall Islands. The damage payment to Bikini is $75 million over 15 y to be paid at a rate of $5 million per year. During each year, $2.4 million is distributed to the total population of Bikinians as a quarterly per capita payment. $2.6 million of this $5 million goes into a trust titled The Bikini Claims Trust Fund (U.S. Public Law 99-239). This trust fund also provides our community with an annual distribution of 35% of the income over a fiscal year. As of 1 March 1996, the Bikini Claims Trust Fund is worth approximately $32 million. While the quarterly payments end in the year 2002, the trust fund shall exist in perpetuity and shall continue to provide the Bikinians with an annual percentage of the income from the trust.

Mayor Tomaki Juda, the current leader of the Bikinian people and the youngest son of King Juda, had this to say about the changes in their culture brought about by the influx of money into their lives:[#]

> The American customs that we have adopted have changed some of the better Marshallese traditions of days gone past. Today we see, increasingly, that this way of life is steadily creeping—uncontrolled—into our society: Our cooperative traditions are eroding. Now, everything we do in our day to day lives involves competition. If you are not educated, you will be one of the poorest of people; if you have a car, and somebody wants to use it, they have to pay rent before they can drive off in it. This is the American way of life, and now we, the Bikinian people, fully understand how it works.
>
> We have incorporated many American customs and practices into our own. After the negotiations were finalized between the U.S. government and the Marshall Islands, both countries considered this new relationship to be one of free association. This tie to the U.S. has further brought to our attention the American styles and ways of life because the money that they give us, and that we use daily, is the American dollar. We buy American goods, in fact, most of the products sold in our stores come from America. Rice, tea, coffee, flour sugar, Spam, cola, corned beef, automobiles, VCR's and television. Our children grow up watching American movies. This causes our children, increasingly, to adopt the American value system and their customs as depicted on film. This phenomena greatly disturbs some of our elders who remember what our lives were like on Bikini. On the other hand, the new technology makes us more comfortable on this tiny island.

THE FUTURE

The tasks now before Mayor Tomaki Juda, Senator Henchi Balos, and the Bikini Council loom large. At the close of fiscal year 1995, all infrastructure for the cleanup of Bikini island was in place on Eneu island. Ground breaking ceremonies on Bikini occurred in February of 1997, just past the 51st anniversary of the peoples original relocation from their homeland. Options for cleanup methods for the island of Bikini are currently being discussed.

Since the early 1980's, the leaders of the Bikinian community have insisted that, because of what happened in the 1970's with the aborted return to their atoll, they want the entire island of Bikini excavated to a depth of about 15 inches. Scientists involved with the Bikinians have stressed that while the excavation method would rid the island of the ^{137}Cs, the removal of the topsoil would do great damage to the environment. The Council, however, feeling a responsibility toward their people, had contended that a scrape of Bikini was the only way to guarantee safe living conditions on their island for their future generations.

One suggestion put forth by the scientists is that they scrape only the living area, which is the lagoon side of Bikini, and then use potassium fertilizer on the remaining land area. After the issuance by the IAEA Advisory group in December of 1996 of its draft report, the Council concluded that it would give "serious consideration" to this option. Some islanders believe that if they scrape the island in a patchwork fashion—as opposed to an all out pancake-like excavation—the environmental impact could be minimized as one section could be refurbished and replanted before moving on to another. With the excess soil that is removed from the island, these Bikinians currently favor a plan to build a causeway between Bikini and Eneu islands. Another option often discussed by the Council regarding the storage of the contaminated soil involves shipping it to Nam island on the northwestern edge of Bikini Atoll where the Bravo crater is located. The soil would be stored on land.

In the long wait for their atoll to be radiologically cleaned, a number of flighty ideas and projects have surfaced for the Council's consideration. For example, during the late 1980's a number of companies expressed interest in salvaging the ships and the copper cable that rest on Bikini's lagoon as a result of Operation Crossroads. None of these schemes ever went forward due to a host of economic and logistical reasons. In 1995, a proposal for a nuclear waste storage project was introduced to the Bikinians for their consideration. With the talk of billions of dollars that might result from such an commercial endeavor, it was not surprising that a number of Council members were interested in studying this proposal. In March of 1995 the Bikini Local Government passed a Council resolution to research the idea of nuclear storage on Bikini. After two months of very emotional debate that weighed the immense profit potential of high-level nuclear waste storage vs. the possible damage that could be done to the atoll and the heavy political fallout for the community that would undoubtedly come from the other Pacific nations, the Bikini Council, in May 1995, passed a resolution stating that

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[#] Personal communication, Juda, T. 1987, 1988.

they were no longer interested in pursuing the idea of nuclear storage for Bikini Atoll.

In early 1996, to provide an economic base for a possible future resettlement of Bikini Atoll and to supplement the income from their already existing trust funds, the Bikini Council signed an agreement with a local business in Majuro to establish dive tourism on Bikini. On the bottom of Bikini's lagoon rests the world's only aircraft carrier available for diving, the *U.S.S. Saratoga*, as well as the *Nagato*—Admiral Yamamoto's flagship from where he ordered the Japanese Imperial Navy's attack on Pearl Harbor at the beginning of World War II, along with seven other capital ships that have been buoyed. In 1996, a number of dive magazines proclaimed Bikini Atoll to be a world class dive destination.

The Bikini leadership continues to lobby the U.S. Congress for additional funding as the islanders maintain that it is the obligation of the U.S. government to provide for the cleanup of the entire atoll rather than just the two main islands.

While maintaining the integrity and the corpus of their trust funds, it has been the goal of the Council to take care of their people—wherever they may be—and at the same time to continue to move forward towards the radiological cleanup, and ultimately, the resettlement of Bikini Atoll. According to Kilon Bauno:**

> I want my future to be one that has no troubled times. I want a calm, peaceful existence for us all. I don't want my people to suffer anymore in my own lifetime or thereafter: I just want things to go along nicely, and for our lives to be normal and without worry. Those events that we experienced many years ago were just horrible. I would hate to see my people drift into that painful state of affairs again.
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> We want the Americans to continue to take care of us, and we want them to be part of our future. When I think of the years and years that it will take to clean Bikini until the poison is totally eradicated and therefore safe for our children, I get extremely depressed. I will die long before this occurs. I know that I won't be able to be buried in what I believe should be my final resting place by our custom, on the land of my ancestors, on Bikini Island.
>
> I hope that my children, grandchildren and great grandchildren will find only peace in their lives. I hope that the islands that they will have to live and survive on will be suitable for them. I want them to refurbish our lands and experience good, wholesome lives together. . . One can't really ask God for anything more than that.

Acknowledgments—I would like to thank Mayor Tomaki Juda and Senator Henchi Balos and the Bikini Local Government Council. I would also like to thank those elders who have shared with me their knowledge about their culture. Kilon Bauno, Lore Kessibuki and Jukwa Jakeo, three of the elders interviewed in this paper, have passed away. I will always be grateful for their kindness and friendship.

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THE NORTHERN MARSHALL ISLANDS RADIOLOGICAL SURVEY: DATA AND DOSE ASSESSMENTS

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Abstract—**Fallout from atmospheric nuclear tests, especially from those conducted at the Pacific Proving Grounds between 1946 and 1958, contaminated areas of the Northern Marshall Islands. A radiological survey at some Northern Marshall Islands was conducted from September through November 1978 to evaluate the extent of residual radioactive contamination. The atolls included in the Northern Marshall Islands Radiological Survey (NMIRS) were Likiep, Ailuk, Utirik, Wotho, Ujelang, Taka, Rongelap, Rongerik, Bikar, Ailinginae, and Mejit and Jemo Islands. The original test sites, Bikini and Enewetak Atolls, were also visited on the survey. An aerial survey was conducted to determine the external gamma exposure rate. Terrestrial (soil, food crops, animals, and native vegetation), cistern and well water samples, and marine (sediment, seawater, fish and clams) samples were collected to evaluate radionuclide concentrations in the atoll environment. Samples were processed and analyzed for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am. The dose from the ingestion pathway was calculated using the radionuclide concentration data and a diet model for local food, marine, and water consumption. The ingestion pathway contributes 70% to 90% of the estimated dose. Approximately 95% of the dose is from ^{137}Cs. ^{90}Sr is the second most significant radionuclide via ingestion. External gamma exposure from ^{137}Cs accounts for about 10% to 30% of the dose. $^{239+240}$Pu and ^{241}Am are the major contributors to dose via the inhalation pathway; however, inhalation accounts for only about 1% of the total estimated dose, based on surface soil levels and resuspension studies. All doses are computed for** ***concentrations*** **decay corrected to 1996. The maximum annual effective dose from manmade radionuclides at these atolls ranges from .02 mSv y^{-1} to 2.1 mSv y^{-1}. The background dose in the Marshall Islands is estimated to be 2.4 mSv y^{-1}. The combined dose from both background and bomb related radionuclides ranges from slightly over 2.4 mSv y^{-1} to 4.5 mSv y^{-1}. The 50-y integral dose ranges from 0.5 to 65 mSv.
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Key words: ^{137}Cs; ^{90}Sr; Marshall Islands; dose assessment

INTRODUCTION

A RADIOLOGICAL survey was conducted from September through November of 1978 in the Northern Marshall Islands prior to the dissolution of the U.S. Trust Territory. The purpose of the survey was to assess the concentrations of persistent manmade radionuclides in the terrestrial and marine environments at 11 atolls and 2 islands. The atolls of the Marshall Islands are shown in Fig. 1. The atolls included in the NMIRS were Likiep, Ailuk, Utirik, Wotho, Ujelang, Taka, Rongelap, Rongerik, Bikar, Ailinginae, Bikini, and Mejit and Jemo Islands. A brief stop was also made at Enewetak Atoll. Two of the atolls, Bikini and Enewetak, were the sites of 66 nuclear tests (Simon and Robison 1997).

A reasonable amount of data existed in 1978 for Enewetak Atoll (U.S. AEC 1973). However, little radiological information was available for most islands at Bikini Atoll or for other atolls that were considered most likely to have received fallout from nuclear tests conducted at the Pacific Proving Grounds between 1946 and 1958. The BRAVO test on 1 March 1954 produced the largest yield (15 MT) of the entire test series in the Pacific. The fallout from BRAVO was the primary contaminating event of Bikini and Eneu Islands at Bikini Atoll and the atolls to the east of Bikini. The general fallout pattern of the BRAVO test is shown in Fig. 1.

The NMIRS was essentially designed as a screening survey, which would be used to determine whether or not further detailed sampling effort might be required at any of the atolls. The survey included an aerial radiological reconnaissance to map the external gamma-ray exposure rates over the islands of each atoll. The logistical support for the entire survey was designed to accommodate this operation.

Shore parties collected appropriate terrestrial and marine samples to assess the radiological dose from pertinent food chains to individuals residing on some of the atolls, future residents of uninhabited atolls, or for those who visit and collect food from these atolls. Soils, vegetation, indigenous animals, cistern water, and groundwater were collected from the islands. Reef and pelagic fish, clams, lagoon water, and sediments were obtained from the lagoons.

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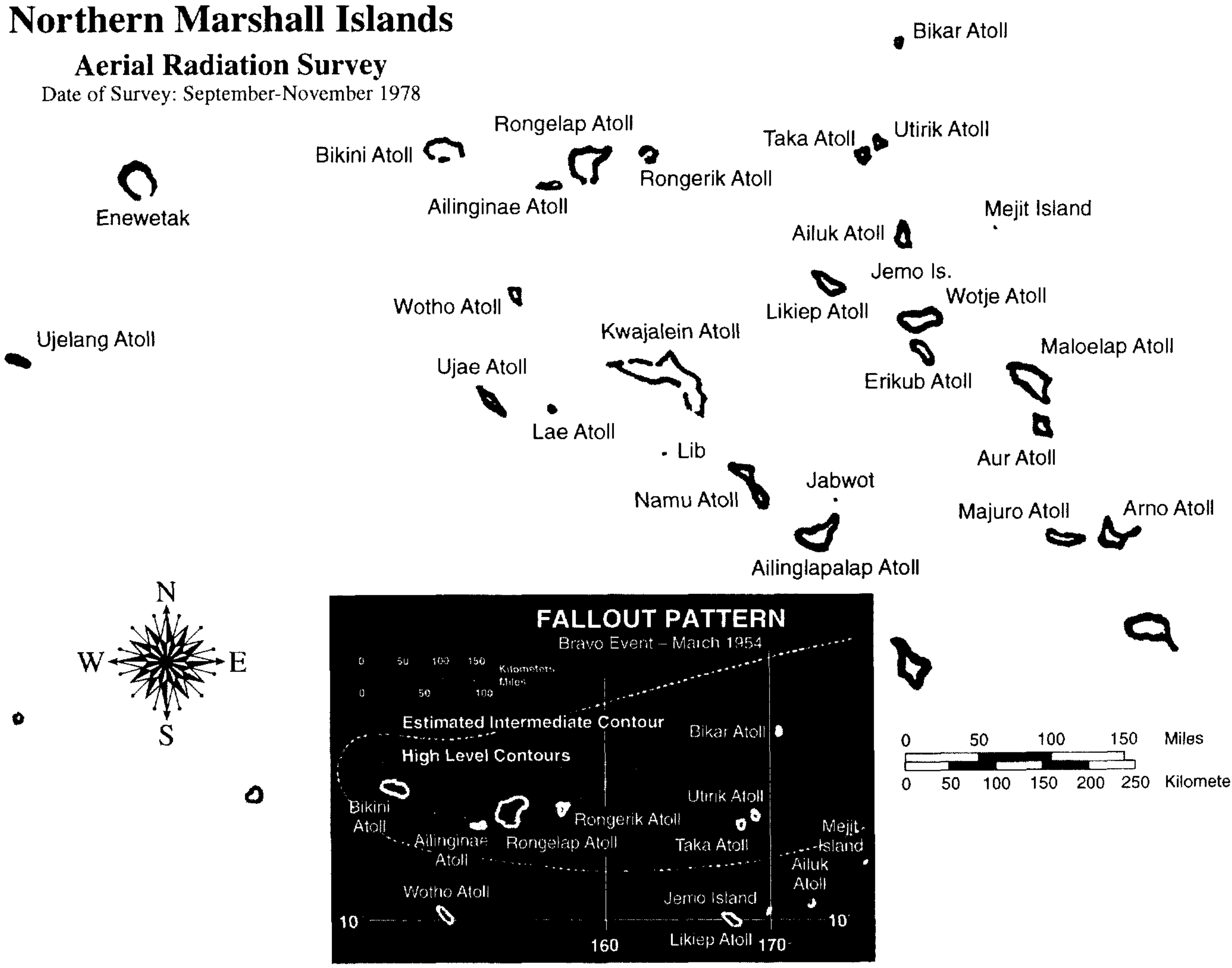

Fig. 1. Atolls and islands of the Northern Marshall Islands radiological survey.

The Lawrence Livermore National Laboratory (LLNL) was responsible for the technical direction of the survey, subsequent sample processing, analytical work, and publishing of results. The Nevada Operations Office (NVOO) of the U.S. Department of Energy (DOE) was responsible for program management in the planning phases and the interaction with other United States agencies and departments and the government and people of the Marshall Islands.

The survey was conducted in three separate segments over a 3-mo period. The first segment of the survey included Rongelap, Taka, Utirik, Bikar, Rongerik, and Ailinginae Atolls. The second segment included Likiep, Ailuk, and Wotho Atolls, and Jemo and Mejit Islands. The concluding third segment included Ujelang and Bikini Atolls, with a limited stop at Enewetak Atoll.

The external gamma aerial survey was conducted from the ship, U.S.N.S. Wheeling, by Edgerton Germeshausen and Grier (EG&G) with the support of a Navy helicopter group, HC-1 Detachment 3, from the North Island Naval Air Station, San Diego, California. The EG&G NaI detector and data analysis system was mounted on one of the two Navy helicopters (Sikorski H-3) carried by the Wheeling and flown by Navy pilots on 46-m grid lines at an altitude of 57 m over the islands at each atoll. A complete report of the external gamma measurement program is available as part of the Northern Marshall Islands survey assessment (Tipton and Meibaum 1981).

The terrestrial and marine programs were conducted primarily with small boats using the Wheeling as an operation base. These two sampling programs were designed as screening surveys to collect adequate samples to make dose estimates for ingestion and inhalation pathways. A second helicopter aboard ship was used to help distribute equipment and marine and terrestrial sampling crews around the atolls. During the first leg of the survey, weather was good and the helicopters were used only for the aerial survey. During the second leg of the survey, only one helicopter was in operation and it was dedicated to the aerial survey. During the third leg, the second helicopter became available and was essential to the terrestrial and marine programs because of adverse weather conditions.

A summary of the numbers and types of samples collected at each atoll is listed in Table 1. Over 5,400 soil, animal, vegetation, fish, clam, sediment, cistern water, and groundwater samples were collected from the 12 atolls and 2 islands during the Northern Marshall Islands survey field operations. All samples were returned to LLNL for processing. The analytical work was conducted both at LLNL and at contract laboratories.

A series of reports were produced that addressed the radionuclide concentrations in cistern water and groundwater, and the estimated doses via ingested water (Noshkin et al. 1981a); the radionuclide concentration in marine species and the associated estimated doses from the marine pathway (Robison et al. 1981b; Noshkin et al. 1981b); the radionuclide concentration in soils, plants, and animals at each of the atolls and islands and the estimated doses via the terrestrial food chain and all other pathways (Robison et al. 1982a); the analytical methods and quality control programs (Jennings and Mount 1983); the data base; and the sampling, processing, and analytical methods and summary (Robison et al. 1981a). A separate report was written for Bikini Atoll (Robison et al. 1982b).

Since the 1978 NMIRS, extensive data bases have been developed for Rongelap, Enewetak, and Bikini Atolls, and separate, more detailed data and dose assessments have been published (Robison et al. 1987, 1988, 1994, 1997; Robison and Conrado 1996a, b).

This report summarizes the radiological concentrations and doses from all pathways developed for the NMIRS. All data are decay corrected to 1996 to represent current conditions. Detailed results are summarized in the original reports.

SAMPLE COLLECTION PROCEDURES

Terrestrial samples (plant, animal, soil, and water)

The field collections were designed to take a representative sample of the locally grown food supplies available to the local populations and to determine the radionuclide concentrations in animals and plants relative to soils for an entire island and atoll. At inhabited atolls, local residents were hired to assist field crews in the collection of the samples.

Representative samples of available local food supplies consisted of animals, fowl, and food grown on the islands. Coconuts are the most common and abundant of the food plants and provided a common type of sample at all atolls. When found by field teams, *Pandanus*, breadfruit, papaya, banana, squash, and *Tacca* (arrowroot) were also collected. If no food crops were available on an island, then native plants such as *Morinda* fruit, and *Scaevola*, *Pisonia*, and *Messerschmedia* leaves were collected so estimates of the radionuclide concentration in food crops could be developed using correlation coefficients (activity per gram in one plant species divided by the activity per gram in a different species).

Pigs and chickens, which represent the major source of meat protein outside of imported canned meats, were collected for analysis of various organs. Coconut crabs were collected when found.

Soil profile samples were collected in the root zone of most of the sampled plants. The radionuclide concentrations measured in the plant tissue could then be compared to concentrations in the soil. Approximately 1 kg sample of soil was taken in the following increments: 0–5, 5–10, 10–15, 15–25, 25–40, and 40–60 cm. A 40-cm-deep profile encompasses most of the active root zone of the subsistence crops that grow in the Northern Marshall Islands. A trench was dug radially from the trees to minimize root damage using either a backhoe or

Table 1. Total number of samples collected and analyzed by atoll or island from the NMIRS.

Atoll	No. of islands	Soil	Vegetation	Animal[a]	Fish[a]	Clams[a]	Cistern water	Ground water	Lagoon water	Lagoon sediment	Total samples
Rongelap[b]	12	398	143	28	149	10	2	2	7	9	748
Taka	3	53	17	0	42	10	0	0	2	4	128
Utirik	5	271	116	22	42	12	1	1	4	6	475
Bikar	3	41	8	0	54	6	0	0	3	4	116
Rongerik	6	161	58	1	84	10	0	0	4	6	324
Ailinginae	10	225	79	2	90	12	1	0	4	10	423
Likiep	10	266	103	24	79	8	3	3	4	9	499
Jemo Island	1	18	6	0	24	0	0	0	0	3	51
Mejit Island	1	48	26	23	6	0	0	0	0	3	106
Ailuk	9	262	102	24	54	6	3	3	4	8	466
Wotho	4	174	48	15	60	7	1	1	4	7	317
Ujelang	7	279	114	14	42	8	1	1	5	5	469
Bikini[b]	15	891	127	0	179	12	2	4	7	11	1,233
Enewetak[b]	5	6	14	0	60	0	0	0	0	0	80
Total	91	3,093	961	153	965	101	14	15	48	85	5,435

[a] Values for animals, fish, and clams are the number of tissues prepared for analysis.

[b] Additional radiological data have been developed over the years (Robison et al. 1987, 1988, 1994, 1997; Robison and Conrado 1996a,b).

shovel. Additional soil profiles were collected at sites around the islands with no associated plant samples.

Groundwater (well water) and cistern water (rainwater collected from dwelling roofs) samples were collected whenever available at the atolls. The groundwater was filtered through 1- and 0.4-μm filters to separate particulates. Cistern water was not filtered.

Marine samples (seawater, sediment, fish, and clams)

Large-volume seawater samples were taken from various locations in each lagoon. All samples were filtered through a 1-μm cylindrical fiber-cartridge filter into plastic barrels to separate particulates. Sediment samples were also collected at these locations. Additional sediment samples were collected from other locations around the inner perimeter of the lagoons.

Throw nets were used exclusively to catch reef fish at the atolls. Large pelagic and benthic fish were collected on sport fishing gear.

Specific species collected represented those commonly eaten by the Marshallese and found in relative abundance at different locations. In addition, we collected species with a variety of feeding habits, and for those which previous radiological data were available.

SAMPLE PROCESSING PROCEDURES

Terrestrial samples

Most vegetation samples were a composite on the average of five individual fruits. The plant samples were washed to remove any soil, dissected into different segments (i.e., meat, skin, and seeds) and weighed. The samples were then freeze-dried, reweighed, and ground to a homogeneous texture. Juices were slowly evaporated in ovens to approximately 200 ml (Robison et al. 1981a). The animal samples were dissected into different organs and tissues, weighed, dried and ground. The soil samples were dried and ball milled to produce a homogenous sample.

The ground vegetation, animal, and soil samples were pressed into an aluminum can or vial, with volumes of 222 cm^3 and 42 cm^3 respectively, and sent for analysis by gamma spectrometry of ^{137}Cs and other gamma emitting radionuclides. Detailed processing procedures are outlined in Stuart (1995).

When gamma analysis was complete, the canned samples were sent to a contract laboratory for wet chemistry analysis for ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Duplicates and standards, blind to the analyst, were included with each group of samples sent for analysis. A complete report on the quality control program is a part of the original series of reports (Jennings and Mount 1983). The quality control program was conducted independently by C. D. Jennings of Western Oregon State College, Oregon.

Marine samples

Filtered water samples were transferred to large, plastic processing containers where they were acidified, and standardized carrier solutions were added. The radionuclides were separated from the water using published procedures (Wong et al. 1994). The filters (particulate fractions) were dry ashed, gamma counted, dissolved, and specific radionuclides separated by standard procedures.

Frozen sediment samples were thawed, weighed wet, and dried in ovens to a constant weight. The sediment was then homogenized using a shaker-type ball mill and placed in the aluminum cans or vials for analysis by gamma spectrometry.

Fish and vertebrate samples from each location were thawed, weighed, measured, and dissected into distinct tissues and organs. Sample tissues from the same catch and species were pooled to produce a large enough sample for analysis. The samples were oven dried, dry ashed, homogenized, and put in aluminum cans or vials for gamma analysis.

Wet chemistry analyses at LLNL were performed by standard methodology (Wong et al. 1994). Each contractor laboratory used their own procedures, but had to meet our quality control criteria (Jennings and Mount 1983).

DOSE CALCULATION METHODOLOGY

The analytical results from the analysis of these samples along with the EG&G external gamma data were the basis for the dose assessments at the atolls and islands.

The dose estimates for each island were calculated for 1996 assuming residence on the island and the consumption of local foods grown on the island. We used Spiers methods (Spiers 1968) in conjunction with models developed by Bennett (1973, 1977), Bennett and Klusek (1978), and Bennett and Harley¶ to calculate the bone marrow dose from ^{90}Sr. For other radionuclides, the dose calculations were made using dose models described in the Bikini Island dose assessment report in this issue (Robison et al. 1997). The gut transfer factors used for $^{239+240}$Pu and ^{241}Am in the 1978 dose calculations were 10^{-4} and 5×10^{-4}, respectively. The biological half-lives used for plutonium and americium were 100 y for bone and 40 y for liver. Plutonium and americium were assumed to be class-W compounds for the inhalation dose calculations.

The radionuclide concentration data used for the ingestion pathway dose estimates are listed in detail for terrestrial foods, marine foods, and water in the original reports (Robison et al. 1981b, 1982a; Noshkin et al. 1981a). A summary for the most important food is given in Tables 2, 3, and 4 for representative islands at each atoll, decay corrected to 1996.

The ingestion doses in this report are based on a diet model that includes both locally grown and imported foods. This diet model, and its relevance to dose estimates in the Marshall Island, is discussed in two reports

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¶ Personal communication, Bennett, B. C.; Harley, J. United States Department of Energy Environmental Measurements Laboratory, New York, NY; 1979.

Table 2. The mean concentrations of radionuclides for the major terrestrial foods collected on representative islands at each atoll.

	Radionuclide concentrations in Bq kg^{-1} wet weight[a]																			
	Drinking coconut meat					Copra meat					Pandanus[b]					Breadfruit				
Atoll/Island	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]
Rongelap *(Northern)*																				
Naen	2	151	—	—	—	2	244	5.8	—	—	1	352	13	1.5×10^{-3}	5.0×10^{-3}	—	—	—	—	—
Kabelle	1	66	—	—	—	2	334	3.1	4.0×10^{-3}	7.4×10^{-3}	—	—	—	—	—	—	—	—	—	—
Rongelap *(Southern)*																				
Rongelap	3	64	—	—	—	18	149	0.55	2.1×10^{-3}	2.9×10^{-3}	9	275	16	1.8×10^{-3}	9.6×10^{-4}	2	65	1.9	9.8×10^{-3}	8.2×10^{-3}
Arbar	1	17	—	—	—	—	—	—	—	—	2	42	28	5.8×10^{-4}	$<8.2 \times 10^{-4}$	—	—	—	—	—
Rongerik																				
Rongerik	2	61	—	—	—	2	55	0.30	$<6.1 \times 10^{-4}$	1.1×10^{-3}	2	60	1.1	$<3.9 \times 10^{-5}$	8.5×10^{-3}	—	—	—	—	—
Enewetak	4	59	0.69	$<8.4 \times 10^{-4}$	$<8.7 \times 10^{-4}$	6	88	0.49	2.0×10^{-3}	3.0×10^{-3}	1	97	1.4	2.7×10^{-3}	2.9×10^{-3}	—	—	—	—	—
Ailinginae																				
Sifo	1	10	—	—	—	3	20	0.61	7.5×10^{-4}	$<4.3 \times 10^{-4}$	1	33	—	—	—	—	—	—	—	—
Utirik																				
Utirik	7	24	—	—	—	11	45	0.073	4.8×10^{-3}	—	9	43	2.3	2.1×10^{-3}	5.2×10^{-3}	2	16	0.44	5.5×10^{-4}	8.9×10^{-4}
Taka																				
Taka	2	3.5	—	—	—	3	10	0.096	$<4.5 \times 10^{-5}$	$<6.7 \times 10^{-4}$	3	3.5	0.59	$<9.8 \times 10^{-5}$	$<2.8 \times 10^{-4}$	—	—	—	—	—
Likiep																				
Likiep	1	6.8	0.072	$<6.1 \times 10^{-4}$	$<1.3 \times 10^{-3}$	4	15	0.056	-3.9×10^{-4}	9.5×10^{-4}	3	9.3	0.93	1.4×10^{-4}	6.8×10^{-4}	2	13	0.10	1.7×10^{-4}	3.9×10^{-4}
Mejit Island	4	19	0.026	-6.8×10^{-4}	-3.0×10^{-4}	1	34	0.027	$<2.3 \times 10^{-4}$	9.7×10^{-4}	3	30	0.26	3.1×10^{-4}	$<8.3 \times 10^{-4}$	3	23	0.023	1.6×10^{-4}	3.6×10^{-4}
Ailuk																				
Ailuk	5	15	0.014	-7.0×10^{-5}	$<2.9 \times 10^{-4}$	2	27	0.037	1.6×10^{-3}	$<4.2 \times 10^{-4}$	2	54	0.53	2.3×10^{-4}	$<3.3 \times 10^{-4}$	3	6.8	0.29	2.2×10^{-4}	4.2×10^{-4}
Wotho																				
Wotho	7	6.2	—	—	—	—	—	—	—	—	3	5.2	0.40	5.2×10^{-4}	7.7×10^{-4}	2	2.1	0.071	2.0×10^{-4}	2.6×10^{-4}
Ujelang																				
Ujelang	7	5.2	0.13	$<1.5 \times 10^{-4}$	$<8.7 \times 10^{-4}$	7	15	0.073	1.1×10^{-3}	1.4×10^{-3}	6	5.2	0.52	4.9×10^{-4}	$<2.3 \times 10^{-4}$	3	14	0.13	4.8×10^{-4}	$<3.7 \times 10^{-4}$
Bikar																				
Bikar	—	—	—	—	—	1	19	—	—	—	—	—	—	—	—	—	—	—	—	—
Jemo Island	2	7.9	—	—	—	1	4.5	—	—	—	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.

[b] Fruit was separated into meat and juice. Specific activity may represent either meat and juice together or individually if either fraction was unavailable.

[c] Number of samples collected. For ^{90}Sr, $^{239+240}$Pu and ^{241}Am, not all samples were analyzed. Each sample consists of approximately five fruits.

[d] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

Table 3. The mean concentrations of radionuclides in muscle tissue from animals collected on representative islands at each atoll.

	Radionuclide concentrations in Bq kg^{-1} wet weight[a]														
	Pork					Chicken					Coconut Crab				
Atoll/Island	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]
Rongelap															
Rongelap	2	212	0.087	1.4×10^{-3}	2.8×10^{-3}	1	64	0.13	2.5×10^{-3}	4.1×10^{-3}	—	—	—	—	—
Arbar	—	—	—	—	—	—	—	—	—	—	2	87	38	0.072	0.028
Ailinginae															
Sifo	—	—	—	—	—	—	—	—	—	—	1	41	2.2	0.025	4.3×10^{-3}
Utirik															
Utirik	2	83	0.036	$<4.0 \times 10^{-4}$	$<7.7 \times 10^{-4}$	1	14	0.19	9.5×10^{-4}	2.3×10^{-3}	—	—	—	—	—
Likiep															
Likiep	2	44	—	—	—	2	2.7	—	—	—	—	—	—	—	—
Mejit Island	2	44	9.7×10^{-3}	1.6×10^{-4}	1.8×10^{-3}	2	12	0.014	1.0×10^{-3}	1.2×10^{-3}	—	—	—	—	—
Ailuk															
Ailuk	2	32	0.094	$<1.7 \times 10^{-4}$	7.7×10^{-4}	1	8.8	0.027	$<3.6 \times 10^{-4}$	1.8×10^{-3}	—	—	—	—	—
Wotho															
Wotho	1	16	1.9×10^{-3}	$<1.4 \times 10^{-4}$	$<1.1 \times 10^{-4}$	1	2.6	4.6×10^{-3}	1.0×10^{-3}	—	—	—	—	—	—
Ujelang															
Ujelang	2	11	0.014	6.6×10^{-4}	5.0×10^{-4}	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.

[b] Number of samples collected.

[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

Table 4. The mean concentrations of radionuclides in muscle tissue from fish and clams collected at each atoll or island. NOTE: Non-detected concentrations are equal to the maximum detection limit and are noted by the < symbol.

	Radionuclide concentrations in mBq kg^{-1} wet weight[a]														
	Reef fish					Pelagic fish					Clams				
Atoll	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[c]
Rongelap	598	586	17	11	1.4	7	684	<7.3	0.22	0.27	3	48	160	81	46
Rongerik	283	317	12	2.6	0.41	7	611	<7.3	0.52	<0.27	3	146	109	13	14
Ailinginae	279	342	12	3.7	0.91	4	537	<7.3	0.37	<0.37	4	<14	24	13	9.1
Utirik	110	298	<21	8.5	0.46	3	469	<9.8	<0.37	<0.46	19	25	<61	16	<2.7
Taka	129	220	12	4.4	0.91	3	684	<4.9	0.19	<0.14	3	<41	<81	15	<9.0
Likiep	294	269	17	1.5	0.91	—	—	—	—	—	4	<20	<34	12	<2.5
Mejit Island	70	171	—	<0.07	—	—	—	—	—	—	—	—	—	—	—
Ailuk	172	220	<12	1.5	<0.46	1	391	<17	0.74	0.23	3	<25	<29	3.7	<1.4
Wotho	298	317	<7.0	1.5	0.46	2	488	4.9	<0.15	0.14	2	<12	<83	3.3	4.6
Ujelang	77	147	5	<0.11	<0.23	87	488	<7.3	0.74	<0.46	13	30	<98	22	16
Bikar	140	415	12	1.5	0.46	4	635	9.8	0.37	<0.46	3	65	<49	4.8	32
Jemo Island	99	391	<24	1.5	<3.7	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.

[b] Number of individual fish or clams collected. Samples were pooled from the same catch and species, and this number does not represent the number of analyses performed.

[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

in this issue (Robison et al. 1997; Robison and Sun 1996).

The external gamma measurements made with the aerial system by EG&G were the main data used at most atolls to determine the external gamma dose at the islands. Detailed data showing specific contours for each island are available in the original report (Tipton and Meibaum 1981). The resolution on island surface for the aerial measurements was about 100 m. Additional external gamma data were available for Bikini and Eneu Islands at Bikini Atoll. A major external gamma survey was conducted at these 2 islands by LLNL in 1975 (Gudiksen et al. 1976). The survey was conducted on the ground using portable gamma-rate meters at 1 m height. The survey on Bikini Island was conducted at 30-m intervals over the whole island resulting in about 2,100 measurements. The external gamma measurements at Eneu were made at 100-m intervals. The EG&G contours for Bikini Island developed from the aerial measurement were very consistent with the contours developed from the ground survey with a 30-m resolution. The surveys also agreed very well at Eneu Island.

The dose estimates for external gamma exposure were made using the island average exposure rate for ^{137}Cs and ^{60}Co. No shielding was included. Dose estimates subsequent to the 1978 publications use established time distributions for various areas of the islands and measurements made inside houses and around the

Table 5. The mean concentrations of radionuclides in soil collected on representative islands at each atoll. NOTE: Non-detected concentrations are equal to the maximum detection limit and are noted by the < symbol.

		Radionuclide concentrations in Bq kg^{-1} dry weight[a]																			
		^{137}Cs					^{90}Sr					$^{239+240}Pu$					^{241}Am[c]				
		Soil increment, cm					Soil increment, cm.					Soil increment, cm					Soil increment, cm				
Atoll/Island	N[b]	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40
Rongelap (Northern)																					
Naen	7	2,374	1,615	1,078	249	83	3,741	2,793	804	344	131	1,070	770	407	83	25	569	435	207	48	17
Kabelle	5	930	318	196	243	82	1,133	422	556	422	136	526	116	131	106	26	309	23	11	23	21
Rongelap (Southern)																					
Rongelap	27	368	256	147	68	34	168	193	144	109	62	117	79	34	10	4.7	46	36	18	7.6	3.6
Arbar	6	303	340	167	58	16	—	—	—	—	—	—	—	—	—	—	173	—	—	—	—
Rongerik																					
Rongerik	7	829	305	134	49	19	740	259	274	114	53	87	20	26	6.1	1.3	223	36	15	3.8	0.73
Enewetak	11	162	97	52	29	20	142	176	43	45	—	92	52	11	2.5	—	54	60	—	2.0	—
Ailinginae																					
Sifo	6	36	32	24	5.6	2.9	36	52	—	—	—	15	12	—	—	—	8.4	8.6	8.0	2.3	—
Utirik																					
Utirik	28	60	28	16	7.4	4.1	34	26	20	8.9	5.8	17	8.8	3.1	0.88	0.57	11	5.5	2.3	0.43	0.80
Taka																					
Taka	8	28	24	10	6.6	2.7	29	20	13	4.2	4.2	4.5	1.3	1.7	0.28	0.18	5.7	3.1	0.92	0.22	0.11
Likiep																					
Likiep	12	17	7.0	4.1	2.5	1.3	6.3	4.3	3.3	2.2	1.0	2.0	1.2	0.45	0.23	0.054	1.5	0.90	0.33	0.15	0.038
Mejit Island	8	12	6.5	4.6	2.1	1.1	7.5	6.3	6.1	5.0	2.1	2.2	1.0	0.70	0.38	0.092	1.6	0.77	0.54	0.20	0.070
Ailuk																					
Ailuk	13	15	7.6	4.6	2.9	1.5	6.3	8.5	6.2	4.0	2.3	3.6	2.4	0.54	0.20	0.066	2.7	0.58	0.47	0.20	0.053
Wotho																					
Wotho	15	10	5.4	4.1	1.5	0.82	3.0	2.7	2.7	1.2	0.66	1.1	0.51	0.18	0.043	0.013	1.0	0.26	2.0	3.1	2.2
Ujelang																					
Ujelang	24	13	8.8	6.6	3.3	1.9	4.9	4.2	3.0	2.5	1.4	1.5	0.96	0.70	0.23	0.089	0.59	0.52	0.20	0.32	0.046
Bikar																					
Bikar	2	11	11	11	12	3.3	21	20	—	—	—	1.7	2.3	—	—	—	4.3	1.8	3.3	4.7	<1.5
Jemo Island	3	8.2	7.4	7.1	1.3	<0.13	5.9	7.4	—	—	—	1.4	1.1	—	—	—	0.49	0.34	<0.87	<0.76	<0.90

[a] Specific activity decay corrected to 1996.

[b] Number of profiles collected and analyzed. For ^{90}Sr, $^{239+240}Pu$ and ^{241}Am, a small percentage did not meet the quality control criteria established and are not included in the reported concentrations.

[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

village center and living areas. These are combined to develop more realistic external dose estimates as described in the Bikini dose assessment in this issue (Robison et al. 1997).

$^{239+240}$Pu and ^{241}Am are the major contributors to radiological dose via the inhalation pathway. The methodology is based on resuspension experiments conducted at 3 different atolls in the Marshall Islands. The dose estimates from the inhalation pathway are based on a mass loading model developed from our Bikini Island resuspension studies and discussed in other reports in this issue (Robison et al. 1997; Shinn et al. 1997). The surface soil (0–5 cm) is the source of $^{239+240}$Pu and ^{241}Am particulates resuspended in the air by wind action and available for inhalation. The dose estimates via inhalation at the various islands were determined by using the $^{239+240}$Pu and ^{241}Am concentration in the surface soils at each island, the mass loading model, and a breathing rate of 22 m^3 d^{-1} to determine the daily inhalation of plutonium and americium. The ICRP lung model used to estimate the dose was the lung model given in ICRP 30 (1982).

RESULTS

The radionuclide concentrations were determined for most of the food items listed in the diet model used for dose assessment. If food samples were available for an island, then the data were used. For those atolls where some food crops and animals were unavailable, the radionuclide concentration was estimated by applying concentration ratios (activity per gram in vegetation divided by the activity per gram in soil) or correlation coefficients that were developed at atolls where such food crops were available, to the soil or plants at those islands where direct data were unavailable. Data for fish and clams, for islands where some species were not caught, were extrapolated for lagoons where similar conditions existed. A total of 26,018 analyses, by both gamma spectroscopy and wet chemistry, resulted from the NMIRS (Robison et al. 1981a).

The mean radionuclide concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am for the major local terrestrial foods found in the Marshallese diet are given for the residence islands or major land masses of each atoll in Tables 2 and 3. These data are representative of each atoll sampled. Data for the other islands at the atolls and minor food items collected can be found in the original reports (Robison et al. 1982a).

Coconut consumption is the major source of radionuclide intake from local foods. Two distinct growth stages exist in the diet model for coconut-drinking and copra. Drinking coconuts have a dry to wet weight ratio of less than 0.45. Copra coconuts have a ratio greater than or equal to 0.45. ^{137}Cs concentrations are much lower in the drinking than the copra coconuts. Calculated doses are dependent on differentiating between the stages of coconut.

The mean radionuclide concentrations for the marine species found in the diet model by atoll or island are found in Table 4. A more detailed breakdown by species and tissue can be found in the original reports (Robison et al. 1981b; Noshkin et al. 1981b). Sediment and sea water can be used for further comparison of radionuclide conditions found in the marine environment. These results can be found in Noshkin et al. (1987a, b).

Cistern and ground water are also found in the diet model. The drinking water pathway contributes a small portion of radionuclides to the total estimated doses. Radionuclide concentrations and dose assessments of cistern and ground water are found in the original reports (Noshkin et al. 1981a).

Soil radiological conditions at the representative islands at each atoll are characterized in Table 5. The mean concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am are listed by increments in the soil profile. The decrease in activity with depth is exponential as shown in Fig. 2. Approximately 80% of the activity is in the top 15 cm of the soil column for atolls and islands sampled.

The external gamma data generated by EG&G used for the dose assessment are listed in Table 6. The mean value was used for calculating the external gamma dose at each island. The range of exposure rate contours that encompass most of the land area for each island are also listed.

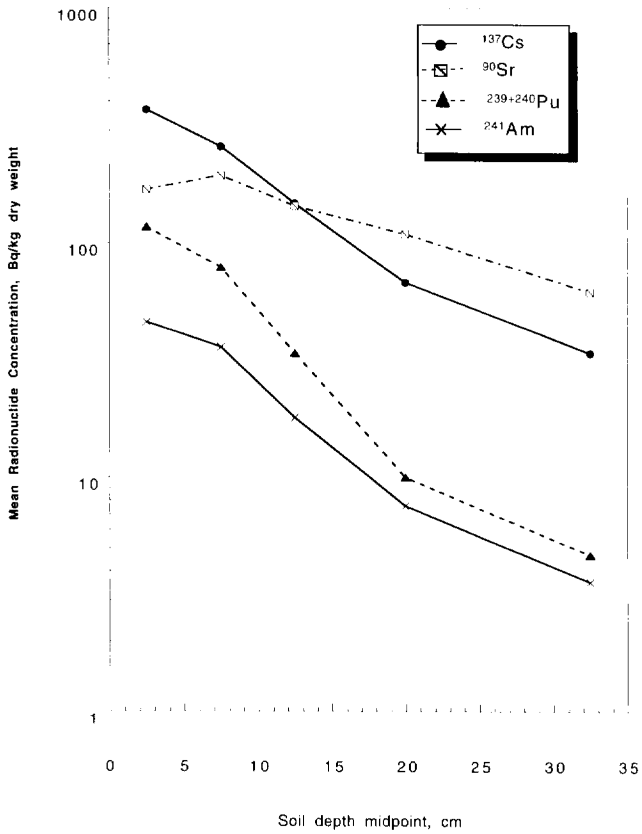

Fig. 2. Mean radionuclide concentrations in soil at Rongelap Island, Rongelap Atoll. The exponential reduction in concentration as a function of soil depth, is representative of soil profiles at other islands and atolls summarized in this report.

Table 6. External gamma exposure rates at atolls and islands included in the NMIRS.[a]

Atoll/Island	Mean $\mu R\ h^{-1}$	Major contours $\mu R\ h^{-1}$
Bikini		
Nam	14	9–40
Iroij	4.5	0.5–5.9
Odrik	1.1	0.23–0.92
Lomilik	14	1.5–13
Aomen	3.0	0.23–1.5
Bikini	20	20–40
Rojkere	9.9	4.0–9.2
Eneu	1.5	0.9–4.0
Aerokojilol	0.33	0.08–0.23
Lele, Eneman	0.86	0.08–0.92
Enidrik	2.8	1.5–9.2
Lukoj	24	9–26
Jelete	29	20–40
Oroken	7.3	2.6–5.9
Rongelap		
Borukka	4.5	2.6–4.0
Kabelle	9.2	4.0–13
Eniaetok	6.6	4.0–9.2
Lomilal	21	13–26
Yugui	25	13–26
Rongelap	3.0	1.5–4.0
Arbar	2.7	1.5–2.6
Naen	28	20–40
Lukuen	18	9–20
Gabelle	5.8	4.0–5.9
Gogan	8.6	1.5–5.9
Busch	3.6	1.5–4.0
Tufa	3.0	0.9–2.6
Rongerik		
Eniwetak	3.2	1.5–2.6
Bigonattam	4.3	4.0–5.9
Lotoback	3.8	2.6–4.0
Brock	5.0	4.0–5.9
Rongerik	4.0	4.0–5.9
Ailinginae		
Ucchuwanen	1.3	0.50–0.92
Knox	0.92	0.50–0.92
Mogiri	1.3	0.23–0.92
Sifo	0.92	0.23–0.92
Ribinouri	1.3	0.50–0.92
Enibuk	1.1	0.50–0.92
Majokoryaan	1.7	0.92–1.5
Utirik		
Aon	0.46	0.43–0.92
Bigrak	0.50	0.43–0.92
Utirik	0.48	0.43–0.92
Taka		
Taka	0.28	0.20–0.43
Likiep		
Jiebaru	0.13	0.09–0.20
Kapenor	0.15	0.09–0.20
Mato	0.14	0.09–0.20
Likiep	0.13	0.09–0.20
	0.18	0.09–0.20
Mejit Island		
Ailuk		
Enejelar	0.17	0.09–0.20
Bigen	0.16	0.09–0.20
Agulue	0.14	0.09–0.20
Aliet	0.15	0.09–0.20
Ailuk	0.13	0.09–0.20
Berejao	0.13	0.09–0.20
Kapen	0.17	0.09–0.20
Wotho		
Medyeron	0.13	0.09–0.20
Wotho	0.13	0.09–0.20
Kabben	0.15	0.09–0.20
Ujelang		
Eimnlapp	0.15	0.09–0.20
Kalo	0.14	0.09–0.20
Daisu	0.14	0.05–0.09
Ujelang	0.13	0.09–0.20
Bikar		
Jaboerukku	0.33	0.20–0.43
Bikar	0.34	0.20–0.43
Jemo Island	0.15	0.09–0.20

[a] Data from Tipton and Meibaum 1981, decay corrected to 1996.

The estimated maximum annual doses (defined as that year when the sum of the dose from all radionuclides and pathways is a maximum) based on the diet model and radionuclide concentrations in food, water, and air and the external gamma exposure at the islands are listed in Table 7. The results are for 1996 conditions at the islands and were generated by correcting the original doses for radiological decay from 1978 to 1996 for both ^{137}Cs and ^{90}Sr. The 50-y integral effective doses from all exposure pathways are also listed in Table 7. The 50-y integral dose can be used for providing risk estimates for the population.

An example of the relative importance of radionuclide and pathway contributions to the total estimated dose can be found in Robison et al. (1997). In general, the ingestion pathway at the various atolls contributes 70% to 90% of the estimated dose mostly from ^{137}Cs (~95%). The external gamma exposure from ^{137}Cs accounts for about 10% to 30% of the estimated dose. Other pathways and radionuclides account for about 3% or less of the estimated dose. The concentrations of ^{90}Sr, $^{239+240}$Pu and ^{241}Am are very low in all edible foods and contribute in a minor way to the total dose. Resuspension at the atolls is very low so that the inhalation dose from $^{239+240}$Pu and ^{241}Am is about 1% of the total estimated dose.

DISCUSSION AND CONCLUSION

The close-in fallout pattern from the BRAVO test, shown in Fig. 1, traveled in an easterly direction from Bikini. Atolls east of Bikini and north of a line drawn from the southern half of Enewetak Atoll in the west to above Mejit Island in the east are more contaminated

Table 7. The estimated maximum annual effective doses and the 50-y integral effective doses in 1996 for atolls and islands included in the NMIRS.

Atoll/Island	Annual dose $\mathrm{mSv\ y^{-1}}$	50-y integral dose, mSv	Atoll/Island	Annual dose $\mathrm{mSv\ y^{-1}}$	50-y integral dose, mSv	Atoll/Island	Annual dose $\mathrm{mSv\ y^{-1}}$	50-y integral dose, mSv
Rongelap			*Taka*			*Ailuk cont.*		
Naen	2.1	64	Taka	0.03	1.0	Berejao	0.03	0.9
Kabelle	0.9	26	Eluk	0.02	0.7	Kapen	0.03	1.0
Mellu	0.6	18.5	Eluk	0.02	0.7	*Wotho*		
Eniaetok	0.6	19	*Likiep*			Medyeron	0.02	0.5
Rongelap	0.4	11	Agony	0.02	0.8	Wotho	0.02	0.5
Arbar	0.2	6.6	Kapenor	0.02	0.6	Kabben	0.02	0.5
Rongerik			Likiep	0.03	1.1	*Bikar*		
Enewetak	0.3	8.6	Rikuraru	0.02	0.7	Jaboerukku	0.04	1.3
Rongerik	0.4	12	*Mejit Is.*	0.04	1.2	Bikar	0.04	1.3
Ailinginae								
Ucchuwanen	0.1	4.6	*Ailuk*			*Jemo Is.*	0.03	0.9
Knox	0.2	5.1	Enijabro	0.03	0.8			
Mogiri	0.2	4.8	Enejelar	0.03	0.9	*Ujelang*		
Sifo	0.1	2.6	Bigen	0.04	1.3	Ujelang	0.02	0.7
Utirik			Agulue	0.03	0.9			
Aon	0.10	3.2	Aliet	0.03	0.8			
Utirik	0.07	2.2	Ailuk	0.03	1.0			

than those lying to the south of this line. The atolls east of Bikini Atoll and north of the above mentioned line received a deposition density of radionuclides that diminished with distance from Bikini Atoll.

For example, the highest radionuclide concentrations in soil and plants, the highest external gamma exposures, and, consequently, the highest estimated doses east of Bikini are at Rongelap Atoll. There is a significant difference between the southern half and the northern half of Rongelap atoll. The concentration of radionuclides in soil and vegetation is about a factor of five lower in the southern half of the atoll (Robison and Conrado 1996a, b). Contamination levels in the northern half of Rongelap are more similar to Bikini Island because the centerline of the fallout pattern crossed the northern half of Rongelap Atoll. The dose estimates in Table 7 reflect this difference with the dose for Rongelap Island being about 0.4 $\mathrm{mSv\ y^{-1}}$ and that for Naen Island in the north being 2.1 $\mathrm{mSv\ y^{-1}}$.

Rongerik Atoll, just east of Rongelap, has the next highest deposition density of radionuclides. Rongerik is an uninhabited atoll, but assuming residence on Rongerik leads to estimated doses of about 0.4 $\mathrm{mSv\ y^{-1}}$.

Ailinginae Atoll, which is owned by the Rongelap people, lies just to the southwest of Rongelap Atoll, and as a result of the location, the deposition density of radionuclides and the resultant estimated doses are less than at Rongelap Island. The estimated doses for residence on Ailinginae are about 0.1 to 0.2 $\mathrm{mSv\ y^{-1}}$.

The deposition density of radionuclides diminishes significantly for atolls south of Ailinginae Atoll and east of Rongerik Atoll. At Utirik Atoll the ^{137}Cs concentrations in the soil and the external gamma exposure are about a factor of 6 less than at Rongelap Island. The estimate dose for Utirik Island is less than 0.1 $\mathrm{mSv\ y^{-1}}$.

The atolls south of the above mentioned line, Ujelang, Wotho, Ailuk, Likiep, Jemo Island, and Mejit Island, all have much lower concentrations of radionuclides in the soil and plants and lower external gamma exposures than the atolls discussed above that lie to their north. The effective dose estimates all range between 0.02 and 0.04 $\mathrm{mSv\ y^{-1}}$ with the 50-y integral effective dose ranging from 0.5 to 1.3 mSv.

The methodology for calculating the uncertainty and interindividual variability in dose estimates at Bikini Island can be found in this issue (Bogen et al. 1997). The results in this report for Bikini Island are indicative of the range of uncertainty and interindividual variability in estimates for other islands.

The background radiation dose in the Marshall Islands is about 2.4 $\mathrm{mSv\ y^{-1}}$ (Table 8) of which a significant fraction (1.8 mSv) comes from naturally occurring ^{210}Po ingested via consumption of fresh fish (Noshkin et al. 1994). Consequently, the combined dose from background and bomb related radionuclides is less than 2.8 $\mathrm{mSv\ y^{-1}}$ at Rongelap Island, about 2.5 $\mathrm{mSv\ y^{-1}}$ at Ailinginae Atoll, less than 2.5 $\mathrm{mSv\ y^{-1}}$ at Utirik, and only slightly over the background dose of 2.4 $\mathrm{mSv\ y^{-1}}$ at the other inhabited atolls of Ujelang, Wotho, Ailuk, Likiep, and Mejit Island.

For comparison, the average background dose worldwide is about 2.4 $\mathrm{mSv\ y^{-1}}$ with some regions of the world having background doses above 10 $\mathrm{mSv\ y^{-1}}$

Table 8. Marshall Islands background dose.

Source	Effective dose rate $\mathrm{mSv\ y^{-1}}$
Cosmic	0.22
Comogenic	0.01
Terrestrial	0.01
^{40}K	0.18
^{210}Po (diet)[a]	1.8
^{210}Pb (diet)[a]	0.20
Total	2.4

[a] Main source is fresh fish in the local diet (Noshkin et al. 1994).

Table 9. ^{137}Cs concentrations in vegetation and soil in the 5–15° latitude band.

	Bq kg^{-1} wet weight[a]								Bq kg^{-1} dry weight[a]			
Locations	N[b]	Drinking coconut meat	N[b]	Drinking coconut juice	N[b]	Breadfruit	N[b]	*Pandanus*	N[b]	Soil 0–5 cm	N[b]	Soil 0–40 cm
Pohnpei[c]	11	5.2	9	1.7	8	4.5	—	—	17	8.1	17	2.8
Pohnpei[d]	1	3.4	—	—	—	—	—	—	3	8.6	—	—
Majuro Atoll[c]	14	3.5	14	1.9	5	1.3	—	—	13	2.9	—	—
Majuro Atoll[d]	2	7.6	—	—	—	—	—	—	1	1.5	—	—
Kwajalein Atoll[c]	13	4.9	14	3.0	2	6.9	1	14	15	6.9	8	2.4
Kwajalein Atoll[e]	1	8.5	—	—	—	—	—	—	—	—	—	—
Guam[d]	2	2.1	—	—	—	—	—	—	2	11	—	—
Truk[d]	3	1.7	—	—	—	—	—	—	1	4.8	—	—
Palau[d]	2	1.0	—	—	—	—	—	—	3	8.3	—	—

[a] Specific activity decay corrected to 1996.

[b] Number of samples.

[c] Specific activity is from samples collected between 1981 and 1990 by LLNL.

[d] Specific activity from Nelson (1979).

[e] Specific activity from Nelson (1977).

(UNSCEAR 1993). The average background dose in the U.S. is about 3 mSv y^{-1} (NCRP 1987). The estimated combined dose at Rongelap Island of less than 2.8 mSv y^{-1} is slightly above the worldwide average of 2.4 mSv y^{-1}, but below the U.S. average of 3 mSv y^{-1}. All other inhabited atolls have combined doses from background and bomb-related radionuclides essentially the same as the world wide average of 2.4 mSv y^{-1}.

The concentration of ^{137}Cs in soils and vegetation from the southern half of Kwajalein Atoll, Majuro Atoll, Pohnpei, Guam, Truk, and Palau that represent worldwide fallout levels for the 5–15°N latitude band, are listed in Table 9. The concentrations of these same radionuclides at Likiep, Ujelang, Wotho, Ailuk, and Jemo and Mejit Islands are about a factor of 2 to 3 above these worldwide fallout levels.

External gamma measurements were performed by Simon and Graham (1994) for the northern and southern atolls in the Marshall Islands. The gamma measurements at the northern atolls of Likiep, Ailuk, and Jemo and Mejit Islands were found to be slightly higher than the southern Marshall Island atolls. The exposure levels at these latter atolls were indistinguishable from worldwide fallout levels at the 0–10°N latitude band.

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Paper

PAST AND PRESENT LEVELS OF SOME RADIONUCLIDES IN FISH FROM BIKINI AND ENEWETAK ATOLLS

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Abstract—**Bikini and Enewetak were the sites in the Northern Marshall Islands that were used by the United States as testing grounds for nuclear devices between 1946 and 1958. The testing produced close-in fallout debris that was contaminated with different radionuclides and which entered the aquatic environment. The contaminated lagoon sediments became a reservoir and source term of manmade radionuclides for the resident marine organisms. This report contains a summary of all the available data on the concentrations of ^{137}Cs, ^{60}Co and ^{207}Bi in flesh samples of reef and pelagic fish collected from Bikini and Enewetak Atolls between 1964 and 1995. The selection of these three radionuclides for discussion is based on the fact that these are the only radionuclides that have been routinely detected by gamma spectrometry in flesh samples from all fish for the last 20 y. Flesh from fish is an important source of food in the Marshallese diet. These radionuclides along with the transuranic radionuclides and ^{90}Sr contribute most of the small radiological dose from ingesting marine foods. Some basic relationships among concentrations in different tissues and organs are discussed. The reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small contaminated area of the lagoon. Therefore, the emphasis of this report is to use this extensive and unique concentration data base to describe the effective half lives and cycling for the radionuclides in the marine environments during the 31-y period between 1964 and 1995. The results from an analysis of the radionuclide concentrations in the flesh samples indicate the removal rates for the 3 radionuclides are significantly different. ^{137}Cs is removed from the lagoons with an effective half life of 9–12 y. Little ^{60}Co is mobilized to the water column so that it is depleted in both environments, primarily through radioactive decay. The properties of ^{207}Bi are different at Enewetak and Bikini. At Enewetak the radionuclide is lost from the environment with an effective half live of 5.1 y. At Bikini only radioactive decay can account for the rate at which the radionuclide is lost from the lagoon. The difference in the binding properties of the sedimentary materials for ^{207}Bi among the two Atolls is not understood.**

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INTRODUCTION

ENEWETAK ATOLL, located at about 11°21′N, 162°21′E, is the northwestern-most atoll in the Western (Ralik) chain of the Marshall Islands. The atoll originally consisted of a ring of 42 (39 remaining) low islands arranged on a roughly elliptical shaped reef, 40.2 by 32.2 km, with the elongated axis in the northwesterly direction. The atoll was one of the two sites in the northern Marshall Islands that was used by the United States as testing grounds for nuclear devices. At Enewetak, 19 of the 43 tests were made from barges anchored in the lagoon. The remaining tests included 2 air drops, 2 underwater tests, 7 ground surface tests and 13 tests with devices fixed to towers. Bikini Atoll, approximately 305 km east of Enewetak, was the first U.S. nuclear test site in the Pacific. It is located at 11°36′N, 165°22′E and consists of 23 coral islands surrounding a lagoon 35 km long, 21 km wide, and 630 km^2 in area. Most of the 23 tests conducted at Bikini were detonated on barges anchored in the lagoon or on the reef. Two tests were air drops, one was underwater, and three were ground surface explosions. Figures showing the Marshallese and U.S. names assigned during the testing program and locations of the islands at Enewetak Atoll and Bikini Atoll appear in other articles of this volume (Noshkin and Robison 1997; Robison et al. 1997).

The U.S. moratorium began on 31 October 1958, and marked the end of all nuclear testing at the atolls. The testing produced close-in fallout debris that was contaminated with different radionuclides and which entered the aquatic environment of the atolls. In the years that followed, the components associated with the lagoon sediments provided a reservoir and source term of manmade radionuclides for the resident marine organisms. These radionuclides are now remobilized, resuspended, assimilated, and transferred continuously within the Atoll environment by physical, chemical, and biological processes. Some of these processes at the atolls are discussed in McMurtry et al. (1985); Nelson and Noshkin (1973); Noshkin et al. (1974); Noshkin et al. (1975); Noshkin and Wong (1980); Schell et al. (1980); Schell (1987); and Spies et al. (1981). Of importance is the fact that the persistent activities are accumulated to different levels by indigenous terrestrial and aquatic plants and organisms that may be used as food by people. Uptake of different radionuclides by fishes can be directly from

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soluble species released to the water and from ingested material passing through the gut (Noshkin et al. 1987).

The first major aquatic survey that developed quantitative data for different radionuclides in fish from Enewetak and Bikini was conducted during 1964, 6 y after the moratorium (Welander et al. 1967; Welander 1969). Samples of fish were again collected by others at Bikini during 1969, 1970, 1972, 1974, 1975, 1976 and 1977 (Held 1971; Lynch et al. 1975; Schell et al. 1978; Nelson 1977) and at Enewetak in 1972–73 (Nelson and Noshkin 1973). Following the radiological aquatic survey at Enewetak in 1973 (Nelson and Noshkin 1973), a more detailed long term study was initiated to assess the behavior and fate of specific radionuclides in the aquatic environment. These studies were extended to Bikini Atoll in 1975. As part of this work a variety of fish was collected between 1975 and 1984 from the atolls for radionuclide analysis. Several reasons prompted these collections and the subsequent radiological analysis. The ultimate objective for obtaining radiological information was to use the data in estimating any potential radiological consequences to individuals from ingestion of indigenous marine foods. Hence, a major effort was devoted to dissections and analysis of the edible muscle tissue from a variety of fish. Other studies were made to evaluate the variability of radionuclides in families of fish; to define the major tissues or organs where radionuclides were concentrated by fish; and to develop concentration factors and relationships to assess the effective half time for some of the long-lived radionuclides using the resident non-migratory reef fish as indicators of environmental change.

The data generated from this effort showed that the radiological dose from manmade radionuclides in the marine food chain contribute less than 0.1% of the total 30-y integral dose equivalent at both Atolls (Robison 1973; Robison et al. 1987; Robison et al. 1997). The ingestion dose was derived principally from 3 gamma emitting radionuclides, ^{137}Cs, ^{60}Co and ^{207}Bi; the transuranic radionuclides, $^{238,239+240}$Pu, ^{241}Am; and ^{90}Sr. The largest contributor to the total marine dose was the ^{137}Cs accumulated in the edible flesh. The transuranic radionuclides and ^{90}Sr contributed little to the total dose from ingestion of marine foods. This collection program was phased out in 1985, but fish samples were again collected in the 1990's to verify the results of the original assessments and to determine what, if any, changes occurred in the concentrations of gamma emitting radionuclides and the transuranics in muscle tissues. Resources only permitted analysis of muscle tissue in these later samples. However, with these new data and results from earlier studies, a valuable data base was available for radionuclides in the flesh of different fish that span the 31-y period from 1964 to 1995. Some reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small area containing the contamination. Decrease in radionuclide concentration in flesh can be used to estimate the effective decay constant and half-lives. The effective half life takes into account loss by physical decay and recycling mechanisms that reduce the available inventory of radionuclides to marine organisms. The general mathematical form of the exponential expression for the change over time in the amount of a radionuclide, using a indicator organism, can be found in Noshkin et al. (1975).

The 1964 and all subsequent data were generated by gamma spectrometry with NaI (Tl) crystals and different solid state Ge(Li) detectors and by radiochemical separations and using detection systems appropriate for the determination of specific radionuclides. Many fission products, activation products, and the transuranium elements were identified and measured in parts of fish. However, only 3 gamma emitting radionuclides, ^{137}Cs, ^{60}Co, ^{207}Bi were measurable in flesh samples by gamma spectrometry over the 31-y period. Most results for these radionuclides from our studies between 1974 and the present have not previously appeared in the literature. The transuranic radionuclides also persist in fish tissues but plutonium-americium results have been discussed in several other publications (Noshkin et al. 1981a; Noshkin et al. 1987; Noshkin et al. 1988; Schell et al. 1978; Schell 1987). There is also a summary of plutonium results in fish from Enewetak Atoll appearing in Noshkin and Robison (1997). Other radionuclides such as ^{90}Sr, ^{55}Fe, and ^{99}Tc may be present in specific tissues of fish but were found at concentrations so low that they contributed very little to the estimated dose and therefore were not measured in most samples on a regular basis. Naturally occurring radionuclides were also determined in many samples but are not discussed in this report.

This report summarizes both our data and those from other sources on the 3 major gamma emitting radionuclides in the flesh of reef and pelagic species of fish. Some basic relationships among concentrations in different tissues and organs will be presented. The concentrations measured in the flesh of several non-migratory reef species are used to estimate the effective half lives for ^{60}Co, ^{137}Cs, and ^{207}Bi during the 31-y period between 1964 and 1995.

SAMPLING AND PROCESSING FISH

Most fish collections on the reef at the Atolls were made using throw nets with assistance from Marshallese fishermen or with gill nets (Welander et al. 1967; Schell et al. 1978). Gill nets were not used after 1972, and reef fishing for our program was done exclusively with throw nets. Reef species are relatively abundant, easy to catch, and are therefore an important food source for the Marshallese. The fish were caught on the reef when and where they were sighted in the surf. Therefore, fish may be collected from different regions of an island in any given year. Variability in radionuclide concentration can then be expected as a function of geographical location even on the same island. However, this "catch when available" method of fishing probably best mimics the manner by which these marine foods are derived by the

Marshallese for consumption. Noshkin and Robison (1997) show what the effects of different fishing locations have on the concentration of ^{137}Cs accumulated in the flesh of surgeonfish from Runit Island of Enewetak Atoll. The other category of fish include larger resident and migratory predator species that were usually more difficult to catch with sport fishing gear while trolling in the lagoon.

Except for the larger fish it was usual to bulk flesh and specific tissues and organs separated from the species collected from an island on any given day. The samples were homogenized, dried (or ashed) and transferred to suitable containers for analysis on gamma spectrometers. A number of samples were then selected for radiochemical analysis of different beta or alpha emitting radionuclides. The common and scientific names for the fish that were eventually processed to determine radionuclides *only* in muscle tissue are shown in Tables 1 and 2 with the sampling locations and a cross reference island locator ID number that is used throughout this report. The concentrations of ^{137}Cs, ^{60}Co, and ^{207}Bi determined in flesh tissue of fish from Enewetak and Bikini appear in the appendices and represent the results in over 300 samples from 4,470 fish. All results are decay corrected to date of sample collection. A cursory examination of the appendices reveals that concentrations in flesh vary with species, over time, and with geographical location in each Atoll. Compositing the tissues from the same species masked any differences in concentration related to weight (size or age) or sex.

Tables 1 and 2 and the Appendices A and B show that 3 reef species, surgeonfish (2nd trophic level), mullet (2nd trophic level), and goatfish (3rd trophic level), are represented in most collections. Obviously, then, these reef fish are easily caught but they are also preferred in the Marshallese diet. Mullet and goatfish were often caught in the same net cast at an island indicating that both species move and feed together. A

Table 1. Fishing sites at Bikini Atoll since 1964 where muscle tissue was separated for analysis from the species indicated.

Island ID	Marshallese Name	Aug[a] 1964	May[b] 1970	May[c] 1972	Nov[d] 1972	Dec[d,e] 1974	Apr[e] 1975	Jul[d] 1976	Jan[f] 1977	Oct[d] 1977	Nov[f] 1978	Sep[f] 1980	Feb[f] 1981	Jun[f] 1982	Aug[f] 1983	Sep[f] 1984	Dec 1992	Nov 1994
B-1	Nam	gr,n,s,t[g]	g	sn	u			cr,n,sn	cr,n	n	cr,n,g,s		cr		cr,n,s,g	g,u,rr	g,cr,n,s	c,n
B-2	Iroij								cr									
B-3	Odrik	bo,gr,j,s,t,w																
B-5	Aomen				g,n,p,q,s						cr,n,s,g		cr,s,g,p	n	cr,s		g,n,s	g,p
B-6	Bikini	sn			p,s,n						s,g	cr,g,sn	cr,n	n	g	cr,g	g,cr,s	g,s
B-9	Enealo					sn												
B-10	Rojkere				g				n		s,g							
B-12	Eneu	da,gr,n,s			p,r,s		gr,p		cr		n,s,g				s,g	n,g		
B-13	Aerokoj								cr		cr,s,g							
B-15	Lele	l								g								
B-16	Eneman																	
B-17	Enidrik				n,p,s,u				n		cr,n,g,p				s	n		
B-21	Oroken																	
B-22	Bokoetoktak													u				
B-23	Borkdrlul	gr,sn,s,t			n,s						n,g							
lagoon				tn	ra,bo	m,s		s		s,bo,ba,m,u	snj,m		m			sn,bo		

[a] Welander et al. (1967)
[b] Held (1971)
[c] Lynch et al. (1975)
[d] Shell et al. (1978)
[e] Nelson (1977)
[f] Noshkin et al. (1988)
[g] ba = barracuda (*Sphyraena sp.*)
bo = bonito (*Euthynnus affinus*)
cr = mullet (*Crenimugil crenilabis*)
da = damselfish (*Abudefduf biocellatus*)
g = goatfish (*Mulloidichthys samoensis*)
gr = grouper (*Epinephelus merra*)
j = jack (*Caranx sp.*)
l = ladyfish (*Albula vulpes*)
m = mackerel (*Grammatorcynus billineatus*)
n = mullet (*Neomyxus chaptalii*)
p = parrotfish (*Scarus sordidus*)
q = queenfish (*S. sancti-petri*)
rr = rainbow runner (*Ellagatis bipinnulatus*)
s = convict surgeon (*Acanthurus triostegus*)
sn = snapper (*Lutjanus bohar*)
t = triggerfish (*Rhineacanthus ractangulus*)
tn = tuna (*Gymnosarda nuda*)
u = ulua (*Caranx melanpygus*)
w = wrasse (*Halichoeres trimaculatus*)

Table 2. Fishing sites at Enewetak Atoll since 1964 where muscle tissue was separated for analysis from the species indicated.

Island ID	Marshallese name	Aug[a] 1964	Nov[b] 1972	Apr–May 1976	Jun 1977	Mar 1978	Nov 1978	Sept 1980	July 1981	June 1982	Aug 1983	Sept 1984	Nov 1993	Feb 1994	Nov 1994	May 1995
E-2	Bokombako	bu,da,gr,sn,sq,s,t,w[c]	cr	cr,s			g,n,s				g,cr,u					
E-5	Bokinwotme	gr,n,p,s,t														
E-9	Boken		cr,sn			cr			g,cr,s							
E-10	Enjebi	gr,j,cr,p,s,t	cr,p	n	n		g,p,s	sn			g,gr,cr,n,sn,s,t	bo,g,u	g,s	ft,g,pa,s	g,s	g,s
E-19	Aomon			n,s	n		s	bo,cr					s			
E-20	Bijile		cr,p,sn,u										g			
E-24	Runit	g,h,s	gr,p,tn,u	n,s			cr,s	g,cr,n,p,sn,s	g,n,s	n,s	ba,cr,n,sn,s		g,s	n,s	ft,g,p,s	g,cr,n,s
E-33	Japtan		p	g,cr,s												
E-35	Medren		sn,u													
E-37	Enewetak		gr,p,sn,u	cr,s			s									
E-38	Ikuren	gr,s	sn	s								cr				
E-39	Mut		p													
E-43	Biken	g,gr,j	cr,p	cr												
E-45	Drekatimon							ba,m,u			m,u	m,u				

[a] Welander et al. (1967)

[b] Nelson and Noshkin (1973)

[c] ba = barracuda (*Sphyraena sp.*)
bo = bonito (*Euthynnus affinus*)
bu = butterflyfish (*Chaetodon auriga*)
cr = mullet (*Crenimugil crenilabis*)
da = damselfish (*Abudefduf biocellatus*)
ft = flagtail (*Kuhlia taeniura*)
g = goatfish (*Mulloidchthys samoensis*)
gr = grouper (*Epinephelus merra*)
h = halfbeak (*Hemirhamphus laticeps*)
j = jack (*Caranx sexfasciatus*)
m = mackerel (*Grammatorcynus bilineatus*)
n = mullet (*Neomyxus chaptalii*)
p = parrotfish (*Scarus sordidus*)
s = convict surgeon (*Acanthurus triostegus*)
sn = snapper (*Lutjanus bohar*)
t = triggerfish (*Rhineacanthus ractangulus*)
tn = tuna (*Thunnus albacares*)
u = ulua (*Caranx melanpygus*)

brief description of the feeding habits can be found elsewhere in this volume (Noshkin and Robison 1997). The feeding habits and trophic level assignments of the remaining reef and pelagic fish shown in Tables 1 and 2 and in the Appendices can be found elsewhere (Hiatt and Strasburg 1965; Noshkin et al. 1988; Welander et al. 1967).

RESULTS AND DISCUSSION

Radionuclides detected in parts of different fish from the atolls

In the 1964 study, sodium iodide detectors were used with multichannel analyzers for non-destructive analysis of the different samples. Spectrum stripping methods were used to determine the levels of several gamma emitting radionuclides accumulated by different fish (Welander et al. 1967). Chemical separations were used to isolate other beta and alpha emitting radionuclides from the samples. Data were generated for the gamma emitting radionuclides ^{54}Mn, ^{57}Co, ^{60}Co, ^{65}Zn, ^{106}Ru, ^{125}Sb, ^{137}Cs and ^{207}Bi (and natural ^{40}K). Radiochemical separations provided information on ^{55}Fe (decay by EC), ^{90}Sr, $^{239+240}$Pu and $^{102\,m}$Rh in the fish. The presence of ^{144}Ce, ^{155}Eu and $^{110\,m}$Ag was verified in some samples. ^{207}Bi had been previously reported in environmental samples from the atolls (Lowman and Palumbo 1962), but it was during this survey that the first determination of the radioisotope was made in fish samples. It was present in fish from Enjebi Island, Enewetak Atoll, in concentrations far exceeding those at other islands of either atoll (Welander et al. 1967). At this time ^{106}Ru and ^{125}Sb were below detection limits in muscle tissue of all fish from Bikini and the photopeak from ^{54}Mn was not evident in any flesh samples from Enewetak. Of the remaining gamma emitting radionuclides only ^{137}Cs, ^{60}Co and ^{207}Bi were detected with regularity.

Samples of fish were again collected by others during sampling programs at Bikini in 1969, 1970, 1972, 1974,1975, 1976 and 1977 (Held 1971; Lynch et al. 1975; Nelson 1977; Schell 1978) and at Enewetak in 1972–1973 (Nelson and Noshkin 1973). Samples from this latter survey (and from the 72, 74, 75 76 and 77 Bikini surveys) were eventually dried and/or ashed and analyzed non-destructively on Ge(Li) detectors at different laboratories. For these latter programs it was possible to resolve, without the spectral interference common to NaI, the concentrations of any gamma emitting radionuclides present in the samples that exceeded detection limits. By 1974 the radionuclides ^{54}Mn, ^{57}Co, ^{144}Ce, ^{110m}Ag, ^{95}Zr and ^{106}Ru had sufficiently decayed so that they were only occasionally found in viscera, liver or gut content samples from specific fish. With the improved Ge(Li) detection systems, the gamma emitting radionuclides ^{241}Am, ^{101}Rh, ^{134}Cs, $^{108\ m}$Ag, and ^{152,154}Eu were identified in parts of some fish along with ^{40}K, ^{60}Co, ^{102m}Rh, ^{125}Sb, ^{137}Cs, ^{155}Eu and ^{207}Bi previously found in the 1964 samples (Welander et al. 1967). Wet chemical separation methods were used with beta-alpha detection instruments to measure ^{241}Pu and ^{238}Pu in addition to ^{90}Sr, ^{55}Fe, ^{63}Ni, and $^{239+240}$Pu. Mass spectrometry was used to determine levels of ^{239}Pu and ^{240}Pu in parts of some of the fish (Noshkin 1980). We identified and quantified levels of ^{99}Tc, ^{242,244}Cm and $^{113\ m}$Cd (Noshkin et al. 1981b) in species of fish collected during the late 1970's. Concentrations of ^{242,244}Cm and ^{99}Tc in flesh were a few percent of the respective $^{239+240}$Pu concentration. The detection of ^{242}Cm ($t_{1/2}$ = 163 d) in environmental samples, 20 y after the end of testing, must indicate the presence of the parent radionuclide, ^{242m}Am, in the environment.

By 1974, only the gamma emitting radionuclides, ^{60}Co and ^{137}Cs, were evident in the majority of muscle tissue samples from reef and pelagic species. ^{207}Bi was poorly concentrated or below detection limits in muscle from most reef fish except the goatfish, parrotfish, and the larger pelagic species from the lagoon (see Appendices). By the late 1970's to the early 1980's, only ^{155}Eu, $^{108\ m}$Ag, $^{102\ m}$Rh were the only other gamma emitters, in addition to ^{60}Co, ^{137}Cs and ^{207}Bi, above detection limits in separated samples of viscera, liver, or gut content (Noshkin et al. 1988; Schell et al. 1978). Isotopes from this former group of radionuclides were never in concentrations above detection limits in large samples of flesh bulked for analysis by gamma spectrometry. In collections made during the 1990's, only the flesh was separated from fish and analyzed. At both atolls ^{207}Bi remained below detection limits in muscle tissue from all reef fish except goatfish. Levels of ^{137}Cs diminished to detection limits in mullet and goatfish at many islands, and ^{60}Co was found everywhere low in concentration or below our limit of detection.

Tissue and organ concentrations of ^{207}Bi, ^{60}Co, and ^{137}Cs and geographical relationships

The larger migratory pelagic species cannot be used as indicators for changes in the availability of the radionuclides over time. The most useful data to assess the temporal change in concentration is from reef species that were repeatedly sampled over time from the same general locations at the Atolls. Therefore, this discussion will be limited to an assessment of the concentrations in 3 common reef species—mullet, surgeonfish, and goatfish—but the appendices can be referenced for levels in the flesh of the other species of fish. Representative whole fish concentrations for ^{137}Cs, ^{60}Co, and ^{207}Bi in mullet, surgeonfish, and goatfish from 1978 are reconstructed from tissue and organ concentration data and the percentages of the respective tissues to whole body weight (Noshkin et al. 1987). Results are shown in Table 3 and are used to compute the percent of the whole body activity associated with the tissues shown. The concentrations determined in the viscera samples are regrettably less descriptive than those for the other tissues because of the matrix of organs and tissues represented. These include large and small intestines with contents, stomach wall, spleen, kidney and mesenteries. The radionuclide concentration of the viscera could often vary with the amount of material in the intestines that often contained quantities of bottom sediment (especially the mullet) labeled with the radionuclide.

Concentrations of ^{137}Cs ($t_{1/2}$=30.1 y) in flesh and viscera of fish are comparable but because of the larger mass, most of the radionuclide accumulated by fish is found associated with the edible flesh; the lowest percentages are associated with bone and liver. Concentrations in the flesh of the three species are approximately equivalent to the concentration in the reconstructed whole body. However, concentrations associated with surgeonfish (see Appendices) were always greater than levels in flesh of goatfish and generally exceeded or were equivalent to the levels in mullet collected at the same time from different islands of the Atolls. The surgeonfish are the better environmental indicators for ^{137}Cs levels. At Bikini, higher concentrations of ^{137}Cs were generally found in flesh of reef fish from the northwest quadrant of the atoll (B-1 to B-5), and the lowest levels were associated with reef species from the eastern reef. At Enewetak, generally higher concentrations were measured in the reef fish from the northern half of the atoll (E2-E-24) and lowest levels were found associated with reef species from the southeastern and southern reef of the atoll.

In 1982, ocean fish fillets purchased from stores in the Chicago area of the United States, contained 0.85±0.07 Bq kg^{-1} of ^{137}Cs derived from global fallout (Karthunen 1982). The appendices show that after 1978 the mean concentrations of ^{137}Cs in reef fish from islands B-10 to B-23 at Bikini and from E-33 to E-38 at Enewetak were comparable to the fallout levels in the U.S. store-purchased fish.

Between 1958 (the end of testing) and 1994, ^{60}Co levels in the environments decreased by a factor of 30 from radioactive decay alone ($t_{1/2}$=5.26 y). However, measurable concentrations are still found in fish collected during the 1990's. From 20 to 50% of the body burden of ^{60}Co is present in the muscle tissue with most of the remainder distributed among the liver, skin, and viscera. Unlike ^{137}Cs, concentrations of ^{60}Co in the flesh of mullet and goatfish were consistently higher than levels in surgeonfish simultaneously caught at the same islands. Therefore, the goatfish and mullet are better environmental indicator species for changes in ^{60}Co concentrations in the lagoon environment. The levels of ^{60}Co in the flesh of the reef fish from different regions of the atolls vary in the same manner as ^{137}Cs and generally

Table 3. Concentrations in tissues and percent of whole body concentration for 3 reef species.

Island locator #	Common name	Muscle[a] Bq kg^{-1}	%[c]	Bone[a] Bq kg^{-1}	%[c]	Skin[a] Bq kg^{-1}	%[c]	Liver[a] Bq kg^{-1}	%[c]	Viscera[a] Bq kg^{-1}	%[c]	Gut contents[a] Bq kg^{-1}	%[c]	Reconstructed[b] whole fish concentration Bq kg^{-1}	Muscle/whole fish activity ratio
^{137}Cs															
B-1	Mullet[d]	14.7	67	0.9	0.5	8.2	9	13.6	1.0	15.3	13	22.0	1.2	12.9	1.14
E-10	Mullet	7.8	38	1.1	0.6	10.1	12	3.7	0.3	36.0	33	43.5	2.6	11.9	0.65
B-6	Surgeonfish	6.2	67	0.2	0.2	10.5	20	3.5	0.4	5.5	6	5.8	0.7	6.1	1.01
E-24	Surgeonfish	14.4	72	0.7	0.5	13.3	12	4.6	0.2	15.8	8	21.5	1.1	13.2	1.09
B-1	Goatfish	5.5	74	2.5	4	4.1	10	4.0	0.3	4.0	5	5.1	0.1	4.9	1.11
E-2	Goatfish	1.5	75	0.1	0.9	1.0	8	0.9	0.3	1.8	9	2.1	0.1	1.3	1.13
															mean = 1.03 ± 0.12
^{60}Co															
B-1	Mullet	33.2	39	32.6	4.4	72.7	20	742.1	13	69.0	15	17.7	0.2	50.7	0.65
E-10	Mullet	1.3	17	4.6	7.4	9.6	32	81.4	17	6.5	17	4.0	0.6	4.3	0.30
B-10	Surgeonfish	1.0	36	1.3	6.1	2.8	19	29.9	12	4.4	17	9.4	3.8	1.7	0.55
E-2	Surgeonfish	3.0	50	3.3	6.4	8.3	24	39.2	6.7	1.9	3	25.2	4.3	4.1	0.75
B-1	Goatfish	21.2	33	17.8	3.3	61.8	17	951.1	9	207.3	31	133.6	0.2	43.2	0.49
E-10	Goatfish	13.2	29	5.4	1.4	36.2	14	306.4	4.2	200.1	44	45.3	0.1	29.8	0.44
															mean = 0.53 ± 0.12
^{207}Bi															
B-1	Mullet	0.1	18	0.1	2.1	0.1	4	4.3	8.1	2.0	45	4.6	6.7	0.5	0.30
E-24	Mullet	0.0	1	0.2	0.5	0.1	0	2.5	0.9	15.5	66	37.2	10.1	2.6	0.02
B-6	Surgeonfish	0.0	14	0.1	9.2	0.1	14	3.8	23	0.5	30	0.7	4.3	0.1	0.21
E-24	Surgeonfish	0.0	5.6	0.3	5.6	0.1	4	19.9	36	2.2	36	3.4	6.2	0.4	0.08
B-17	Goatfish	8.1	67	4.4	4.4	9.0	13	26.0	1.3	9.1	7	2.9	0.0	8.0	1.00
E-10	Goatfish	241.9	71	65.6	2.3	173.0	9	276.4	0.5	354.2	10	45.3	0.0	224.9	1.08
															mean mullet & surgeonfish = 0.15 ± 0.11
															mean goatfish = 1.04 ± 0.04

[a] Muscle, skin, bone, liver, viscera and gut contents account for 93–95% of total fish weight.

[b] Bq kg^{-1} whole fish = $[\Sigma$ (Bq kg^{-1} wet tissue) $\times$ (% tissue of whole body wt)$] \times (\Sigma$ % tissue of whole body wt$)^{-1}$.

[c] Percent of total body activity in respective tissue or organ.

[d] Mullet = Crenimugil crenilabis.

reflect the differences found in the distribution of activities associated with lagoon sediments.

Most striking were the differences found for ^{207}Bi ($t_{1/2}$ = 32.2 y) among the tissues of the reef species. In mullet and surgeonfish, ^{207}Bi was usually below detection limits by gamma spectrometry in many parts separated from the fish. The radionuclide was consistently detected in the muscle and other organs of goatfish and the pelagic lagoon fish. About 70% of the whole body activity of ^{207}Bi in goatfish is associated with flesh whereas less than 20% (when detected) is found in the flesh of mullet and surgeonfish. Highest levels were consistently found in flesh of goatfish collected on the reef of Enjebi Island (E-10), Enewetak Atoll. Levels in comparable species from islands of Enewetak Atoll generally exceeded concentrations at Bikini Atoll. Goatfish are clearly the better indicator among different fish for ^{207}Bi levels in the lagoon environment.

Previous estimates of the effective half-life of ^{137}Cs, ^{60}Co, and ^{207}Bi using reef fish concentration data

Radiological dose assessments for the marine food chain from ingestion of marine food have been made assuming that the time necessary to reduce the concentrations in the food (and the environment) by a factor of two is related only to the radioactive half-life of a radionuclide. Clearly, if other processes are operating in the environment that reduced the availability of a radionuclide, the dose received by individuals over time would be less. The concentrations in flesh from the reef fish are used to describe the change in the activity levels of ^{137}Cs, ^{60}Co, and ^{207}Bi in the environment over a 30-y period of time.

There have been other attempts to model the changes in environmental concentrations using radiological data retained in fish parts. During the 1972–1973 radiological survey of Enewetak, Nelson and Noshkin (1973) compared the activity levels in 5 samples of viscera from surgeonfish with those in samples from fish collected at the same islands of the atoll in 1964. The average fraction of ^{60}Co and ^{207}Bi found in 1972 viscera was 0.11±0.04 and 0.32±0.19, respectively, of the amounts measured in 1964. The effective half lives computed from these data were 2.6±0.9 y for ^{60}Co and 5.0±3.0 y for ^{207}Bi.

Schell (1987) used concentration data in the viscera of mullet (*Neomyxus chaptalii*) collected at Nam (B-1) Island, Bikini Atoll, between 1964 and 1977 to assess the combined effect of physical decay and removal by lagoon processes. The value of the slope from a least square fit of the natural log (ln) of the respective concentration with time (in years), yielded effective half lives for ^{137}Cs, ^{60}Co, and ^{207}Bi of 4.1±0.5, 3.0±0.4, and 6.3±1.7 y, respectively. The values for ^{60}Co and ^{207}Bi are in generally good agreement with the values determined at Enewetak and tend to indicate that, over the time period, the decline of these radionuclides within the lagoons was more rapid than radioactive decay alone.

Effective half-life of ^{137}Cs, ^{60}Co, and ^{207}Bi using concentration data in flesh of reef species

The data in the Appendices were treated in several manners. Only measurable radionuclide concentrations with less than 100% counting error for mullet, convict surgeonfish, and goatfish were considered. No error was quoted for the measurements associated with the 1964 collections (Welander et al. 1967). A 10% error was arbitrarily assigned to each reported concentration. Fallout background levels of ^{137}Cs were estimated in the flesh from values in species from other Northern Marshall Atolls (Noshkin et al. 1987), concentration factors, and equatorial water concentrations determined over time. These values ranged from 0.3 to 0.9 Bq kg^{-1} and varied with the species over time of collection. All ^{137}Cs data were corrected before plotting the results to estimate the effective decay constants. When sufficient measurements of a radionuclide were available for fish from one island, the data were plotted on a semilog graph (using a spreadsheet program), essentially in the manner used by Schell (1987), to determine the decay constant using a least square fitting (LSF) procedure. All applicable data points from the collections made between 1964 and 1995 were used to generate the curves. An example is shown in Noshkin and Robison (1997) where the ^{137}Cs levels in the flesh of convict surgeonfish from North Runit Island, Enewetak Atoll, are plotted against the date of collection. A least square fit to the data yields a slope (λ) with a value of 0.104 ± 0.012 y^{-1}. The error term is the uncertainty in the estimation of the slope. The computed effective decay constant (λ) consists of a physical (λ_r) and environmental (ecological = λ_e) decay constant. The effective and ecological half-lives ($t_{1/2}$, $t_{1/2e}$) can be computed. The latter half-life requires use of the physical half-lives for the radionuclides that were provided in a previous section and given again in Table 4. This procedure was followed at several other islands where there was sufficient long term data for a specific radionuclide. The computer generated results are shown in Table 4.

There were clearly differences in radionuclide concentration measured in the same species collected from different parts of the Atolls during any one period and over time. It was therefore impossible to construct a single plot, for example, to show all ^{137}Cs concentrations in surgeonfish at Enewetak over time. It was, however, possible to normalize concentrations to a value in the

Table 4. Effective and ecological decay constants and half-lives of ^{137}Cs, ^{60}Co and ^{207}Bi determined from concentrations in flesh of fish from locations within Enewetak and Bikini Atolls. The error is the uncertainty in the estimation of the value for the constants.

Location	Data used	Data points	Isotope	Radiological half-life (y)	λ (y^{-1})[a]	$t_{1/2}$[a] (y)	λ_e (y^{-1})[b]	$t_{1/2e}$[b] (y)
Enewetak Atoll								
E-24	Surgeonfish	13	^{137}Cs	30.00	0.104 ± 0.012	6.7 ± 0.7	0.081 ± 0.012	8.6 ± 1.3
E-10	Surgeonfish	9	^{137}Cs	30.00	0.063 ± 0.011	11.0 ± 1.9	0.040 ± 0.011	17.3 ± 4.8
E-2	Surgeonfish	4	^{137}Cs	30.00	0.044 ± 0.024	15.8 ± 8.6	0.021 ± 0.024	33 ± 38
E-2,-10,-24	Surgeonfish	26[c]	^{137}Cs	30.00	0.069 ± 0.010	10.0 ± 1.4	0.046 ± 0.010	15.1 ± 3.3
All locations	All reef fish	58[c]	^{137}Cs	30.00	0.060 ± 0.010	11.6 ± 1.9	0.037 ± 0.010	18.7 ± 5.1
E-24	Surgeonfish	7	^{60}Co	5.26	0.195 ± 0.022	3.6 ± 0.4	0.062 ± 0.022	11.2 ± 4.0
E-24	Goatfish	6	^{60}Co	5.26	0.147 ± 0.067	4.7 ± 2.1	0.015 ± 0.067	46 ± 205
E-10	Goatfish	6	^{60}Co	5.26	0.143 ± 0.027	4.8 ± 0.9	0.011 ± 0.027	63 ± 155
E-2	Surgeonfish	4	^{60}Co	5.26	0.190 ± 0.010	3.6 ± 0.2	0.058 ± 0.010	12.0 ± 2.1
All locations	All reef fish	58[c]	^{60}Co	5.26	0.173 ± 0.024	4.0 ± 0.6	0.041 ± 0.024	17 ± 10
E-24	Goatfish	7	^{207}Bi	32.20	0.093 ± 0.018	7.4 ± 1.4	0.071 ± 0.018	9.8 ± 2.5
E-10	Goatfish	8	^{207}Bi	32.20	0.208 ± 0.068	3.3 ± 1.1	0.186 ± 0.068	3.7 ± 1.4
All locations	Goatfish	26[c]	^{207}Bi	32.20	0.136 ± 0.025	5.1 ± 0.9	0.114 ± 0.025	6.1 ± 1.3
Bikini Atoll								
B-1	Surgeonfish	5	^{137}Cs	30.00	0.103 ± 0.047	6.7 ± 3.1	0.080 ± 0.047	8.7 ± 5.1
B-5	Surgeonfish	4	^{137}Cs	30.00	0.064 ± 0.017	15.6 ± 4.1	0.041 ± 0.017	17 ± 7
B-6	Surgeonfish	4	^{137}Cs	30.00	0.034 ± 0.024	20 ± 14	0.011 ± 0.024	>60
All locations	Surgeonfish	16[d]	^{137}Cs	30.00	0.073 ± 0.022	9.5 ± 2.9	0.050 ± 0.022	14 ± 6
B-1	All reef fish	22[d]	^{137}Cs	30.00	0.097 ± 0.023	7.1 ± 1.7	0.074 ± 0.023	9.4 ± 2.9
B-1	All reef fish	11[d,e]	^{137}Cs	30.00	0.126 ± 0.034	5.5 ± 1.5	0.103 ± 0.034	6.7 ± 2.2
All locations	All reef fish	54[d]	^{137}Cs	30.00	0.079 ± 0.015	8.8 ± 1.7	0.056 ± 0.015	12.4 ± 3.3
B-1	All reef fish	20[d]	^{60}Co	5.26	0.151 ± 0.027	4.6 ± 0.8	0.019 ± 0.027	36 ± 51
B-1	All reef fish	12[d,e]	^{60}Co	5.26	0.230 ± 0.039	3.0 ± 0.5	0.098 ± 0.039	7.1 ± 2.8
All locations	All reef fish	53	^{60}Co	5.26	0.131 ± 0.013	5.3 ± 0.5	0.000 ± 0.013	>53
B-1	Goatfish	4	^{207}Bi	32.20	0.025 ± 0.009	28 ± 10	0.003 ± 0.009	>58
All locations	Goatfish	11	^{207}Bi	32.20	0.023 ± 0.009	30 ± 12	0.001 ± 0.009	>77

[a] Effective decay constant and half-life.
[b] Ecological decay constant and half-life.
[c] Data normalized to 8/83.
[d] Data normalized to 7/78.
[e] Only data between 1964 and 1978 used for comparison with values generated using fish viscera samples (Schell 1987).

same species from an island measured on a common collection date. Relative concentrations could then be plotted against time using measurements in all reef species from one island or for all species from the entire Atoll. At Enewetak, a number of measurements for the 3 species from islands E-2, E-10, and E-24 were made in August 1983. At Bikini, common collections were made at B-1, B-5, B-6, B-12, and B-17 on November 1978. For example, consider the data entries for ^{60}Co in fish from island B-1, abstracted from the Appendix, shown in Table 5. Concentration measured in flesh of the different fish during the November 1978 collections are shown in bold type. Goatfish data from all collections was divided by 6.70 Bq kg^{-1} to generate the set of relative concentration values shown in column 6 of Table 5. Likewise, the Mullet-C (*Crenimugil crenilabis*), Mullet-N (*Neomyxus chaptalii*), and Surgeonfish (*Acanthurus triostegus*) measurements were divided by the respective concentration (shown in bold type) determined in the species collected in November 1978. The normalized values are shown in column 6, and column 7 contains the standard deviation computed for the ratio. This procedure was followed with the fish data from other islands. At Enewetak concentrations were normalized to the values from the August 1983 collections. The relative concentration ratios were transferred to semilog plots and a LSF procedure was applied to the data sets to assess the effective decay constants (λ) and the uncertainty in the estimated value of the constant. Plots for relative (normalized) concentrations of ^{137}Cs in all reef fish from Bikini and Enewetak over time are shown in Figs. 1 and 2. A best fit to the results yields the trend line shown in the figures and the computed effective decay constants. Regression lines from a best fit to the normalized ^{60}Co data in reef fish from the two Atolls are shown in Fig. 3.

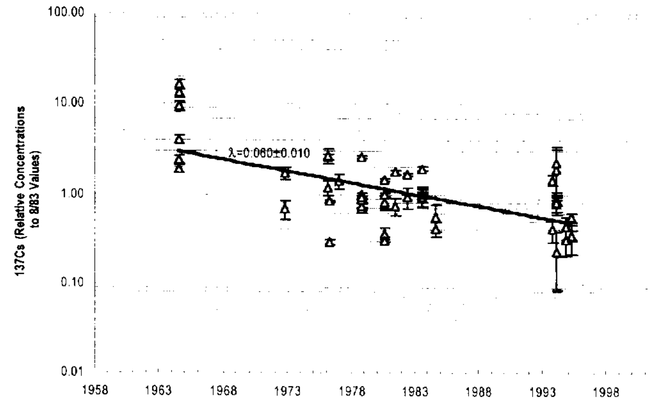

Fig. 1. Relative concentration of ^{137}Cs in flesh of reef fish from Enewetak Atoll as a function of collection time. Concentration data are normalized to values in fish from August 1983 collections. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix A.

Fig. 4 shows the relative change for ^{207}Bi in goatfish (the only reef species with consistently detected concentrations in the flesh) from Enewetak. The computed decay constants and the respective half-lives from these analyses and others (not shown with accompanying figures in this report to conserve space) along with calculated uncertainties are summarized in Table 4. Values for correlation coefficients (R^2) of the different regression equations ranged from 0.5 to 0.9 showing moderate to strong correlation among the results.

The effective decay constants were also computed using fish data from 1964 to 1978 at Nam Island to determine if the flesh concentrations provided compara-

Table 5. Data from Appendix B for ^{60}Co concentration in flesh of reef fish from island B-1, Bikini Atoll.

Island	Common name	Collection date	Concentration Bq kg^{-1} wet	Error as % of measured concentration	Concentration normalized to amount measured in 11/78	± Error in relative ratio
B-1	Goatfish	May-70	101.39	3	4.78	0.15
B-1	Goatfish	Nov-78	**21.19**[a]	1	1.00	0.01
B-1	Goatfish	Aug-83	6.70	4	0.32	0.01
B-1	Goatfish	Dec-92	6.13	10	0.29	0.03
B-1	Mullet-C	Jul-76	12.33	7	0.37	0.03
B-1	Mullet-C	Jan-77	11.24	2	0.34	0.01
B-1	Mullet-C	Nov-78	**33.21**[a]	1	1.00	0.01
B-1	Mullet-C	Feb-81	8.22	3	0.25	0.01
B-1	Mullet-C	Aug-83	2.53	26	0.08	0.02
B-1	Mullet-N	Aug-64	798.52	10	50.19	5.04
B-1	Mullet-N	Jul-76	15.68	6	0.99	0.06
B-1	Mullet-N	Jan-77	18.80	3	1.18	0.04
B-1	Mullet-N	Oct-77	13.12	7	0.82	0.06
B-1	Mullet-N	Nov-78	**15.91**[a]	1	1.00	0.01
B-1	Mullet-N	Dec-92	6.48	13	0.41	0.05
B-1	Surgeonfish	Aug-64	67.63	10	7.84	0.79
B-1	Surgeonfish	Nov-78	**8.63**[a]	1	1.00	0.01
B-1	Surgeonfish	Aug-83	1.24	6	0.14	0.01
B-1	Surgeonfish	Aug-83	1.64	7	0.19	0.01
B-1	Surgeonfish	Dec-92	1.87	20	0.22	0.04

[a] November 1978 data in bold (see text).

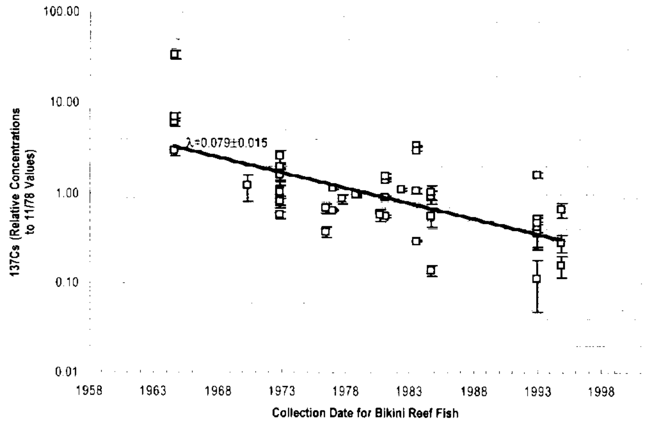

Fig. 2. Relative concentration of ^{137}Cs in flesh of reef fish from Bikini Atoll as a function of collection time. Concentration data is normalized to values in fish from November 1978 collections. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix B.

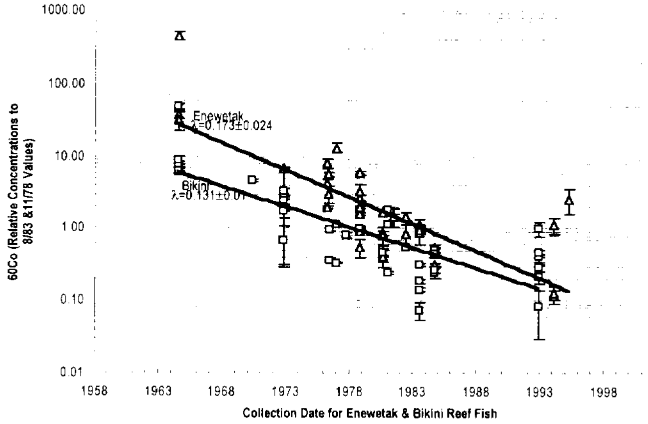

Fig. 3. Relative concentrations of ^{60}Co in flesh of reef fish from both Enewetak and Bikini as a function of collection time. Regression lines showing best fit to change in concentration with tie at each Atoll are shown. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendices A and B.

ble decay constants to the values derived from viscera samples by Schell (1987) in his analysis. These values are identified in Table 4 for ^{137}Cs and ^{60}Co.

Surgeonfish were the best indicator species for ^{137}Cs. Results at Enewetak in Table 4 indicate that the effective rate for ^{137}Cs removal might be more rapid at Runit (E-24), located on the eastern rim of the Atoll, than at islands E-2 and E-10 in the northwest part of the Atoll. One could argue that the physical form of material with bound ^{137}Cs is different over areas of the lagoon and release of the radionuclide occurs at different rates over time. However, the 3 values are within 2 sigma of the mean λ (0.069±0.010) computed from the normalized surgeonfish measurements from the three islands. This later value was equivalent to the effective decay constant using the normalized data from the 58 measurements in reef fish from all locations. The best estimate for the effective half-life of ^{137}Cs in the lagoon at Enewetak is therefore about 12±2 y. The ecological half-life is 19±5 y. Subtle differences that may be related to geography and/or test location are masked by the error derived from the analysis.

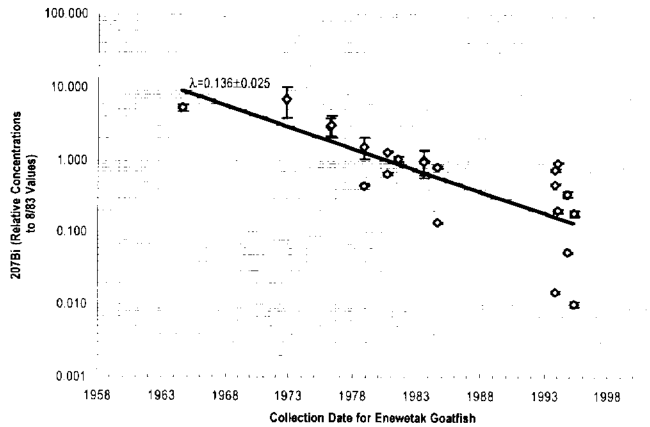

Fig. 4. Relative concentration of ^{207}Bi in flesh of reef fish from Enewetak Atoll as a function of collection time. Error bars represent the standard deviation computed for each ratio from the 1 σ error terms in Appendix A.

At Bikini the surgeonfish results also tended to show a geographical dependence on the computed effective half-live from island B-1 in the northwest to B-6 on the eastern rim of the Atoll. As with Enewetak, all 3 values are within 2 sigma of the mean computed from surgeonfish at all lagoon locations. The error term again masks any difference with might be attributed to geography. The effective half-life using muscle data from all fish collected at Nam (B-1) prior to 1978 was 5.5±1.5 y. This is in good agreement with the value of 4.1±0.5 found by Schell (1987) using data for mullet viscera. A somewhat longer effective half-life (7.1±1.7) results when all data are used to generate the effective decay constant. The difference between the computed half lives could indicate the rate of ^{137}Cs release from the environmental sedimentary components has diminished since 1978. This value is also in good agreement with the half-life of 9±2 y computed from the 54 data points for all reef fish from all lagoon locations. Although it is inferred from the results, it would be difficult to argue strongly (because of the uncertainty) that there is a difference in the effective and ecological half-lives of ^{137}Cs between islands or the Atolls of Bikini and Enewetak. An effective half live of from 9 to 12 y indicates ^{137}Cs is removed from the lagoon by processes that exceed the rate of radiological decay alone.

Results from different species generate similar effective half lives. For example, there is good agreement seen in the computed values for ^{60}Co in Table 4 derived from Surgeonfish and Goatfish from islands at Enewetak. Analyses of the reef fish data from B-1 sampled prior to 1978 gave an effective half life for ^{60}Co of 3.0±0.5 y. This value is in good agreement with the value of

3.0±0.4 y determined from the viscera samples by Schell (1987). However, a much different effective half life results when the entire data set of 53 measurements from 1964 to 1994 from the entire lagoon is used to generate the decay constant. The computed effective half-life of 5.3±0.5 y from this analysis is no different than the radiological half life. Over the long term the loss of ^{60}Co from Bikini lagoon occurs principally by radioactive decay or the rate of release from the environmental components diminished after 1978. At Enewetak the effective half life from the analysis of 58 data points using a regression analysis is 4.0±0.6 y. This half life is similar in value to one determined by Nelson and Noshkin (1973) comparing viscera data from fish caught in 1964 and 1972, but on the other hand it cannot be argued to be significantly different from the value of the radiological half-life (5.26 y). There may be a somewhat faster rate of depletion at Enewetak, but the true value is again masked by the errors generated from the analysis. At best, the effective half life from the majority of results indicates a value of 4 to 5.2 y at both atolls.

The behavior of ^{207}Bi is different at the 2 Atolls. In 26 samples of goatfish from Enewetak lagoon the best fit to all data yielded an effective half-life of 5.1±0.9 y. This value is in agreement with the Nelson and Noshkin (1973) result of 5.0±3.0. This removal half-time from all goatfish results is clearly faster than the radiological half-life of 32.2 y. At Bikini there was substantially less usable data. However, the LSF for the 11 samples generated an effective half-life of 30±12 y, which is equivalent to the radiological half-life. Too little data were available at B-1 prior to 1978 to compare with the Schell (1987) viscera result. Because of the large error associated with the effective half-life, any definitive conclusions regarding ^{207}Bi at Bikini are not clear cut. It suggests that any significant loss of ^{207}Bi from the lagoon environment is probably only by radioactive decay. If true, the radionuclide must be in a chemical or physical form very different from that associated with sediments source terms in Enewetak lagoon.

CONCLUSIONS

A variety of different radionuclides was found accumulated in all species of fish from Bikini and Enewetak lagoons. Over the years many of the radionuclides have diminished by radioactive decay and by natural processes. Fish collected in the 1980's and 1990's show only low concentrations of a few remaining long-lived radionuclides in flesh and other tissues. The data generated from the marine studies show that the radiological dose from manmade radionuclides in the marine food chain contribute less than 0.1% of the total 30-y integral dose equivalent at both Atolls (Robison 1973; Robison et al. 1987; Robison et al. 1997). The ingestion dose was derived principally from 3 gamma-emitting radionuclides, ^{137}Cs, ^{60}Co and ^{207}Bi; the transuranic radionuclides $^{238,239+240}$Pu and ^{241}Am; and ^{90}Sr. The largest contributor to the total marine dose was from ^{137}Cs accumulated in the edible flesh. The transuranic radionuclides and ^{90}Sr contributed little to the total dose from ingestion of marine foods. Our collection program was phased out in 1985, but fish samples were again collected in the 1990's to verify the results of the original assessment and to determine what, if any, changes occurred in the concentrations of gamma emitting radionuclides in edible muscle tissue. Resources only permitted analysis of muscle tissue in these samples after dissections. Of the gamma emitting radionuclides generated by the nuclear tests, only ^{60}Co, ^{137}Cs and ^{207}Bi remain above detection limits by gamma spectrometry in flesh of some but not all fish.

These new data and the results from our earlier studies and work by others provide a large, valuable and unique data base for radionuclides in the flesh of different fish that span 31 y, from 1964 to 1995. Some reef fish can be used as indicator species because their body burden is derived from feeding, over a lifetime, within a relatively small area containing the contamination. The change in body concentration over time is related to the local diagenic processes that are responsible for the release and recycling of the radionuclides. The change in concentrations observed in several non-migratory reef species is used to describe the effective half lives for ^{60}Co, ^{137}Cs, and ^{207}Bi in the lagoon environments during the 31-y period between 1964 and 1995. This half life consists of a physical decay term and a recycling or environmental decay term. This latter term is related to the processes which control the removal and transport of a radionuclide from the environment. Sufficient measurements for ^{137}Cs, ^{60}Co and ^{207}Bi were available for some reef species of fish repeatedly sampled from specific locations at Bikini and Enewetak to determine an effective environmental decay constant from a least square analysis (LSF) of the data.

The results of the analysis indicate the removal rates for the 3 radionuclides are significantly different. ^{137}Cs is removed from the marine environments of Bikini and Enewetak with an effective half life of 9–12 y that is significantly less than the radiological half life. The natural processes acting on ^{137}Cs in the environment will reduce any radiological exposure from ingestion of marine foods. Every 9–12 y the inventory of ^{137}Cs in the sedimentary reservoirs is reduced in half and radiological decay accounts for about 21% of the loss. The remaining 29% was remobilized from the environment to the water column in a dissolved state over the 9–12-y period. Within the lagoon, excess dissolved ^{137}Cs has been measured in water samples taken on our sampling programs from all areas of both atolls for many years (see, for example, Noshkin and Robison 1997; this volume). The lagoon water mass containing the ^{137}Cs is continuously transported over the reef or through the passes and eventually exits the atoll and mixes with the north equatorial Pacific water mass.

Some slight difference could be assigned to the estimated effective half-life for ^{60}Co at Enewetak and Bikini. However, it would appear that most of the radionuclide is lost from both environments by radioactive decay. Little enters the water column from the sediments as a dissolved species. Most ^{60}Co accumulated by fishes must be derived from food and sedimentary particles passing through the gut rather than direct uptake from water.

The results from the analysis of the ^{207}Bi in the indicator fish species suggest a difference in behavior at the two Atolls. At Enewetak the radionuclide is lost from the environment with an effective half life of 5.1 y. The radionuclide is mobilized from the sedimentary reservoir at a rate similar to ^{137}Cs and is then diluted with ocean water and is eventually transported from the Atoll. On the other hand, only radioactive decay may account for the rate at which the radionuclide is disappearing from Bikini lagoon. Again most body burdens of ^{207}Bi in fish from Bikini must be derived from material passing through the gut rather than from the water. The different behavior of ^{207}Bi at the Atolls must be controlled by different chemical-physical properties of the contaminated particles retaining the radionuclide.

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■ ■

APPENDIX A

Table A1. Concentration of ^{137}Cs, ^{60}Co, and ^{207}Bi in flesh (muscle) of fish caught between 1964 and 1995 from islands of Enewetak Atoll.

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
(1)[c]	Butterflyfish	Aug-64	2	3	13.9		105.9			
(1)	Damselfish	Aug-64	2	10	15.5		70.1			
9109	Goatfish	Nov-78	2	22	1.5	4	6.4	2	12.3	2
g509	Goatfish	Aug-83	2	26	2.0	6	4.0	3	26.5	2
(1)	Grouper	Aug-64	2	1	11.4		11.4		15.5	
(1)	Grouper	Aug-64	2	1	8.1		32.6		17.9	
(2)[d]	Mullet-C	Nov-72	2	1	5.1	14	30.1	5	1.1	38
2610	Mullet-C	Apr-76	2	4	7.8	2	8.9	2	0.4	7
g586	Mullet-C	Aug-83	2	9	3.0	6	4.8	4	0.1	>100
g552	Mullet-C	Aug-83	2	6	5.9	2	4.0	3	0.2	26
9103	Mullet-N	Nov-78	2	17	2.5	4	9.0	2	0.2	18
(1)	Snapper	Aug-64	2	1	27.7		51.3		26.9	
(1)	Squirrelfish	Aug-64	2	3	9.0		23.6		6.9	
(1)	Surgeonfish	Aug-64	2	1	18.7		43.2			
5286	Surgeonfish	May-76	2	52	8.1	2	6.4	2	0.4	11
9115	Surgeonfish	Nov-78	2	22	6.7	3	3.0	6	0.1	>100
g529	Surgeonfish	Aug-83	2	16	9.6	2	1.1	7	0.1	30
(1)	Triggerfish	Aug-64	2	3			203.7		21.2	
g822	Ulua	Aug-83	2	1	6.2	4	2.1	7	11.4	2
(1)	Wrasse	Aug-64	2	6			75.0			
(1)	Grouper	Aug-64	5	9	4.7		30.1		8.1	
(1)	Grouper	Aug-64	5	2			21.2		36.7	
(1)	Mullet-N	Aug-64	5	2			171.1			
(1)	Parrotfish	Aug-64	5	2	17.9		6.3			
(1)	Surgeonfish	Aug-64	5	3			37.5			
(1)	Surgeonfish	Aug-64	5	5	130.4		211.9			
(1)	Triggerfish	Aug-64	5	1			75.0			
msa394	Goatfish	Jul-81	9	34	1.7	5	10.3	2	49.0	1
(2)	Mullet	Nov-72	9	1	35.0	5	163.0	3	1.6	45
5302	Mullet-C	Mar-78	9	16	7.8	2	1.3	5	0.1	>100
msa677	Mullet-C	Jul-81	9	62	3.1	7	27.2	1	0.1	>100
(2)	Snapper	Nov-72	9	4	17.1	8	89.6	4	1	>100
msa548	Surgeonfish	Jul-81	9	52	15.3	2	2.4	5	0.1	>100
j286	Bonito	Sep-84	10	1	6.8	4	9.9	3	4.5	5
z417	Flagtail	Feb-94	10	1	1.8	44	2	>100	1	>100
7385	Goatfish	Nov-78	10	26	1.4	11	13.2	2	241.9	2
g637	Goatfish	Aug-83	10	27	1.9	13	14.0	2	524.5	2
j424	Goatfish	Sep-84	10	18	0.8	13	4.5	3	75.0	1
j428	Goatfish	Sep-84	10	17	1.1	30	8.0	4	437.2	2
z420	Goatfish	Nov-93	10	3	0.3	>100	1	>100	8.2	4
z409	Goatfish	Feb-94	10	5	1.5	21	1.7	15	109.9	6
z838	Goatfish	Feb-94	10	16	0.2	>100	1.8	29	495.4	1
z861	Goatfish	Nov-94	10	7	0.9	>100	1	>100	29.2	1
z846	Goatfish	May-95	10	8	1	>100	2	>100	5.6	8
(1)	Grouper	Aug-64	10	5	7.2					
(1)	Grouper	Aug-64	10	1	29.3					
g809	Grouper	Aug-83	10	10	2.1	5	0.8	11	15.2	1
(1)	Jack	Aug-64	10	1	10.6		57.0		48.9	
(1)	Mullet-C	Aug-64	10	5	25.3		464.4			
(2)	Mullet-C	Nov-72	10	2	1.1	23	3.6	91	0.4	60
g621	Mullet-C	Aug-83	10	15	1.5	4	1.0	5	0.0	>100
2633	Mullet-N	Apr-76	10	19	0.9	6	2.4	3	0.2	14

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
9266	Mullet-N	Jan-77	10	30	0.5	6	4.0	1	0.5	3
g627	Mullet-N	Aug-83	10	34	0.3	18	0.3	15	0.0	>100
z410	Papio	Feb-94	10	3	0.9	>100	1	>100	9.0	3
(1)	Parrotfish	Aug-64	10	1	97.8		13.0		10.6	
(2)	Parrotfish	Nov-72	10	1	8.0	9	2	>100	0.6	>100
5312	Parrotfish	Nov-78	10	1	6.9	3	0	>100	0.1	>100
msa144	Snapper	Sep-80	10	1	1.9	15	6.3	8	31.2	1
g813	Snapper	Aug-83	10	4	1.1	17	1.5	11	12.0	2
g815	Snapper	Aug-83	10	4	2.5	6	4.0	3	38.7	1
(1)	Surgeonfish	Aug-64	10	1	12.2		5.8			
(1)	Surgeonfish	Aug-64	10	5	20.4					
7377	Surgeonfish	Nov-78	10	54	5.1	2	0.4	8	0.1	>100
g632	Surgeonfish	Aug-83	10	31	5.0	3	0	>100	0.1	>100
z421	Surgeonfish	Nov-93	10	11	2.1	28	2	>100	1	>100
z411	Surgeonfish	Feb-94	10	10	4.3	9	1	>100	0.6	>100
z837	Surgeonfish	Feb-94	10	12	1.2	63	1	>100	1	>100
z865	Surgeonfish	Nov-94	10	58	2.2	28	2	>100	1	>100
z863	Surgeonfish	May-95	10	24	2.8	13	1	>100	0.5	>100
(1)	Triggerfish	Aug-64	10	2			31.0			
g811	Triggerfish	Aug-83	10	1	0.5	30	9.0	2	12.5	2
j289	Ulua	Sep-84	10	2	7.0	2	0.8	6	3.5	2
msa138	Bonito	Sep-80	19	1	2.3	7	5.1	3	6.9	3
msa98	Mullet-C	Sep-80	19	5	0.8	20	1.5	21	0.1	>100
msa92	Mullet-C	Sep-80	19	35	3.5	4	3.2	4	0.1	>100
2641	Mullet-N	Apr-76	19	29	0.4	8	1.3	4		
9260	Mullet-N	Jun-77	19	58	0.3	5	1.0	3	0.2	6
5270	Surgeonfish	May-76	19	28 ocean	4.0	20	0.8	8	0.0	>100
5278	Surgeonfish	May-76	19	40 ocean	2.3	4	0.9	9	0.0	>100
7275	Surgeonfish	Nov-78	19	46	9.2	1	1.0	8	0.0	>100
z077	Surgeonfish	Nov-93	19	11	1.0	40	1	>100	0.9	>100
z078	Goatfish	Nov-93	20	7	2	>100	2	>100	4	>100
(2)	Mullet	Nov-72	20	1	1	>100	1.5	0	0.7	>100
(2)	Parrotfish	Nov-72	20	1	3.4	17	2	>100	0.2	>100
(2)	Snapper	Nov-72	20	2	2.6	28	2	>100	0.7	>100
(2)	Snapper	Nov-72	20	1	1.1	21	0	>100	1.0	25
(2)	Snapper	Nov-72	20	4	1	>100	1	>100	1	>100
(2)	Ulua	Nov-72	20	1	2.0	21	0	>100	2.0	26
g820	Barracuda	Aug-83	24	1	1.6	13	0.8	14	7.1	2
z852	Flagtail	Nov-94	24	9	1.1	31	1	>100	0.8	>100
(1)	Goatfish	Aug-64	24	5			264.1		102.2	
msa24	Goatfish	Sep-80	24	42	0.6	4	0.3	1	12.6	2
msa30	Goatfish	Sep-80	24	42	1.4	2	5.7	1	25.0	1
msa692	Goatfish	Jul-81	24	34	2.0	7	22.6	2	19.9	8
z088	Goatfish	Nov-93	24	16	1	>100			14.4	2
z834	Goatfish	Nov-93	24	15	0.5	63	6.0	10	9.1	3
z848	Goatfish	Nov-94	24	29	1	>100	2.4	21	6.6	7
z850	Goatfish	May-95	24	57	1	>100	1.2	32	3.7	9
z867	Goatfish	May-95	24	18	0	>100	2	>100	3.6	11
(2)	Grouper	Nov-72	24	1	2.8	27	6.3	16	21.3	4
(1)	Halfbeak	Aug-64	24	10			67.3			
9165	Mullet-C	Nov-78	24	22	1.0	2	5.5	2	0.0	32
msa44	Mullet-C	Sep-80	24	14	1.1	3	1.5	2	0.0	27
msa36	Mullet-C	Sep-80	24	30	0.3	5	0.8	5	0.0	34
g647	Mullet-C	Aug-83	24	33	1.1	5	0.9	6	0.0	>100
z862	Mullet-C	May-95	24	6	0.0	>100	1	>100	0.6	>100
2618	Mullet-N	Apr-76	24	22	0.8	2	6.6	2	0.5	11
msa66	Mullet-N	Sep-80	24	29	0.6	4	0.7	23	0.0	80
msa74	Mullet-N	Sep-80	24	29	0.3	8	0.7	6	0.0	25
msa467	Mullet-N	Jul-81	24	21	0.5	12	2.3	3	0.0	>100
msa834	Mullet-N	Jun-82	24	16	0.7	20	2.2	7	0.1	>100
g642	Mullet-N	Aug-83	24	5	0.7	18	1.5	10	0.1	>100
z414	Mullet-N	Feb-94	24	5	1.4	64	1.7	23	1	>100
z836	Mullet-N	Feb-94	24	17	1.6	49			2	>100
z866	Mullet-N	May-95	24	55	1	>100	2	>100	1	>100
msa62	Parrotfish	Nov-72	24	2	4.2	61	1	>100	0.5	>100
(2)	Parrotfish	Sep-80	24	2	2.6	3	0.6	5	0.1	24
z857	Parrotfish	Nov-94	24	6	5.6	4	1	>100	0.4	>100
msa82	Snapper	Sep-80	24	1	1.8	3	10.3	2	9.7	2

Sample ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			E-							
msa88	Snapper	Sep-80	24	1	4.9	1	3.7	1	7.1	2
g807	Snapper	Aug-83	24	1	1.8	5	2.6	3	6.7	1
(1)	Surgeonfish	Aug-64	24	10	52.0		23.0			
5294	Surgeonfish	May-76	24	28 ocean	1.6	5	2.2	6	0.0	>100
7377	Surgeonfish	Nov-78	24	10	5.1	2	0.4	8	0.0	>100
9171	Surgeonfish	Nov-78	24	51	14.4	2	2.3	3	0.0	>100
msa58	Surgeonfish	Sep-80	24	28 south	1.7	2	0.3	8	0.0	35
msa52	Surgeonfish	Sep-80	24	74	7.9	2	0.6	8	0.1	29
msa686	Surgeonfish	Jul-81	24	50	9.7	2	1.0	10	0.1	>100
msa828	Surgeonfish	Jun-82	24	57	9.1	2	0.6	17	0.1	>100
g652	Surgeonfish	Aug-83	24	27	5.4	3	0.7	27	0.1	>100
z091	Surgeonfish	Nov-93	24	5	8.1	14	3	>100	2	>100
z412	Surgeonfish	Feb-94	24	8	4.7	11	1	>100	0.6	>100
z835	Surgeonfish	Feb-94	24	42	4.5	6	1	>100	0.5	>100
z849	Surgeonfish	Nov-94	24	62	1.7	33	1	>100	1	>100
z851	Surgeonfish	Nov-94	24	60			2	>100	1	>100
z843	Surgeonfish	May-95	24	46	1.8	35	2	>100	1	>100
z844	Surgeonfish	May-95	24	9	1.9	11	1	>100	0.4	>100
z845	Surgeonfish	May-95	24	5	1	>100	1.8	26	0.9	>100
(2)	Tuna	Nov-72	24	1	3.7	11	9.4	10	9.4	10
(2)	Tuna	Nov-72	24	1	2.4	21	6.8	10	7.4	9
(2)	Tuna	Nov-72	24	1	1.3	33	3.2	14	2.0	17
(2)	Ulua	Nov-72	24	2	3.9	22	11.1	9	2.8	33
9254	Goatfish	Apr-76	33	58	0.3	16	6.9	2	29.3	1
2602	Mullet-C	Apr-76	33	6	0.5	13	0.9	11	0.1	13
(2)	Parrotfish	Nov-72	33	2	0.6	83	0.4	>100	0.3	>100
5232	Surgeonfish	May-76	33	52	0.8	13	0.4	35	0.0	>100
(2)	Snapper	Nov-72	35	1	1.1	38	3.1	14	2.9	12
(2)	Ulua	Nov-72	35	1	4.6	15	10.2	10	7.8	7
(2)	Grouper	Nov-72	37	1	4.5	13	1	>100	17.8	5
(2)	Grouper	Nov-72	37	1	4.3	18	3.7	26	5.4	11
2625	Mullet-C	Apr-76	37	8	0.2	28	0.4	11	0.1	23
(2)	Parrotfish	Nov-72	37	1	15.0	6	2	>100	0.6	>100
(2)	Snapper	Nov-72	37	1	0.9	>100	1	>100	0.6	>100
5239	Surgeonfish	May-76	37	37	0.5	9	0.1	32	0.1	>100
7176	Surgeonfish	Nov-78	37	8	1.8	11	0	>100	0.1	>100
(2)	Ulua	Nov-72	37	1	3.1	28	18.7	9	48.0	3
(1)	Grouper	Aug-64	38	10			6.3		5.8	
(1)	Grouper	Aug-64	38	1			6.6		12.8	
j736	Mullet-C	Sep-84	38	8	0.2	11	1.1	3	0.0	>100
(2)	Snapper	Nov-72	38	1	2.6	33	5.6	16	16.2	5
(1)	Surgeonfish	Aug-64	38	10			11.9			
5247	Surgeonfish	May-76	38	40	1.0	7	1.8	5	0.4	8
(2)	Parrotfish	Nov-72	39	1	0.3	25	2	>100	0.9	>100
(1)	Goatfish	Aug-64	43	5			68.9		64.6	
(1)	Grouper	Aug-64	43	1	85.0		15.3		12.8	
(1)	Grouper	Aug-64	43	1			20.4		54.4	
(1)	Jack	Aug-64	43	1	10.2		59.5		7.0	
(2)	Mullet-C	Nov-72	43	2	1.0	17	9.4	18	0.5	>100
2594	Mullet-C	Apr-76	43	11	2.8	4	9.0	4	0.9	3
(2)	Parrotfish	Nov-72	43	1	2.4	18	1	>100	0.3	>100
msa132	Barracuda	Sep-80	45	1	2.1	11	1.8	12	12.5	3
msa158	Mackerel	Sep-80	45	1	2.4	9	4.3	6	1.8	10
g497	Mackerel	Aug-83	45	7	1.7	5	1.9	4	1.2	5
j283	Mackerel	Sep-84	45	2	1.5	17	0	>100	0.1	>100
msa126	Ulua	Sep-80	45	1	8.2	1	3.7	2	5.8	10
g503	Ulua	Aug-83	45	3	2.9	3	1.4	5	1.3	4
j290	Ulua	Sep-84	45	2	2.1	8	1.1	10	3.0	4

[a] Sample ID used at Lawrence Livermore National Lab.

[b] No error was given for the 1964 data set. Elsewhere the 1 σ counting error is expressed as the percent of the value listed.

[c] (1) data from Welander et al. (1967).

[d] (2) data from Nelson and Noshkin (1973).

Notes:

2,579 total fish processed for 178 samples between 1964 and 1995. All results reported on date of collection.

163 measurements for ^{137}Cs; 90% reported above detection limits.

173 measurements for ^{60}Co; 76% reported above detection limits.

159 measurements for ^{207}Bi; 57% reported above detection limits.

APPENDIX B

Table 2A. Concentration of ^{137}Cs, ^{60}Co and ^{207}Bi in flesh (muscle) of fish caught between 1964 and 1994 from islands of Bikini Atoll.

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	$\mathrm{Bq\ kg^{-1}}$ wet ^{137}Cs	% error[b]	$\mathrm{Bq\ kg^{-1}}$ wet ^{60}Co	% error[b]	$\mathrm{Bq\ kg^{-1}}$ wet ^{207}Bi	% error[b]
			B-							
(2)[d]	Goatfish	May-70	1	14	6.8	33	101.4	3	62.9	3
9121	Goatfish	Nov-78	1	33	5.5	3	21.2	1	50.4	2
g576	Goatfish	Aug-83	1	11	6.0	6	6.7	4	36.0	4
z423	Goatfish	Dec-92	1	5	2.2	35	6.1	10	37.2	2
(4)	Mullet-C	Jul-76	1	6	5.6	15	12.3	7		
2896	Mullet-C	Jan-77	1	8	9.7	3	11.2	2	0.0	100
9133	Mullet-C	Nov-78	1	12	14.7	1	33.2	1	0.1	21
a356	Mullet-C	Feb-81	1	14	8.4	3	8.2	3	0.0	100
g561	Mullet-C	Aug-83	1	11	4.4	2	2.5	26		
z415	Mullet-C	Dec-92	1	1	1.7	58	3	100	2	100
z859	Mullet-C	Nov-94	1	8	2.4	28	2	100	10.4	
(1)[e]	Mullet-N	Aug-64	1	10	52.1		798.5			
(4)	Mullet-N	Jul-76	1	6	5.1	13	15.7	6		
a458	Mullet-N	Jan-77	1	14	8.6	3	18.8	3	0.0	100
(4)	Mullet-N	Oct-77	1	10	6.5	13	13.1	7		
9127	Mullet-N	Nov-78	1	18	7.3	2	15.9	1	0.0	100
z422	Mullet-N	Dec-92	1	4	2.7	34	6.5	13	1	100
z853	Mullet-N	Nov-94	1	39	1	100	0.8	100	0.6	100
(3)[e]	Snapper	May-72	1	6	7.9	8	25.6	3	36.8	2
(4)[f]	Snapper	Jul-76	1	4	4.4	15	8.0	10	8.8	10
(1)	Surgeon	Aug-64	1	7	171.1		67.6			
9159	Surgeon	Nov-78	1	4	4.9	1	8.6	1	0.1	100
g515	Surgeon	Aug-83	1	36	17.1	1	1.2	6	0.1	31
g521	Surgeon	Aug-83	1	37	15.0	1	1.6	7	0.1	100
z419	Surgeon	Dec-92	1	11	8.2	6	1.9	20	0.6	100
(1)	Trigger	Aug-64	1	1	97.8		260.7			
(4)	Ulua	Nov-72	1	1	10.6	8	5.8	10	4.1	11
(4)	Goatfish	Nov-72	S of B-1	1	11.2	17	112.4	2	11.2	8
(4)	Goatfish	Nov-72	S of B-1	10	1.5	24	12.8	7	2.3	11
(4)	Mullet-N	Nov-72	S of B-1	13	5.8	16	81.9	2		
2880	Mullet-C	Jan-77	2	21	14.1	2	10.1	1	0.0	100
(1)	Butterfly	Aug-64	3	1			114.1			
(1)	Grouper	Aug-64	3	5			12.2			
(1)	Jack	Aug-64	3	1			32.6			
(1)	Surgeon	Aug-64	3	4	24.4		26.9			
(1)	Triggerfish	Aug-64	3	1			97.8			
(1)	Wrasse	Aug-64	3	1			37.5			
(4)	Goatfish	Nov-72	5	3	5.0	16	40.0	2	43.5	2
7251	Goatfish	Nov-78	5	22	1.9	4	13.8	2	3.3	8
a233	Goatfish	Feb-81	5	44	3.1	5	16.0	2	2.1	4
z413	Goatfish	Dec-92	5	6	0.5	100	6.4	11	10.1	7
z868	Goatfish	Nov-94	5	33	1.3	19	0.7	100	0.5	100
7245	Mullet-C	Nov-78	5	8	13.8	1	9.0	1	0.0	100
a186	Mullet-C	Feb-81	5	7	12.6	2	6.4	2	0.1	100
(4)	Mullet-N	Nov-72	5	14	3.7	14	17.2	5		
7224	Mullet-N	Nov-78	5	24	2.2	3	9.0	1	0.0	100
g372	Mullet-N	Jun-82	5	33	2.5	3	4.9	2	0.0	100
z418	Mullet-N	Dec-92	5	4	0.9	100	0.8	64	0.7	100
(4)	Parrotfish	Nov-72	5	1	3.5	18				
a240	Parrotfish	Feb-81	5	3	8.6	4	1.5	14	0.2	100
z869	Parrotfish	Nov-94	5	6	0.3	100	1	100	0.9	100
z860	Perch	Nov-94	5	7	0.6	90	2	100	0.9	100
(4)	Queenfish	Nov-72	5	1	29.1	3	23.8	4	6.7	8
(4)	Surgeon	Nov-72	5	17	17.1	5	5.0	7		
7257	Surgeon	Nov-78	5	20	8.4	1	2.0	5	0.0	100
a224	Surgeon	Feb-81	5	33	11.8	3	3.8	7	0.2	100
z416	Surgeon	Dec-92	5	12	4.4	12	2.0	22	0.6	100
7370	Goatfish	Nov-78	6	39	0.8	6	2.4	3	0.7	4
a841	Goatfish	Sep-80	6	39	0.5	14	1.2	8	0.7	7
j420	Goatfish	Sep-84	6	58	0.7	16	1.3	10	1.6	6
j422	Goatfish	Sep-84	6	26	0.4	24	1.1	14	1.2	7
z81	Goatfish	Dec-92	6	9	0.5	100	2	100	1	100
z855	Goatfish	Nov-94	6	8	1	100	0.7	100	0.5	100

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
			B-							
a372	Mullet-C	Sep-80	6	14	1.9	3	6.5	1	0.0	100
a848	Mullet-C	Sep-80	6	7	3.9	4	8.3	3	0.0	100
a253	Mullet-C	Feb-81	6	8	2.2	4	4.8	2	0.0	100
j734	Mullet-C	Sep-84	6	12	2.0	2	3.4	1	0.0	100
z82	Mullet-C	Dec-92	6	2	1.8	20	0.9	45	0.9	100
a401	Mullet-N	Feb-81	6	38	1.1	10	3.3	8	0.1	100
g363	Mullet-N	Mar-82	6	31	0.8	8	1.9	6	0.0	100
(4)	Parrotfish	Oct-72	6	1	8.6	10	2.2	26		
(1)	Snapper	Aug-64	6	1	19.6		61.1		26.1	
(1)	Snapper	Aug-64	6	1	6.7		5.6			
(4)	Surgeon	Nov-72	6	3	3.6	7	1.3	19		
7352	Surgeon	Nov-78	6	55	6.2	2	0.7	7	0.0	100
z83	Surgeon	Dec-92	6	7	2.9	22	2	100	1.0	100
z864	Surgeon	Nov-94	6	53	1.8	21	2.8	15	0.6	100
(4)	Mullet-N	Nov-72	B-6 ocean	14	2.0	19	11.3	3		
(4)	Parrotfish	Nov-72	B-6 ocean	3	4.5	15	0.7	72		
(4)	Snapper	Dec-74	9	1	0.9	60	2.2	42		
7263	Goatfish	Nov-78	10	42	0.5	6	1.5	3	0.8	3
2888	Mullet-N	Jan-77	10	43	0.6	10	7.8	2	0.1	30
7269	Surgeon	Nov-78	10	46	1.7	4	1.0	14	0.0	100
(4)	Goatfish	Nov-72	12	10	0.7	33	7.1	4	1.8	14
7200	Goatfish	Nov-78	12	42	0.7	6	3.5	2	1.6	2
j415	Goatfish	Sep-84	12	13	0.7	18	0.9	18	1.8	7
(1)	Grouper	Aug-64	12	5	8.1					
(5)	Grouper	Apr-75	12	1	3.9	23	1.4	63		
2860	Mullet-C	Jan-77	12	11	1.0	6	2.8	6	0.0	100
(1)	Mullet-N	Aug-64	12	3			26.9			
7194	Mullet-N	Nov-78	12	21	0.3	11	3.7	2	0.0	100
(4)	Parrotfish	Nov-72	12	3	4.0	6	0.4	60		
(5)	Parrotfish	Apr-75	12	1	3.3	19				
(4)	Rudderfish	Nov-72	12	1			1.2	36		
(1)	Surgeon	Aug-64	12	3	14.7		7.7			
(1)	Surgeon	Aug-64	12	5	6.9		5.5			
(4)	Surgeon	Nov-72	12	6	2.5	13	0.6	57		
7188	Surgeon	Nov-78	12	64	2.3	2	0.8	6	0.0	100
2851	Mullet-C	Jan-77	13	22	0.8	5	2.4	5	0.0	100
a530	Mullet-N	Feb-81	13	23	0.4	14	1.7	8	0.0	100
(4)	Goatfish	Oct-77	15	7	7.2	14	16.3	10	52.1	5
(1)	Ladyfish	Aug-64	15	2			42.4		57.9	
7281	Goatfish	Nov-78	17	37	1.8	4	9.8	2	8.4	2
7293	Mullet-C	Nov-78	17	9	3.3	2	5.3	2	0.0	100
j730	Mullet-C	Sep-84	17	31	0.5	13	1.4	7	0.0	100
(4)	Mullet-N	Nov-72	17	14	1.6	18	12.3	2		
2872	Mullet-N	Jan-77	17	58	1.5	4	14.0	1	0.2	13
7299	Mullet-N	Nov-78	17	18	0.4	100	46.1	2	0.4	100
(4)	Parrotfish	Nov-72	17	6	4.2	5	2.3	10		
7287	Parrotfish	Nov-78	17	5	5.2	2	0.7	9	0.0	100
(4)	Surgeon	Nov-72	17	13	8.3	4	5.6	6		
g621	Surgeon	Aug-83	17	70	1.6	5	0.2	25		
(4)	Ulua	Nov-72	17	1	7.9	5	4.1	10	0.7	43
(4)	Ulua	Nov-72	17	1	2.5	10	5.5	6	0.3	100
a967	Ulua	Jun-82	22	1	14.0	4	1.8	4	4.1	10
g421	Ulua	Jun-82	22	2	13.4	2	2.0	5	1.4	5
7311	Goatfish	Nov-78	23	47	1.8	6	14.3	1	22.2	1
(1)	Grouper	Aug-64	23	1			30.1		10.6	
(4)	Mullet-N	Nov-72	23	8	0.5	80	27.6	3		
7305	Mullet-N	Nov-78	23	35	0.8	7	15.2	1	0.2	20
(1)	Snapper	Aug-64	23	1			74.1		13.9	
(1)	Snapper	Aug-64	23	1			89.6		10.6	
(1)	Snapper	Aug-64	23	1			21.2		5.8	
(1)	Snapper	Aug-64	23	1			130.4		18.7	
7346	Snapper	Nov-78	23	1	5.4	3	7.6	2	12.2	2
(1)	Surgeon	Aug-64	23	1			97.8			
(4)	Surgeon	Nov-72	23	3	4.7	16	7.9	10		
(1)	Trigger	Aug-64	23	2			244.4			
(2)	Tuna	May-72	lagoon	1	26.3	3	13.6	7	77.1	1
(3)	Tuna	May-72	lagoon	1	7.5	5	3.3	12	0.7	43

ID[a]	Fish common name	Collection date	Island locator	Number of fish/sample	Bq kg^{-1} wet ^{137}Cs	% error[b]	Bq kg^{-1} wet ^{60}Co	% error[b]	Bq kg^{-1} wet ^{207}Bi	% error[b]
(4)	Rainbow	Oct-72	B-lagoon	1	1.5	63				
(4)	Rainbow	Nov-72	lagoon	1	9.9	9	37.8	2	3.7	10
(4)	Bonito	Nov-72	lagoon	1	4.9	8	9.0	5	0.7	43
(5)[g]	Mackerel	Dec-74	lagoon	1	6.9	6	17.7	6		
(5)	Snapper	Dec-74	lagoon	1			0.8	50		
(4)	Snapper	Jul-76	lagoon	1	10.1	8	5.9	13	16.8	5
(4)	Snapper	Jul-76	lagoon	1	21.1	8	9.7	17	34.9	5
(4)	Snapper	Jul-76	lagoon	1	41.5	7	13.3	11	25.9	6
(4)	Snapper	Jul-76	lagoon	1	50.1	5	18.2	8	31.9	5
(4)	Snapper	Jul-76	lagoon	1	28.4	8	15.4	16	15.4	8
(4)	Snapper	Oct-77	lagoon	1	40.4	6	9.5	18	30.1	5
(4)	Barracuda	Oct-77	lagoon	4	6.4	11	3.1	16	5.3	8
(4)	Barracuda	Oct-77	lagoon	1	18.5	9	5.6	16	26.9	5
(4)	Bonito	Oct-77	lagoon	1	5.7	19	2.9	30	1.6	33
(4)	Mackerel	Oct-77	lagoon	1	2.1	46	4.1	28		
(4)	Ulua	Oct-77	lagoon	1					6.5	16
7322	Jack	Nov-78	lagoon	1	9.5	2	12.0	2	4.5	2
7334	Mackerel	Nov-78	lagoon	1	2.9	3	2.0	5	0.1	25
7328	Snapper	Nov-78	lagoon	2	0.4	17	0.2	65	6.2	2
7340	Snapper	Nov-78	lagoon	1	1.8	4	3.1	4	0.4	10
a247	Mackerel	Feb-81	lagoon	1	3.7	5	2.4	7	0.3	32
j293	Bonito	Sep-84	lagoon	1	6.5	3	7.4	3	6.6	3
j291	Rainbow	Sep-84	lagoon	1	2.3	8	1.6	11	0.2	100
j292	Snapper	Sep-84	lagoon	1	6.4	3	1.6	8	1.2	8
j294	Ulua	Sep-84	lagoon	1	7.1	2	3.6	2	4.1	2

[a] Sample ID used at Lawrence Livermore National Lab.

[b] No error was given for the 1964 data set. Elsewhere the 1 σ counting error is expressed as the percent of the value listed.

[c] (1) data from Welander et al. 1967.

[d] (2) data from Held 1971.

[e] (3) data from Lynch, et al. 1975.

[f] (4) data from Schell et al. 1978.

[g] (5) data from Nelson 1977.

Note: 1,890 total fish processed for 155 samples between 1964 and 1994. All results reported on date of collection.

138 measurements for 137Cs; 95% reported above detection.

150 measurements for Co; 94% reported above detection.

111 measurements for 207Bi; 58% reported above detection.

Paper

FINDINGS OF THE FIRST COMPREHENSIVE RADIOLOGICAL MONITORING PROGRAM OF THE REPUBLIC OF THE MARSHALL ISLANDS

Steven L. Simon[*†] and James C. Graham[*‡]

***Abstract*—The Marshall Islands was the primary site of the United States atomic weapons testing program in the Pacific. From 1946 through 1958, 66 atomic weapons were detonated in the island country. For several decades, monitoring was conducted by the U.S. Department of Energy (or its predecessor agencies) on the test site atolls and neighboring atolls. However, 70% of the land area of the over 1,200 islands in the Marshall Islands was never systematically monitored prior to 1990. For the 5-y period from 1990 through 1994, the Government of the Republic of the Marshall Islands undertook an independent program to assess the radiological conditions throughout its 29 atolls. The scientific work was performed under the auspices of the Section 177 Agreement of the Compact of Free Association, U.S. public law 99-239, signed in 1986 by President Ronald Reagan. Although the total land area of the nations is a scant 180 km^2, the islands are distributed over 6 × 10^5 km^2 of ocean. Consequently, logistics and instrumentation were main considerations, in addition to cultural and language issues. The core of the monitoring program was *in-situ* gamma spectrometry measurements made on more than 400 islands. Native foods including coconuts and other tropical fruits were sampled as well as more than 200 soil profiles and more than 800 surface soil samples. The fruits, soil profiles and surface soil samples have been analyzed for all gamma emitters with an emphasis on determining concentrations of ^{137}Cs; the surface soil samples were also analyzed for $^{239+240}$Pu. All measurements were conducted in a radiological laboratory built in the capital city of the Marshall Islands specifically for the purposes of this study. The program was extensively assisted in the field and in the laboratory by Marshallese workers. The interpretation of environmental radiation data in the Marshall Islands required thoughtful analysis because the atolls lie along a latitude and precipitation gradient that effected the deposition of local and global fallout. The objective of this paper is to report findings for all atolls of the Marshall Islands on the ^{137}Cs areal inventory (Bq m^{-2}) and the external effective dose-rate (mSv y^{-1}), the projected internal effective dose-rate (mSv y^{-1}) from an assumed diet model, and surface soil concentrations of ^{239,240}Pu (Bq kg^{-1}) for selected northern atolls. Interpretation is also provided on the degree of contamination above global fallout levels. This report provides the first comprehensive summary of the radiological conditions throughout the Marshall Islands.**

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Key words: Marshall Islands; atomic bomb; fallout; ^{137}Cs

INTRODUCTION

THE U.S. Atomic Testing Program in the Pacific was conducted from 1946 through 1958 almost entirely in the Marshall Islands. Though various monitoring programs of the test site atolls and the atolls near the test sites have been conducted during the 50 y since the testing program began, the entire Marshall Islands had not been systematically monitored for residual radioactivity prior to 1990. For the 5-y period 1990 through 1994, the Republic of the Marshall Islands (RMI) Government undertook a radiological study of its 29 atolls to assess the radiological conditions at locations nationwide. The scientific work was performed as conceived by the Section 177 Agreement of the Compact of Free Association (COFA), an agreement between the former Trust Territory of the Pacific (now the RMI) and the United States (P.L. 99-239, 1986). The COFA, which provided the RMI with compensation for damages resulting from the U.S. Atomic Weapons Testing Program in the Pacific, specified the sum of $3 million to be used for radiological monitoring activities and medical surveillance. The purpose of this report is to present findings from the first comprehensive radiological monitoring program of the entire Marshall Islands.

In February of 1988, the Nitijela (Marshallese parliament) of the RMI adopted Resolution No. 3, which requested that the Cabinet of the RMI contract with scientists to investigate the levels of residual radiation in the Marshall Islands. The Nuclear Claims Tribunal[§] undertook an international search for a suitable director scientist and a group of advisor scientists. In late 1989, a principal resident scientist (S.L.S.) was hired and an

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[§] The Nuclear Claims Tribunal is a judicial body appointed by the Nitijela whose purpose is to weigh evidence and provide financial awards for damages from the atomic testing program.

advisory group of non-US scientists was chosen (see McEwan et al. 1997 for a report of the activities of that advisory group).

Through the Section 177 Agreement of the COFA, the authors of the Compact ensured that the RMI would have the opportunity to conduct a monitoring program of its own design and with consideration of issues important to their nation. Though the technical design of the radiological monitoring program was a product of the primary author and the Scientific Advisory Panel, various leaders of the Marshall Islands government had input into the administration of the project. Thus, through a cooperative effort between leaders of the RMI Government, the resident scientist and advisors of varied expertise, an independent study was conducted with complete geographic coverage of the nation.

Historical context

Atomic weapons testing in the Marshall Islands was conducted by the United States during the years 1946 through 1958 at Bikini and Enewetak Atolls in the northwest corner of the archipelago. The early years of the testing program, 1946 through 1951, were relatively inactive (see Simon and Robison 1997). The total explosive yield of the Marshall Islands testing program was reported to be 1.07×10^8 tons TNT (U.S. DOE 1994): 71.8% of the yield was from the tests at Bikini Atoll and 28.2% was from those at Enewetak Atoll.

Bikini was the site of 24 tests including the first two atomic explosions following the end of WWII (Operations Crossroads, shots ABLE and BAKER). Bikini was also the site of the largest test the U.S. ever conducted: CASTLE BRAVO (15 MT explosive yield). That particular test caused the most severe consequences of any of the tests as a result of the exposure of Marshallese on several atolls downwind and due to the contamination of land outside the test site atoll. Enewetak Atoll was the site of 42 tests.

The people of Bikini and Enewetak were moved to other locations before the onset of testing on their home atolls. Up to the present time, neither group of people has ever recovered the full use of their lands though the communities are in various stages of rebuilding infrastructure and facilities for residence and industry. The era of atomic weapons testing in the Marshall Islands left a chronicle of technical data as well as social disruption, misunderstanding about radiation, and, for the Bikini and Enewetak people, several decades of displacement. The history of the movement of the Bikini people is described by Niedenthal (1997).

Radiological monitoring of the test site atolls and a number of other limited locations was conducted numerous times during and after the testing program. These various surveys were mainly conducted by the Atomic Energy Commission (AEC) and its successor agencies, the Energy Research and Development Administration (ERDA), and later the Department of Energy (DOE) or its contractor laboratories. In particular, the AEC Health and Safety Laboratory (HASL) conducted aerial gamma surveys of the atolls immediately following the tests of the IVY (Eisenbad 1953) and CASTLE (Breslin and Cassidy 1955) series. HASL also accumulated data on ground contamination by a network of fixed gamma measurement instruments at many atolls. In addition, one station of the HASL worldwide gummed film monitoring network was located at Kwajalein Atoll in the Marshall Islands. In addition to monitoring Rongelap Atoll in 1957, the AEC also monitored and cleaned Bikini to Department of Defense and AEC specifications in 1969. ERDA again monitored Bikini in 1957 and Brookhaven National Laboratory conducted an external radiation survey of five northern atolls in 1976. A large scale cleanup program of Enewetak was conducted by the Defense Nuclear Agency (DNA) in 1978–1980; the DNA program included a large laboratory and *in-situ* monitoring program. In 1978 the DOE contracted an aerial survey and ground sampling program of eleven northern atolls and two islands using the services of EG&G Energy Measurements Group, Lawrence Livermore National Laboratory and Brookhaven National Laboratory. The latter survey covered about 30% of the nation's area. Of these various monitoring programs, the aerial measurements conducted by HASL had the widest geographic coverage though the Northern Atoll Radiological Survey of 1978 was conducted with the highest level of spatial resolution. However, the Marshall Islands nation was not systematically monitored in its entirety until the implementation of the RMI Nationwide Radiological Study.

Data from a nationwide monitoring program were seen as potentially useful to a compensation program under design by the Nuclear Claims Tribunal. Thus, the Nationwide Radiological Study was designed and implemented to provide radiological monitoring of the complete geographic area of the chain of atolls that forms the RMI as well as to provide interpretation concerning possible radiation effects on human health and the environment (Simon et al. 1993).

The Nationwide Radiological Study (NWRS) was designed to fulfill the following goals:

1. To establish the geographic extent of fallout radioactivity throughout the RMI and to determine the present and future levels of radioactivity. Where possible, the past levels were to be determined;
2. To reassess the radiological conditions of Bikini, Enewetak, Rongelap and Utrik Atolls;
3. To provide advice to the RMI Government and to the Nuclear Claims Tribunal on (i) effects likely to be associated with the derived radiation exposure levels, (ii) health conditions related to radiation exposure, and (iii) to assist in the determination of exposure and risk to individuals where appropriate or possible; and
4. To provide information to the public of the Marshall Islands which explain and clarify the findings and to participate in educational activities concerning radiation and radioactivity and its potential health and environmental effects.

MATERIALS AND METHODS

Study design

During the planning phases of this study, numerous options were explored to determine the most appropriate and cost-effective technology for conducting a radiological monitoring program. Various technologies were considered, including an aerial survey with large volume scintillator detectors. However, because of the limited budget of the study and the remoteness of the Marshall Islands, the use of helicopters or fixed-wing aircraft was viewed as excessively expensive. Other factors were considered, including the simultaneous need to construct a laboratory to support the staff and perform radioactivity measurements on food and soil samples. Ground-level *in-situ* gamma spectrometry was determined to be most appropriate method in terms of providing useful data, minimizing expense, minimizing fear among the indigenous population—as can occur with aerial surveys—and providing an opportunity to employ Marshallese to assist in the monitoring program. These attributes were viewed as significant and important advantages over other methods.

A laboratory was designed and built in Majuro, the capital of the Marshall Islands. The laboratory office building provided facilities for drying fruit, tissue, and soil samples, crushing and grinding soil, storing samples, and performing wet chemistry including the extraction of plutonium from soil. The laboratory also contained facilities for gamma and alpha spectrometry as well as office space for staff. This laboratory became the first Marshall Islands Government institution of its type.

Sampling design considered sampling location within each atoll and sample size (i.e., the number of *in-situ* gamma spectrometry measurements per atoll). Islands greater than approximately 500 m in length in all atolls received at least a single measurement. The choice of sampling locations on each island was normally made during the course of the radiological survey by first evaluating visual cues and other environmental evidence to locate areas on each island with the least amount of natural or artificial disturbance. Within these areas, sampling locations were chosen at random except where necessary to maintain a minimum distance of about 30 m from the shoreline or manmade structures.

The interpretation of *in-situ* spectrometry data from situations with aged fallout is generally based on the exponential model to describe the vertical radioactivity distribution in the soil column (Beck et al. 1972). Many locations with aged fallout and without historical disturbance have been documented to show an exponential decline of radioactivity with increasing depth. Publications specific to the Marshall Islands have discussed the variation in relaxation length; typical values reported range from 7 cm to 15 cm (EG&G 1982; Graham and Simon 1996).

The number of *in-situ* gamma spectrometry measurements (sample size per atoll) was determined by considerations of resource allocation as well as expressions of the government or the local populace for information of high detail such as might be needed for evaluation of claims of land damage or to design remediation programs. At the atolls of the southern Marshall Islands, the sample size for *in-situ* gamma measurements was determined by the total counting time available during a single survey mission. Atoll surveys depended on logistical support from an ocean going vessel. The types of support necessary included transportation to and from the atoll, transportation between islands, providing food, drinking water, shelter, electricity for recharging instruments, and cargo space for carrying supplies of liquid nitrogen for HPGe detectors and for samples collected during the trip. Typically, ship support for the survey of a single atoll was restricted to a maximum of 10 d with 7 d as typical because of the limitations for carrying fuel and freshwater. *In-situ* counting time during the survey of a single atoll was generally limited to 2 h per measurement. Counting times of that length would allow two teams (three to five members each) to conduct up to sixty measurements during a week-long survey.

At atolls where historical data indicated significant contamination, public and government interest was generally greater. At these atolls, systematic sampling was used to ensure uniform geographic coverage of the islands. Square grids on 200-m centers were measured by compass and tape; *in-situ* measurement sites were chosen near to the center point of each grid square except as necessary to avoid shorelines, disturbed areas or manmade structures. The overall average spatial density of *in-situ* gamma spectrometry measurements in the NWRS was 10 per km^2 (see Table 1).

Description of samples

Samples of several different types were obtained to provide supplementary data to assist in the calibration of *in-situ* spectrometry instruments and also to provide necessary data for assessment calculations. Sample analysis was also necessary to answer questions from the local population concerning radioactivity in the environment and possible food contamination. At some locations, measurements with a high pressurized argon gas ionization chamber and electrometer were made to acquire data on the total gamma exposure-rate. Ionization chamber measurements were not made routinely because of manpower limitations. Every sampling location, however, was characterized by an *in-situ* gamma measurement with a counting time sufficiently long to ensure that the statistical counting error at one sigma confidence level be not greater than ± 10%. Standard geometry was maintained with a 1-m high downward facing crystal.

Surface soil samples were also obtained at many measurement sites for the purpose of laboratory analysis of transuranic radionuclides as well as for corroborative measurements of gamma emitting nuclides. Three surface soil samples, each 15 cm × 15 cm × 5 cm, were obtained at random locations within 15 m of the HPGe detector. The three subsamples were pooled to form a composite surface soil sample that was intended to be representative of the location of each *in-situ* gamma measurement.

Table 1. Summary data of monitoring program.

Atoll or island	Number of islands monitored in each atoll	Number of profiles per km^2	Number of *in-situ* measurements per km^2	Number of *in-situ* measurements per profile	Max/Min soil ^{137}Cs	Ratio of observed ^{137}Cs to global fallout estimates
Jabat Island	1	1.8	3.5	2.0	1.1	1.0
Knox	4	1.0	4.0	4.0	5.2	1.0
Lib Island	1	2.2	5.4	2.4	5.4	1.0
Namorik	2	0.7	2.5	3.5	2.5	1.0
Arno	20	0.3	2.4	7.7	50.9	1.1–2.1
Ebon	9	0.5	3.6	7.0	9.7	1.0–1.2
Ujae	6	1.6	6.8	4.3	32.4	1.0–1.3
Kili Island	1	0.5	4.3	8.3	8.0	1.0–1.4
Majuro	8	1.2	4.8	4.0	15.4	1.0–1.4
Ailinglaplap	21	0.3	2.5	9.1	16.6	1.0–1.5
Aur	10	0.5	3.0	5.7	3.4	1.0–1.6
Maloelap	16	0.4	2.8	6.7	13.6	1.0–1.8
Namu	16	0.6	6.8	10.7	6.3	1.0–1.8
Kwajalein	48	0.6	5.2	9.5	34.6	1.0–4.3
Jaluit	21	0.4	3.2	9.1	25.0	1.0–10.7
Lae	5	2.1	6.7	3.2	7.5	1.1–2.1
Mili	18	0.3	2.2	8.0	66.9	1.1–2.1
Taongi	6	0.9	5.0	5.4	6.8	1.1–2.1
Erikub	6	1.3	4.7	3.6	3.2	1.3–2.6
Bikar	3	2.0	10.0	5.0	2.3	1.4–2.7
Wotho	7	0.7	4.0	5.7	4.7	1.5–3.0
Ujelang	13	3.5	21.2	6.1	16.0	1.7–3.4
Wotje	21	0.5	3.3	6.7	3.4	1.9–3.8
Jemo Island	1	6.2	25.0	4.0	1.6	2.1–4.2
Likiep	25	0.6	5.3	9.2	9.7	3.9–7.7
Taka	4	7.0	17.5	2.5	24.6	4.8–9.7
Mejit Island	1	0.6	7.1	11.5	22.3	4.9–9.8
Ailuk	20	0.6	7.0	12.6	10.0	5.3–11.0
Utrik	4	1.6	20.4	12.8	6.8	11.0–21.0
Ailinginae	19	4.3	22.9	5.3	130.0	33.0–66.0
Rongerik	8	5.4	23.5	4.4	190.0	99.0–200.0
Rongelap	41	5.3	35.6	6.7	2900.0	140.0–1530.0
Enewetak	31	2.6	28.5	11.0	34100.0	200.0–1300.0
Bikini	15	2.8	16.5	5.9	3900.0	820.0–1650.0
Total	432	n/a[a]	n/a	n/a	n/a	n/a
Mean	12.7	1.8	9.6	6.6	1224.6	n/a
Median	8.5	1.0	5.3	6.0	9.9	n/a

[a] n/a = not applicable.

Soil profiles sampled in 5-cm increments to a total depth of 30 cm were also an important part of the sampling and measurement program. Characterization of the vertical profile of ^{137}Cs activity is a parameter of considerable importance to estimating the areal inventory. Over 200 soil profiles were acquired during the survey of the Marshall Islands. Generally a ratio of 1 soil profile to each 6 *in-situ* gamma measurements was maintained. Acquisition of all soil samples in the NWRS was by non-mechanized means except in a few instances when the NWRS was participating in intercomparison exercises with DOE contractors (limited to Bikini and Rongelap Atoll). Soil was carefully excavated by hand from the sides of a hand dug pit and taken to the laboratory in Majuro for processing and analysis. Further details of the soil profile sampling methodology and the findings are presented in Graham and Simon (1996).

Samples of locally grown food products were obtained in limited numbers to assist in the determination of the radiological conditions of the atolls. Generally plant concentrations for a single radionuclide (e.g., ^{137}Cs) are proportional to the specific activity of the radionuclide in the soil within the root zone of the plant. However, significant variations in uptake even at a single atoll are often observed due to local variations of both the contamination and soil characteristics such as drainage, composition, particle size, organic matter, stable element content, past salt intrusion, disturbance, etc., as well as the health and age of the plants.

There are also substantial variations in plant:soil ratios among different plant species. The most commonly used food plant in the Marshallese culture and the most common type of tree is the coconut palm (*Cocos nucifera*). Coconuts are used at many different stages of growth and in a variety of prepared foods. The clear liquid of the young coconut is an important source of fluid replenishment for Marshallese. Thus, coconuts, mainly of the young drinking stage, were sampled at all atolls. The sample size for coconuts was not uniform among the atolls due to manpower and time constraints during each survey. The liquid of the young coconuts (*ni*, pronounced as "nee" by Marshallese) was emptied into sampling bottles in the field; the soft meat of these coconuts (*mede* or "mé-dee" in Marshallese) was scooped out and stored in plastic containers for return to the laboratory.

Other sample types were obtained during the NWRS though sample size was not equal among the atolls. These sample types included breadfruit (*Artocarpus altilis*), Pandanus (*Pandanus spp.*), arrowroot (*Tacca leontopetaloides*), lime (*Citrus aurantifolia*), coconut crabs (*Birgus latro*) and meat of the giant clam (*Tridacna* clam). An ancillary study was made of the ^{137}Cs concentrations in plants used in traditional Marshallese medicine. The methodology and findings of that study were reported by Duffy (1993).

Instrumentation and laboratory methodology

Sample preparation and analysis were conducted according to laboratory protocols established during the initial phases of the project. All fruit, animal, and soil samples were dried to near 99%. Soils were crushed and ground to a particle size of less than 1.3 mm and thoroughly mixed in a rotating ball mill.

Laboratory precision and quality control was established by implementing several programs including the use of radioactivity standards traceable to NIST, repetitive measurements, use of internal tracers for plutonium analysis, participation in international intercomparisons conducted by the IAEA Laboratory in Monaco, and by conducting an in-house blind measurement intercomparison program with four international laboratories: Lawrence Livermore National Laboratory (Livermore, CA), the GSF Institut for Strahlenschutz (Munich, Germany), the National Radiation Laboratory of New Zealand (Christchuch, NZ) and Colorado State University (Ft. Collins, CO). One gauge of the level of agreement was the ratio of measurements obtained by the RMI laboratory to that of another participating institution. For example, in a comparison with LLNL, the ratios for ^{137}Cs in coconut fluid, coconut meat and soil were 0.94 ± 0.06 (1 SD, $n = 12$), 1.15 ± 0.08 (1 SD, $n = 12$), and 0.94 ± 0.28 (1 SD, $n = 61$), respectively. In a measurement of $^{239+240}$Pu in soil with three of the above laboratories, there was a 2.7% coefficient of variation among values reported. Corroboration of *in-situ* gamma spectrometry measurements was more difficult to determine as there was no direct intercomparison exercise conducted. However, comparison was made of external exposure-rates on the islands of Bikini Atoll derived from two independent sets of environmental measurement data: (1) ground level *in-situ* spectrometry measurements made with HPGe detectors in 1993 by the NWRS, and (2) aerial (25 m) gamma spectral measurements made with NaI detectors in 1987 by a contractor of the U.S. Department of Energy (EG&G 1982). The data were decay corrected to the same point in time. Almost without exception, islands that were very small in size had poorer agreement than larger islands. For Bikini Island, the average ratio between the two data sets was nearly 1.0. The average of all 99 values compared was 0.78; 81% of the ratios fell between 0.5 and 2.0.

In-situ gamma spectrometry measurements were made with high purity germanium detectors (HPGe) of 40% nominal efficiency (relative to a 3 in. × 3 in. NaI detector). These detectors were attached to 7 L liquid nitrogen cryostats, which could maintain suitably low temperatures in a tropical environment for over 3 d time. The minimum detectable *in-situ* count-rate for ^{137}Cs was estimated to be 0.0085 c s^{-1} for a counting time of 2 h. That count-rate corresponds approximately to 15 Bq m^{-2} of ^{137}Cs. *In-situ* detection limits for ^{241}Am and ^{60}Co were determined to be approximately 100 and 10 Bq m^{-2}, respectively.

Laboratory measurements for gamma emitters were conducted with two electro-cooled HPGe detectors of 40% efficiency with extended low-energy response. Detectors were each housed in 1-inch-thick lead shields, which were located in an air-conditioned building of wood construction. The counting facility was built on a bed of crushed coral that was dredged from the Majuro lagoon. The building was surrounded on 3 sides by the lagoon, approximately 4 m from the building, thus ensuring a low background environment. The minimum detectable concentrations for ^{241}Am, ^{137}Cs and ^{60}Co were estimated to be 2.0, 0.3, and 0.2 Bq kg^{-1}, respectively, for a 12-h counting period.

Gamma emitters, other than naturally occurring radioactivity, that were sometimes detected included ^{60}Co, ^{137}Cs, ^{152}Eu, ^{155}Eu, ^{102}Rh, ^{207}Bi and ^{241}Am. The detection of ^{152}Eu, ^{155}Eu, ^{102}Rh, and ^{207}Bi was limited to samples from the test site atolls.

Measurement of transuranic radioactivity was made by gamma spectrometry in the case of ^{241}Am and by alpha spectrometry for ^{238}Pu, ^{239}Pu, and ^{240}Pu. Plutonium extraction was based on the method of leaching, extraction with an ion exchange column followed by microprecipitation onto neodymium fluoride mounting. Minimum detectable concentration for plutonium isotopes was not explicitly calculated because in our procedure the sample mass was adjusted, based on a prior gamma spectrometry measurement of the ^{241}Am, to maintain approximately equal counting times necessary to maintain a measurement precision of ± 10% at 1 sigma confidence level. The minimum detectable concentration was empirically observed to be on the order of 0.04 Bq kg^{-1} for a 12-h counting period.

Measurement of ^{90}Sr/^{90}Y in soils and plants is also of interest for purposes of determining contamination by regional fallout and for assessing doses; however, these radionuclides were not measured by the NWRS for two reasons. First, resource limitations prevented incorporating measurements of strontium into the laboratory program. Second, previous measurement programs of food crops (e.g., Robison et al. 1988) showed that the concentration of ^{90}Sr in coconut milk was over 500 × less than for ^{137}Cs. Consequently, strontium normally contributes only 5–10% of the total projected dose.

Dosimetric evaluation

The radiological measurement data were used to estimate the expected effective dose-rate in 1994 using an assumed set of lifestyle and dietary assumptions. Methodology used for estimating prospective doses is discussed in Simon and Graham (1996) using a dietary model reported by Dignan et al. (1994) and external and internal dose factors from ICRP (1987; 1989).

For calculations of external exposure, building shielding was incorporated based on the assumptions of 9 h per day indoors and the combination of house building materials (wood) plus a coral gravel layer spread around the house reduces the exposure-rate from ^{137}Cs by 50%. The value used for effective dose equivalent per unit exposure from ^{137}Cs was 0.00613 Sv R^{-1}, interpolated from data in ICRP (1987). Age-dependent dose factors for internal dose were used for an assessment to the Rongelap population (Simon 1995); in all other cases, adult dose factors were used.

The dietary assumptions are an important determinant to the magnitude of estimated doses. The dietary data reported by Dignan et al. (1994) indicated that locally grown food contributed about 18% of the total caloric intake for the Rongelap community presently residing on a small island in Kwajalein Atoll. Total caloric intake-rates were estimated to be 1,900 ± 100 (1 SE, n = 48) and 2,750 ± 146 (1 SE, n = 68) kcal d^{-1} for women and men, respectively. The residence of the Rongelap people in Kwajalein Atoll, however, is temporary until resettlement of Rongelap Atoll can take place. Because this group of people is receiving surplus USDA food and financial compensation, their diet is minimally applicable to other Marshallese communities.

The dietary model for the internal dose calculations reported here assumes that 75% of the dietary intake is from a mixture of locally grown food, the remainder being imported rice. The relative proportions of locally grown food were extrapolated from the diet of Dignan. It is acknowledged that few Marshallese eat a diet containing this high of a proportion of locally produced food; however, this diet describes a traditional lifestyle diet (including rice), which may be chosen by some Marshallese. Regardless of the likelihood that individuals will consume such a diet in the future, the calculations presented here provide useful information to members of the community who are considering resettlement of Rongelap. Doses from other proportions of local food can be easily estimated by scaling the findings presented here.

Assessment calculations explicitly used radiological measurement data from the atoll surveys or parameter values estimated from the data. Soil concentrations of ^{137}Cs were estimated from the *in-situ* gamma spectrometric measurements by averaging the area inventory over the approximate root zone depth (30 cm). Those data were combined either with empirical data on concentrations in food or used with plant:soil concentration factors determined during the course of this study or reported by other investigators (e.g., Robison et al. 1982) to predict radioactivity levels in food and the subsequent intake.

RESULTS AND DISCUSSION

The findings of the NWRS are presented here in the same general form as presented to the Marshall Islands Government (Simon and Graham 1995a,b,c,d,e) though space limitations prohibit presenting findings of all radionuclides for all locations and for all of the various food products. The complete set of soil measurement data is shown for the purpose of indicating the range of data as well as the distribution of values. The data, shown in graphical form, are presented by island from which the samples were obtained. This presentation design best supports the needs of the Marshallese since their traditional lifestyle is to build the main community on the largest island and to use smaller islands of the atoll for food gathering purposes.

Previous reports (e.g., Robison et al. 1982; Robison and Phillips 1989) have shown that ^{137}Cs easily contributes most of the external and internal dose to present and future inhabitants of the atolls. This premise was examined both by measurement and computation and appears to be a valid conclusion. Hence, the findings presented here emphasize ^{137}Cs. Measurements of transuranic radioactivity were also made for completeness and because of public interest though calculations show that the dose commitment is small under any but extremely unusual circumstances. The importance of plutonium measurements may lie more within the realm of public perception of risk. The graphs of plutonium measurement data that are presented here also indicate the range and distribution as well as spatial variation among islands.

The *in-situ* gamma spectrometric measurement data were used to produce estimates of external exposure-rate from the primary gamma emitting radionuclides still present in the terrestrial environment, including ^{137}Cs, ^{241}Am and ^{60}Co. Because of the low environmental levels of ^{60}Co and the low penetrating power of ^{241}Am photons, only ^{137}Cs contributes significantly to the exposure-rate and, hence, to the external dose. Only the exposure-rate due to ^{137}Cs in the soil is reported here because the addition of the exposure-rate from ^{241}Am and ^{60}Co increases the exposure-rate by less than a few percent, well within the possible error of the ^{137}Cs dose estimates.

Fig. 1 shows the data set of areal activities (Bq m^{-2} ^{137}Cs) estimated from *in-situ* gamma spectrometry measurements. The atolls are ordered from left to right in this figure by the maximum value observed at each atoll. The atolls of Kwajalein, Rongelap, and Enewetak are divided into north (N) and south (S) sections either because of the extraordinarily large size of the atoll (Kwajalein) or because of a significant south to north contamination gradient over the atoll. The areal activity values, as well

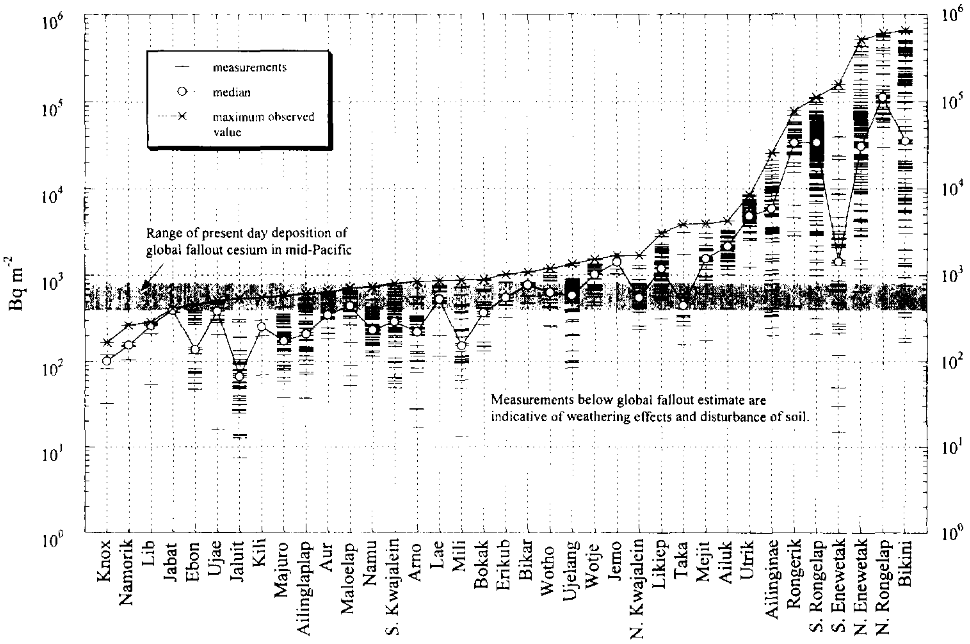

Fig. 1. Areal inventories of ^{137}Cs (Bq m^{-2}) at all atolls as estimated from *in-situ* gamma spectrometry measurements, ordered left to right by maximum observed value at each atoll (Kwajalein, Rongelap and Enewetak are divided into south and north portions).

as the external effective dose-rates, span five orders of magnitude. The data for about 10 atolls are not significantly different from the mean expected value of global fallout ^{137}Cs today at mid-Pacific latitudes.

Estimates of global fallout in the mid-Pacific were obtained from published data (Harley et al. 1960; Larsen 1985) and decay corrected to 1994. Data of ^{90}Sr deposition were used to derive cesium estimates by assuming a production ratio of ^{137}Cs/^{90}Sr of 1.6. The data on global fallout have been examined with respect to latitudinal and precipitation variation. Generally, global fallout deposition increases with increasing latitude in the northern hemisphere though it is also a strong function of annual precipitation rate. Within the Marshall Islands archipelago, a strong north-south rainfall gradient exists with annual precipitation of 300 cm typical in the southern atolls and 100 cm in the northern atolls. Thus, the possibility of higher deposition in the northern atolls was likely offset by the lower rainfall there. We believe the expected contribution from global fallout across the atolls of the Marshall Islands to be relatively constant because of this opposing effect and is estimated to be presently between 400 and 800 Bq m^{-2} of ^{137}Cs.

The activity ratio of ^{137}Cs to $^{239+240}$Pu from global fallout was investigated in the early 1970's by the AEC Health and Safety Laboratory (HASL) and determined to be a constant value in the north temperate zone. Based on further data collected by the HASL in 1979, the best estimate of the ratio in 1979 was determined to be 53 ± 0.5 (1 SD) (Beck and Krey 1983). Decay correcting this value to 1993, the mean date of the RMI measurements, would give a ratio of cesium to plutonium of 38.4 ± 0.36. Thus, the best estimate for plutonium in the environment of the Marshall Islands from global fallout is between 11 and 22 Bq m^{-2}. Assuming unit density for the top 5 cm of soil and a uniform distribution within this layer, the contribution of plutonium from global fallout is estimated to be between 0.2 and 0.4 Bq kg^{-1}. Different units have been used to describe the global contributions for cesium and plutonium because plutonium has not migrated downward to any significant degree and is almost entirely resident in the top 5 cm except where the soil has been overturned by natural events, animals or humans.

The external exposure-rates in only a very few locations, e.g., the northern islands of Enewetak, Rongelap and Bikini Atoll, would be considered to be at levels inappropriate for public residence (several mSv y^{-1}). These locations correspond to areal inventories greater than 10^5 Bq m^{-2}. There are a greater number of locations where careful consideration needs to be given to the interpretation and advice offered to Marshallese concerning radioactive contamination of food crops. The mobility of ^{137}Cs into plants via root uptake is enhanced in the coral soil environment relative to most continental locations because of the absence of clay minerals and the very low levels of potassium in the soil. Thus, in some locations on the atolls of Enewetak, Bikini and Rongelap, concentrations of ^{137}Cs in important food crops may be higher than 1,000 Bq kg^{-1} by up to a factor of 10× or 20×.

There is little international guidance available to suggest limits on radioactivity in foods except for the purpose of limiting international commerce of contaminated foods as set by the Codex Alimentarius Commission (WHO 1988; FAO 1991) of the Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). Similar levels were recommended by the International Atomic Energy Agency (IAEA 1994) as a generic intervention level to be applied following the accidental release of radionuclides for the specific case where alternative food supplies are readily available. Neither of these situations, however, are exactly applicable to previously contaminated lands. Because coconut milk and coconut meat are so important to the traditional Marshallese diet, and the fluid in some cases is the main source of liquid replenishment, careful evaluation is required concerning any recommendations to limit the use of local foods. The Codex limit of 1,000 Bq kg^{-1} has been useful, however, for judging the severity of contamination. Recommendations have been given to the Marshallese that lands should be remediated if they are contaminated to a degree such that food concentrations result significantly in excess of the Codex recommendations. Remediation for ^{137}Cs may be accomplished most easily by soil amendments of potassium (Robison and Stone 1992).

At each atoll, a range of soil cesium values or exposure-rates was observed (see Table 1). Ratios of the observed maximum to minimum values were usually less than a range of 50 (80% of atolls) though many were closer to a range of 25 (70% of atolls) and the median range was 10. This range of values is considered to be the result of both variations in the original deposition over the atoll as well as the result of weathering effects (downward migration, erosion) and human or animal disturbance to the soil.

Some indication of historical soil disturbance was evident by the percentage of deep soil profiles (0–30 cm) that deviated from the negative exponential model. Nearly half of 202 profiles sampled from the entirety of the Marshall Islands did not strictly fit a negative exponential model as indicated by a regression coefficient of determination (r^2) $\leq$ 90% (Graham and Simon 1996), though only a few deviated severely. Profiles showing extreme evidence of disturbance were generally limited to very small, erosion prone islands. Such deviations lead to increased uncertainty in calculations of soil inventory and exposure-rate; however, locations where there was evidence of previous soil movement or construction activities were generally avoided for making measurements. The range of data was not exaggerated by using sites expected to be unusually low; sample sites were chosen to avoid beach or highly eroded areas. Only five atolls had an observed maximum to minimum ratio for soil cesium that exceeded 100: Ailinginae, Rongerik, Rongelap, Bikini and Enewetak.

Other summary information of the measurement program is provided in Table 1. Included in this table is the number of islands monitored from each atoll, the number of soil profiles per km^2 in each atoll, the number of *in-situ* gamma spectrometry measurements per km^2 in each atoll and the number of *in-situ* measurements per soil profile. Generally, higher values for the three latter variables were indicative of small, separate reef islands (e.g., Jemo, Lib, etc.) or atolls of greater public interest.

For purposes of communicating with the public on the issue of relative contamination of the atolls, each atoll was ranked according to the relative degree that its deposition exceeded that from global fallout (Table 1). Four atolls (12%) had soil cesium levels not different from the mean expected global fallout level. Another nine atolls (22%) were possibly not different or only slightly above the mean global deposition. Seven atolls (21%) exceed the mean global fallout level by more than 10 times and 4 atolls (12%) exceeded it by more than 100 times.

A distinct pattern of increasing soil inventory with increasing latitude was observed. This pattern was generally expected due to the location of the test sites in the northern part of the nation and because the normal direction of the tradewinds is roughly along lines of constant latitude. Fig. 2 shows the maximum value of areal inventory of ^{137}Cs (Bq m^{-2}) from each atoll plotted as a function of latitude.

The maximum value of deposition at each atoll can be interpreted to be closest to the original value of deposition at each atoll after accounting for radioactive decay. This is most likely a good assumption for atolls that lie at distances of 100 km or more from the test sites though it is less certain for the test sites or nearby atolls. All islands in the Marshall Islands are coral and are virtually flat with highly porous soil with the result that precipitation is quickly absorbed into the soil. Standing water following storms is very rare; furthermore, there is no apparent erosion from runoff that might lead to collection of radioactivity in localized areas. The weathering process, in general, decreases the radioactivity inventory in the upper soil horizons over whole islands and does not result in localized variations. Regardless of the soundness of these hypotheses, the strong gradient in areal inventory with changes in latitude was clearly observed. Atolls at latitudes greater than 9° N show some evidence of having received local fallout deposition.

The predicted external plus internal effective dose-rate from ^{137}Cs ordered by atoll median for the diet of 75% locally grown food is shown in Fig. 3. The range of uncertainty (95% confidence interval) was determined to be approximately a multiplicative factor of 2.5 in either direction. This range was determined from stochastic calculations discussed in detail in Simon (1995) and in brief in Simon and Graham (1996). The calculations account for the variability of caloric intake among individuals, plant:soil concentration ratios and the range of soil concentrations typically encountered in a single atoll environment. In these calculations, however, the proportion of local food is set to be a constant value because various scenarios for the proportion of local food were examined separately.

Detailed data are presented in this paper for the islands of the test site atolls Bikini and Enewetak as well

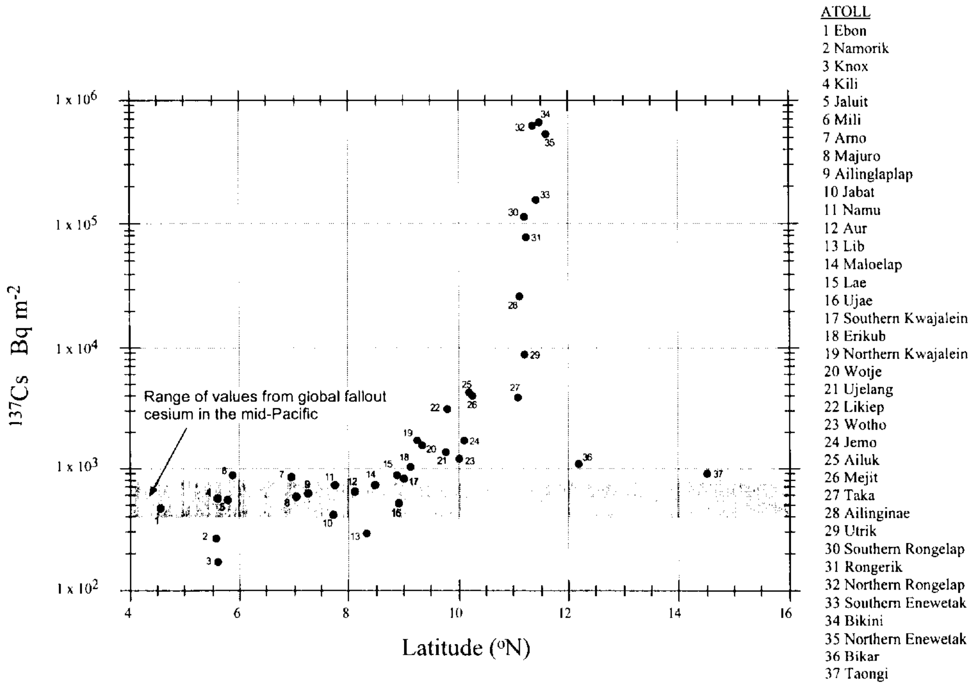

Fig. 2. Maximum observed value of ^{137}Cs in soil of atolls of the Marshall Islands (Bq m^{-2}) as a function of latitude (Kwajalein, Rongelap and Enewetak are divided into south and north portions).

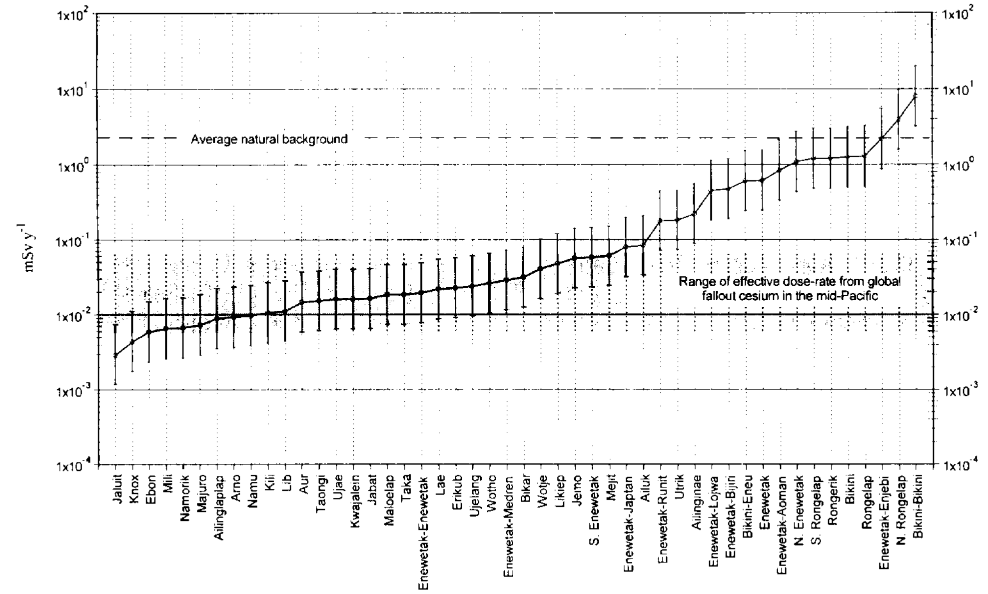

Fig. 3. All atolls: median predicted external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

as the islands of the other northern atolls within or near to the centerline of the fallout trajectory of the BRAVO event (see DNA 1979 for four similar cloud trajectory projections). Those atolls include Rongelap, Rongerik, Ailinginae, and Utrik. The remaining figures in this section present data for individual islands within these atolls. Three figures are shown for each of the atolls listed above: external effective dose-rate (mSv y^{-1}) from ^{137}Cs, external plus internal dose-rate from ^{137}Cs for the 75% local food diet (mSv y^{-1}), and measurements of ^{239,240}Pu in soil (Bq kg^{-1}). Figs. 4 through 6 are for Enewetak Atoll, Figs. 7 through 9 are for Bikini Atoll, Figs. 10 through 12 are for Rongelap Atoll, Figs. 13 through 15 are for Ailinginae Atoll, Figs. 16 through 18

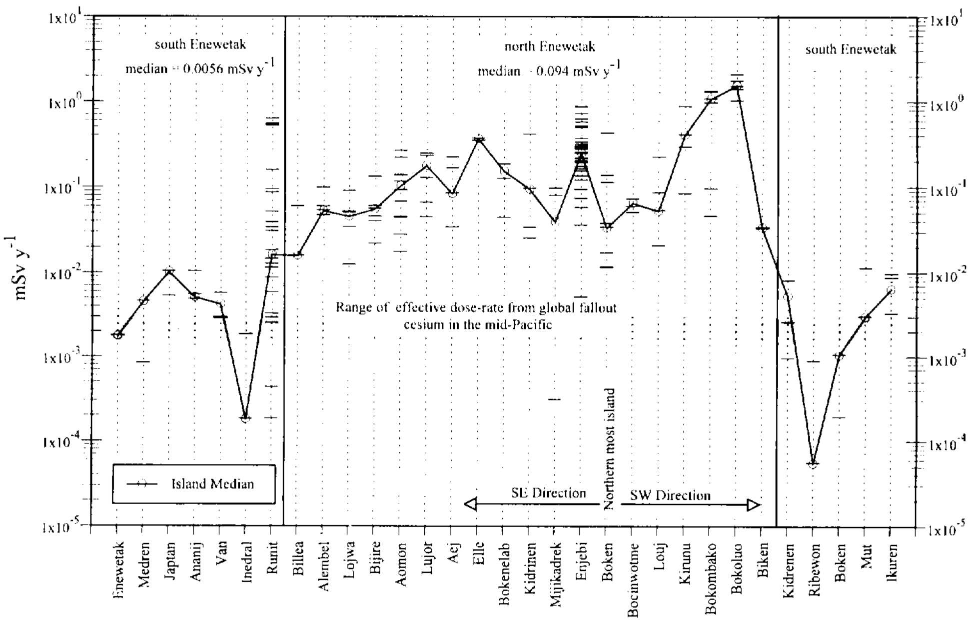

Fig. 4. Islands of Enewetak Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

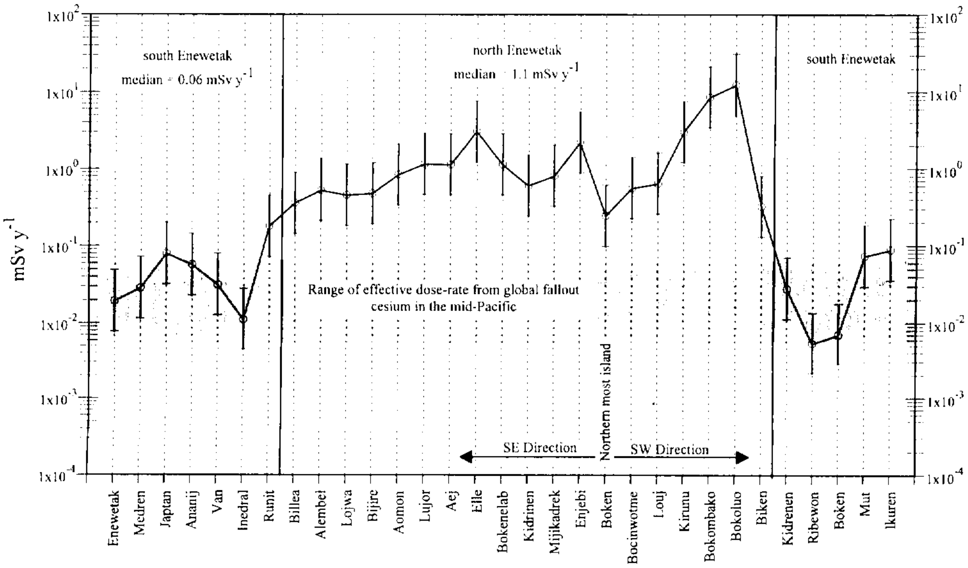

Fig. 5. Islands of Enewetak Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

are for Rongerik Atoll, and Figs. 19 through 21 are for Utrik Atoll.

For each figure, there are two reference values useful for comparison purposes: the level of radioactivity resulting from global fallout and the average background radiation dose to typical Marshallese. For those figures showing only external dose-rate (Figs. 4, 7, 10, 13, 16, 19), a useful comparison is the external effective dose-rate from global fallout cesium. This value (gray band) is based on our estimate of 400–800 Bq m^{-2} deposition of ^{137}Cs in the mid-Pacific. Our calculated dose-rates for this case are between 1.5×10^{-3} and 3×10^{-3} mSv y^{-1}. For those figures showing external plus internal dose-rate (Figs. 3, 5, 8, 11, 14, 17, 20), a useful comparison is the external plus internal dose-rate from global fallout cesium and based on a diet of 75% locally produced food. The range of possible dose-rates in this case is wider than for the external dose-rate by a factor of 2.5× to account for the additional uncertainties in food-chain transport and in dietary assumptions. Our calculated dose-rates for

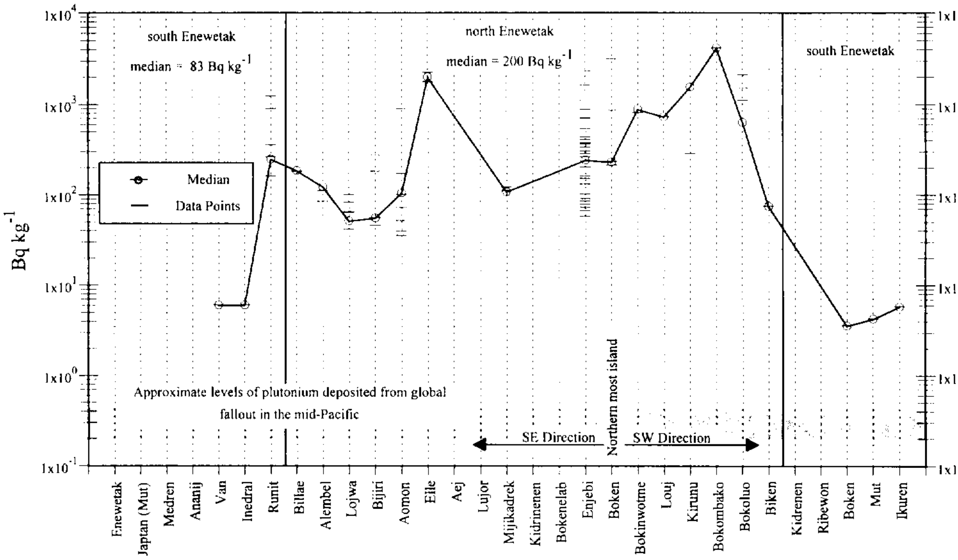

Fig. 6. Islands of Enewetak Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

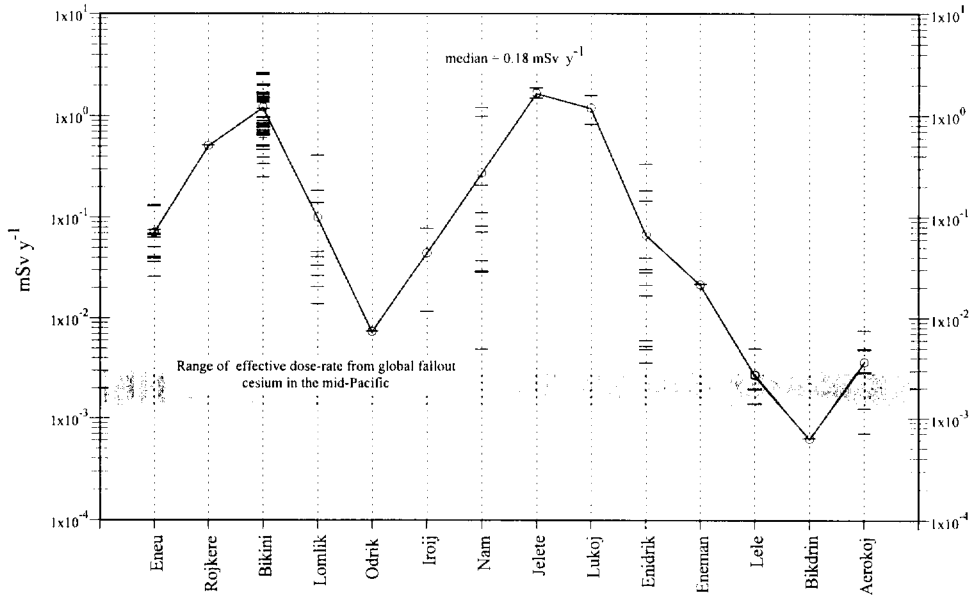

Fig. 7. Islands of Bikini Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

this case are between 5.6 × 10^{-3} and 6.75 × 10^{-2} mSv y^{-1}. For those figures showing surface soil concentrations of $^{239+240}$Pu (see Figs. 6, 9, 12, 15, 18, 21), a useful comparison is the concentration of plutonium expected in the soil from global fallout. Our estimated concentrations range from 0.21 to 0.42 Bq kg^{-1}. That range of values was derived from the ratio of cesium:plutonium discussed earlier and the deposition of cesium expected from global fallout.

An additional reference value useful for developing a perspective of the dose-rates shown here is the average background radiation dose received by typical Marshallese. It has been known for decades that natural radioactivity in the terrestrial environment is much lower in coral soils than in volcanic soils and the contribution of cosmic rays is lower at locations close to sea level. Thus, without dietary sources of radiation, the background dose in the Marshall Islands would be much lower (approximately 0.24 mSv y^{-1} for the sum of terrestrial and cosmic radiation) than at continental locations. However, because the typical diet of the indigenous people of the Marshall Islands depends greatly on seafood, the back-

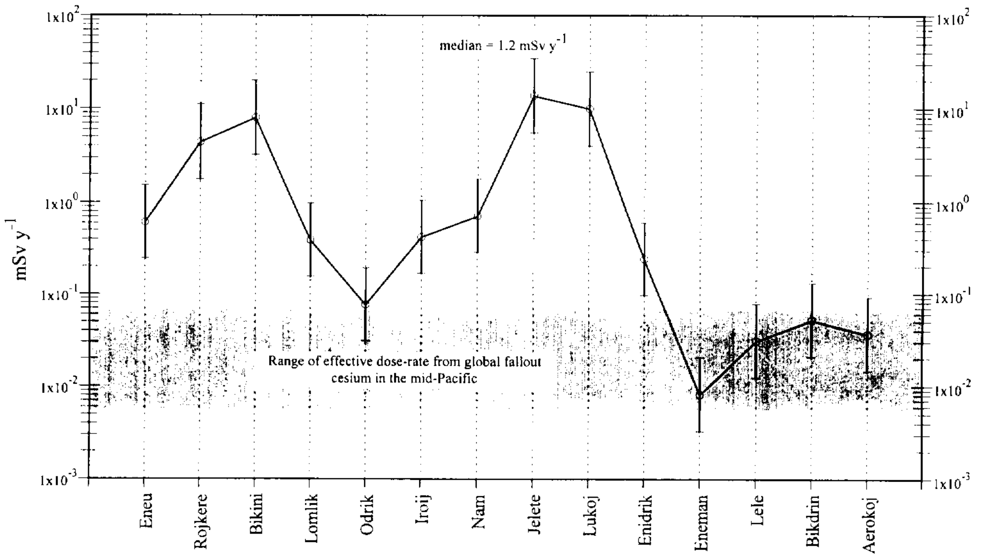

Fig. 8. Islands of Bikini Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

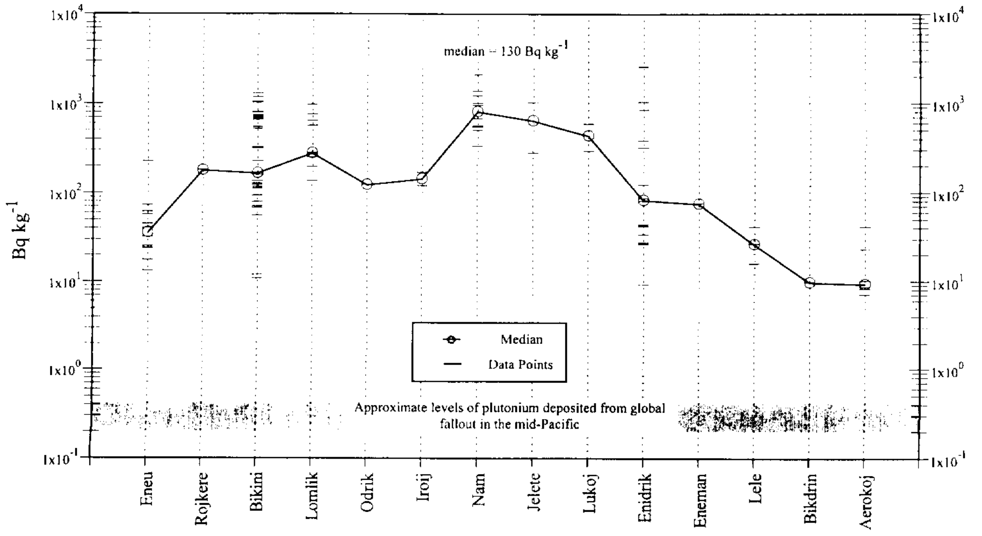

Fig. 9. Islands of Bikini Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

ground radiation dose is substantially increased due to ingestion contributions of ^{210}Po and ^{210}Pb in fish. The total average background radiation dose to Marshallese was reported by Noshkin et al. (1994) to be approximately 2.4 mSv, not much different than experienced elsewhere. However, as discussed, the primary source of that radiation dose is dietary rather than from radon and terrestrial gamma rays.

Two general trends in the measurement data were observed: (1) Terrestrial soil contamination levels at atolls other than the test site atolls generally do not vary by more than a factor of 50 among the islands of a single atoll, variations of a factor of 25 are more common; and (2) Small islands (i.e., less than 500 m length or 100 m width) invariably display lower concentrations of radioactivity in soil than do larger islands within the same atoll. Presumably smaller islands are more susceptible to erosion and washover by storm waves as well as to changes in the shape and mass of the island from deposition of new coral sand during tidal changes and storms. Furthermore, smaller islands have less developed vegetation, less litter; small islands also have poorly

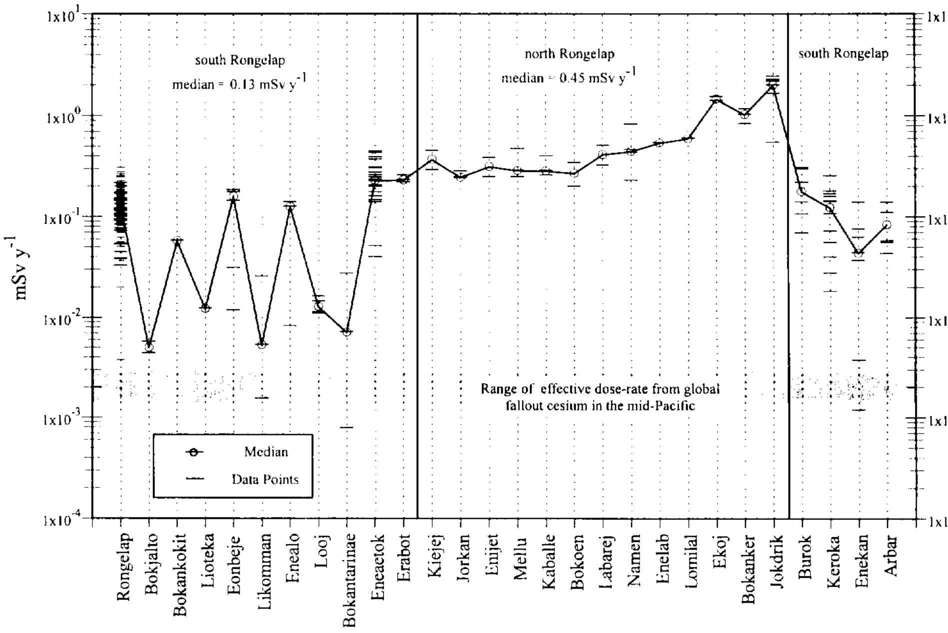

Fig. 10. Islands of Rongelap Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

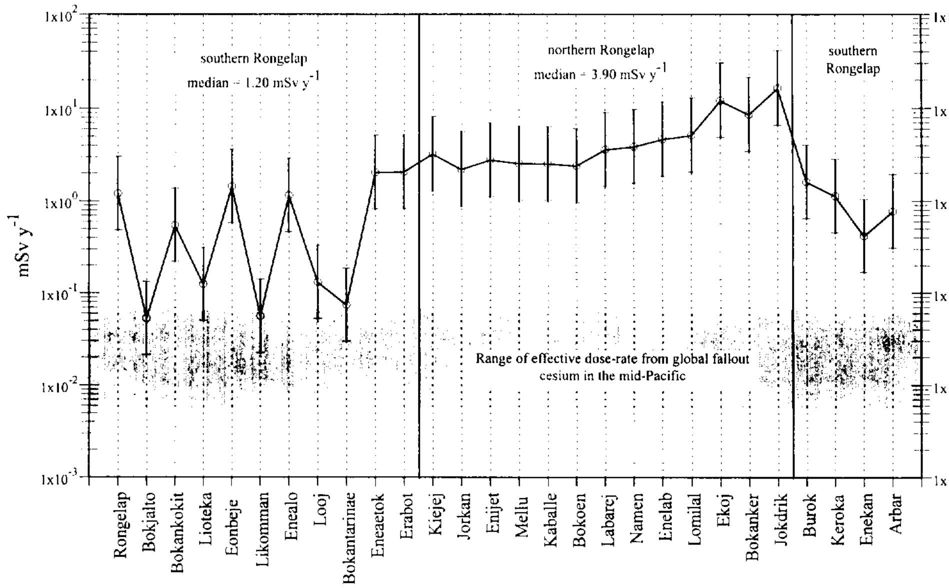

Fig. 11. Islands of Rongelap Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

developed soil with which to bind radioactivity deposited there.

SUMMARY

The NWRS has documented for the first time the present day levels of residual weapons fallout radioactivity throughout the entirety of the Marshall Islands. Radionuclide specific activities in the soil of islands in the mid-Pacific from global fallout sources are estimated from the literature to be approximately 400 to 800 Bq m^{-2} for ^{137}Cs and 0.2 to 0.4 Bq kg^{-1} for ^{239,240}Pu. Based on our observations, there are four atolls that show no evidence of having received local fallout from the

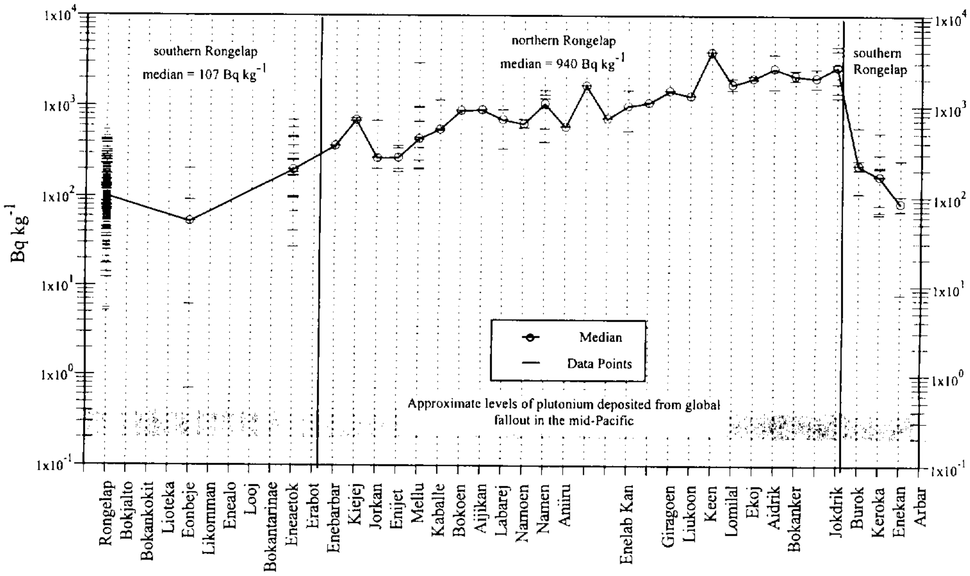

Fig. 12. Islands of Rongelap Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}) (unidentified locations are small unnamed islets).

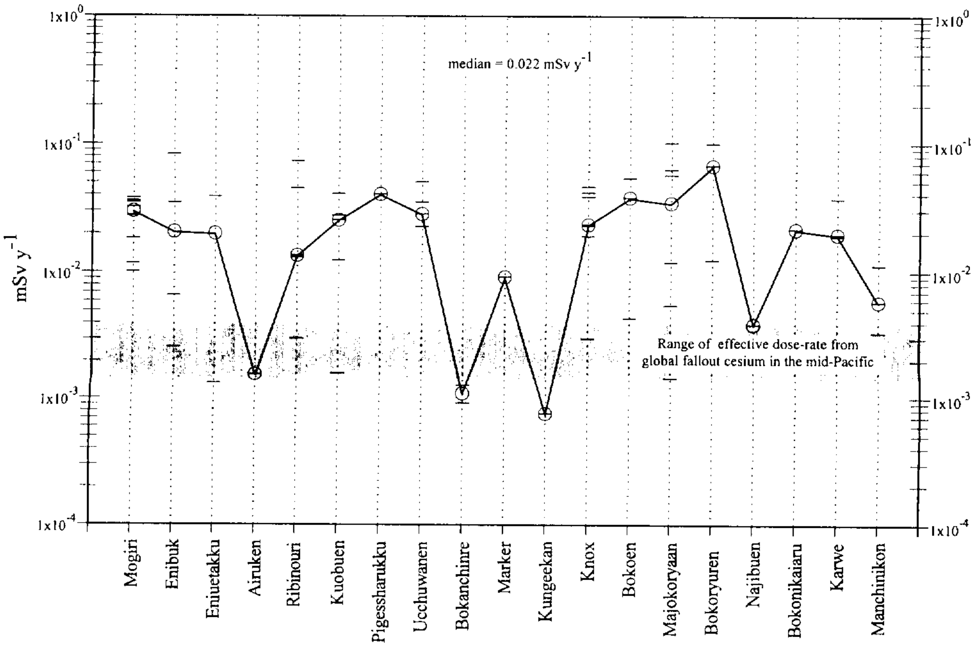

Fig. 13. Islands of Ailinginae Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

tests at Bikini and Enewetak. There are another ten atolls for which we cannot conclusively determine whether or not they received any local fallout or whether they are above the expected global background value.

Though most of the southern atolls in the RMI are near the expected global background level, some measurements were below this. Explanations for this phenomenon include weathering effects resulting in downward migration, dilution with clean humic material by litter fall or with coral material brought up from deep soil horizons by human or animal disturbance, erosion from ocean waves or coverage of the surface with new material from tides and waves.

A quantitative evaluation of the increase of fallout radioactivity with an increase in latitude has been documented for the first time. Specific activities in soil remain nearly constant over the latitude range of 4° N to 9° N. Values of ^{137}Cs in the terrestrial environment at locations

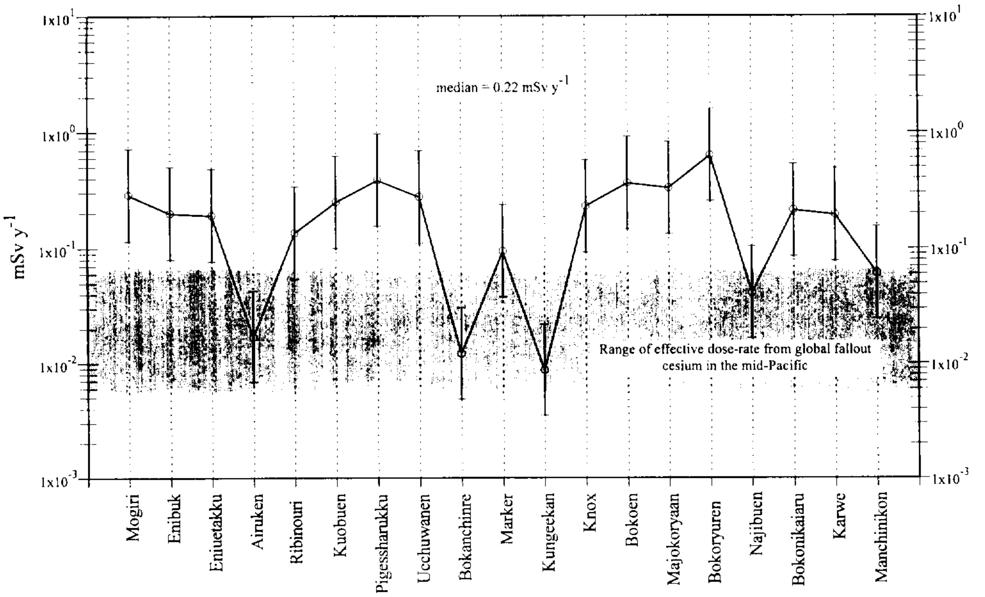

Fig. 14. Islands of Ailinginae Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

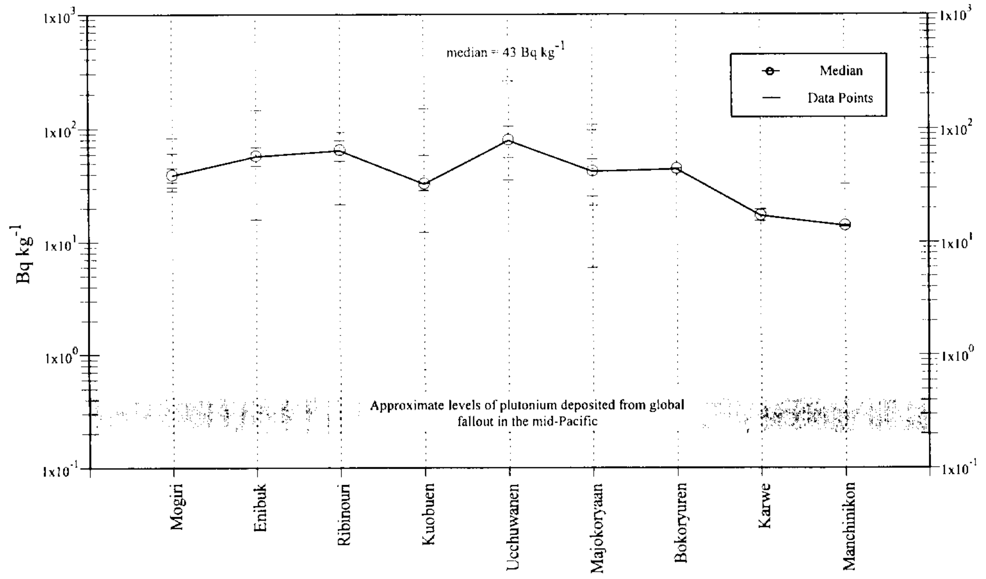

Fig. 15. Islands of Ailinginae Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

north of 9° increase rapidly to a latitude of 11.5° N where Bikini is located. At locations on three atolls, soil ^{137}Cs is more than 1,000 times the global background level.

It is apparent from our measurements that relatively small amounts of fallout reached locations as far south as Kwajalein Atoll. This conclusion corroborates the data of the HASL gummed film station which reported detectable radioactivity during the entire CASTLE and HARDTACK II series of tests conducted from 1954 through 1958.

The small amounts of residual radioactivity at the mid-latitude atolls (9° to 10.5° N) do not pose any measurable health hazard today or in the future. A number of islands in the atolls of Enewetak, Bikini and Rongelap require limited remediation before communities should be encouraged to return and live traditional lifestyles. This recommendation is contingent on the reasonable assumption that Marshallese will continue to consume locally grown food.

During its operational period, the NWRS received continuous oversight and peer review through the activities of the Scientific Advisory Panel. The laboratory of the NWRS successfully participated in international intercomparison exercises as part of a quality control

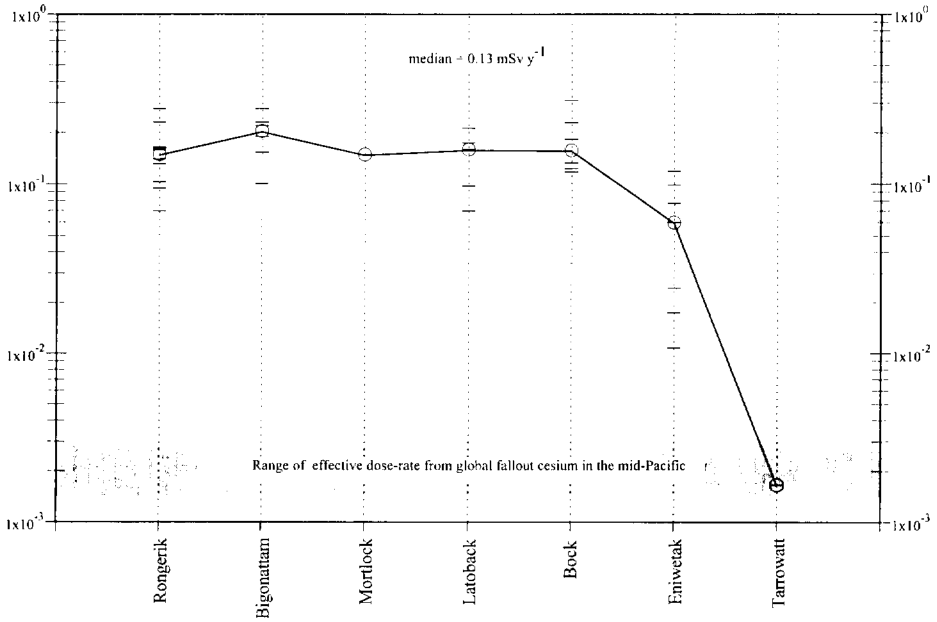

Fig. 16. Islands of Rongerik Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

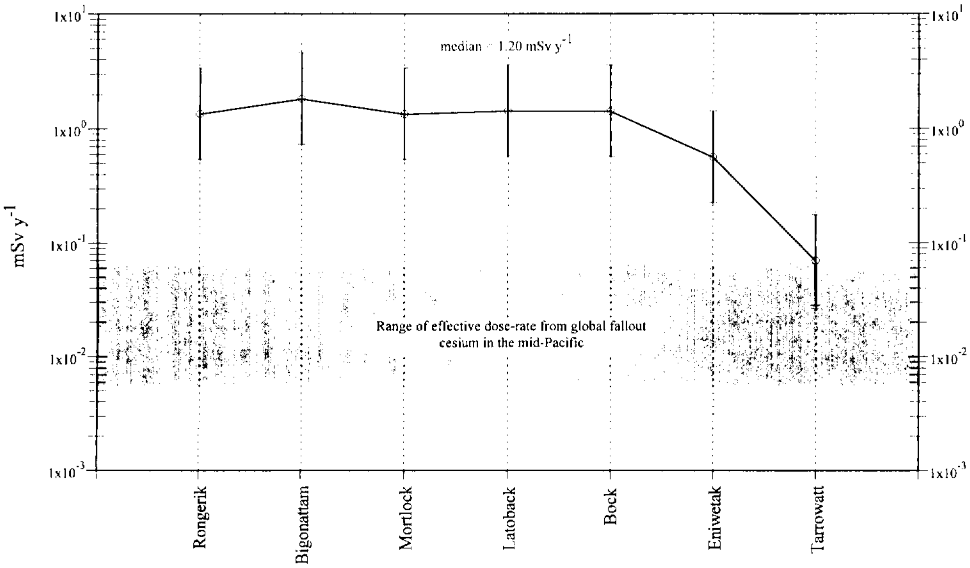

Fig. 17. Islands of Rongerik Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

program. Findings for locations previously monitored by the DOE were in good agreement. An assessment by the NWRS of the projected doses that might be received at Rongelap Atoll was similar both to findings of a National Academy of Sciences review group (NRC 1994) and to those of LLNL (Robison et al. 1994). Similarly, the findings of the NWRS for Bikini Atoll were reviewed and endorsed by an expert advisory group assembled by the International Atomic Energy Agency in December 1995 (IAEA 1996). These various activities have served to confirm the precision of the measurements and assessments reported by the NWRS.

Public perception of the dangers of residual radioactivity has been compounded among Marshallese as a result of continuing publicity over the last 40+ y, both by the popular media and by scientists. It is our observation that significant misunderstanding has been generated by the ongoing process of scientific study. Even the process of sampling foods or providing health examinations tends to add credence to local convictions of extensive radioactive contamination and latent health damage.

Adequate data on the radiological conditions of the Marshall Islands now exists such that the RMI government or local atoll authorities may determine the suit-

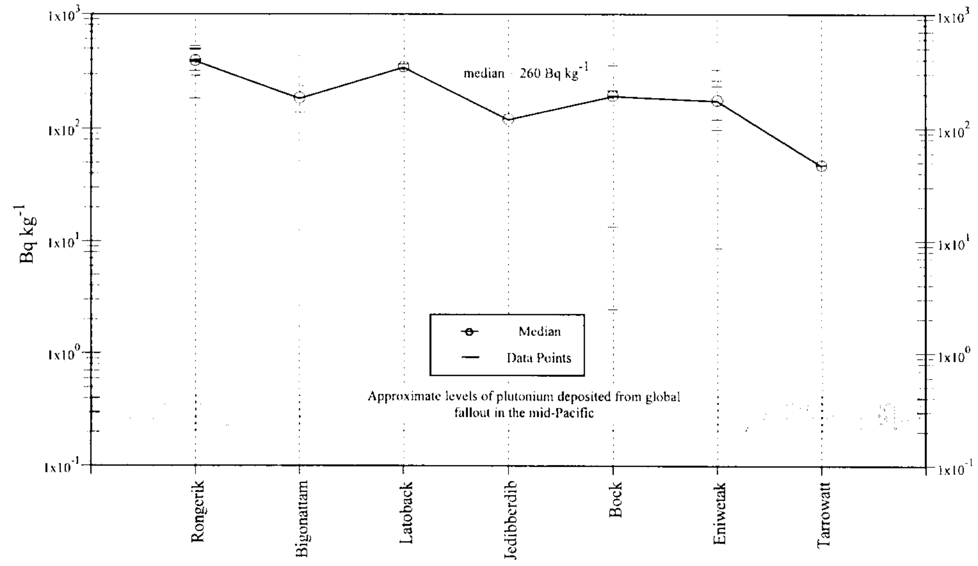

Fig. 18. Islands of Rongerik Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

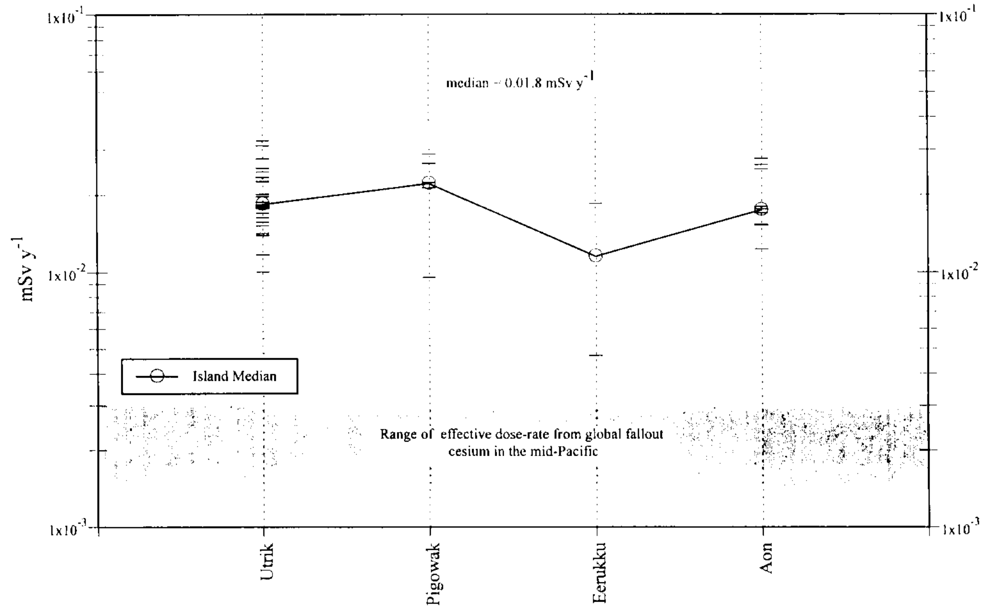

Fig. 19. Islands of Utrik Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

ability of any location for habitation and food gathering. The main challenge with respect to the radiological conditions of the Marshall Islands, other than remediation of limited locations, is in increasing the understanding of government leaders, health care workers, teachers, the media and the public about the true risks of radioactivity and about natural causes for cancer and other common diseases which, only in some instances, may be radiogenic in origin.

Acknowledgments—The Government of the Republic of the Marshall Islands provided financial support to the Nationwide Radiological Study. Administrative support was provided by the Office of the Chief Secretary and the Ministry of Foreign Affairs; liaison support was provided by Peter Oliver. Andrew Barron and Susan Duffy were an integral part of the original field survey team. Shiela Como and Andy Borchert served as laboratory radiochemists. Numerous Marshallese provided important assistance to the field and laboratory program, including Helkenna Anni, Antonio Jackson, Alee Jonas, Randy Thomas, Tom Schmit, Rosen Jorbwij, Ransey Larron, Glasses Mokroro, Alexander Noah, Renny Ohwiler, Fred Opet. Dirk H. R. Spenneman provided background information documents to support several of the atoll surveys. The Scientific Advisory Panel [A. C. McEwan (Chairman), K. F. Baverstock, H. G. Paretzke, K. Sankaranarayanan and K. R. Trott] were eminently helpful in designing and guiding the study and personally provided assistance on a wide range of technical issues and activities. Merril Eisenbud provided a great deal of direction to the principal scientist in matters of acquiring historical data and in setting

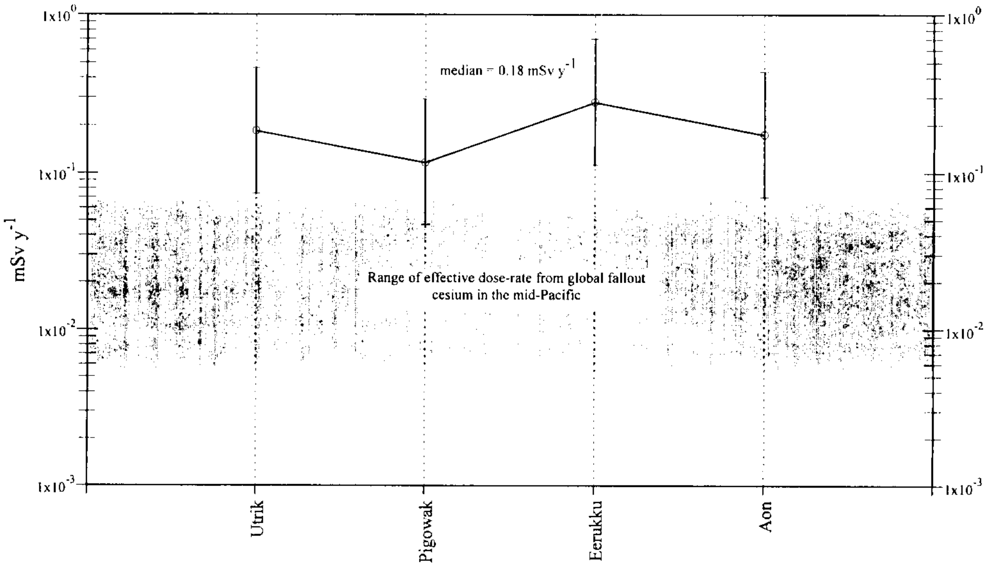

Fig. 20. Islands of Utrik Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

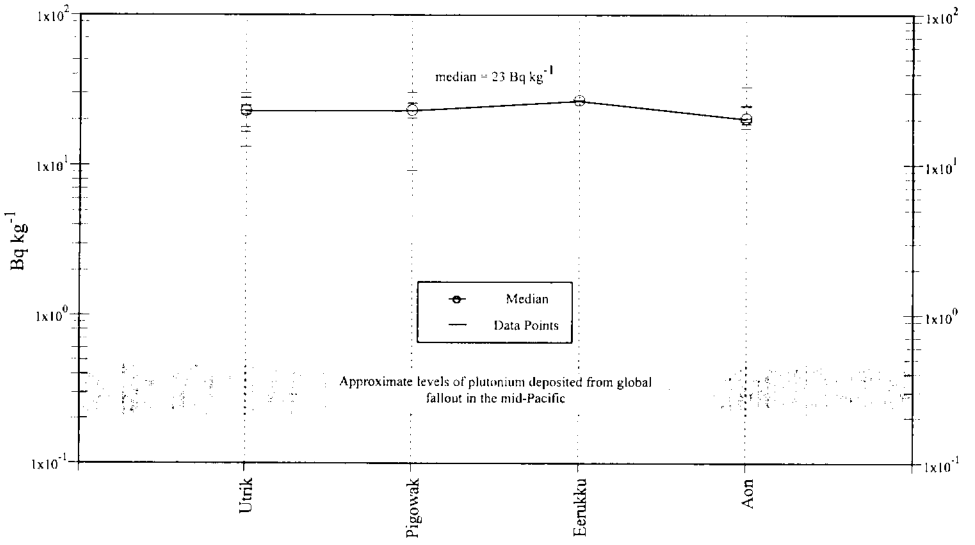

Fig. 21. Islands of Utrik Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

an example of how to conduct a study with scientific integrity. Staff of the U.S. Department of Energy and its contractor laboratories were helpful on many occasions, in particular, William Robison, Casper Sun, Harry *Pettingill* and Tom Bell. A number of individuals including the late Jeton Anjain, the late Henry Kohn, Harold Beck, Shawki Ibrahim and others contributed various kinds of support, advice or technical guidance. We thank the communities and local governments of the Marshall Islands for their cooperation and assistance during the intrusion into their lives by our atoll surveys. Rita Escher provided editorial comments on a draft of this manuscript. Finally, we thank our families and the families of the other staff who endured the long study with great patience.

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^{137}Cs EXPOSURE IN THE MARSHALLESE POPULATIONS: AN ASSESSMENT BASED ON WHOLE-BODY COUNTING MEASUREMENTS (1989–1994)

L. C. Sun, J. H. Clinton, E. Kaplan, and C. B. Meinhold*

Abstract—**The Marshall Islands were the site of numerous tests of nuclear weapons by the United States. From 1946 to 1958, nuclear devices were detonated at Enewetak and Bikini Atolls. Following the inadvertent contamination of the northern islands downwind of the 1954 Bravo Test, Brookhaven National Laboratory became involved in the medical care and the radiological safety of the affected populations. One important technique employed in assessing the internally deposited radionuclides is whole-body counting. To estimate current and future exposures to ^{137}Cs, data from 1989 to 1994 were analyzed and are reported in this paper. During this period, 3,618 measurements were made for the Marshallese. The cesium body contents were assumed to result from a series of chronic intakes. Also, it was assumed that cesium activity in the body reaches a plateau that is maintained over 365 d. We estimated the annual effective dose rate for each population, derived from the recommendations of the International Commission on Radiological Protection. The average ^{137}Cs uptake measured by the whole-body counting method varies from one population to another; it was consistent with measurements of external exposure rate. The analysis, though based on limited data, indicates that there is no statistical support for a seasonal effect on ^{137}Cs uptake. The critical population group for cesium uptake is adult males. Within the 5-y monitoring period, all internal exposures to ^{137}Cs were less than 0.2 mSv y^{-1}. Similarly, a persistent average cesium effective dose rate of 2 μSv y^{-1} was determined for Majuro residents.**

Health Phys. 73(1):86–99; 1997

Key words: Marshall Islands; whole body counting; cesium; dose assessment

INTRODUCTION

THE REPUBLIC of the Marshall Islands (RMI) is located in the central Pacific Ocean about 3,500 km southwest of Hawaii and 4,500 km east of Manila, Philippine Islands; the islands lie near the intersection of the Equator and the International Dateline (Fig. 1). The RMI consists of 29 coral atolls and 5 coral islands, all just above sea level. The total land area is about 180 km^2 (Patterson 1986). In 1946, the RMI was chosen for nuclear testing because of its remoteness, extremely low population density, and its geological features (DNA 1981).

Between 1946 and 1958, numerous nuclear devices and weapons were tested in the northern RMI at Bikini and Enewetak Atolls. Although these tests were considered vital to the defense of the free world during the cold war, the resulting radiological contamination and clean-up efforts remain as critically important consequences. Environmental contamination still is a health and safety issue for the RMI population (Lane 1989; Kohn 1988, 1989; National Research Council 1982, 1994; Baverstock et al. 1995). Many technical and non-technical reports on environmental, medical, radiological, health, and safety impacts on the Marshallese populations are available (AEC 1956a, 1956b; Committee on Atomic Energy 1957; Conard et al. 1975; ERDA 1977; DOE 1980; Tipton and Meinbaum 1981; U.S. Committee on Interior and Insular Affairs 1989; U.S. Committee on Energy and Natural Resources 1991; Conard 1992; U.S. Committee on Natural Resources 1994).

^{137}Cs, a product of uranium fission, has a considerable public-health impact because of its high yield and relatively long half-life of 30 y in the environment. In recent whole-body counting (WBC) field missions, ^{137}Cs was the only long-lived, gamma-emitting, weapons-related isotope detected in the Marshallese. Even the 5-y half-life of ^{60}Co, a common activation product generated in nuclear tests, is below our determined minimum detectable amount (MDA). Cesium compounds in the environment are water soluble and, therefore, may be transported and widely dispersed. Cesium also adheres to many components of soil from which uptake into the biota occurs. The major exposure pathways of cesium intake in the monitored populations are from inhalation of contaminated dust particles resuspended in the air, and from ingestion of contaminated foods stuffs, drinking water, and soil particulates (NCRP 1977, 1985a; UNSCEAR 1993; IAEA 1988). The effective half-life of ^{137}Cs in humans is about 110 d, which is much shorter than its radiological decay half-life ($T_{½} \approx$ 30-y) (NCRP 1977). Once in the body, cesium is quickly and uni-

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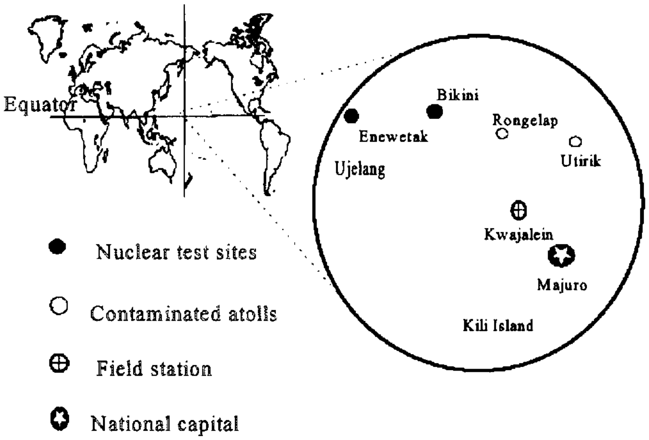

Land and water areas are 180 and 2,500,000 km^2, respectively.

Fig. 1. View of the Republic of the Marshall Islands' global location.

formly distributed.

The U.S. Department of Energy (DOE) Office of Health assigned responsibility for the Marshallese radiological assessments to Brookhaven National Laboratory (BNL) and Lawrence Livermore National Laboratory (LLNL). The two laboratories use independent methodologies for radiological monitoring and dose assessment. BNL has used whole-body counting and radiological analyses of urine samples (Cohn 1956, 1963; Cohn and Gusmano 1965; Greenhouse et al. 1977, 1979, 1980; Miltenberger et al. 1980, 1981; Lessard et al. 1980a, 1980b, 1984; Sun et al. 1991, 1992, 1993, 1995). LLNL researchers have based their assessments upon data from measuring levels of radionuclides in the environment (e.g., soil, water, plants, animals), from assessments of intake and distribution pathways for radionuclides entering the body, and from analyses of dietary patterns (Noshkin et al. 1979, 1988, 1994; Jennings and Mount 1983; Robison 1983; Shingleton et al. 1987; Robison and Stone 1992; Robison et al. 1980, 1982, 1987, 1988; Kercher and Robison 1993). The local foods in the northern atolls of RMI are coconuts, leaves, breadfruit, pandanas, taro, arrow root, birds, and a variety of seafood. Many assessments of cesium doses among Marshallese have considered the correlation between dietary patterns and nuclide concentrations in foodstuffs (Held et al. 1965; Hardy et al. 1964; Naidu et al. 1980; Robison 1983; Simon and Graham 1996). The BNL and LLNL determinations of Marshallese ^{137}Cs uptakes were first presented together during the 19th Annual Meeting of the NCRP (Robison 1983), and later, along with their results on ^{239}Pu uptake, at the Eighth International Radiation Protection Association Congress (Sun et al. 1992). Both ^{137}Cs and ^{239}Pu doses determined by the two laboratories substantially agree.

In March 1990, a six-member Marshall Islands Independent Scientific Advisory Committee (MIISAC)[†] reviewed BNL's quality assurance performance for all components of the bioassay monitoring and internal dose assessment programs for the Marshallese. The Committee stated that the WBC procedures used for estimating Marshallese body contents of ^{137}Cs, ^{60}Co, and ^{40}K conformed to recognized standards for measuring these nuclides *in vivo* (Hall et al. 1990).

In vivo WBC is a simple, accurate, and effective method of determining the quantity of gamma emitters in the body. WBC missions were conducted by BNL for the people of Bikini, Enewetak, Rongelap, and Utirik in 1989, 1991, 1993, and 1994. During this period, ^{137}Cs was the only fission product that was detected in these populations. This paper compiles the WBC results and associated dose analyses for these populations from 1989 to 1994.

On 21 February 1992, the DOE and RMI signed a Memorandum of Understanding (MOU 1992). Two action limits were agreed upon as conditions of the Rongelap Resettlement: (1) Rongelap residents would not receive a calculated annual effective dose of 1 mSv above local natural background, and (2) they would not be exposed to more than 630 Bq kg^{-1} (17 pCi g^{-1}) of transuranium elements in the soil of inhabited areas or food-gathering ones. Where these limits were exceeded, radiological dose-reduction methods would be initiated. For this reason, the cesium effective dose rate (μSv y^{-1}) is reported in this paper.

MATERIALS AND METHODS

Whole-body counting system

Whole-body counting was performed in two shadow-shielded chairs transported within RMI using a contracted vessel. Each WBC unit has a single thallium-doped sodium iodide detector, 29.2 cm (11.5 inch) diameter by 10.2 cm (4 inch) thick, manufactured by Bichron.[‡] The WBC detector is mounted on a pivoted arm allowing it to be centered across the front of the chair during counting and moved out of the way to allow access to the chair (Fig. 2). Since 1989, a Canberra System 100 (S-100)[§] multichannel analyzer (MCA) has been used in conjunction with an IBM[‖] personal computer (model Thinkpad 750). The counting signal is registered through the MCA's circuit board and the isotopes identified and their activity assessed with Canberra's GAMMA-AT[§] software.

The WBC system is calibrated with a bottle mannequin absorber (BOMAB) phantom. Energy identifications are based on four distinct photon peaks: 0.662

[†] The members were Roscoe Hall (Chairman, deceased; Savannah River National Laboratory), Norman Cohen (Environmental Measurement Laboratory), Keith Eckerman (Oak Ridge National Laboratory), Henry Kohn (Rongelap Reassessment Laboratory), Leonard Newman (BNL), and Hylton Smith (National Radiological Protection Board).

[‡] Bichron, 6801 Cochran Road, Solon, OH 44139.

[§] Canberra, 800 Research Parkway, Meriden, CT 06450.

[‖] IBM, http://www.ibm.com/.

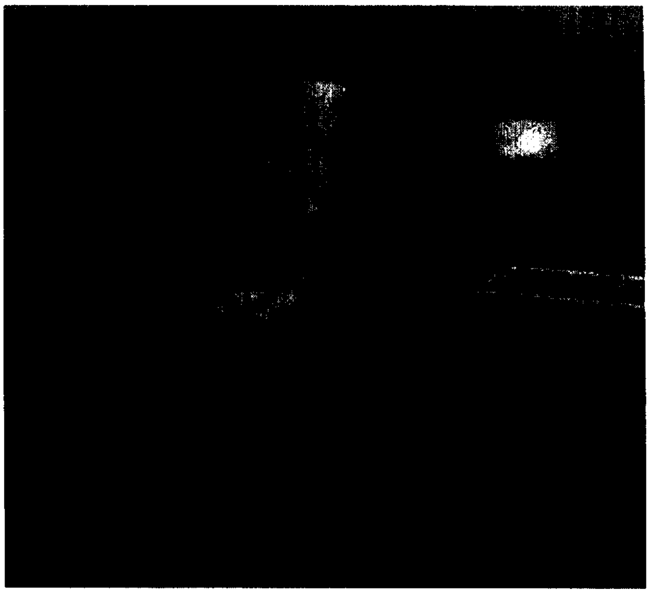

Fig. 2. Brookhaven's WBC system with BOMAB.

(^{137}Cs), 1.17 and 1.13 (^{60}Co), and 1.46 MeV (^{40}K). Counting efficiencies are established for four geometries by selecting whole or partial sets of the BOMAB phantom's segments called large, medium, small, and infant. The counting efficiency obtained with the large geometry is used to analyze spectra from persons weighing 60 kg or more, the medium geometry for people between 40 and 60 kg, and the small geometry for youngsters age 3 y or older who weigh less than 40 kg. The infant geometry is used for children younger than 3 y (weighing 8–15 kg). For an empty chair, the MDA of ^{137}Cs and ^{60}Co at the 95% confidence level for the present WBC system was established at 60 and 52 Bq, respectively (NCRP 1985b), in a 15-min count.

RESULTS AND DISCUSSIONS

Whole-body measurements and cesium activities

During BNL's 1989 field mission (July and August), staff visited Ebeye, Enewetak, Majuro, Mejatto, Utirik, and Bikini Islands. In 1991 and 1993, there were two missions each year, one in January–February (winter season), and the other in June–August (summer season). Weather and sea conditions during the winter season prohibit WBC operations at Mejatto Island, restricting all visits there to summer. The most recent WBC mission was conducted at Bikini, Enewetak, Mejatto, and Ebeye Islands in summer, 1994. All measurements were made on volunteers from among the Marshallese who either were directly exposed to fallout radiation, or resided on the Bikini, Enewetak, Rongelap, and Utirik Atolls. As a quality assurance procedure, 5% of the volunteers at each counting location were re-counted, either in the same chair or in the second chair. Table 1 shows that 3,618 WBC measurements were made on the Marshallese during these 5 y, including 13 Bikinian DOE employees who were working on Bikini Island, Bikini Atoll. The numbers given are for each population group, irrespective of where the whole-body counts were made. No attempt was made to examine the former inhabitants of Bikini located on Kili Island.

Table 1. Distribution of WBC measurements.[a]

Population	1989	1991	1993	1994
Enewetak	228	355	442	283
Rongelap	273	446	216	333
Utirik	423	290	316	—
Bikini[b]	8	—	—	5
Column sum:	932	1,091	974	621

[a] Number of participants is about 10% fewer due to quality assurance by double counting.

[b] These Bikinians were DOE workers and members of their immediate families.

Enewetak

As Fig. 3 shows, in December 1947, before the nuclear testing program began on Enewetak Atoll, all residents of Enewetak were relocated to Ujelang, Ujelang Atoll, RMI (~250 km southwest of Enewetak) (DNA 1981). After the tests ended, a major radiological cleanup and rehabilitation program was conducted during the late 1970's and early 1980's. After the cleanup, the people of Enewetak began to resettle the southeastern part of Enewetak Atoll (Enewetak, Japtan and Medren Islands) in 1980, at which time a routine WBC program was started.

Table 2 summarizes the ^{137}Cs body content of Enewetak volunteers measured during the 1989, 1991,

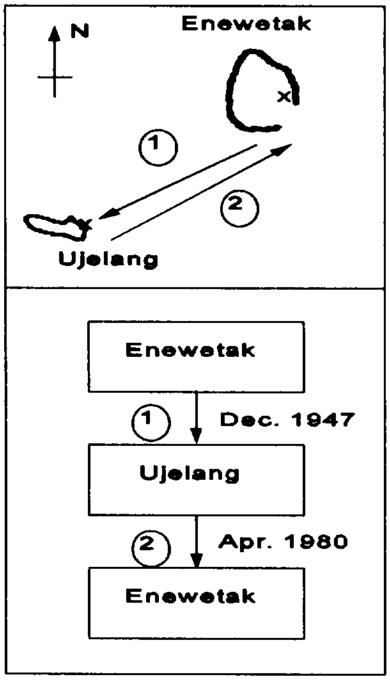

Fig. 3. Relocation timeline for Enewetak population.

Table 2. Comparison of ^{137}Cs measurements of the Enewetak population by age and gender.

	July–August 1989					February 1991					February 1993					August 1994				
Value	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
	Both sexes					*Both sexes*					*Both sexes*					*Both sexes*				
No. counted	146	58	24	0	228	245	62	47	1	355	261	86	91	4	442	105	35	125	18	283
Mean	615	398	180		514	1,043	575	192	50	846	276	94	63	39	195	365	146	69	40	187
SD[b]	676	564	155		629	1,427	744	222		1,267	351	63	51	13	289	354	96	50	20	261
Maximum	4,059	3,189	715		4,059	14,122	3,589	939		14,122	3,646	283	346	55	3,646	2,463	378	346	113	2,463
Median	419	253	112		318	632	272	62		448	165	74	43	36	87	320	128	54	33	88
	Males					*Males*					*Males*					*Males*				
No. counted	80	24	15	0	119	129	30	23	0	182	131	47	47	2	227	58	26	63	8	155
Mean	829	553	190		693	1,271	884	233		1,076	358	102	69	29	242	457	139	74	45	227
SD	818	798	180		791	1,683	944	224		1,508	439	60	58	2	362	416	91	49	29	315
Maximum	4,059	3,189	715		4,059	14,122	3,589	826		14,122	3,646	260	346	31	3,646	2,463	315	281	113	2,463
Median	579	300	113		454	824	490	169		628	210	87	43		110	389	119	59	35	108
	Females					*Females*					*Females*					*Females*				
No. counted	66	34	9	0	109	116	32	24	1	173	130	39	44	2	215	47	9	62	10	128
Mean	355	289	163		319	790	286	153	50	604	194	85	57	49	145	252	167	64	36	138
SD	285	274	108		275	1,023	281	218		891	201	65	42	10	171	212	111	50	8	163
Maximum	1,582	1,423	293		1,582	5,809	1,067	939		5,809	1,171	283	290	55	1,171	1,145	378	346	52	1,145
Median	303	219	112		253	462	186	46		348	104	61	44		61	173	158	49	33	71

[a] All values are in the unit Bq, exept counts.

[b] Standard deviation.

1993, and 1994 field missions. All these values were based on individual weight and later were classified by age and sex. The Marshallese age groups were defined as follows: adult (A) were individuals 16 y and older; teenage (T) were 11–15 y; juvenile (J) were children of 3–10 y; and infants encompassed birth through 2 y of age.

Table 2 shows that 146 adults were measured in 1989: 80 males and 66 females. The arithmetic mean ($\bar{x}$) and standard deviation (SD) of this group was 615 ($\bar{x}$) ± 676 (1 SD) Bq. The median value was 419 Bq, and the measured values ranged from 4,059 Bq to less than the MDA.

Table 2 also shows that ^{137}Cs body contents in the Enewetak population increased from 1989 to 1991, then decreased in 1993, and rose somewhat in 1994. Since cesium uptake directly reflects dietary intake and is proportional to the environmental concentration of cesium, the changes cannot be completely explained from dietary patterns (discussed later). However, they may reflect the consumption of contaminated food from the northern islands. In 1991, the highest measurement of ^{137}Cs body content obtained during any mission, 14 kBq (about 0.2 mSv effective dose based on a single acute ingestion), was from an adult male on Enewetak. A few weeks earlier he had camped on Enjebi, an uninhabited northern island in the Enewetak Atoll where the median ^{137}Cs activity in the soil was about 100 times greater than in the inhabited southeastern islands (ERDA 1977), and had eaten the local food; this could account for his elevated body content.

Measurement of external exposure rate is the quickest method to assess ground contamination resulting from fallout. For example, Simon and Graham (1995) reported the median external effective dose rate from ^{137}Cs on Enewetak, Medren, Japtan, and Enjebi Islands was about 2, 5, 10, and 200 μSv y^{-1}, respectively. The low dose rate for Enewetak Island was an overall result of removing the top 30 cm of soil during the DNA cleanup program. Since then, the entire population has relied primarily on imported food from the United States Department of Agriculture. Further, the major local food supplies, such as coconuts, leaves, and vegetables must be collected from neighboring islands (e.g., Medren and Japtan). Hence, the WBC measurements should not be expected to correlate with the reported low exposure rates at Enewetak Island. Our WBC measurements also show that the adult male group encompasses the maximum individual and the highest average cesium body content. Cesium distributes uniformly throughout the body so that a larger body mass retains more cesium (ICRP 1990; 1993). Although ICRP uses the same model for both genders, apparently the average content of adult females is approximately half that of the males for the people of Enewetak. This difference may reflect fishing and other outdoor activities by males and their associated consumption of foods in which cesium has been concentrated from the northern islands of the atoll.

Coefficient of variation (CV = $\bar{x}$/SD) analysis often is used to assess the stability of data. The CV values associated with the 1991 WBC data are larger than all other years. Since cesium uptake is proportionally related to its concentration in food stuffs, the scattered data may be influenced by the consumption of local foods from other islands. Since the CV values in 1994 were less than unity, the corresponding WBC results are expected to better represent cesium body content for the Enewetak population.

Rongelap

The inclusion of the Rongelap and Utirik populations in BNL's WBC program resulted from the 1954

Bravo test when, due to a large unexpected yield and tropospheric transport, radioactive dust was carried eastward (AEC 1956b). Two hundred and ninety people [64 Rongelapese, 18 Ailinginaese, 157 Utirikese, 28 American servicemen (Cronkite and Bond 1956), and 23 Japanese fishermen (Kumatori et al. 1980)] were exposed to this dust. The estimated external radiation was about 1.75 Gy for the Rongelap population and 0.14 Gy for the Utirik population (Sondhaus et al. 1956); each population was evacuated elsewhere in the Marshall Islands, for 3 y and for 3 mo, respectively. Fig. 4 shows their detailed relocation timeline, including the 1985 relocation of the Rongelapese to Mejatto Island, Kwajalein Atoll, because of their concern with the health and environmental effects of residual fallout (U.S. Committee on Interior and Insular Affairs 1989; U.S. Committee on Energy and Natural Resources 1991; Baverstock et al. 1995; Sun et al. 1995).

Table 3 summarizes WBC data for the Rongelapese living on Mejatto Island. The average cesium body content in the population has decreased slightly over the 5-y monitoring period. The latest data show that cesium intake at this location is similar to levels in the southern RMI areas unaffected by Bravo fallout. It is important to note that because of the low level of intake and the relatively short effective half-life of ^{137}Cs in humans (110 d), the measurement could only detect post-intake of cesium within 160 d ($\sim 110 \div 0.693$). Therefore, the current estimates represent peoples' diet and lifestyle on Mejatto Island only. Simon and Graham (1995) reported that the median external effective dose rate from ^{137}Cs on Mejatto Island (N. Kwajalein Atoll) and Rongelap Island were at about 2 and 150 μSv y^{-1}, respectively. These values suggest that ^{137}Cs exposure upon return to Rongelap might be significantly greater than the values reported in Table 3.

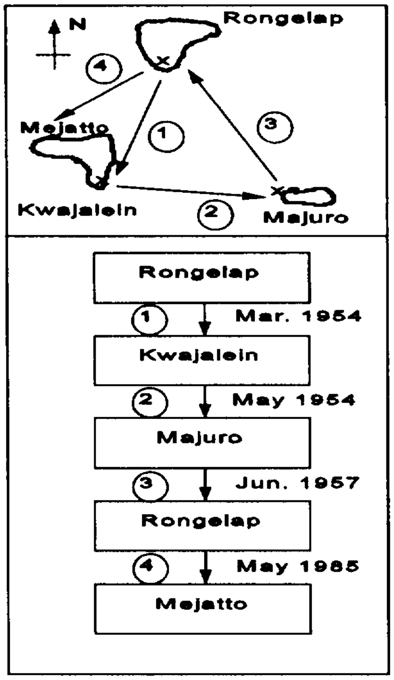

Fig. 4. Relocation timeline for Rongelap population.

Utirik

The people of Utirik remained on their island, except for 3 mo after the Bravo detonation (Fig. 5). Table 4 summarizes the statistical WBC parameters from 1989 to 1993 for the Utirikese. The average cesium body content in the Utirik population was 761 ± 778 (1 SD), 904 ± 766 (1 SD), and 310 ± 357 (1 SD) Bq in the 1989, 1991, and 1993 missions, respectively; cesium exposures increased from 1989 to 1991, and decreased from 1991 to 1993. Many Utirikese reside on Majuro and Ebeye Islands for economic and social reasons. Majuro Island is the capital of the RMI and has become the most socioeconomically developed island in the Marshall archipelago. Ebeye Island attracts many Marshallese people because of the job opportunities at the nearby Kwajalein U.S. Military Base. Due to the short retention time of cesium in the body and changes in dietary intake of cesium at each location, it is difficult to obtain a reliable population average value for Utirik inhabitants without separating the population according to each WBC location. Therefore, neither the annual average cesium burdens nor the trend of population uptake, shown in Table 4, is expected to be representative of the people living on Utirik Island.

Table 5 lists the values of WBC measurements obtained from the Utirik population at the location where the WBC was performed: Ebeye, Majuro, and Utirik Islands. These islands are more than 200 km apart, and only Utirik lies in the downwind direction that received fallout from the Bravo test. At each place, the lifestyle and foods vary as do the environmental cesium levels.

The median external effective dose rates from ^{137}Cs on Ebeye Island (S. Kwajalein Atoll), Majuro Island, and Utirik Island were about 1.5, 0.1, and 18 μSv y^{-1}, respectively (Simon and Graham 1995). Simon and Graham indicate that the ^{137}Cs concentrations in soil on both Majuro and Ebeye Islands are only slightly above those expected from global fallout deposition. Thus, although the values in Table 5 can be used to determine baselines for cesium uptake for inhabitants of Majuro and Ebeye, it is only the values obtained on Utirik Island that reflect cesium intake related to the United States nuclear tests done in the Marshall Islands, and, therefore, are appropriate for dose estimations of Utirik populations.

Bikini

Bikini residents were first relocated to Rongerik Atoll before testing began in 1946, and then moved to Kili Island in 1948. For radiological safety reasons, they have been unable to resettle in their homes, except for a short period in the 1970's when the island was thought to be safe for habitation (Greenhouse and Miltenberger 1977; Greenhouse et al. 1977, 1979, 1980; Robison 1983; Lessard et al. 1980b, 1984). Today, the majority of

Table 3. Comparison of ^{137}Cs measurements of the Rongelap population by age and gender.

	July–August 1989					June 1991					July–August 1993					August 1994				
Value	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
	Both sexes					*Both sexes*					*Both sexes*					*Both sexes*				
No. counted	193	63	17	0	273	257	113	76	0	446	129	54	33	0	216	199	69	63	2	333
Mean	90	66	66		83	78	56	47		67	70	63	40		64	70	56	42	35	61
SD[b]	51	16	27		45	40	26	16		36	39	34	11		36	45	34	13	2	40
Maximum	435	131	129		435	283	168	146		283	249	194	71		249	370	205	83	37	370
Median	74	68	50		72	63	46	44		57	53	49	36		49	55	42	36		49
	Males					*Males*					*Males*					*Males*				
No. counted	90	29	9	0	128	124	60	41	0	225	63	33	15	0	111	98	34	35	1	168
Mean	95	67	65		87	84	63	47		72	70	68	41		65	75	66	44	37	66
SD	61	16	27		54	45	34	19		41	41	38	13		39	43	35	14		39
Maximum	435	103	119		435	283	168	146		283	249	194	71		249	211	167	83		211
Median	76	68	49		73	65	47	44		58	50	56	36		50	57	52	37		51
	Females					*Females*					*Females*					*Females*				
No. counted	103	34	8	0	145	133	53	35	0	221	66	21	18	0	105	101	35	28	1	165
Mean	85	66	67		80	73	48	46		63	71	55	40		62	65	47	39	34	56
SD	39	16	30		36	34	10	11		30	37	25	10		34	46	31	11		41
Maximum	246	131	129		246	229	80	107		229	222	130	69		222	370	205	69		370
Median	73	68	59		71	63	46	44		56	58	42	35		48	51	37	36		43

[a] All values are in the unit Bq, exept counts.
[b] Standard deviation.

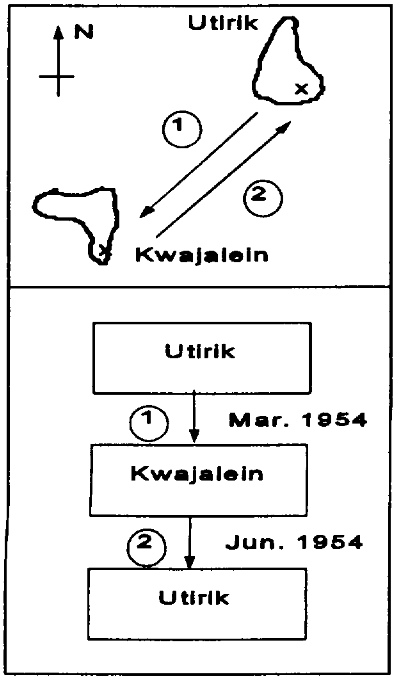

Fig. 5. Relocation timeline for Utirik population.

the Bikini people still live on Kili Island (Ellis 1986). Fig. 6 gives a detailed account of when and where the Bikinians were relocated. The median external effective dose rates from ^{137}Cs on Kili and Bikini Island were measured at about 1 and 600 μSv y^{-1}, respectively (Simon and Graham 1995). Plans are being studied for a radiological cleanup at Bikini.

Table 6 gives the WBC measurements for 13 Bikini residents who either worked for DOE or were family members of DOE workers at Bikini in 1989 and 1994. Their food was imported, and their living conditions were more modern so that measurements of cesium intake are likely to be completely different and inappropriate for estimating uptake of inhabitants with a more traditional style.

Seasonal variations

In both 1991 and 1993, there were two field missions on Majuro Island. The summer seasons' and winter seasons' WBC results were compared to establish whether there are seasonal variations in cesium uptake. Such seasonal variations have been reported and were attributed to increased water consumption during the summer and to seasonal variations in the concentration of the isotope in food stuffs (Hanson et al. 1964; UNSCEAR 1993). Table 7 compares all the measurements obtained on Majuro Island. These data suggest that 1) for adults (male and female), the cesium average in February is higher than in July, and 2) unlike adults, there is no seasonal difference for youths. Statistical comparisons of the 1991 and 1993 seasonal data only partially support these statements because of the high standard deviations. The apparent variations for the adults may reflect more outdoor activity in the summer, such as sailing and fishing, and less in the winter due to ocean waves and strong winds. Possibly because of increased activity in the summer, people may eliminate fluid faster, which lowers cesium concentration. Youths' land-based, outdoor activities are more consistent throughout the year; in fact, the difference in temperature and precipitation between February and July are small in the RMI.

The data in Table 7 were derived from a mixed, exposed population (i.e., Enewetak, Rongelap, and Utirik) whose whole-body counts were taken at Majuro Island. Hence, these WBC data should neither be com-

Table 4. Comparison of ^{137}Cs measurements of the Utirik population by age and gender.

	July–August 1989					February 1991					July–August 1993				
Value[a]	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
	Both sexes					*Both sexes*					*Both sexes*				
No. counted	316	80	27	0	423	212	47	27	4	290	184	82	50	0	316
Mean	810	673	449		761	997	780	492	185	904	400	263	53		310
SD[b]	784	794	554		778	772	835	317	106	766	405	249	55		357
Maximum	3,537	2,946	1,936		3,537	3,992	3,352	1,342	329	3,992	2,048	1,289	285		2,048
Median	682	193	77		585	904	585	491	158	801	260	191	36		137
	Males					*Males*					*Males*				
No. counted	164	42	11	0	217	106	27	14	3	150	95	39	26	0	160
Mean	975	821	646		929	1,187	929	572	215	1,063	481	286	51		363
SD	876	934	631		878	865	1,037	356	107	882	466	244	42		411
Maximum	3,537	2,946	1,936		3,537	3,992	3,352	1,342	329	3,992	2,048	809	209		2,048
Median	902	167	848		830	1,171	642	674	200	889	390	231	36		179
	Females					*Females*					*Females*				
No. counted	152	38	16	0	206	106	20	13	1	140	89	43	24	0	156
Mean	632	510	314		585	807	580	407	96	732	315	242	55		255
SD	625	574	468		609	614	375	256		574	307	255	67		283
Maximum	2,579	2,322	1,327		2,579	3,544	1,290	806		3,544	1,300	1,289	285		1,300
Median	450	193	67		318	829	523	390		752	162	174	35		95

[a] All values are in the unit Bq, except counts.
[b] Standard deviation.

Table 5. Comparison of ^{137}Cs measurement of the Utirik population obtained on various islands.

	July–August 1989					February 1991					July–August 1993				
Value[a]	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
	Utirik					*Utirik*					*Utirik*				
No. counted	154	37	10	0	201	156	30	20	4	210	106	47	6	0	159
Mean	1,297	1,316	1,109		1,291	1,268	1,044	583	185	1,150	609	407	171		533
SD[b]	703	721	345		692	698	809	267	106	721	387	229	98		358
Maximum	3,537	2,946	1,936		3,537	3,992	3,352	1,342	329	3,992	2,048	1,289	285		2,048
Median	1,120	1,135	963		1,120	1,109	788	571	158	988	558	397	178		483
	Majuro					*Majuro*					*Majuro*				
No. counted	111	29	9	0	149	56	17	7	0	80	57	26	32	0	115
Mean	456	149	63		373	240	315	233		255	143	81	38		100
SD	616	303	18		566	347	676	322		430	243	113	13		184
Maximum	3,323	1,648	93		3,323	1,996	2,126	705		2,126	1,519	460	109		1,519
Median	146	74	50		82	81	58	46		71	54	40	35		45
	Ebeye										*Ebeye*				
No. counted	51	14	8	0	73						21	9	12	0	42
Mean	111	59	60		95						48	37	35		42
SD	132	9	12		113						14	3	1		12
Maximum	791	71	79		791						106	42	36		106
Median	70	62	59		68						46	35	35		40

[a] All values are in the unit Bq, except counts.
[b] Standard deviation.

pared to those of Table 5, nor used to develop a cesium baseline for Majuro Atoll.

Cesium retention model and dose calculation

For a single acute uptake, the ICRP recommended the following two-exponential-term function to describe the systemic retention of cesium in the body (1978, 1990, 1993):

$$R(t) = ae^{-\left(\frac{\ln 2}{T_1}\right)t} + (1-a)e^{-\left(\frac{\ln 2}{T_2}\right)t}, \tag{1}$$

where a and T_1 are the distribution fraction and effective half-time, respectively. The recommended adult values for a, T_1, and T_2 are 0.1, 2 d, and 110 d, respectively.

Because of the short half-time (T_1) and a low distribution fraction, the first component of the cesium retention function is relatively unimportant for assessing dose. However, the long half-time component of cesium for the Marshallese people was investigated in detail by Hardy et al. (1964) and Miltenberger et al. (1981), and the overall results agree with ICRP's (1978, 1990, 1993) suggested value of 110 d. Henrichs et al. (1989) report cesium gut-transfer coefficient (f_1) values for adult males and females of 0.75 ± 0.06 (1 SD) and 0.81 ± 0.06 (1 SD), respectively. However, the f_1 value recommended by the ICRP gives more conservative dose estimates, implying that uptake equals intake. Therefore, the ICRP

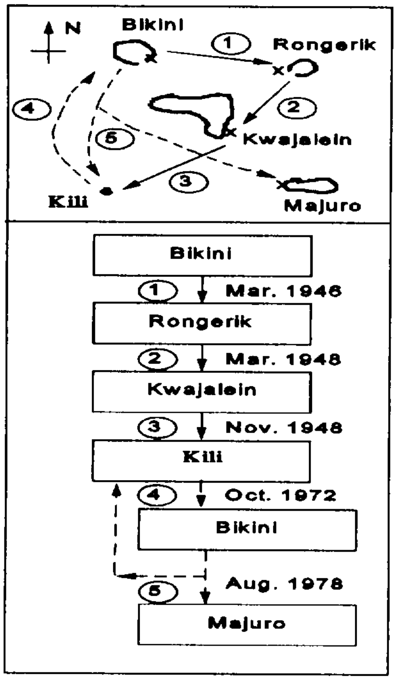

Fig. 6. Relocation timeline for Bikini population.

age-specific dose conversion factors (DCFs) for ingestion intake of cesium can be used directly to interpret the WBC data.

We based the computation of ^{137}Cs doses on ICRP's (1990, 1993) age-specific biokinetic data and retention function for radiation protection purposes. The difference between DCF's derivation in the two publications arises solely from the tissue-weighting factor recommended by ICRP Publications 26 (1977) and 60 (1991). Table 8 compares the two sets of values for each age-specific DCF; the difference between each corresponding value is not large due to the rapid solubility and short retention time of cesium in the body. For conservative reasons, a DCF of 1.4×10^{-2} μSv Bq^{-1} was used for all teenage and adult dose calculations in this study, and a DCF of 2.1×10^{-2} μSv Bq^{-1} was used for infants. The product of DCF and intake yield a committed effective dose from the year of intake to age 70 y.

Cesium body contents in Marshallese must be interpreted on the basis of chronic intakes (Lessard et al. 1980a; Sun et al. 1991, 1992; Kercher and Robison 1993). A computational algorithm was developed to interpret the dose from a chronic exposure pattern using the ICRP DCFs, which had been designed for single, acute intakes. From the biokinetic data for an adult given in Table 8-1 of ICRP Publication 56, an effective dose rate attributable to a steady-state, chronic uptake of cesium in an adult (A) can be estimated by the following equation:

$$\text{Effective dose rate } (\mu\text{Sv y}^{-1})_{\text{Adult}} = 2.55 \times 1.4 \times 10^{-2}\ (\mu\text{Sv Bq}^{-1}) \times \text{Body Content (Bq)}, \quad (2)$$

where 2.55 is a constant factor used to convert from committed effective dose to annual effective dose rate in Reference Man (ICRP 1975). The Appendix describes the computational algorithm. It accounts for the fact that 90% of the committed effective dose will be received within the first year of intake and that the build-up constant for chronic intakes of cesium is the ratio of an integrated transformation in this first year due to a chronic intake to that of a single, recent acute intake. Similarly, the conversion factors for committed effective dose to individuals of 3 mo, 1 y, 5 y, 10 y, and 15 y are, respectively, 15.8, 19.5, 12.3, 6.88, and 3.25. Therefore, the annual effective dose rate attributable to a steady-state and chronic uptake of cesium in teens (T), juveniles (J), and infants (birth to 2 y) can be estimated by the following equations:

$$\text{Effective dose rate } (\mu\text{Sv y}^{-1})_{\text{Teen}} = 3.25 \times 1.4 \times 10^{-2}\ (\mu\text{Sv Bq}^{-1}) \times \text{Body Content (Bq)}, \quad (3)$$

$$\text{Effective dose rate } (\mu\text{Sv y}^{-1})_{\text{Juvenile}} = 6.88 \times 1.4 \times 10^{-2}\ (\mu\text{Sv Bq}^{-1}) \times \text{Body Content (Bq)}, \quad (4)$$

$$\text{Effective dose rate } (\mu\text{Sv y}^{-1})_{\text{Infant}} = 19.5 \times 1.2 \times 10^{-2}\ (\mu\text{Sv Bq}^{-1}) \times \text{Body Content (Bq)}. \quad (5)$$

This annual dose is likely to be conservative because it is assumed that a constant body content will be maintained over 1 y. In addition, based on ICRP's (1990, 1993) retention and excretion model, the younger the individual, the faster the elimination rate.

Dose estimates and discussion

Table 9 shows the mean and standard deviation of cesium effective dose rate (μSv y^{-1}) values for people living on Enewetak, Mejatto (Rongelap population), and Utirik Islands. The effective dose rates were calculated from measurements of the average cesium body content of a whole population. The Enewetak and Rongelap annual effective dose rates are based on the data in Tables 2 and 3, respectively. The Utirik annual effective dose rates are based on information in Table 5 separated by gender (not on Table 4 due to the spread of the population over three major locations).

In general, the environmental decay and dilution of radiocesium will decrease the cesium uptake. The data in Table 9 support this phenomenon, except for the Enewetak 1991 data. There, the increase in two years apparently was the result of people eating more food harvested from contaminated islands. The large coefficient of variation (CV) for the 1991 dose rate suggests that the data are most likely perturbed for the same reason.

Estimates of annual effective dose rates for the Rongelap population at Mejatto remained relatively constant from 1989 to 1994 (unlike the Enewetak and Utirik populations). The lower average dose rates for the people of Rongelap reflect the lower amounts of ^{137}Cs environ-

Table 6. Comparison of ^{137}Cs measurements of the Bikini population by age and gender.[a]

	July–August 1989					August 1994				
Value[b]	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
		Both sexes						*Both sexes*		
No. counted	8	0	0	0	8	3	1	1	0	5
Mean	880				880	76	33	63		65
SD[c]	1,342				1,342	26				26
Maximum	3,726				3,726	93				93
Median	219				219	90				63
		Males						*Males*		
No. counted	8	0	0	0	8	2	0	0	0	2
Mean	880				880	70				70
SD	1,342				1,342	33				33
Maximum	3,726				3,726	93				93
Median	219				219	70				70
		Females						*Females*		
No. counted	0	0	0	0	0	1	1	1	0	3
Mean						90	33	63		62
SD										28
Maximum										90
Median										63

[a] Limited to DOE workers and immediate family members.
[b] All values are in the unit Bq, except counts.
[c] Standard deviation.

Table 7. Comparison of ^{137}Cs measurement obtained on Majuro Island in two different seasons.

	1991					1993				
Value[a]	Adults	Teens	Juveniles	Infants	All	Adults	Teens	Juveniles	Infants	All
		February						*February*		
No. counted	108	36	25	0	169	112	27	22	0	161
Mean	328	207	97		268	122	41	41		97
SD[b]	583	498	183		529	189	10	11		162
Maximum	4,051	2,126	705		4,051	1,150	87	76		1,150
Median	87	46	45		64	51	39	37		47
		July						*July*		
No. counted	77	29	13	0	119	98	37	48	0	183
Mean	73	52	53		66	106	71	38		82
SD	40	14	23		35	190	96	12		148
Maximum	241	90	107		241	1,519	460	109		1,519
Median	61	47	44		57	50	41	35		45

[a] All values are in the unit Bq, except counts.
[b] Standard deviation.

mental activity on Mejatto Island (approximate background for the RMI environment), similar to the levels on Majuro and Ebeye Islands. Other than global fallout, both islands are recognized as areas which were not contaminated by the Bikini or Enewetak nuclear tests. Therefore, the cesium baseline for the Rongelapese who may return to their homeland could be within the estimated 3 ± 2 μSv y^{-1} value.

Since 1985, the people of Rongelap have resided on Mejatto Island. The estimate of annual effective dose rate in Table 9, therefore, is not representative of the exposure that would result from living on Rongelap Island. By comparing WBC measurements taken at Rongelap to those at Utirik over the 4 y before to the Rongelapese relocation in 1985, Lessard et al. (1984) reported a ratio of 3 (upper bound). Therefore, the 26 ± 15 μSv y^{-1} determined in 1993 for Utirik adult males gives an estimated effective dose rate of 78 ± 45 μSv y^{-1} if they had lived on Rongelap Island during 1993. This predicted average annual effective dose rate agrees with the prediction of 63 μSv y^{-1} by Lessard (Lane 1989).

Table 8. Comparison of ICRP-56 and ICRP-67 age-specific dose conversion factors μSv Bq^{-1}.

Age at intake[a]	ICRP 56 (1990)	ICRP 67 (1993)
0–12 mo	2.0×10^{-2}	2.1×10^{-2}
1–2 y	1.1×10^{-2}	1.2×10^{-2}
3–7 y	9.0×10^{-3}	9.7×10^{-3}
8–12 y	9.8×10^{-3}	1.0×10^{-2}
13–17 y	1.4×10^{-2}	1.3×10^{-2}
Adult (>17 y)[b]	1.3×10^{-2}	1.4×10^{-2}

[a] The age ranges are consistent with ICRP Publication 56 (1990).
[b] The dose conversion factors are derived on the basis of an integrated dose over the 50 y following a single acute intake. For all other age groups, the integration dose period is to age 70 y.

Moreover, doses from cesium estimated for populations living on Bikini, Enewetak, Rongelap, and Utirik

Table 9. Annual effective dose rate (μSv y^{-1}) estimates by location, year, age, and sex using WBC measurements, mean ± 1 standard deviation.

Location	Year	Adults (A)		Teens (T)		Juveniles (J)	
		M	F	M	F	M	F
Enewetak	89	30 ± 29	13 ± 10	25 ± 36	13 ± 12	18 ± 17	16 ± 10
	91	45 ± 60	28 ± 37	40 ± 43	13 ± 13	22 ± 22	15 ± 21
	93	13 ± 16	7 ± 7	5 ± 3	4 ± 3	7 ± 6	5 ± 4
	94	16 ± 15	9 ± 8	6 ± 4	8 ± 5	7 ± 5	6 ± 5
Mejatto[a]	89	3 ± 2	3 ± 1	3 ± 1	3 ± 1	6 ± 3	6 ± 3
	91	3 ± 2	3 ± 1	3 ± 2	2 ± 0	5 ± 2	4 ± 1
	93	2 ± 1	3 ± 1	3 ± 2	3 ± 1	4 ± 1	4 ± 1
	94	3 ± 2	2 ± 2	3 ± 2	2 ± 1	4 ± 1	4 ± 1
Utirik[b]	89	53 ± 27	39 ± 20	75 ± 34	44 ± 24	109 ± 41	104 ± 23
	91	53 ± 27	37 ± 19	65 ± 47	32 ± 13	63 ± 32	50 ± 17
	93	26 ± 15	18 ± 10	19 ± 10	18 ± 11	14 ± 6	20 ± 13

[a] Rongelap population center.

[b] Utirik population living on Utirik Island.

Islands employed dietary intake and food-chain pathway analyses (Robison 1983; Kohn 1988, 1989; Kercher and Robison 1993; Simon and Graham 1995, 1996). Kercher and Robison (1993) report better precision in predicting cesium burden using environmental measurements for individuals with slower metabolism. Furthermore, an overestimate of the dose resulting from using age-specific or age-dependent DCFs for younger age groups was reported by the World Health Organization (WHO 1987); this suggests that the effective dose rates given in Table 9 may overestimate the exposure of teens and younger age groups.

Table 10 compares the external cesium effective dose rates for adults reported by Simon and Graham (1995) and the estimates of internal cesium dose rates using WBC measurements. The table shows the consistencies between external and internal dose rates at Ebeye, Mejatto, and Utirik, but inconsistencies at Enewetak and Bikini. Cesium body contents and the concentrations in the biota are expected to correspond to one another, depending on lifestyle and intake rates of local foods and water. Therefore, the inconsistencies in Table 10 are ascribed primarily to the latter. For example, the internal cesium dose rate for Enewetakese more likely reflects the consumption of local foods from Japtan, Medren, and Enjebi Islands, which have higher reported levels of external cesium dose rates. On the other hand, the external dose rate from cesium at Bikini is far more than the internal dose rate, which indicates that the main diet of the Bikini workers is not local food, but imported foods. This finding may indicate that ingestion intakes are more important in assessing cesium uptake than is inhalation.

Table 10. Comparison of external and internal cesium effective dose rates (μSv y^{-1}) at various locations.

Atoll	Island	External dose rate[a]	Internal dose rate[b]
Bikini	Bikini	600	3 ± 1 (1 SD)
Enewetak	Enewetak	2	13 ± 13
Enewetak	Enjebi	25	—
Enewetak	Japtan	10	—
Enewetak	Medren	5	—
Kwajalein	Ebeye	2	2 ± 1
Kwajalein	Mejatto	2	2 ± 1
Majuro	Majuro	<1	5 ± 9
Utirik	Utirik	18	22 ± 14

[a] Measurements reported by Simon and Graham (1995).

[b] Based on the 1994 or the latest WBC average from adults (male and female).

During the missions, parents were encouraged to bring infants for whole-body counting. Unfortunately, the water in the lagoon was rough during the missions, and it was unsafe to transport infants to the boat. Therefore, only a few infants were measured (see Tables 2, 3, and 4). In 1991, one infant from Enewetak had a body content below the MDA of 50 Bq, while the contents in four infants from Utirik were approximately 96, 117, 200, and 329 Bq. Assuming that an equilibrium condition would be established in the body due to steady-state intake in the next 365 d, an annual effective dose rate of 77 μSv for the infant with the largest burden was calculated using the ICRP recommended retention function and biokinetic data for a 3-mo-old (shown in the Appendix).

CONCLUSIONS

The impact of the nuclear tests conducted at Bikini and Enewetak Atolls from 1946 to 1958 is still being felt because of the continued concern about radiological contamination that affected the Marshallese. This paper presents the WBC results obtained from 1989 through 1994 during field missions. During these five years, ^{137}Cs was the only fallout-related radionuclide detected by whole-body counting. In general, the effective dose rates from cesium are decreasing and are lower than those reported earlier by Conard et al. (1956, 1975), Miltenberger et al. (1980), and Lessard et al. (1980a, 1980b, 1984).

Tables 2, 3, 4, and 5 indicate that median values are often less than mean values. The former are more robust, but, for conservative dose estimates, mean values were used to construct Table 9. Our estimates of the cesium body content are based on data collected over 5 y, and the assessment of annual effective dose rates for all age-specific groups is based on the internationally recommended dosimetric models and parameter values (ICRP 1990, 1993). For example, our latest measurements (Table 9) indicated that male adults who lived in Enewetak, Mejatto, and Utirik in 1993 had received 16, 3, and 26 μSv, respectively, in a year.

Our WBC data suggest the critical group is adult males because of the consistently higher average cesium body contents in comparison with other sex and age groups. Unfortunately, intake of weapons-generated cesium is inevitable, especially for the inhabitants of the northern four atolls (Bikini, Enewetak, Rongelap, and Utirik). The UNSCEAR 1993 Report states that the total effective dose commitment from external and internal ^{137}Cs produced in atmospheric nuclear weapons tests is about 0.5 mSv for the world population, and even more for the north temperate zone populations. Further, Noshkin et al. (1994) indicate that the total annual effective dose rate from natural background in the Marshall Islands is 2.4 mSv y^{-1}, like other areas of the world. Within the 5-y monitoring period, all internal exposures to ^{137}Cs were less than 0.2 mSv y^{-1}.

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APPENDIX

Method for calculating annual dose using ICRP 56 data

During chronic intakes, the body content of cesium may reach a plateau as it comes into equilibrium with the environmental cesium level. It is assumed that the body content measured by a 15-min WBC is maintained at a constant level over a 1-y period. ICRP 56 (1990) biokinetics data for adults can be integrated for any specific time interval. The following integration function gives the total cesium transformations in the body in T days after a single acute intake.

$$Y(T) = \int_0^T (0.1e^{-0.347\,t} + 0.9e^{-0.0063\,t})\,dt. \tag{A1}$$

Then, Y (1 y) = 129 and Y (50 y) = 143. Also, the number of transformations due to a chronic intake of one unit per day over 1 y is 365. These values are needed for computing effective dose rates using the ICRP Publication 56 committed effective dose coefficient.

The adult group adjusting factors are $Y(1\ \text{y})/Y(50\ \text{y}) = 0.9$ and $365/Y(1\ \text{y}) = 2.8$. The former means that 90% of the committed effective dose will be received within the first year of cesium intake. The latter is the ratio of the total transformations within the first year of intake from a steady-state, uniform, chronic intake and from a single, acute intake of cesium. Thus, the conversion factor from committed effective dose to an annual effective dose rate for adults is 2.55 (i.e., 0.9 × 2.8). Similarly, the conversion factors for children of 3 mo, 1 y, 5 y, 10 y, and 15 y are 15.8, 19.5, 12.3, 6.88, and 3.25, respectively.

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AN UPDATED DOSE ASSESSMENT FOR RESETTLEMENT OPTIONS AT BIKINI ATOLL—A U.S. NUCLEAR TEST SITE

William L. Robison, Kenneth T. Bogen, and Cynthia L. Conrado*

***Abstract*—On 1 March 1954, a nuclear weapon test, codenamed BRAVO, conducted at Bikini Atoll in the northern Marshall Islands contaminated the major residence island. There has been a continuing effort since 1977 to refine dose assessments for resettlement options at Bikini Atoll. Here we provide a radiological dose assessment for the main residence island, Bikini, using extensive radionuclide concentration data derived from analysis of food crops, ground water, cistern water, fish and other marine species, animals, air, and soil collected at Bikini Island as part of our continuing research and monitoring program that began in 1978. The unique composition of coral soil greatly alters the relative contribution of ^{137}Cs and ^{90}Sr to the total estimated dose relative to expectations based on North American and European soils. Without counter measures, ^{137}Cs produces 96% of the estimated dose for returning residents, mostly through uptake from the soil to terrestrial food crops but also from external gamma exposure. The doses are calculated assuming a resettlement date of 1999. The estimated maximum annual effective dose for current island conditions is 4.0 mSv when imported foods, which are now an established part of the diet, are available. The 30-, 50-, and 70-y integral effective doses are 91 mSv, 130 mSv, and 150 mSv, respectively. A detailed uncertainty analysis for these dose estimates is presented in a companion paper in this issue. We have evaluated various countermeasures to reduce ^{137}Cs in food crops. Treatment with potassium reduces the uptake of ^{137}Cs into food crops, and therefore the ingestion dose, to about 5% of pretreatment levels and has essentially no negative environmental consequences. We have calculated the dose for the rehabilitation scenario where the top 40 cm of soil is removed in the housing and village area, and the rest of the island is treated with potassium fertilizer; the maximum annual effective dose is 0.41 mSv and the 30-, 50-, and 70-y integral effective doses are 9.8 mSv, 14 mSv, and 16 mSv, respectively.**

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Key words: Marshall Islands; fallout; dose assessment; weapons

INTRODUCTION

Bikini Atoll was one of the two sites in the Northern Marshall Islands that was used by the United States as testing grounds for the nuclear weapons program. Bikini Atoll, and the other test site Enewetak Atoll, are located in the northern part of the Marshall Islands at a latitude of about 11.5° N (Fig. 1). Twenty-three nuclear tests were conducted from 1946 to 1958 at Bikini Atoll with a total yield of 77 megatons. The BRAVO test, on 1 March 1954, had an explosive yield that greatly exceeded expectations, with the result that heavy fallout was experienced at the major residence islands of Bikini and Eneu, and lesser fallout at atolls east of Bikini Atoll. The aerial photo montage of Bikini Atoll (Fig. 2) shows the location of the BRAVO test and of Bikini and Eneu Islands. The Bikini people, since their initial relocation to Rongerik Island in 1946, have had a continuing desire to return to their homeland. In 1968, a general cleanup of debris and buildings as well as the planting of coconut, breadfruit, *Pandanus*, papaya, and banana trees began at Bikini Atoll, and a radiological survey and dose assessment were completed. Houses were then built on Bikini Island, and some Bikini families moved back to Bikini Island in 1970.

A radiological survey was conducted in 1975 when a second phase of housing was being considered, but few samples of locally grown food crops were available to confidently establish the radionuclide concentrations on Bikini Island to reliably estimate the dose; predictions based on the preliminary data indicated that when food crops matured and were available for consumption that the body burden of ^{137}Cs and resulting doses would exceed federal guidelines (Robison et al. 1977). In 1978, when the coconut trees started producing fruits, the Brookhaven National Laboratory (BNL) whole body counting confirmed that ^{137}Cs body burdens in the people on Bikini were well above the U.S. recommended level (Miltenberger and Lessard 1987). Consequently, in August 1978, Trust Territory officials arrived at Bikini Island and relocated the people to Kili Island.

Subsequently, we have developed an extensive data base for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am concentration in the atoll ecosystem by collecting and analyzing samples of soil, vegetation, animals, ground water, cistern water and marine species in an effort to refine dose assessments for all exposure pathways for resettlement options at Bikini Atoll. Also, detailed resuspension studies have been made at Bikini, Enewetak, and Rongelap Atolls to determine the potential dose from inhalation of suspended soil containing $^{239+240}$Pu and

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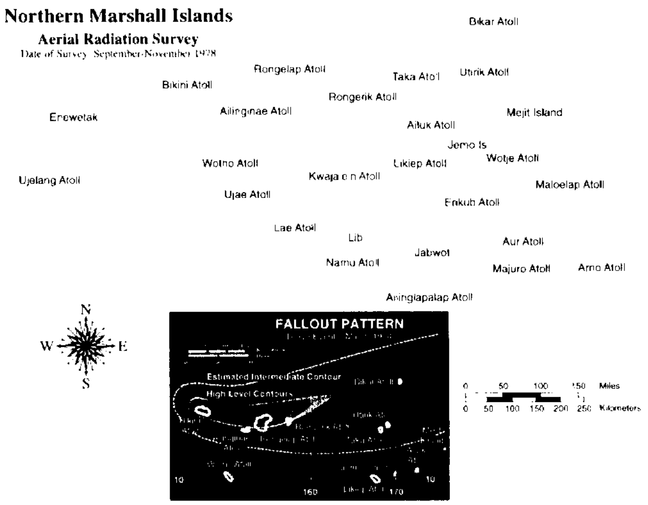

Fig. 1. A map of the Marshall Islands showing the location of the two nuclear test sites, Bikini and Enewetak Atolls.

^{241}Am. These dose assessments have been essential to define the critical radionuclides and pathways, evaluate various living patterns, and provide the communities with a basis for making informed decisions on resettlement options. A dose assessment of Bikini Island in 1982, and an earlier dose assessment of Enewetak Atoll, indicated that the most significant potential exposure pathway at the contaminated atolls was uptake of ^{137}Cs in the terrestrial food chain (Robison et al. 1980; Robison et al. 1982).

We have also conducted a research program to evaluate the effectiveness of various remedial actions designed to reduce the dose from ^{137}Cs in the food chain. The remedial measures have included excavation of the top 40 cm of the island, soil amendments (clay, zeolites), leaching (salt water irrigation), cropping (growing and harvesting sequential stands of vegetation), and chemical competition [potassium (K) addition]. Excavation of the top 40 cm of the soil column is an effective method to reduce the radionuclide concentration in the soil and subsequently the food crops, thereby reducing the dose via the food chain and external gamma. However, it does lead to a severe environmental impact on the island. Consequently, we designed our field research program to look at various remedial measures for reducing the ^{137}Cs in soil and/or blocking the uptake into food crops to give the people resettling the contaminated atolls an option to the excavation of the top soil on their islands. The most effective method of all the tested methods, and by far the easiest to implement, is the addition of K to the soil. Not only does the K treatment reduce the intake of ^{137}Cs from the direct ingestion of the food crops, but it also reduces the ^{137}Cs intake from coconut crabs, pigs, and chickens that feed on the vegetation.

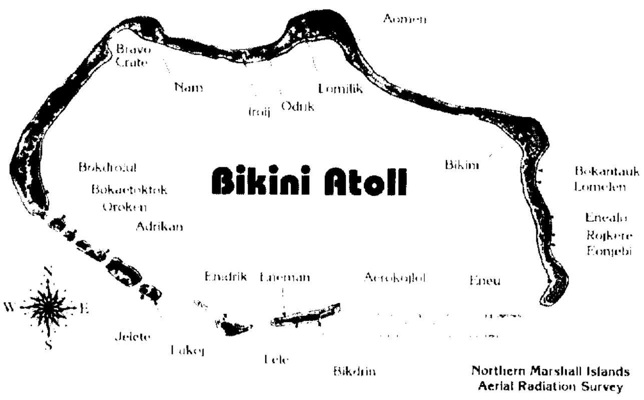

Fig. 2. A photographic montage of Bikini Atoll showing the location of the various islands.

In this report we present the most recent dose estimates before and after the K countermeasure designed to reduce the dose to people resettling Bikini Island.

EXPOSURE PATHWAYS

The radiological dose to inhabitants at the atoll occurs from both external and internal exposure. Each of these two categories can be broken down further into the following exposure pathways: (1) External exposure: natural background radiation; nuclear test-related radiation, (2) Internal exposure: natural background radiation; nuclear test-related radiation—radionuclides in terrestrial foods, marine foods, drinking water and radionuclides inhaled.

The external natural background radiation in the Northern Marshall Island Atolls is 9.0×10^{-10} C kg^{-1} (3.5 μR h^{-1}) or 0.22 mSv y^{-1} (Gudiksen et al. 1976) due to cosmic radiation; the external background dose due to terrestrial radiation is very low in the Marshall Islands because of the composition of the soil. The internal effective dose is about 2.2 mSv y^{-1} for natural occurring radionuclides such as ^{40}K, ^{210}Po, and ^{210}Pb that result from consumption of local and imported foods (Noshkin et al. 1994; Robison et al. 1997). The natural background dose is not included in the doses presented in the paper unless specifically stated.

DATA BASES

External exposure measurements

The external exposure rates at Bikini Atoll were measured by Edgerton Germeshausen and Grier (EG&G) as part of the aerial survey conducted in the 1978 Northern Marshall Islands Radiological Survey (NMIRS) (Tipton and Meibaum 1981). The average exposure rate on Bikini Island as measured by EG&G in 1978 was about 8×10^{-9} C kg^{-1} (31 μR h^{-1}). In 1986 and 1988, additional external gamma measurements were made by LLNL of ^{137}Cs and ^{60}Co inside and outside houses and other buildings, and around the village area; crushed coral placed around the buildings provides shielding in addition to the buildings. Measurements at Bikini Island indicate that the average exposure inside the houses is about 5.4×10^{-10} C kg^{-1} (2.1 μR h^{-1}) while in the immediate area around the houses it is 2.8×10^{-9} C kg^{-1} (11 μR h^{-1}).

External beta-particle exposure

The unshielded beta contribution to the external dose was estimated at Enewetak Atoll in 1980 (Crase et al. 1982). Studies at Bikini Atoll using new, thinner thermoluminescent dosimeters (TLDs) indicate that the dose over open ground at 1 cm height is about three times that of 1 m height (Shingleton et al. 1987). Thus, the unshielded beta dose at 1 cm on Bikini Island could be equal to or slightly greater than the external gamma dose. However, for a significant part of the day the eyes, upper body, and gonads are at 0.8 m or more in height above the ground surface. The walls and floors of the houses and the crushed coral customarily put around houses and the village area absorb most of the beta radiation. In addition, any clothing, shoes, zories, *Pandanus* mats, or other coverings also greatly reduce exposure to beta radiation.

Airborne radionuclide concentrations

Airborne concentrations of $^{239+240}$Pu and ^{241}Am are estimated from data derived from resuspension experiments conducted at Enewetak Atoll in 1977, Bikini Atoll in 1978, and Rongelap Atoll in 1991. We briefly describe the resuspension methodology here; more detail can be found in Shinn et al. (1997). Four simultaneous experiments were conducted: (1) a characterization of the normal (background) suspended aerosols and the contributions of sea spray off the windward beach leeward across the island; (2) a study of resuspension of radionuclides from a field purposely laid bare by bulldozers as a worst-case condition; (3) a study of resuspension of radioactive particles by vehicular and foot traffic; and (4) a study of personal inhalation exposure using small air samplers carried by volunteers during daily routines. The "normal" or "background" mass loading (the mass of solid material per unit volume of air) measured by gravimetric methods for the atolls is approximately 55 μg m^{-3}. The data from the Bikini experiments indicate that 34 μg m^{-3} of this total is due to sea salt that is present across the entire island as a result of ocean, reef, and wind actions. The mass loading due to terrestrial origins is, therefore, about 21 μg m^{-3}. The highest terrestrial mass loading observed was 136 μg m^{-3} immediately after bulldozing.

Concentrations of $^{239+240}$Pu were determined for collected aerosols (1) for normal ground cover and conditions in coconut groves, (2) for high-activity conditions, i.e., areas being cleared by bulldozers and being tilled, and (3) for stabilized bare soil, i.e., cleared areas after a few days' weathering. The plutonium concentration in the collected aerosols changes with respect to the plutonium concentration in surface soil for each of these situations. We have defined an enhancement factor (EF) as the $^{239+240}$Pu concentration in the collected soil-aerosol mass divided by the $^{239+240}$Pu surface-soil (0- to 5 cm) concentration. The EF of less than 1 (EF <1) for the normal, open-air conditions is apparently the result of selective particle resuspension in which the resuspended particles have a different plutonium concentration than is observed in the total 0- to 5-cm soil sample. Similarly, the enhancement factor of 3 for high-resuspension conditions results from the increased resuspension of particle sizes with a higher plutonium concentration than observed in the total 0- to 5-cm soil sample.

We have developed additional personal-enhancement factors (PEF) from personal air-sampler data. These data represent the enhancement that occurs around individuals due to their daily activities. The total enhancement factor used to estimate the amount of suspended plutonium is the EF (0.82 for normal resuspension and 3.1 for high resuspension) multiplied by the PEF (1.9 for normal resuspension and 0.92 for high resuspension). Consequently, the total enhancement used for normal resuspension conditions is 1.5 and for high-resuspension conditions is 2.9.

To calculate inhalation exposure, we assume that a person spends 1 h d^{-1} in high-resuspension conditions, 23 h d^{-1} under normal resuspension conditions, and has a breathing rate of 22 m^3 d^{-1} (1.2 m^3 under high-resuspension conditions and 20.9 m^3 under normal-resuspension conditions). An analysis of breathing rates based on energy expenditure indicates that the volume of air breathed in a 24 h period may be significantly less than the 22 m^3 d^{-1} recommended by ICRP (Layton, 1993). The radionuclide concentrations in surface soil (0- to 5-cm) for Bikini Island complete the information necessary for calculation of plutonium and americium intake through inhalation.

Radionuclides in marine foods, soil, and terrestrial food

The average concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am in marine foods and terrestrial foods are listed in Table 1. Most of the data for the marine foods is a result of work conducted by Noshkin et al. (1988). The data for the terrestrial foods are part of our continuing program where samples have been collected and analyzed from 1975 through 1993 on Bikini Island. The number of samples analyzed are as follows: 812 drinking coconut meat, 747 drinking coconut juice, 188 copra meat, 177 copra juice, 69 *Pandanus*, 41 breadfruit, 93 papaya, 53 squash, 39 banana and 36 animals. The median concentration of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am in soil profiles are listed in Table 2. The soil data are also part of our continuing program.

Radionuclides in drinking water

The major source of water used in cooking and for drinking is rainwater collected from roofs of houses and other buildings that is stored in cisterns. If extreme drought conditions occur, then the freshest groundwater available is used; the groundwater is contaminated with radionuclides from the soil column. The concentrations of radionuclides in both cistern water and groundwater are listed in Table 1. For the dose estimates, we use an

Table 1. Diet model for adults greater than 18 y living on Bikini Island for current conditions and for the soil removal and potassium treatment option.

						Specific activity in 1999 (Bq g^{-1} wet wt.)				
	Imported foods diet		Local foods only diet			Current conditions	Scrape + K option	Common to both current and scrape + K option		
Local Food	g d^{-1}	Kcal d^{-1}	g d^{-1}	Kcal d^{-1}	Kcal g^{-1}	^{137}Cs	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish	24.2	33.8	86.8	121	1.40	2.9×10^{-3}	2.9×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Tuna	13.9	19.4	72.0	101	1.40	4.5×10^{-3}	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Mahi Mahi	3.56	3.92	21.4	23.5	1.10	4.5×10^{-3}	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Marine Crabs	1.68	1.51	19.5	17.6	0.90	1.4×10^{-3}	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Lobster	3.88	3.49	35.2	31.7	0.90	1.4×10^{-3}	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Clams	4.56	3.65	58.1	46.5	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Trochus	0.10	0.080	0.24	0.19	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Tridacna Muscle	1.67	2.14	11.4	14.6	1.28	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Jedrul	3.08	2.46	19.4	17.4	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Coconut Crabs	3.13	2.19	24.9	17.5	0.70	3.7×10^{-1}	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Land Crabs	0.00	0.00	0.00	0.00	0.70	3.7×10^{-1}	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Octopus	4.51	4.51	49.0	49.0	1.00	1.8×10^{-3}	1.8×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Turtle	4.34	3.86	17.8	15.8	0.89	2.8×10^{-4}	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Chicken Muscle	8.36	14.2	31.2	53.0	1.70	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Liver	4.50	7.38	17.7	29.0	1.64	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Gizzard	1.66	2.46	3.32	4.91	1.48	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Muscle	5.67	25.5	13.9	62.6	4.50	7.0×10^{0}	1.6×10^{0}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Kidney	NR	0.00	NR	0.00	1.40	6.5×10^{0}	1.4×10^{0}	6.2×10^{-3}	3.5×10^{-5}	1.2×10^{-5}
Pork Liver	2.60	6.27	6.70	16.1	2.41	3.6×10^{0}	8.1×10^{-1}	2.9×10^{-3}	1.2×10^{-4}	5.2×10^{-5}
Pork Heart	0.31	0.60	0.62	1.21	1.95	4.2×10^{0}	9.8×10^{-1}	1.5×10^{-3}	5.9×10^{-6}	1.8×10^{-5}
Bird Muscle	2.71	4.61	26.4	44.8	1.70	2.5×10^{-3}	2.5×10^{-3}	2.3×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Bird Eggs	1.54	2.31	22.8	34.1	1.50	6.7×10^{-4}	6.7×10^{-4}	3.6×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Chicken Eggs	7.25	11.8	41.2	67.2	1.63	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Turtle Eggs	9.36	14.0	235	352	1.50	2.8×10^{-4}	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Pandanus Fruit	8.66	5.20	63.0	37.8	0.60	3.9×10^{0}	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Pandanus Nuts	0.50	1.33	2.00	5.32	2.66	3.9×10^{0}	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Breadfruit	27.2	35.3	186	242	1.30	3.8×10^{-1}	1.9×10^{-2}	6.9×10^{-2}	1.8×10^{-6}	1.2×10^{-6}
Coconut Juice	99.1	10.9	333	36.6	0.11	1.2×10^{0}	5.8×10^{-2}	4.5×10^{-4}	1.0×10^{-6}	8.5×10^{-6}
Coconut Milk	51.9	179	122	421	3.46	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Tuba/Jekero	0.00	0.00	0.00	0.00	0.50	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Drinking Coco Meat	31.7	32.3	181	184	1.02	2.9×10^{0}	1.5×10^{-1}	5.9×10^{-3}	2.7×10^{-6}	3.6×10^{-6}
Copra Meat	12.2	50.3	71.3	295	4.14	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Sprout. Coco	7.79	6.23	122	97.8	0.80	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Marsh. Cake	11.7	39.2	0.00	0.00	3.36	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Papaya	6.59	2.57	27.0	10.5	0.39	2.2×10^{0}	1.1×10^{-1}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Squash	NR	0.00	NR	0.00	0.47	1.2×10^{0}	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Pumpkin	1.24	0.37	5.44	1.63	0.30	1.2×10^{0}	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Banana	0.020	0.018	0.58	0.51	0.88	1.8×10^{-1}	8.9×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Arrowroot	3.93	13.6	94.9	328	3.46	5.4×10^{-2}	5.4×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Citrus	0.10	0.049	0.20	0.10	0.49	1.2×10^{-1}	6.0×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Rainwater	313	0.00	629	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Wellwater	207	0.00	430	0.00	0.00	4.5×10^{-3}	4.5×10^{-3}	1.2×10^{-3}	6.1×10^{-7}	4.4×10^{-7}
Malolo	199	0.00	0.00	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Coffee/Tea	228	0.00	0.00	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Soil[a]	0.10	0.00	0.10	0.00	0.00	1.3×10^{0}		9.9×10^{-1}	2.0×10^{-1}	1.2×10^{-1}
Soil[b]	0.10	0.00	0.10	0.00	0.00		3.9×10^{-1}	7.3×10^{-1}	5.5×10^{-2}	4.7×10^{-2}
Total Local	1,322	547	3,083	2,783						

[a] Soil represents the current conditions on Bikini Island, Bq g^{-1} dry wt.

[b] Soil represents the soil removal and potassium treatment option for Bikini Island, Bq g^{-1} dry wt.

intake of 1 L d^{-1} of drinking water. We assume for the dose assessment that cistern water is available for 60% of the year and that groundwater is used for 40% of the year. The rainfall during the dry part of the year (December through April) can sometimes be very low, such that fresh water supplies are exhausted and the people resort to the use of brackish but potable ground water. The 40% intake of groundwater over a lifetime is very conservative in that this process does not occur every year, and some years for only a month or two. Soda and fruit drinks are frequently available and account for some of the daily fluid intake. The total daily drinking fluid intake from all these sources is between 2 and 2.5 L d^{-1}.

Diet

The radiological dose from the ingestion pathway will scale directly with the total intake of radionuclides, which is proportional to the quantity of locally grown

Table 2. Median (and mean) concentrations in Bq g^{-1} dry weight of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am in soil at Bikini Island.

Soil depth, cm	No. of samples	^{137}Cs	No. of samples	^{90}Sr	No. of samples	$^{239+240}$Pu	No. of samples	^{241}Am
Interior of island								
0–5	254	2.3 (3.0)	55	1.7 (2.1)	54	0.32 (0.42)	157	0.26 (0.30)
5–10	254	1.2 (1.8)	55	2.0 (2.4)	55	0.29 (0.44)	151	0.19 (0.27)
10–15	253	0.58 (1.0)	55	1.5 (2.3)	55	0.15 (0.34)	127	0.081 (0.18)
15–25	248	0.19 (0.48)	54	0.73 (1.4)	51	0.053 (0.16)	80	0.026 (0.11)
25–40	246	0.071 (0.19)	47	0.47 (0.77)	46	0.0081 (0.061)	59	0.012 (0.051)
40–60	217	0.018 (0.019)	13	0.32 (0.65)	13	0.011 (0.035)	23	0.017 (0.073)
0–40	240	0.70 (0.91)	47	1.1 (1.5)	45	0.17 (0.21)	53	0.11 (0.14)
Village area								
0–5	74	1.2 (2.0)	44	1.0 (2.0)	43	0.20 (0.40)	63	0.11 (0.22)
5–10	73	1.0 (1.6)	44	1.2 (2.0)	43	0.30 (0.40)	62	0.13 (0.20)
10–15	72	0.81 (1.2)	44	1.5 (1.7)	43	0.22 (0.28)	63	0.12 (0.19)
15–25	71	0.53 (1.0)	44	0.90 (1.6)	41	0.14 (0.25)	59	0.064 (0.15)
25–40	71	0.18 (0.80)	43	0.62 (1.7)	42	0.064 (0.25)	52	0.059 (0.13)
40–40	46	0.028 (0.23)	18	0.32 (1.2)	17	0.0058 (0.11)	20	0.012 (0.11)
0–40	71	0.67 (1.1)	43	1.6 (1.5)	41	0.24 (0.29)	51	0.13 (0.17)

Note: Decay corrected to 1999. Number in parentheses is the arithmetic mean.

foods that are consumed. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. Our laboratory, and others, in concert with local government authorities, with the legal representatives of the people, and with Peace Corps representatives, and anthropologists have endeavored to establish and document pertinent trends, cultural influences and economic realities. The diet model we use for estimating the intake of local plus imported foods (IA diet model) is presented in Table 1. The basis of this diet model was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and the Marshallese school teacher on Ujelang (Robison et al. 1983). A diet based on consumption of only local foods, i.e., imported foods unavailable (IUA), is also listed in Table 1.

The ^{137}Cs concentration in most dietary items is based on direct measurement. There are a few special cases for animals or fowl that may roam the island. Treatment is assumed to affect ingested ^{137}Cs in pork to the extent that pigs eat treatment-affected vegetation and soil from areas where soil has or has not been removed. Food intakes for penned pigs are assumed to be 90% vegetation and 10% village area soil, while those for unpenned pigs are assumed to be 90% vegetation and 10% soil from areas outside the village. The pork from penned and unpenned pigs are each assumed to comprise 50% of total pork consumed. Chicken is assumed to correspond to the scenario assumed for unpenned pigs. Coconut crabs are assumed to be taken from the western islands of Bikini Atoll where they are plentiful.

DOSE METHODOLOGY

External exposure

Gamma radiation—Current conditions. The external exposure calculations for gamma radiation are based on measurements made on Bikini Island in 1978 and 1988 that are decay corrected to 1999. The following arbitrary distribution of time was used to develop the average external exposure:

- Ten h d^{-1} are spent in the house where the exposure rate is 4.1×10^{-10} C kg^{-1} (1.6 μR h^{-1});
- Nine h d^{-1} around the house and village area where the exposure rate is assumed to be 2.2×10^{-9} C kg^{-1} (8.5 μR h^{-1}) (weighted average of outside house and general village sites);
- Three h d^{-1} in the interior region of the island where the average exposure is 4.9×10^{-9} C kg^{-1} (19 μR h^{-1}) (Tipton and Meibaum 1981);
- Two h d^{-1} on the beach or lagoon where the exposure is 2.58×10^{-11} C kg^{-1} (0.1 μR h^{-1}), based on EG&G data (Tipton and Meibaum 1981).

Although the selection of this particular time distribution is arbitrary, general discussions with Marshallese people and observations while we have been in the islands make the selection reasonable. The resultant contributions of ^{137}Cs to the average dose equivalent from a year's occupancy of various island areas described in the above scenario are as follows: inside houses, 0.045 mSv; elsewhere in the housing and village area, 0.21 mSv; island interior, 0.16 mSv; beaches and lagoon, 0.55 μSv. The total average external dose attributable to such occupancy in 1999 on Bikini Island is about 0.42 mSv y^{-1}. Natural external background is about 0.22 mSv y^{-1}.

Gamma radiation—Soil removal in the housing and village area. The interior portion of the island is assumed to remain the same, i.e., 4.9×10^{-9} C kg^{-1} (19

μR h^{-1}), as listed under the current conditions. The time distributions are also the same.

The exposure rate in the village area and inside the houses after soil removal and placement of crushed coral on the ground surface is assumed to be 5.2×10^{-11} C kg^{-1} (0.2 μR h^{-1}) and 2.58×10^{-11} C kg^{-1} (0.1 μR h^{-1}), respectively.

The resultant contributions of ^{137}Cs to the average dose equivalent from a year's occupancy of various island areas described in the above scenario are as follows: inside houses, 0.0028 mSv; elsewhere in the housing and village area, 0.0050 mSv; island interior, 0.16 mSv; beaches and lagoon, 0.55 μSv. The total average external effective dose attributable to such occupancy in 1999 on Bikini Island is about 0.17 mSv y^{-1}. Natural external background is about 0.22 mSv y^{-1}.

Beta radiation. It is impossible to predict precisely what the beta dose to the skin will be, but it is clear that the "shallow dose" due to both beta particles and external gamma exposure will be only slightly greater than the dose estimated for external gamma whole-body exposure. This higher "shallow dose" will occur primarily to the most exposed parts of the body, usually the arms, lower legs, and feet. The skin is a much less sensitive organ to radiation than other parts of the body; consequently, the beta contribution to the total effective dose is extremely small.

Internal exposure

^{137}Cs. The conversion from the intake of ^{137}Cs to the dose equivalent for the adult is based upon the ICRP methods described in ICRP Publications 56, 61 (ICRP 1990, 1991), which are based on Leggett's model (Leggett 1986). The biological half-life of ^{137}Cs is determined as a function of mass (i.e., age) by the methods described in the Leggett (1986). In a separate report we estimated the comparative doses between adults and children (Robison and Phillips 1989). The results indicate that the estimated integral effective dose for adults due to ingestion of ^{137}Cs and ^{90}Sr can be used as a conservative estimate for intake beginning at any other age. In this report we calculate only the doses to adults.

^{90}Sr. The model developed by Leggett et al. (1982) is based on the structure and function of bone compartments as generally outlined in the ICRP model (ICRP 1990). The bone is assumed to be composed of a structural component associated with bone volume, which includes the compact cortical bone, a large portion of the cancellous (trabecular) bone, and a metabolic component associated with bone surfaces. We will not discuss further details of these models, but refer the reader to the original articles and their associated references for additional discussion and clarification (Leggett et al. 1982; Cristy et al. 1984). Doses listed in this paper are calculated from the Leggett model

Transuranic radionuclides ($^{239+240}$Pu and ^{241}Am)

Ingestion. We calculated the dose equivalent from ingestion of transuranic radionuclides ($^{239+240}$Pu and ^{241}Am) by ICRP methods (ICRP 1986, 1993a). The amount of ingested plutonium or americium crossing the gut wall to the blood is assumed to be 5×10^{-4} for plutonium and americium in vegetation, and 10^{-5} (Harrison et al. 1989) and 5×10^{-4} for the fraction of plutonium and americium, respectively, ingested via soil. Of the fraction of plutonium or americium reaching the blood, 45% is assumed to go to bone and 45% to the liver (ICRP 1986, 1993a). The biological half-life is 50 y in bone and 20 y in liver for both elements (ICRP 1986, 1993a). The quality factor is 20 for the alpha particles.

Inhalation. The dose equivalent from inhalation for the transuranic radionuclides is based on the intake determined from the assumptions discussed in the section on a airborne, respirable radionuclide concentrations of this paper and the ICRP new lung model dose methodology (ICRP 1986, 1990, 1994). The $^{239+240}$Pu and ^{241}Am are considered class W particles, and the quality factor is 20 for the alpha particles. Other parameters are as described in the ICRP method previously discussed for the ingestion of transuranic radionuclides. The activity-median aerodynamic diameter (AMAD) is assumed to be 1 μm, which provides a slightly conservative dose estimate (i.e., slightly higher dose) because the observed AMAD was about 2.5 μm in the Bikini experiment (Shinn et al. 1997).

^{210}Po, ^{210}Pb. The estimated dose from ingestion of natural ^{210}Po and ^{210}Pb is based on ICRP data and methods (ICRP 1991). The weighted committed dose equivalent per unit intake of activity for ^{210}Po is 2.2×10^{-7} Sv Bq^{-1}, and for ^{210}Pb it is 1×10^{-6} Sv Bq^{-1}.

Body weights and biological half-life of ^{137}Cs

Data from Brookhaven National Laboratory (BNL) have been summarized to determine the body weights of the Marshallese people (Conard et al. 1959, 1960, 1963, 1975; Miltenberger et al. 1980a[‡], 1980b). The average adult male body weight is 72 kg for Bikini, 71 kg for Enewetak, and 69 kg for Utirik. We have used 70 kg as the average male body weight in our dose calculations. The average biological half-life for the long-term compartment for ^{137}Cs in adults is listed as 110 d in ICRP (1990) and NCRP (1977). This is consistent with data obtained by BNL on the half-time of the long-term compartment in Marshallese (Miltenberger et al. 1981; Miltenberger and Lessard 1987). The distribution of biological half-life in 23 Marshallese adult males is lognormal with a median of 115 d, a mean of 119 d, and a range of 76–178 d. We used the 110 d half-life because

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[‡] Personal communication, Miltenberger, R. P.; Greenhouse, N.; Cua, F.; Lessard, E. Working Draft: Dietary radioactivity intake from bioassay data a model applied to cesium-137 intake by Bikini Island residents. Brookhaven National Laboratory; 1980.

it is based on a much larger sample population and the difference between it and the 115 d half-life observed in 23 Marshallese males is minimal.

COUNTERMEASURES—MITIGATION OF FOOD-CHAIN DOSE

All remedial actions were evaluated against the criteria of reducing the estimated average maximum annual effective dose to about the world-wide average background effective dose of 2.4 mSv. A countermeasure is not recommended to the communities for consideration if it cannot lead to a dose below this criterion. Countermeasures evaluated to reduce the dose from ^{137}Cs through the terrestrial food chain include salt water irrigation (leaching), zeolites and mineral clay soil amendments, repeated cropping, soil removal (excavation), and potassium (K) treatment. All but the last two options have been discarded as either less effective or difficult to implement or both.

Experiments at Eneu Island at Bikini Atoll using potassium-rich fertilizers (16N-16P-16K) or KCl show a reduction of about 20-fold in the concentration of ^{137}Cs in coconut meat and fluid; the ^{137}Cs concentrations in foods grown without potassium-rich fertilizer range from 0.24 to 1.3 Bq g^{-1} wet weight, while the ^{137}Cs concentrations in foods grown using potassium-rich fertilizer are less than 0.074 Bq g^{-1} (Robison and Stone 1992). We began a similar experiment on Bikini Island where the ^{137}Cs concentrations in soil, coconut, breadfruit, and other local foods are about 8 to 10 times higher than at Eneu Island. The results of that experiment through May 1994 show that we have reduced the ^{137}Cs concentration in coconut meat and fluid from a range of 5.6 to 11 Bq g^{-1} wet weight to about 0.55 to 0.74 Bq g^{-1} wet weight; in those trees where the initial concentration was between 1.9 to 3.7 Bq g^{-1} wet weight, the potassium treatment has reduced the ^{137}Cs concentration to less than 0.35 Bq g^{-1} (Robison and Stone 1992). A second treatment 51 mo after the original K application showed a further reduction in the ^{137}Cs concentration in drinking coconut meat (Fig. 3). Moreover, one row of coconuts (K1000 1 treatment) that has received no K since the original treatment shows only a slight increase in ^{137}Cs concentration after about 6 y. Several other experiments with coconuts support the above results (Robison and Stone 1992). The same reduction in the uptake of ^{137}Cs has also been observed in breadfruit, *Pandanus* fruit, papaya, and several grain and vegetable crops.

Of course, excavation of the top 30 to 40 cm of soil over the whole island also will effectively reduce the potential dose, both external and internal. This option, however, would entail significant environmental cost, as well as high dollar cost. The removal of the top 30 to 40 cm of soil would carry with it the removal of essentially all of the organic material—material that has taken centuries to develop and that contains most all of the nutrients needed for plant growth and provides water-retention capacity of the coral soil. Moreover, this would obviously require removing all the mature coconut, breadfruit, *Pandanus*, lime, and other trees that supply food, windbreak, and shade at the island and take years to mature. This option would thus necessitate a very long-term commitment to rebuild the soil and revegetate the island. Such a commitment would, in turn, seem to suggest a continuous infusion of effort and expertise, the availability of which does not now seem assured. We have not addressed the matter of the disposal of the very large quantity of removed soil and vegetation, but recent experiences at other locations indicate that this would present a formidable problem of both acceptance and cost.

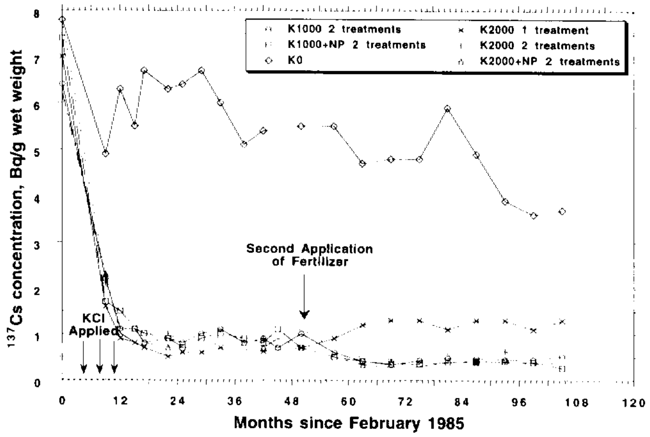

Fig. 3. The reduction in the uptake of ^{137}Cs into drinking coconuts at Bikini Island after an initial and a second application of potassium.

UNCERTAINTY AND INTERINDIVIDUAL VARIABILITY IN ESTIMATED BIKINI DOSES

Doses estimated as described in the Dose Methodology section are based on distributed quantities reflecting either *uncertainty* (i.e., lack of knowledge concerning "the true" value) or *interindividual variability* (which hereafter will be referred to simply as "variability," i.e., heterogeneity in values pertaining to different people), or both; consequently, predicted dose will necessarily reflect both of these characteristics as well. To characterize such uncertainty and variability it is necessary to systematically distinguish these attributes as each or both may pertain to each input variate (Bogen and Spear 1987; IAEA 1996; Bogen 1991; NRC 1993). Another paper in this issue (Bogen et al. 1997) provides a detailed analysis of the methodology and results of the uncertainty and interindividual variability in the estimated doses at Bikini Islands.

RESULTS

The estimated maximum annual and integral effective dose for people resettling Bikini Island are calculated using our diet model, the average radionuclide concentrations in foods, the average biological removal rates and depositions for the radionuclides in organs or the whole body, and the average external dose rates. Doses are presented for two cases: imported foods available (IA), and imported foods unavailable (IUA); that is, consumption of only local foods. The IA diet consists of about 60% imported foods and 40% locally grown foods. The doses listed under the case "IUA" are calculated assuming no imported foods are available and that only local foods are consumed over the entire lifetime of the people's residence on Bikini Island. Our observations lead us to conclude that the latter case is unrealistic over any extended period of time and highly conservative. Nonetheless, even though such a diet will never again exist in the Marshall Islands, the dose based on such a diet are presented here so that the reader may apply different assumptions, or the results of future observations, and develop an apportioned dose estimate.

The doses are also calculated for both the current island conditions (i.e., no remediation) and for the cleanup scenario, where the top 40 cm of soil is removed from the housing and village area where people spend most of their time, and the rest of the island (coconut grove) is treated with potassium fertilizer.

As part of a recent National Academy of Sciences review of our program it was recommended that we double the calorie intake of the diet consisting of only local foods (IUA) from the survey because the diet as developed from the survey data would lead to weight loss and could not be sustained for long periods of time. We did this by doubling the intake of all foods for the original IUA diet. The doses listed in the following tables for the IUA diet are, consequently, based on twice the radionuclide daily intakes.

Estimated doses for resettlement for current conditions on Bikini Island

The average maximum annual effective dose estimated for residents on Bikini Island when imported foods are available (Table 3) is 4.0 mSv. The 30-, 50- and 70-y integral effective dose for residents of Bikini Island, for IA, and local foods only (IUA) diets are listed in Table 4. The doses are presented by internal and external exposure pathways and by radionuclide so that the contribution of each pathway and nuclide can be evaluated. The 30-, 50- and 70-y integral effective doses are 91 mSv, 130 mSv, and 150 mSv, respectively; the same doses for the local foods only diet (IUA) are 350 mSv, 480 mSv, and 560 mSv.

The relative contribution of each of the exposure pathways is presented in Table 5. The dose from the terrestrial food-chain pathway accounts for about 90% of the total estimated 30-y integral effective dose; ^{137}Cs accounts for about 96% of this dose, and ^{90}Sr for about 1%. Any procedure that would either block the uptake of ^{137}Cs into food crops and/or eliminate it from the soil column would substantially reduce the potential exposure of the people living on Bikini Island. The external gamma exposure is next in significance and contributes about 10% of the 30-y integral effective dose.

Estimated doses for resettlement after soil removal in the housing and village area and potassium treatment of the rest of the island

The average maximum annual effective dose for this scenario is estimated to be 0.41 mSv for the IA diet, and 1.2 mSv for the IUA diet (Table 6). The 30-, 50-, and 70-y integral doses for the IA diet are 9.8 mSv, 14 mSv, and 16 mSv; and for the IUA diet they are 31 mSv, 43 mSv, and 50 mSv, respectively (Table 7). For both diet models the counter measure scenario leads to about a 10-fold reduction in the dose. The relative contribution for each pathway for this countermeasure scenario is listed in Table 8.

A summary of the doses for the two island conditions and two diet scenarios showing the dose reductions

Table 3. The maximum annual organ dose equivalent and effective dose rate in mSv y^{-1} for Bikini Island residents for current island conditions when imported foods are available.

		Dose equivalent rate, mSv y^{-1}			
	Weight factor	External gamma	Internal ingestion	Internal inhalation	Total organ
Bone marrow	0.12	0.40	4.0	0.0021	4.4
Bone surface	0.01	0.40	4.2	0.024	4.6
Gonads	0.20	0.40	3.7	0.00031	4.1
Lung	0.12	0.40	3.4	0.0033	3.7
Breast	0.05	0.40	3.0	0.000063	3.4
Thyroid	0.05	0.40	3.4	0.000063	3.8
Liver	0.05	0.40	3.6	0.0049	4.0
Colon	0.12	0.40	3.7	0.000068	4.1
Stomach	0.12	0.40	3.6	0.000063	3.9
Bladder	0.05	0.40	3.7	0.000063	4.1
Oesophagus	0.05	0.40	3.5	0.000063	3.8
Skin	0.01	0.40	2.9	0.000063	3.2
Remainder	0.05	0.40	3.7	0.000063	4.1
Total effective dose equivalent rate[a]					4.0

[a] Weighting factor multiplied by total organ dose.

Table 4. The 30-, 50- and 70-y integral effective dose for Bikini Island residents for current island conditions when imported foods are available and when only local foods are consumed. Numbers in parentheses are the doses for the "local food only" diet (IUA).

	Integral effective dose, mSv					
	30 y	30 y	50 y	50 y	70 y	70 y
External	9.1	(9.1)	13	(13)	15	(15)
Internal						
Ingestion						
^{137}Cs	81	(330)	110	(460)	130	(530)
^{90}Sr	0.85	(5.9)	1.2	(8.6)	1.5	(10)
$^{239+240}$Pu	0.011	(0.098)	0.028	(0.24)	0.051	(0.44)
^{241}Am	0.018	(0.062)	0.043	(0.15)	0.075	(0.26)
Inhalation						
$^{239+240}$Pu	0.069	(0.069)	0.16	(0.16)	0.23	(0.23)
^{241}Am	0.050	(0.050)	0.11	(0.11)	0.15	(0.15)
Total[a]	91	(350)	130	(480)	150	(560)

[a] The total dose may vary in the second decimal place due to rounding.

Table 5. The 30-, 50-, and 70-y integral effective dose for the various exposure pathways for the imported foods available diet.

	Effective integral equivalent dose, mSv		
Exposure pathway	30 y	50 y	70 y
Terrestrial food	82	110	130
External gamma	9.1	13	15
Marine food	0.048	0.096	0.16
Cistern and ground water	0.15	0.21	0.25
Inhalation	0.12	0.27	0.38
Total[a]	91	130	150

[a] The total dose may vary in the second decimal place due to rounding.

associated with the countermeasure option is listed in Table 9.

VALIDATION OF ENVIRONMENTALLY DERIVED DOSE ASSESSMENT

We assessed the "environmental data/model" approach by comparing our estimates of the body burden (i.e., dose) in people residing on Rongelap Atoll using our environmental data, the models and methods outlined in this paper, and three diet models with the actual whole-body measurements conducted by BNL.[†] The LLNL diet model predicts very closely the results of the whole-body measurements over an 8-y period. Two other proposed diet models lead to estimated body burdens far in excess of those observed by whole-body measurements. Results from Utirik Atoll are similar in that the LLNL diet model predicts actual observation while the other two proposed diets once again significantly exceed the observations. A more detailed analysis of this validation is given in a comparison paper in this issue (Robison and Sun 1997).

The estimated effective doses from plutonium based on the concentrations in food, soil and air are very similar to those calculated by BNL based on the analysis of plutonium in urine of the Rongelap people (Sun et al. 1992). These two very independent methods are in excellent agreement on the magnitude of the dose from the transuranic radionuclides as shown in Table 10. The estimated average committed effective dose for 50-y residence from plutonium based on environmental data and models is 0.26 mSv (0.10 mSv 50-y integral effective dose). The value of 0.40 mSv committed effective dose from urine analyses is based on the detection limit of the analytical method used for detection of plutonium in urine. The median value for plutonium in the urine of all the people analyzed is below this detection limit value. The people have been living on Rongelap Island for about 28 y subsequent to the fallout from BRAVO where the plutonium concentration in the surface soil is about 0.11 Bq g^{-1}. Consequently, both methods indicate that the effective committed dose from plutonium at Rongelap Island is below 0.40 mSv for residence between 30 and 50 y.

DISCUSSION

Comparison of estimated doses to adopted guidelines and to background doses

Perspective can be obtained by comparing these estimated doses for Bikini Island with natural background sources in the United States. The average annual effective dose from natural background sources in the United States is about 3 mSv y^{-1}; the breakdown by source is given in NCRP (1987a). The world-wide average background effective dose is 2.4 mSv y^{-1} with some areas over 10 mSv y^{-1} (UNSCEAR 1988). The maximum annual effective dose for current conditions on Bikini Island in 1999, using average values for parameters in the dose model, is 4.0 mSv y^{-1} when imported foods are available. This, of course, is above the average natural background doses in the U.S., but below that in some locations in the world (UNSCEAR 1988). The natural background dose in the Marshall Islands is about 2.4 mSv y^{-1} of which a significant fraction comes from

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[†] Personal communications, Lessard, E. T.; Miltenberger, R., Brookhaven National Laboratory, Upton, NY; 1979.

Table 6. The maximum annual organ dose equivalent and effective dose rate in mSv y^{-1} for Bikini Island residents for the soil removal and potassium treatment option.

		Dose equivalent rate, mSv y^{-1}					
		Common to both diet 1 and 2		Diet 1[a] Imports available		Diet 2[b] Imports unavailable	
	Weight factor	External gamma	Internal inhalation	Internal ingestion	Total organ	Internal ingestion	Total organ
Bone marrow	0.12	0.16	0.0014	0.37	0.53	1.8	2.0
Bone surface	0.01	0.16	0.016	0.43	0.61	2.2	2.4
Gonads	0.20	0.16	0.00021	0.25	0.41	0.97	1.1
Lung	0.12	0.16	0.0023	0.22	0.38	0.87	1.0
Breast	0.05	0.16	4.3E-05	0.20	0.36	0.77	0.93
Thyroid	0.05	0.16	4.3E-05	0.23	0.39	0.89	1.1
Liver	0.05	0.16	0.0034	0.24	0.40	0.94	1.1
Colon	0.12	0.16	4.7E-05	0.27	0.43	1.2	1.4
Stomach	0.12	0.16	4.3E-05	0.23	0.39	0.92	1.1
Bladder	0.05	0.16	4.3E-05	0.24	0.40	0.97	1.1
Oesophagus	0.05	0.16	4.3E-05	0.23	0.39	0.89	1.1
Skin	0.01	0.16	4.3E-05	0.19	0.35	0.74	0.90
Remainder	0.05	0.16	4.3E-05	0.24	0.40	0.96	1.1
Total effective dose equivalent rate[c]					0.41		1.2

[a] Diet 1 = imported foods available diet (IA).

[b] Diet 2 = local foods only diet, i.e., imported foods unavailable (IUA).

[c] Weighting factor multiplied by total organ dose.

Table 7. The 30-, 50- and 70-y integral effective dose for Bikini Island residents for the soil removal/K treatment option when imported foods are available and when only local foods are consumed.

	Integral effective dose, mSv					
	30 y	30 y	50 y	50 y	70 y	70 y
External	3.6	(3.6)[a]	49	(49)	5.7	(5.7)
Internal						
Ingestion						
^{137}Cs	5.3	(21)	7.2	(28)	8.5	(33)
^{90}Sr	0.84	(5.9)	1.2	(8.6)	1.5	(10)
$^{239+240}$Pu	0.011	(0.098)	0.028	(0.24)	0.051	(0.44)
^{241}Am	0.011	(0.055)	0.026	(0.13)	0.045	(0.23)
Inhalation						
$^{239+240}$Pu	0.043	(0.043)	0.10	(0.10)	0.14	(0.14)
^{241}Am	0.04	(0.04)	0.08	(0.08)	0.11	(0.11)
Total[a]	9.8	(31)	14	(42)	16	(50)

[a] Numbers in parentheses are the doses for the "local food only" diet.

[b] The total dose may vary in the second decimal place due to rounding.

^{210}Po via consumption of fresh fish (Noshkin et al. 1994; Robison et al. 1997). Thus, the natural background dose plus the manmade component of the dose totals about 6.4 mSv, which is above the U.S. and world-wide average background dose, but still less than locations in some parts of the world (UNSCEAR 1988).

Guidance of 1 mSv y^{-1} for the general public from the International Commission and Radiological Protection (ICRP 1990) and the National Council on Radiation Protection (NCRP 1987b) are often quoted for reference. However, these guidelines are developed for controlling prospective dose; that is, for controlling future dose above a natural background baseline dose for practices such as nuclear power plants, uranium mining operations, fuel reprocessing plants, storage facilities, etc., that have a potential of exposing the general public. This

Table 8. The 30-, 50-, and 70-y integral effective dose for the soil removal/K treatment option for the various exposure pathways when imported foods are available.

	Effective integral equivalent dose, mSv		
Exposure pathway	30 y	50 y	70 y
Terrestrial food	6.0	8.3	9.8
External gamma	3.6	5	5.7
Marine food	0.048	0.096	0.16
Cistern and ground water	0.15	0.21	0.25
Inhalation	0.08	0.18	0.25
Total[a]	9.8	14	16

[a] The total dose may vary in the second decimal place due to rounding.

Table 9. Comparison of estimated effective doses for two diet models and two island conditions.

	Imports available		Local foods only (imports unavailable)	
Diet model Island status	Current conditions	Soil + K treatment	Current conditions	Soil removal and K treatment
Maximum average annual effective dose, mSv	4.0	0.41	15	1.2
30 y integral dose, mSv	91	9.8	350	31
50 y integral dose, mSv	130	14	480	43
70 y integral dose, mSv	150	16	560	50

Table 10. The average committed effective dose from plutonium and americium at Rongelap Island in mSv.

	Method		
	Environmental (LLNL)[a]		Urine analysis (BNL)
	Committed effective dose	50-y integral effective dose	Committed effective dose
Plutonium	0.26	0.10	0.40[b]
Americium	0.23	0.078	No estimate

[a] Two significant figures to show slight difference between plutonium and americium.

[b] Based on the detection limit; actual dose is below this number.

guidance is not relevant to a situation such as in the Marshall Islands or other regions that have been contaminated where people wish to live.

For situations such as the Marshall Islands and areas contaminated by the Chernobyl accident, a new baseline of dose to the population has been created. The reduction of the new dose level by intervention strategies should be evaluated based on the reduced risk of detriment expected from the intervention relative to the dollar and social cost, environmental impact, and possible dose substitution resulting from the proposed remediation strategies. In other words, intervention should be considered only if it will do more good than harm.

Consequently, the decision to initiate intervention efforts will vary from case to case depending on the accompanying circumstances and issues. No specific guidance for an intervention level is given by any governing body, commission or board, but general guidance from the ICRP and IAEA can be used to infer an operational level. The ICRP (ICRP 1993b) has indicated that remedial actions, such as moving from one's house or paying for expensive remodeling, for people continually exposed in their homes to natural radon, is probably justified if the annual equilibrium radon concentration is above 600 Bq m^{-3} (an annual effective dose of about 10 mSv). This is based on intervention principles set forth in ICRP Publication 39 (ICRP 1984). This is a direct commentary on the difference in a policy or guidance designed for practices to limit the dose to the public where prospective dose can be controlled and limited in order to reduce even a small risk, and the case where previous contamination of a region is negatively affecting peoples lives. In the latter case, the guidance recognizes the fact that the risk is small from radiation doses that are above the prospective dose guidance but below about 10 mSv; such doses should not be used *a priori* as a basis for negatively affecting peoples lives, creating hardship, causing great expenditure of resources, or preventing people from occupying homes and lands. It is also a statement on the conservative nature of the prospective dose guidance.

The International Atomic Energy Agency (IAEA) in their Basic Safety Standards (BSS) (IAEA 1996) also indicate that the action level for remedial action for radon in dwellings should fall between 200 and 600 Bq m^{-3} yearly average concentration. Below this range remedial action would not be required. Moreover, the BSS state that lifetime doses, if projected to lead to a dose exceeding 1 Sv, should lead to permanent resettlement. With the radiological decay of ^{137}Cs over 70 y, this would translate into an initial dose rate below about 20 mSv y^{-1} for an action level. Some 51 countries and most organizations concerned with radiation protection were involved in the review and endorsement of the BSS.

The general consensus from major commissions and agencies is that below about 10 mSv y^{-1} the situation should be reviewed, and if a cost effective, socially-neutral impact, environmentally-sound remediation strategy can be found to reduce the dose further, then it should be considered. If not, resettlement of homes and lands should not necessarily be prohibited.

The application of potassium to the surface soil and the subsequent dissolution and transport into the root zone during periods of rainfall is very effective in reducing the concentration of ^{137}Cs in edible foods. If a reasonable agricultural program is implemented that includes periodic use of fertilizer, the dose from ^{137}Cs through the food chain will be greatly reduced, and the growth and productivity of some plants and food crops will be enhanced. The variety of food crops at Bikini Island that have been treated with potassium in our field experiments have shown a reduction in the concentration of ^{137}Cs to about 5% of pretreatment concentrations. The resulting ^{137}Cs concentration in food crops is between 100 and 200 Bq kg^{-1}.

The Codex Alimentarius Commission has established guidelines for the concentration of various radionuclides in foodstuffs that may be shipped across international borders (FAO/WHO 1991). The concentrations below which foods can be transported across international boundaries and used for general food consumption are listed in Table 11. The concentration for ^{137}Cs in foods is 1,000 Bq kg^{-1}. The ^{137}Cs concentration in food products at Bikini fall between 100–200 Bq kg^{-1} after potassium treatment, which is well below the Codex Alimentarius guidelines.

This use of potassium fertilizer, coupled with the soil removal and addition of crushed coral in the housing and village areas, could reduce the average maximum annual dose from about 4.0 mSv to about 0.41 mSv. Consequently, the combined natural background and manmade dose after potassium treatment is 2.8 mSv y^{-1} (2.4 mSv y^{-1} + 0.41 mSv y^{-1}), which is similar to the U.S. average annual background dose of 3 mSv. The average background dose in the U.S. over a 50-y period is 150 mSv. The average background dose in the Marshall Islands over 50 y is estimated to be 120 mSv (Robison et al. 1997); the 50-y integral effective dose at Bikini Island after the soil removal/potassium treatment remedial action is estimated to be 14 mSv. Consequently, the combined dose at Bikini, natural background plus manmade, for a 50-y period is about 134 mSv, after the remedial action. Thus, because of the radiological decay of ^{137}Cs, the combined natural background dose and the dose from the manmade component (^{137}Cs, ^{90}Sr, $^{239+240}$Pu, ^{241}Am) over 50 y is about the same as the 50-y natural background dose in the U.S. and the world-wide average. The ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am are still in the soil although the ^{137}Cs uptake into foods is greatly reduced. However, the half-life of ^{137}Cs is 30.1 y (and 28 y for ^{90}Sr) so that in 120 y the ^{137}Cs will be about 6% of the current concentrations. That will in effect bring the ^{137}Cs concentration to levels that don't require a remedial action. This is less time than it will take to rebuild the soil if the top 40 cm of the island is excavated and discarded.

Moreover, we continually see ^{137}Cs in the groundwater at all contaminated atolls; the turnover time of the groundwater is about 5 y. The ^{137}Cs can only get to the groundwater by a leaching process through the soil column when a portion of the soluble fraction of ^{137}Cs is transported to the groundwater when rainfall is heavy enough to cause recharge of the lens. Environmental processes are causing a loss of ^{137}Cs out of the root zone of the plants that provides a loss constant (λ env) in addition to radiological decay. Consequently, there is an effective rate of loss, λ eff = λ rad + λ env that is the sum of the radiological and environmental-loss decay constants. We have had, and continue to have, a vigorous program to determine the rate of the environmental loss process. What we do know at this time is that the loss of ^{137}Cs over time is greater than that estimated based on only radiological decay.

Table 11. Generic action levels for foodstuffs.

Radionuclides	Foods destined for general consumption (kBq kg^{-1})	Milk, infant foods and drinking water (kBq kg^{-1})
^{134}Cs, ^{137}Cs, ^{103}Ru ^{106}Ru, ^{89}Sr	1	1
^{131}I		0.1
^{90}Sr	0.1	
^{241}Am, ^{238}Pu, ^{239}Pu	0.01	0.001

CONCLUSIONS

The dose to populations resettling contaminated atolls in the Northern Marshall Islands is dominated by ^{137}Cs that is transported from soil to the edible portions of plants. The dose from ^{137}Cs uptake via the terrestrial food chain accounts for about 90% of the estimated dose at Bikini Island. ^{90}Sr contributes a very small percentage of the estimated dose because of the unique Ca CO_3 soil system. In fact, the relative uptake of ^{137}Cs and ^{90}Sr in food crops at the atolls is totally reversed from that observed in continental, silica-based soils. Most all the data in the literature are based on experiments and observations from silica-based soils. The transuranic radionuclides, $^{239+240}$Pu and ^{241}Am, contribute in a minor way to the estimated dose, but they will, of course, have a long-term presence at the atolls. External gamma is the second most significant pathway because of the dose resulting from ^{137}Cs (Ba) gamma rays. The inhalation, drinking water, and marine food pathways contribute only slightly to the estimated dose at the atolls.

The estimated dose to the returning populations under current island conditions will exceed background doses elsewhere in the world. However, two different remedial actions, excavation of the top soil and treatment with potassium fertilizer, will reduce the dose at Bikini Atoll so that the combined natural background dose plus the dose from manmade radionuclides of bomb origins will be less than natural background dose in the continental United States and Europe. Both remedial methods will reduce the concentration of ^{137}Cs in food crops to levels well below the Codex Alimentarius guidelines of 1000 Bq kg^{-1} (Codex 1994). Foods with a concentration of ^{137}Cs below 1,000 Bq kg^{-1} are allowed to be shipped across international borders for general use in the food supply.

Based upon the extensive data base of radionuclide concentrations in the Bikini Island environment, the dose assessments based on detailed evaluation of all exposure pathways, and field experiments to evaluate remedial options, several measures are identified to reduce the dose to returning populations along with commentary on their effectiveness and the positive and negative aspects of each:

1. Remove the surface soil (0 to 30 cm) in the area where the village will be established and for 10 to 15 m around each of the sites where houses will be built to minimize the external gamma and beta and alpha

exposure in the areas where people spend most of their time. The estimated gamma dose can be reduced by 40% by such action. The additional cost to remove 15 to 20 cm of soil from the relatively small area included around each house and the village area would be minimal, compared with the overall costs of resettlement, since scraping and clearing is required to begin construction and resettlement. There would essentially be no adverse environmental effects from such an action.

2. Place a 10-cm layer of crushed coral around the village site and in a 5 to 10-m radius around each house to provide some additional reduction in any beta and gamma rays emanating from the soil subsequent to the soil removal and greatly reduce exposure to any residual beta radiation. This should be acceptable, as it is common practice in Marshallese villages to use crushed coral around homes for both appearance and dust suppression. The combination of the soil removal and application of crushed coral can significantly reduce the external exposure and provide small reductions in internal exposure.
3. Treat the entire agricultural area of the island, where coconut, breadfruit, and *Pandanus* fruit are growing, with potassium chloride (KCl) or complete fertilizer (nitrogen, phosphorus, and potassium) to reduce the uptake of ^{137}Cs into food crops. A high-potassium fertilizer can also be used in any family-type gardening for the same reason. This option reduces the estimated dose to 5% of pretreatment estimates and minimizes the environmental impact. The major portion of the island will be left intact including the mature coconut grove, the surface soil that contains nearly all of the organic material of the soil that has taken centuries to develop, and the natural vegetation windbreaks along the shoreline. The organic soil layer is very important for growing natural vegetation and food crops; it provides most all of the nutrients required for plant growth, and increases the water retention capacity of the soils. The potential reduction in estimated dose from the food chain can be 95%. This plan, coupled with the soil removal and addition of crushed coral in the housing and village areas would have two positive effects. First, it could reduce the maximum annual dose (assuming a mixed diet of local and imported foods) from 4.0 mSv to about 0.41 mSv and the total estimated 30-y, integral effective dose at Bikini Island from 91 mSv to about 9.8 mSv. Second, it would be helpful to crop production by increasing the growth rate and productivity of some food crops. The ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am are still in the soil although the ^{137}Cs uptake into foods is greatly reduced. Thus, the potassium treatment can solve the major dose problem until natural radionuclide decay reduces the ^{137}Cs to insignificant levels in about 90 y. The dose from ^{90}Sr is very low because of all the excess calcium and stable strontium in the calcareous, coralline soils that greatly reduces the uptake of ^{90}Sr in food crops. The ^{90}Sr has a slightly shorter half life than ^{137}Cs and will also be reduced to insignificant levels within about 100 y.
4. Design adequate water catchment systems so that fresh water will always be available, even during extended dry periods, thus avoiding use of the contaminated ground water. Although the reduction in the estimated dose from the ground-water pathway (it contributes less than 0.05% of the estimated dose) is very much less than for the external gamma and terrestrial food pathways, it is not an expensive proposition to expand somewhat the water catchment systems that will be a necessary part of any housing and community design. Again, apart from radiological considerations, this measure should be found acceptable because of the obvious community benefits of expanded and improved water catchment systems. Consequently, another potential source of exposure, albeit very low, can essentially be eliminated.
5. Of course, excavation of the top 30 to 40 cm of soil over the whole island also will effectively reduce the potential dose, both external and internal. This option, however, would entail environmental cost, as well as high dollar cost. The removal of the top 30 to 40 cm of soil would carry with it the removal of essentially all of the organic material—material that has taken centuries to develop and that contains most all of the nutrients required for plant growth and that increases water-retention capacity of the coral soil. This would obviously require removing all the mature coconut trees and other trees that supply food, windbreak, and shade at the island. This option would thus necessitate a very long-term commitment to rebuild the soil and revegetate the island. Such a commitment would, in turn, seem to suggest a continuous infusion of effort and expertise, the availability of which does not now seem assured.

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Paper

UNCERTAINTY AND VARIABILITY IN UPDATED ESTIMATES OF POTENTIAL DOSE AND RISK AT A U.S. NUCLEAR TEST SITE—BIKINI ATOLL

Kenneth T. Bogen, Cynthia L. Conrado, and William L. Robison*

Abstract—**Uncertainty and interindividual variability were assessed in estimated doses for a rehabilitation scenario for Bikini Island at Bikini Atoll, in which the top 40 cm of soil would be removed in the housing and village area, and the rest of the island would be treated with potassium fertilizer, prior to an assumed resettlement date of 1999. Doses were estimated for ingested ^{137}Cs and ^{90}Sr, external gamma-exposure, and inhalation+ingestion of ^{241}Am + $^{239+240}$Pu. Two dietary scenarios were considered: imported foods are available (IA); imported foods are unavailable with only local foods consumed (IUA). After $\sim$5 y of Bikini residence under either IA or IUA assumptions, upper and lower 95% confidence limits on interindividual variability in calculated dose were estimated to lie within a $\sim$threefold factor of its in population-average value; upper and lower 95% confidence limits on uncertainty in calculated dose were estimated to lie within a $\sim$twofold factor of its expected value. For reference, the expected values of population-average dose at age 70 y were estimated to be 16 and 52 mSv under IA and IUA dietary assumptions, respectively. Assuming that 200 Bikini resettlers would be exposed to local foods (under both IA and IUA assumptions), the maximum 1-y dose received by any Bikini resident is most likely to be approximately 2 and 8 mSv under the IA and IUA assumptions, respectively. Under the most likely dietary scenario, involving access to imported foods, this analysis indicates that it is most likely that no additional cancer fatalities (above those normally expected) would arise from the increased radiation exposures considered.**

Health Phys. 73(1):115–126; 1997

Key words: cesium; Marshall Islands; fallout; dose assessment

INTRODUCTION

THIS PAPER supplements updated dose assessments for Bikini Island at Bikini Atoll conducted by Robison et al. (1994a, 1995, 1997), which address doses estimated under two resettlement options: (1) current conditions assuming no environmental remediation, and (2) resettlement after soil removal in the housing and village area, and potassium treatment of the rest of the island. The present detailed analysis of uncertainty and interindividual variability in estimated doses to potential Bikini resettlers focuses only on resettlement option (2), under the two dietary scenarios considered by Robison et al. (1995, 1997), referred to as IA (imported foods will be available and will comprise 60% of the diet) and IUA (local foods only—considered unlikely; see Robison et al. 1995, 1997). Estimated dose is typically a function of distributed quantities reflecting either uncertainty (lack of knowledge concerning "the true" value of a variate) or interindividual variability (or simply "variability," referring to heterogeneity in true variate values pertaining to different people at risk). Consequently, predicted dose typically involves joint uncertainty and interindividual variability (JUV). This paper illustrates an application of analytic and Monte Carlo methods for JUV analysis pertaining to estimated fallout-related doses to hypothetical Bikini resettlers. Specifically, 70-y and maximum 1-y doses to hypothetical Bikini resettlers are calculated, as described below, using analytic and Monte Carlo procedures to characterize JUV in estimated dose as a function of distributed input variates involved.

METHODS

Dose models

If dose variability is simply treated as dose uncertainty, the latter is constrained to refer only to an individual selected at random from the exposed population and not to any specific (e.g., relatively highly exposed) individual(s) who may be of particular concern. To characterize JUV in estimated dose, appropriate methods must therefore be used to distinguish and treat these attributes systematically as each or both pertain to each input variate (Bogen and Spear 1987; Nazaroff et al. 1987; IAEA 1989; Bogen 1990, 1995; NRC 1994). We used such methods to recalculate dose to potential Bikini residents as a function of several distributed input variates. Uncertainty and variability were characterized for predicted total integrated doses arising from (1) external gamma-ray exposure, (2) ^{241}Am and $^{239+240}$Pu inhalation and ingestion, (3) ^{90}Sr ingestion, and (4) ^{137}Cs ingestion. Expected values of the relatively minor source-specific doses (1–3) were all calculated using the

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same ICRP models (Leggett 1986; ICRP 1988, 1990, 1991) employed by Robison et al. (1995, 1997) to calculate adult doses from these sources, except for one modification accounting for greater absorption of ingested ^{90}Sr in children (discussed below). To facilitate JUV analysis of total integral dose, the dominant source of potential radiological exposure on Bikini, ^{137}Cs ingestion (see Robison et al. 1995, 1997), was treated somewhat differently. Specifically, the one-compartment ICRP (1990) model for ingested ^{137}Cs was replaced by the following structurally equivalent model:

$$q_{ij}(t_i) = FBR_{ij}\exp(-\lambda t_i) \qquad \text{at any time } t_i, \quad 0 \le t_i \le t, \tag{1}$$

$$q'_{ij}(u) = -(\beta K + \lambda)q_i(u) \qquad \text{for any time } u, \quad t_i \le u \le t, \tag{2}$$

$$q_{ij}(u) = BFR_{ij}\exp(-\lambda t_i \exp[-(\beta K + \lambda)u] \qquad \text{for any time } u, \quad t_i \le u \le t, \tag{3}$$

where $q_{ij}(u)$ is the activity (in Bq kg^{-1} body weight of ^{137}Cs) in the whole body at any time u following ingestion of an activity R_{ij} (in Bq kg^{-1} body weight) of ^{137}Cs contained in a food item of type j at time t_i; B represents a dietary-dose-model bias (i.e., a dose-estimation uncertainty factor) associated with R_{ij}, prime ($'$) denotes differentiation with respect to time, λ is the radiological decay rate of ^{137}Cs, $K = \text{Ln}(2)H^{-1}$ is the biological loss rate of ^{137}Cs from the dominant "slow" metabolic compartment of a reference adult (see ICRP 1990), F is the fraction of ingested dose entering this slow metabolic compartment, and β is a factor representing uncertainty associated with H. Henceforth, angle brackets, $\langle\ \rangle$, are used to denote mathematical expectation only with respect to uncertainty, and an overbar is used to denote expectation only with respect to interindividual variability (Bogen 1995).

Daily intakes R_{ij} in Bq kg^{-1} d^{-1} of ^{137}Cs, as well as corresponding intakes of ^{90}Sr, in local food items of type j were assumed to be obtained from independent random samples of such items collected n_j days per year from among the possible selections of the type available on Bikini. The corresponding cumulative dose $D(t)$ from all exposure sources was estimated as

$$\begin{aligned} D(t) = {} & D_x(t) + D_{\text{AmPu}}(t) + D_{\text{Sr}}(t) \\ & + \int_0^t \sum_j \sum_{i=1}^{n_j} \frac{365}{n_j}\, cq_{ij}(u)\,\mathrm{d}u, \end{aligned} \tag{4}$$

where $D_x(t)$ is the external-gamma dose modeled as interindividually variable (and not uncertain), $D_{\text{AmPu}}(t)$ is the unmodified ICRP-model estimate of total Am+Pu inhalation+ingestion dose (modeled as neither uncertain nor variable, in view of its relatively minor role), $D_{\text{Sr}}(t)$ is the dose due to ^{90}Sr ingestion (modeled as both uncertain and interindividually variable, similar to the approach taken for ^{137}Cs—see Appendix), and c is a unit-conversion constant. Eqn (4) was evaluated using a combination of analytic and Monte-Carlo methods detailed in the Appendix.

Parameter distributions

Using the angle-bracket and overbar notation discussed above, specific assumptions regarding distributions for each variable and/or uncertain parameter appearing or implied in eqn (4) are discussed individually below. These assumptions are summarized in Table 1.

External gamma dose. $\overline{D_x(t)}$ was modeled using the assumptions of Robison et al. (1995, 1997) for average daily occupancies and exposure rates in house and beach/lagoon areas (12 h × 0.1z), house-surrounding and village areas (9 h × 0.2z), and island-interior areas ($\bar{T} \times 19$z), with $\bar{T} = 3$ h and z = 0.0717 pC kg^{-1}s^{-1} which imply a time-weighted average exposure rate of 0.18 pC kg^{-1} s^{-1}. Variability in mean daily time T (h) spent in the island interior (the principal source of gamma dose) was assumed to be triangularly distributed over a range of 1 to 5 h. Thus, it was assumed that, $D_x(t) = X_\gamma \overline{D_x(t)}$, where the exposure-variability factor X_γ is triangularly distributed over the range 1 ± (19/30).

Metabolic factors for ^{137}Cs. Variability in the fraction, F, of ingested ^{137}Cs input to the dominant biological compartment was assumed to be uniformly distributed between an uncertain lower bound ranging between 0.71 and 0.89 and an upper bound of 1. Thus, uncertainty in $\bar{F}$ was assumed to be uniformly distributed within ± 5% of an assumed expected value of 0.9, and variability of $\langle F \rangle$ was assumed to be uniformly distributed between 0.8 and 1. These assumptions approximately characterize the empirical data on the value of F obtained for 17 individuals reported by Schwartz and Dunning (1982).

Interindividual variability in the biological half-time, H, of the dominant slow compartment was modeled as lognormally distributed based on the data pertaining to 23 Marshallese males indicating a median of 115 d and a geometric standard deviation (SD$_g$) of 1.23, as shown in Figure 4 of Robison et al. (1995). For the present analysis, however, it was assumed that $\bar{H} = 110$ d and that SD$_g$ = 1.32 for H, based, respectively, on the ICRP (1979) reference mean value (used earlier) and on data reviewed by Schwartz and Dunning (1982) indicating slightly greater variability associated with the parameter among 53 individuals from whom measurements were available. A geometric mean (GM) value of H (105.9 d) consistent with the values selected for and SD$_g$ was obtained using the method of moments. Uncertainty pertaining to H was represented by the independent factor β assumed to be uniformly distributed (between 0.9 and 1.107), such that the true value of H pertaining to any specific individual was taken to lie within 10% of the expected value for that individual.

Table 1. Parameters used in analysis of uncertainty/variability in estimated dose to hypothetical bikini residents.

Parameters[a]	Symbol	Variate type[b]	Value or distribution model[c]	Unit
Effective unit-conversion factor	c	C	2.419×10^{-3}	mSv kg Bq^{-1} y^{-1}
Radiological decay rate of ^{137}Cs	λ	C	0.0230	y^{-1}
External gamma exposure variability factor	X_γ	V	Tri(11/30, 1, 49/30)	unitless
Fraction input to slow compartment for ^{137}Cs	F	UV	$\text{U}(2\bar{F} - 1, 1)$	unitless
Variability expectation of F	$\bar{F}$	U	U(0.855, 0.945)	unitless
Biological half-life of slow compartment	H	V	$\text{LN}(\bar{H} - (h^2/2), h)$	y
Population-average value of H	$\bar{H}$	C	110/365	y
Uncertainty associated with H	β	U	U(0.9, 1.107)	unitless
SD of Ln(H)-variability	h	C	0.275	unitless
Annual dietary intake of ^{137}Cs	R	UV	$\text{LN}(\bar{R} - (r^2/2), r)$	Bq kg^{-1} y^{-1}
Population-average value of R	$\bar{R}$	U	$\text{N}(\langle R \rangle, \langle R \rangle g_R)$	Bq kg^{-1} y^{-1}
Expected 1999 values of $\bar{R}$/365 d	$\langle R \rangle$/365 d	C	50.1/70 (IA diet), 196.7/70 (IUA diet)	Bq kg^{-1} y^{-1}
SD of Ln(R) variability	r	C	0.8217	unitless
CV of $\langle R \rangle$ variability	g_R	C	0.9821	unitless
CV in R due to annual diet sample uncertainty	γ_R	C	0.039	unitless
Cumulative dose due to ^{90}Sr ingestion by time t	$D_{\text{Sr}}(t)$	UV	(see text)	mSv
Factor for variability in adult ^{90}Sr GI absorption	G	V	U(0.50, 1.5)	unitless
Uncertainty (model bias) associated with R	B	U	LN(−0.04309, 0.2936)	unitless
Uncertainty risk per unit dose	Z	U	LN(−4.828, 0.5064)	mSv^{-1}

[a] IA = imports available, IUA = imports unavailable, SD = standard deviation, CV = SD/mean.

[b] C = constant, U = uncertainty, V = interindividually variable (i.e., heterogeneous), UV = both uncertain and heterogeneous.

[c] U (a,b) = uniformly distributed between a and b, LN (a,b) = lognormally distributed with a geometric mean of $\exp(a)$ and a geometric SD (SD_g) of $\exp(b)$, $\text{N}(a,b)$ = normally distributed with mean a and SD b, $\text{Tri}(a,b,c)$ = triangularly distributed with bounds a and c and mode b.

Metabolic factors for ^{90}Sr. Cumulative dose, $D_{\text{Sra}}(t)$, by age t due to ^{90}Sr ingestion by adults, was obtained using the ICRP (1990) adults-only model for ^{90}Sr employed by Robison et al. (1995, 1997). In contrast to the situation for potential Rongelap Island resettlers, for whom ingested ^{90}Sr would be a relatively negligible source of radiation exposure (Robison et al. 1994b), ^{90}Sr would contribute a nonnegligible fraction of total dose for potential Bikini resettlers, albeit a relatively small one compared to that due to ^{137}Cs (Robison et al. 1995). Data are available from which models of uncertainty and interindividual variability in ^{90}Sr uptake and distribution and consequent dosimetry could be constructed (e.g., Rivera 1967; Bennett 1973, 1977, 1978; Papworth and Vennet 1973, 1984; Klusek 1979; Leggett et al. 1982; Christy et al. 1984; Christy and Eckerman 1987a,b). Because ^{90}Sr would contribute a relatively minor dose to Bikini resettlers, cumulative lifetime ^{90}Sr dose, $D_{\text{Sr}}(t)$, by age t was instead modeled first as $D_{\text{Sr}}(t) = G \times W(t) \times D_{\text{Sra}}(t)$, where the factors G and $W(t)$ are explained as follows.

The factor G was used to model variability in ^{90}Sr uptake about its population-average value and was assumed to be uniformly distributed between 0.5 and 1.5 based on measured ranges reported in ICRP (1990). The (deterministic) factor $W(t)$ was used to adjust for the fact that $D_{\text{Sra}}(t)$ underestimates $D_{\text{Sr}}(t)$, due to increased ^{90}Sr uptake in infancy/childhood and other factors (ICRP 1990). This factor was calculated as $W(t) = \int_0^t d_{\text{Sr}}(u)\,du / [t\,d_{\text{Sr}}(70)]$, where $d_{\text{Sr}}(t)$ refers to a linear interpolation of the age-specific effective ^{90}Sr dose equivalent values listed ICRP (1990, Table 3-2). For example, $W(1) = 3.41$ and $W(70) = 1.17$. Additional metabolic uncertainty and variability in $D_{\text{Sr}}(t)$ was assumed to be proportional to and (as a conservative assumption) completely correlated with that associated with dietary ^{137}Cs intake (see Appendix). All maximum 1-y effective doses were calculated (conservatively) assuming a resettling cohort arriving at age 0 (thus incurring a maximal ^{90}Sr dose).

Dietary intake of ^{137}Cs and ^{90}Sr. The population-average value of expected annual intake, $\langle R \rangle$, of total ^{137}Cs activity in the LLNL model diet for hypothetical Bikini residents as of 1999 (assuming imports are available) was taken to be (365 d) × (0.716 Bq kg^{-1} d^{-1}) for a reference adult, based on the analysis of food consumption survey data for 34 adult Ujelang females discussed in Robison et al. (1994b). Interindividual variability in corresponding expected daily intakes, $\langle R_{ij} \rangle$ was modeled using the empirical distribution of average daily uptakes in Bq kg^{-1} calculated from the food-survey data for these same 34 adult Ujelang females, which was multiplicatively scaled to have expected daily population average values equal to 100% of the total mean daily ^{137}Cs intakes corresponding to each of the two dietary scenarios considered. For potential Bikini resettlers, these expected values of food-specific ^{137}Cs activities and intakes are summarized in Table 2 for the 11 major local-food items likely to be consumed. The scaled empirical distribution of ^{137}Cs intake does not significantly differ from a lognormal distribution with a shape parameter of $\text{SD}_g = 0.8217$ (Fig. 1); $p > 0.15$ using Stephen's modified Kolmolgorov-Smirnov, Cramer-von-Mises, or Watson tests (Stephens 1970; Pearson and Hartley 1972). We used this lognormal distribution as the

Table 2. Diet model-bikini island for adults for ^{137}Cs ingestion.[a,b]

					^{137}Cs intake					
			^{137}Cs activity		Local only			Imports available		
Local foods	Intake: Local foods only (g d^{-1}) L	Intake: Local + imported (g d^{-1}) I	Mean (Bq g^{-1}) C	SD/ Mean γ_C	Mean (Bq d^{-1}) $A = LC$	Var (Bq d^{-1})^2 σ^2	SD/ Mean γ	Mean (Bq d^{-1}) $B = IC$	Var (Bq d^{-1})^2 σ^2	SD/ Mean γ
Coconut										
Milk[d]	122	51.9	0.268	0.644	32.6	442		13.9	80.2	
Meat	181	31.7	0.147	0.739	26.6	386		4.66	11.9	
Copra	71.4	12.2	0.268	0.644	19.1	152		3.27	4.43	
Juice	334	99.1	0.0577	0.777	19.3	224		5.72	19.7	
Total[c]	708		0.138		97.6		0.355			
Total[c]		195	0.141					27.6		0.391
Pork										
Heart	0.620	0.310	0.980	1.10	0.608	0.447		0.304	0.112	
Muscle	13.9	5.67	1.57	0.635	21.9	193		8.90	32.0	
Liver	6.70	2.60	0.812	0.912	5.44	24.6		2.11	3.71	
Total[c]	21.24		1.31		27.9		0.529			
Total[c]		8.58	1.32					11.3		0.528
Chicken										
Muscle	31.2	8.36	0.0213	0.635[e]	0.665	0.178		0.178	0.0128	
Liver	17.7	4.50	0.0213[f]	0.912[g]	0.377	0.118		0.0959	0.00764	
Gizzard	3.32	1.66	0.0213[f]	0.912[g]	0.0707	0.00416		0.0354	0.00104	
Total[c]	52.2		0.0213		1.11		0.493			
Total[c]		14.52	0.0213					0.309		0.474
Breadfruit	186	27.2	0.0190	0.584	3.54	4.27	0.584	0.517	0.0911	0.584
Pandanus	65.0	9.16	0.194	0.848	12.6	114	0.848	1.78	2.27	0.848
Sprouting coconut[d]	122	7.79	0.268	0.644	32.8	446	0.644	2.09	1.81	0.644
Papaya	27.0	6.59	0.110	1.34	2.97	15.8	1.34	0.725	0.944	1.34
Arrowroot	94.8	3.93	0.0543	0.413	5.15	4.52	0.413	0.213	0.00777	0.413
Pumpkin	5.44	1.24	0.0587	1.18	0.319	0.142	1.18	0.0728	0.00738	1.18
Marsh. Cake[d]	0.00	11.7	0.268	0.644	0.00	0.00	0.00	3.14	4.08	0.644
Coconut crabs	25.0	3.13	0.366	0.604	9.15	30.5	0.604	1.15	0.479	0.604
Subtotal	1,307		0.148		193		0.0274[h]			
Subtotal		289	0.169					48.9		0.0392[h]
% of Total	42	22			98.2			97.5		

[a] Three significant figures are shown for the purpose of calculating corresponding mean, standard deviation (SD), variance (σ^2) and coefficient-of-variation (γ) values.

[b] Local-foods-only, local + imported foods intakes and ^{137}Cs activities for specific foods decay corrected to 1999, are from Robison et al. (1995).

[c] Mean and SD values for totals listed under coconut, pork and chicken were calculated using subitem-specific intake weights. For example, for a given food item (e.g., coconut, consisting of m = 4 constituents) with the local foods only diet,

$$A_i = L_i C_i, \quad \sigma_i = A_i \gamma_{ci}, \quad \gamma = \left(\sum_{i=1}^{m} \sigma_i^2 \right)^{1/2} \left(\sum_{i=1}^{m} A_i \right)^{-1}.$$

[d] Assumed to equal copra meat.

[e] Assumed to equal pork muscle.

[f] Assumed to equal chicken muscle.

[g] Assumed to equal pork liver.

[h] The γ value given for the subtotal of all 14 items listed, e.g., from a local-foods-diet, is the annual value calculated as

$$g = \left(\sum_{j=1}^{11} A_j \right)^{-1} \left(\sum_{j=1}^{11} A_j^2 g_j^2 n_j^{-1} \right)^{1/2}$$

where n_j is the number of samples of food type j eaten per year, assumed to be 12, 52, and 182.5 for pork-related, chicken-related and other items, respectively (see Appendix).

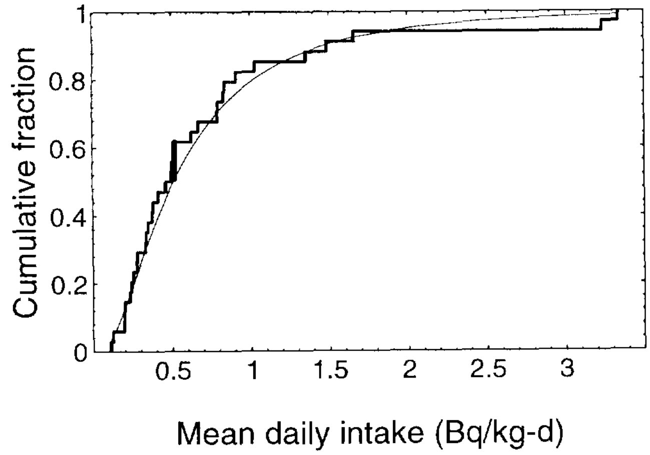

Fig. 1. Sample distribution of interindividual variability in daily intake of ^{137}Cs per unit body weight based on survey data for 34 adult Ujelang females (bold), shown here fit to a lognormal distribution (light) with SDg = 2.274 and a mean value scaled to equal 0.7157 Bq kg^{-1} d^{-1}, the expected value for 1999 Bikini resettlers assuming imported foods are available. The Ujelang survey data are discussed further in Robison et al. (1994b).

basis of our model of variability in $\langle R \rangle = \langle R_{ij} \rangle$ for the hypothetical Bikini resettlement population. By the method of moments (Aitchison and Brown 1957), this distribution has a corresponding coefficient of variation (CV) [i.e., standard deviation (SD) divided by expected value] with respect to modeled variability equal to g_R = 0.9821.

The distributional form and g_R value assumed for ^{137}Cs intake discussed above was assumed also to pertain to interindividual variability in lifetime-average daily ingestion of ^{90}Sr. Food-specific ^{90}Sr activities and intakes for potential Bikini resettlers, under the two dietary scenarios considered, are summarized in Table 3. A comparison of Tables 2 and 3 reveals that ^{137}Cs and ^{90}Sr intakes for the 11 major local-food items considered are uncorrelated under both dietary scenarios ($|r| \langle 0.16, p \approx 1$). Persons who might consume relatively large amounts of relatively ^{137}Cs-rich items therefore would not be expected to consume large ^{90}Sr doses relative to others. It follows that the simplifying assumption made in the present analysis, that interindividual variabilities in lifetime average rates of ^{137}Cs and ^{90}Sr ingestion are completely correlated, is conservative.

Uncertainty will arise from random dietary sampling associated with daily ^{137}Cs intake for any given individual about that individual's mean daily level. This uncertainty was estimated under diet-model assumptions stated above, such that local foods of type j are randomly and independently sampled n_j times per year from among Bikini sources. Table 2 lists predicted amounts and measured inter-sample variability of ^{137}Cs in 11 major food items local to Bikini. Activities associated with these 11 items were scaled to correspond to an assumption that they comprise 100% of local foods in either dietary scenario. Each corresponding CV, $\gamma_{R_{ij}} = \sigma_{R_{ij}}/\langle R_{ij} \rangle$, with respect to presumed dietary sampling error (Table 2) was assumed to pertain to all individuals. For this purpose, the local food items appearing in Table 2 were divided into three types (and the corresponding indicated annual sample sizes were assumed): pork-related items (n_1 = 12), chicken-related items (n_2 = 52), and other items (n_3 = 182.5). It follows that uncertainty due to random daily dietary sampling associated with annual ^{137}Cs intake is expected to be approximately normally distributed about its expected value, with an SD value inversely proportional to the square root of the total exposure time considered (see Appendix).

The Gaussian uncertainty model for random dietary sampling associated with daily ^{137}Cs intake also pertains to ingested ^{90}Sr. Because the CV values for approximate total dietary ^{137}Cs (Table 2) and ^{90}Sr (Table 3) are similar, the distribution for uncertainty in ^{90}Sr intake due to dietary sampling was taken to be that of ^{137}Cs, after scaling for the relative difference between the population-average values assumed for dietary ^{137}Cs and ^{90}Sr intakes (see Appendix). Measured concentrations of ^{137}Cs and ^{90}Sr in samples of drinking-coconut meat (a major local-food item) obtained from 70 different coconuts on Bikini Island were found to be uncorrelated (r = 0.15, p = 0.15) (Bogen et al. 1995). Thus, uncertainty in ^{90}Sr ingestion due to dietary sampling of different activities present on Bikini was assumed to be statistically independent of that pertaining to ^{137}Cs.

Model uncertainty (misspecification error) was estimated directly from data shown in Figure 3 of Robison et al. (1994b) relating LLNL model-diet predictions assuming imported foods are available, and corresponding Brookhaven National Laboratory measurements of whole-body ^{137}Cs dose among different samples of Marshallese people tested during the period 1977–1983. The mean of the six measured- to predicted-burden ratios shown is 1.25 ± 0.37 (differing insignificantly from 1, $p > 0.16$ by t-test). Based on these data, an uncertainty-CV of 30% was assumed, and model uncertainty for the LLNL model diet assuming imported foods are available was characterized as a corresponding lognormally distributed factor B with expectation 1 and SD$_g$ = 1.34. This factor was assumed also to apply to estimated ^{90}Sr dose.

Population risk

Predicted population risk I (the number of fallout-induced cancer fatalities) necessarily depends on the size, N, and age distribution of the population involved. To estimate I under both dietary models considered, it was assumed that resettlement occurs in 1999 and (a) that n = 200 or (b) that n = 2,000 but (due to the carrying capacity of a resettled Bikini) that only 200 resettlers would be eating non-imported foods (under either dietary scenario). The uncertainty distribution of I was used to calculate Prob(I=0), the probability of zero cases. This distribution was approximated by the method of Bogen and Spear (1987), treating I as compound-Poisson-distributed with an uncertain (population-average-dose)

Table 3. Diet model-bikini island for adults for ^{90}Sr ingestion.[a,b]

					^{90}Sr intake					
			^{90}Sr activity		Local only			Imports available		
Local foods	Intake: Local foods only (g d^{-1}) L	Intake: Local + imported (g d^{-1}) I	Mean (Bq g^{-1}) C	SD/Mean γ_C	Mean (Bq d^{-1}) $A = LC$	Var (Bq d^{-1})^2 σ^2	SD/Mean γ	Mean (Bq d^{-1}) $B = IC$	Var (Bq d^{-1})^2 σ^2	SD/Mean γ
Coconut										
Milk[d]	122	51.9	0.00321	0.915	0.391	0.128		0.167	0.0232	
Meat	181	31.7	0.00586	0.612	1.06	0.420		0.186	0.0129	
Copra	71.4	12.2	0.00321	0.915	0.229	0.0440		0.0392	0.00128	
Juice	334	99.1	0.000452	0.682	0.151	0.0106		0.0448	0.000933	
Total[c]	708		0.00259		1.83		0.424			
Total[c]		195	0.00224					0.436		0.449
Pork										
Heart	0.620	0.310	0.00150	0.512	0.000930	2.27×10^{-7}		0.000465	5.67×10^{-8}	
Muscle	13.9	5.67	0.00152	0.500	0.0212	0.000112		0.00862	1.86×10^{-5}	
Liver	6.70	2.60	0.00292	1.06	0.0196	0.000430		0.00759	6.48×10^{-5}	
Total[c]	21.2		0.00196		0.0417		0.559			
Total[c]		8.58	0.00194					0.0167		0.548
Chicken										
Muscle[e]	31.2	8.36	0.00152	0.500	0.0474	0.000562		0.0127	4.04×10^{-5}	
Liver[e]	17.7	4.50	0.00152	0.500	0.0269	0.000181		0.00684	1.17×10^{-5}	
Gizzard[e]	3.32	1.66	0.00152	0.500	0.00505	6.37×10^{-6}		0.00252	1.59×10^{-6}	
Total[c]	52.2		0.00152		0.0793		0.345			
Total[c]		14.5	0.00152					0.0221		0.332
Breadfruit	186	27.2	0.0690	0.898	12.8	133	0.898	1.88	2.84	0.898
Pandanus	65.0	9.16	0.120	1.10	7.80	73.6	1.10	1.10	1.46	1.100
Sprouting coconut[d]	122	7.79	0.00321	0.915	0.393	0.129	0.915	0.0250	0.000524	0.915
Papaya	27.0	6.59	0.0486	0.580	1.31	0.579	0.580	0.320	0.0345	0.580
Arrowroot	94.8	3.93	0.0676	0.563	6.41	13.0	0.563	0.266	0.0224	0.563
Pumpkin	5.44	1.24	0.0676	0.563	0.368	0.0429	0.563	0.0838	0.00223	0.563
Marsh. Cake[d]	0.00	11.7	0.00321	0.915	0.00	0.00	0.00	0.0376	0.00118	0.915
Coconut crabs	25.0	3.13	0.0518	0.534	1.30	0.478	0.534	0.162	0.00750	0.534
Subtotal	1,307		0.0248		32.4		0.0340[f]			
Subtotal		289	0.0150					4.35		0.0358[f]
% of Total	42	22			97.8			92.5		

[a] Three significant figures are shown for the purpose of calculating corresponding mean, standard deviation (SD), variance (σ^2) and coefficient-of-variation (γ) values.

[b] Local-foods-only, local + imported foods intakes and ^{90}Sr activities for specific foods decay corrected to 1999, are from Robison et al. (1995).

[c] Mean and SD values for totals listed under Coconut, Pork and Chicken were calculated using subitem-specific intake weights (see Table 2, note [c]).

[d] Assumed to equal copra meat.

[e] Assumed to equal pork muscle.

[f] The γ value given for the subtotal of all 14 items listed (see Table 2, note [h]).

parameter here taken to be $N\overline{ZD(70)}$, where Z is an uncertain "risk" factor specifying total cancer (leukemia + nonleukemia) mortality risk-per-unit dose. Based on the BEIR V (NRC 1990) prediction of total cancer (leukemia + nonleukemia) fatalities for males and females likely to be caused by chronic low-LET radiation exposure, and associated analysis of statistical and model-related errors, a risk factor Z_b was taken to be approximately lognormally distributed, with expectation 0.008 mSv^{-1} and SD$_g$ = 0.5064, for a cohort resettling Bikini at birth. The value of 0.008 mSv^{-1} is the BEIR V (NRC 1990) recommended population-weighted average value of 0.008 mSv^{-1} for acute low-LET radiation exposure, divided by the approximate factor of two recommended as an adjustment for estimating risk due to cumulative chronic exposure, and multiplied by a second approximate factor of two recommended as an adjustment for estimating risk associated with exposures specifically during childhood (given that a disproportionate amount of cumulative dose to Bikini resettlers would occur during the earlier years post resettlement, due to radiological decay of ^{137}Cs and ^{90}Sr).

Because the latter factor of two would not apply to adults accompanying resettling infants and youth, Z_b was assumed to pertain to a fraction f of the resettling population, and $Z_b/2$ was assumed to pertain to $100(1-f)\%$ of the resettling population. The SD_g value was estimated by the method of moments, given that, from the BEIR V analysis, the 90% upper confidence limit on Z_b is ~2.3 times its median value. Based on the likelihood that there would be a high proportion of infants and children among potential Bikini resettlers, the fraction f was assumed to be 0.5. Thus, the overall risk factor Z was taken to be equal to Z_b and $Z_b/2$ with equal likelihood. The factor Z (conservatively) does not reflect the possibility, given current fundamental radiobiological uncertainties, that the true fallout-related risk on Bikini may be zero.

RESULTS

The results of the JUV analysis of estimated dose to potential Bikini resettlers are summarized in Table 4 and Figs. 2–4. Specifically, Figs. 2a and 2c plot the calculated distributions for $\langle D(70)\rangle$ (characterizing interindividual variability in expected 70-y effective integral dose) and $\overline{D}(70)$ (characterizing uncertainty in population-average 70-y effective integral dose), and their corresponding Monte-Carlo sampling errors, under the assumption that imported foods will be available. Figs. 2b and 2d plot the calculated distributions for $\langle D(70)\rangle$ and $\overline{D}(70)$, and their corresponding Monte-Carlo sampling errors, under the assumption that imported foods will not be available (i.e., for a local-foods-only diet). Note that the 99.5th percentile values of $\overline{D}(70)$ listed in Table 4 are the maximum-likelihood values of dose to corresponding persons receiving the maximum 70-y doses among all persons exposed under the IA and IUA diet assumptions, assuming an exposed population size of 200 (NRC 1994; Bogen 1995).

Figs. 3a and 3c plot the calculated distribution for $\mathrm{Max}(\langle D(1)\rangle)$ (characterizing interindividual variability in the maximum value of expected 1-y effective integral doses, regardless of occurrence year, and its corresponding Monte-Carlo sampling error), assuming that imported foods will be available. Figs. 3b and 3d plot the corresponding distribution and sampling error assuming that imported foods will not be available. The estimated maximum 1-y doses are predicted to fall in years 1999, 2000, 2001, and 2002 for ~0.1%, 38.5%, 59.5% and 1.9% of residents (imports available), or for ~0%, 4.5%, 88.1% and 7.4% of residents (imports not available). The year of each individual's predicted maximum 1-y dose is primarily a function of the corresponding value of H (the half-life for the dominant ^{137}Cs metabolic compartment). Note that the 99.5th percentile values of $\mathrm{Max}(\langle D(1)\rangle)$ listed in Table 4 represent the maximum-likelihood values of dose to the corresponding persons receiving the maximum 1-y doses among all persons exposed under the IA and IUA diet assumptions, assuming an exposed population size of 200 (NRC 1994; Bogen 1995).

Figs. 4a–d plot the population-average values of $\langle D(1)\rangle$ (expected effective integral dose as a function of time t) and their 95% confidence limits (95%CL) with respect to interindividual variability for the imports-available and local-foods-only diets, both in absolute terms as well as values relative to the population-average at time t. Figs. 4e–h plot the expected values of $\overline{D}(t)$ (population-average effective integral dose over time t) and their 95%CL with respect to uncertainty for the imports-available and local-foods-only diets, both in absolute terms and as values relative to the expected value at time t.

Table 4. Summary of uncertainty and interindividual variability in estimated integral effective doses for hypothetical Bikini island residents, assuming 1999 resettlement after soil removal/K treatment and availability and nonavailability of imported foods.

		Dose and exposure scenario[a]			
Dietary model ⟶		IA	IUA	IA	IUA
Exposure duration ⟶		Max 1-y	Max 1-y	70 y	70 y
Distributed characteristic	Estimator[b]	(mSv)	(mSv)	(mSv)	(mSv)
Interindividual variability	Q(0.025)	0.17	0.31	6.5	1.2
	Q(0.50)	0.36	1.0	13	3.8
	EV	0.45	1.4	16	5.2
	Q(0.975)	1.3	4.9	45	18
	Q(0.995)	2.0	8.2	73	31
Uncertainty	Q(0.025)	—	—	11	30
	Q(0.50)	—	—	16	50
	EV	—	—	16	52
	Q(0.975)	—	—	24	87
	Q(0.995)	—	—	28	100

[a] IA = model diet assuming that "imported foods are available"; IUA = model diet assuming availability of "local foods only," i.e., that "imported foods are unavailable." Values listed are rounded to two significant digits; — = not calculated.

[b] Q(p) = the pth quantile or fractile = 100pth percentile; EV = expected value. The Monte Carlo coefficients of variation of the mean (or standard error of the mean divided by the mean) of all listed fractile estimates are <2%, and those of listed EV values are <0.2%.

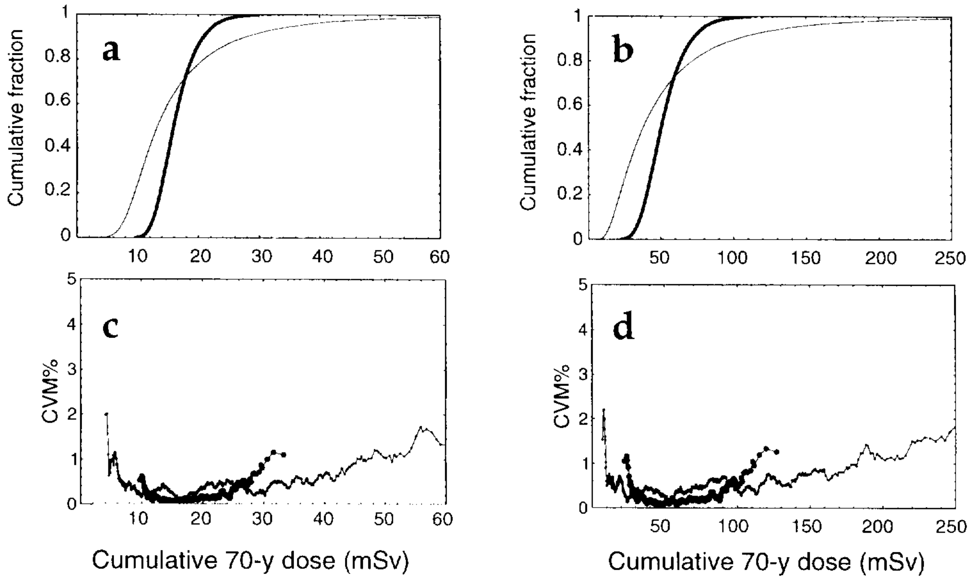

Fig. 2. (a–b): Cumulative relative-frequency distributions for ⟨D(70)⟩ (light curves, characterizing interindividual variability in expected 70-y effective integral dose) and (70) (bold curves, characterizing uncertainty in population-average 70-y effective integral dose). (c–d): Corresponding Monte-Carlo sampling errors, defined as the standard error of the mean divided by the mean of the *i*th ordered value of 10 samples of 2,000 simulated variate values, for $i = 1, 2, \ldots, 2{,}000$ (light and bold point sets refer to ⟨D(70)⟩ and $\overline{\mathrm{D}(70)}$, respectively). Plots pairs (a, c) and (b, d) correspond to imports-available and local-foods-only diet assumptions, respectively.

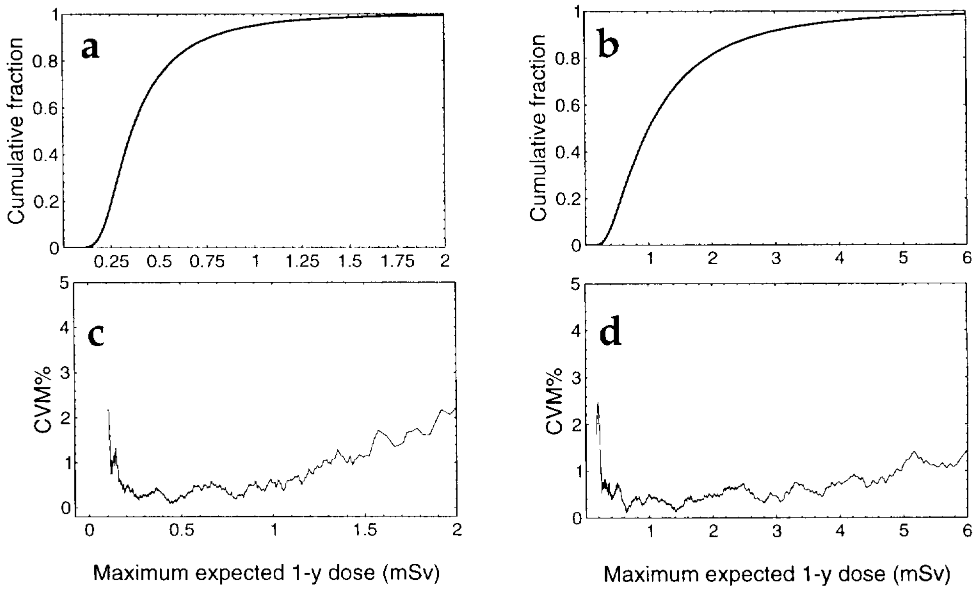

Fig. 3. (a–b): Cumulative relative-frequency distributions for Max(⟨*D*(1)⟩) characterizing interindividual variability in the maximum value of expected 1-y effective integral doses, regardless of occurrence year. (c-d): Corresponding Monte-Carlo sampling errors (see Fig. 4). Plot pairs (a, c) and (b, d) correspond to imports-available and local-foods-only diet assumptions, respectively.

Based on the hypothetical Bikini-remediation/resettlement scenario described above starting in 1999, population risk was estimated as described above from the characterizations of uncertainty in population-average lifetime dose $\overline{D(70)}$ obtained under the different dietary (IA, IUA) and population-size (N = 200, N = 2,000) assumptions considered. Each scenario implies a population-risk expectation, $\langle I \rangle$, and a corresponding probability of zero cases, $p_0 = \mathrm{Prob}(I{=}0)$. Under the {IA, N = 200} scenario, $\langle I \rangle \approx 0.20$ cases

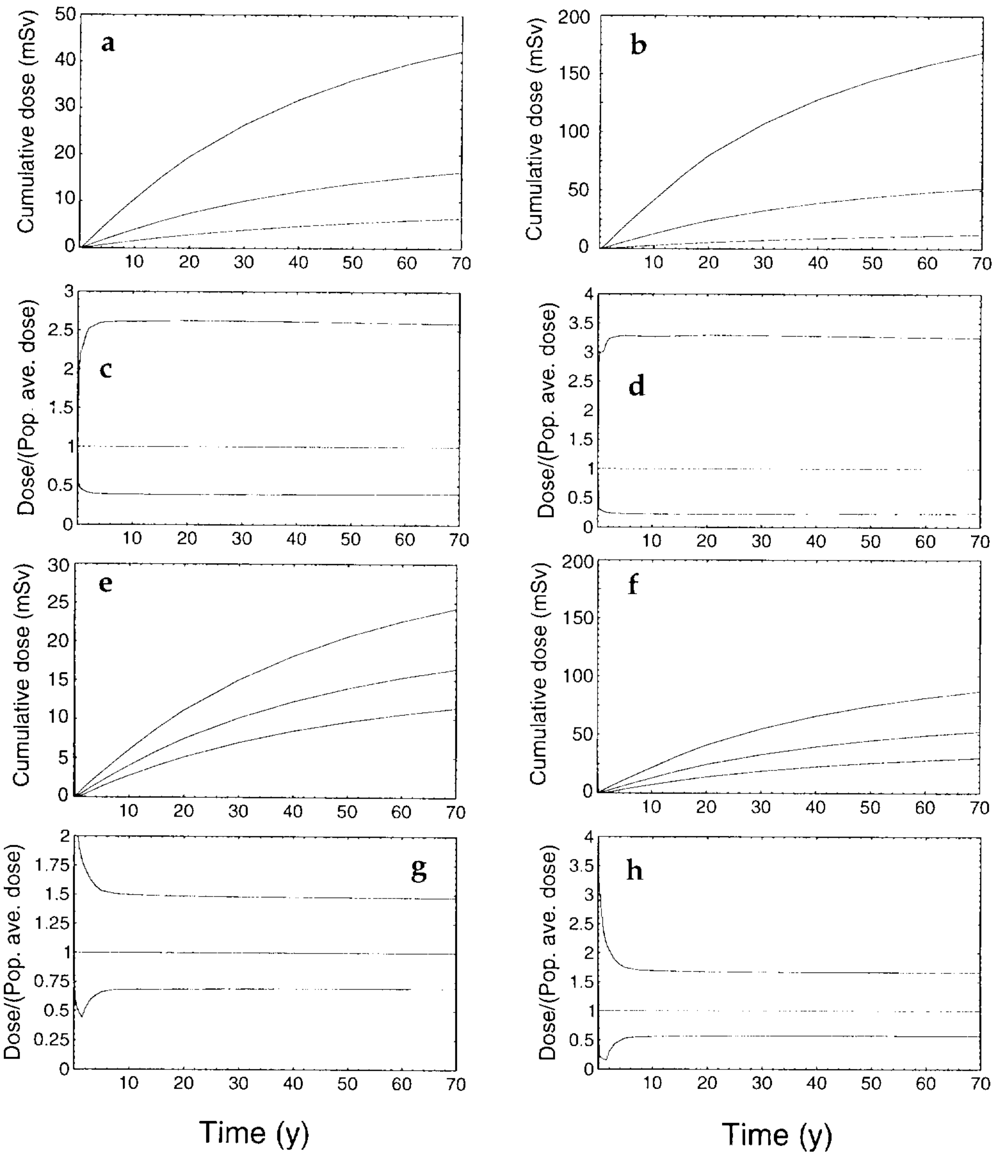

Fig. 4. (a-b): Values of $\langle D(t) \rangle$ (expected effective integral dose over time t); in each plot: middle curve = population-average value, upper and lower curve = corresponding 95% confidence limits (95%CL) with respect to interindividual variability. (e-f): Values of $\overline{D(t)}$ (population-average effect integral dose over time t); in each plot: middle curve = expected value function, upper and lower curves = corresponding 95%CL with respect to uncertainty. (c, d, g, h): Plots a, b, e and f shown as values relative middle curve of each, respectively. Plots a, c, e and g correspond to an imports-available diet, and the other plots to a local-foods-only diet.

and p_0 = 83%; i.e., under this scenario it is rather more likely than not that zero cancer deaths will arise as a result of fallout-related exposures on Bikini. Under the {IA, N = 2,000} scenario, $\langle I \rangle \approx$ 0.86 cases and p_0 = 43%. Under the {IUA, N = 200} scenario, $\langle I \rangle \approx$ 0.63 cases and p_0 = 58%; i.e., even under this scenario it is more likely than not that zero cancer deaths will arise as a result of fallout-related exposures on Bikini. Under the {IUA, N = 2,000} scenario, $\langle I \rangle \approx$ 1.3 cases and p_0 = 30%.

DISCUSSION AND CONCLUSION

A detailed analysis of uncertainty and interindividual variability in estimated doses was conducted for a rehabilitation scenario for Bikini Island at Bikini Atoll, in which the top 40 cm of soil would be removed in the housing and village area, and the rest of the island is treated with potassium fertilizer, prior to an assumed resettlement date of 1999. Predicted doses were considered for fallout-related exposure by inhalation and ingestion pathways, and two dietary scenarios were considered. Corresponding calculations of uncertainty and variability in estimated dose showed that after ~5 y of residence on Bikini under either IA or IUA assumptions, the upper and lower 95% confidence limits on uncertainty in calculated dose are estimated to lie within a ~twofold factor of its expected value; the upper and lower 95% confidence limits on interindividual variability in calculated dose are estimated to lie within a ~threefold factor of its population-average value. For reference, the expected values of population-average dose at age 70 y are estimated to be 16 and 52 mSv under the IA and IUA dietary assumptions, respectively (Robison et al. 1995, 1997). Assuming that 200 Bikini resettlers would be exposed to local foods, the maximum 1-y dose received by any Bikini resident is most likely to be approximately 2 and 8 mSv under the IA and IUA assumptions, respectively. Under the most likely dietary scenario, involving access to imported foods, this analysis indicates that it is most likely that no additional cancer fatalities (above those normally expected) would arise from the increased radiation exposures considered.

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APPENDIX

Analytic and Monte-Carlo methods used to characterize uncertainty and interindividual variability in estimated doses to hypothetical Bikini residents

Define annual intake R_j of ^{137}Cs in Bq kg^{-1} y^{-1} from local foods of type j as $R_j = \Sigma_i^{n_j} 365/n_j\, R_{ij}$ and corresponding total annual ^{137}Cs intake as $R = \Sigma_j R_j$. From eqns (1)–(3) and the notation, assumptions and definitions given in the text, integrated whole-body dose, $Q_{ij}(t-t_i)$ after t years due to ingestion of ^{137}Cs in a food item of type j at time $t_i \leq t$ is given by

$$Q_{ij}(t - t_i) = \int_{t_i}^{t} c q_{ij}(u)\, du \tag{A1}$$

$$= cFBR_{ij}\left\{\frac{e^{-\lambda t_i}\left(1 - e^{-(\beta K + \lambda)(t - t_i)}\right)}{\beta K + \lambda}\right\}$$

$$\equiv cFBR_{ij}S. \tag{A2}$$

For large n_j and for t_i distributed randomly throughout each year, it follows that total integrated whole-body dose $Q(t)$ in Bq kg^{-1} after time t (y) is approximately

$$FB\left\{c\sum^{t} RS\right\} \equiv FBX, \tag{A3}$$

where X is defined here as the braced quantity in eqn (A3), for uniformly distributed t_i between 0 and t. Thus, e.g., $\langle Q(t)\rangle = \langle X\rangle = \langle R\rangle\langle S\rangle$, where $\langle S\rangle$, the expectation of S with respect to both t_i and β, is given by

$$\langle S\rangle = 1 + \frac{\{\Delta\beta + e^{-\lambda t}[\mathrm{Ei}(b_1) - \mathrm{Ei}(b_0)] - \mathrm{Ei}(c_1) + \mathrm{Ei}(c_0) + \mathrm{Ln}(c_1/c_0)\}}{\Delta\beta \mathrm{K}\lambda \mathrm{t}},$$

$$b_i = -\beta_i Kt, \qquad i = 0, 1, \tag{A4}$$

$$c_i = b_i - \lambda t, \qquad i = 0, 1, \quad \text{and}$$

$$\Delta\beta = (\beta_1 - \beta_0) = (1.107 - 0.9) = 0.207,$$

in which $\mathrm{Ei}(z)$ is the exponential integral $\int_{-z}^{\infty} x^{-1}e^{-x}dx$. The (unsubscripted) constant c was estimated to be 2.419×10^{-3} mSv kg Bq^{-1} y^{-1} from values of cumulative whole-body-equivalent ^{137}Cs dose for adults predicted from the equivalent ICRP (1990) model.

From eqns (A3)–(A4) and corresponding assumptions (see text), interindividual variability in expected dose $\langle D(t)\rangle$ by time t was characterized by evaluating

$$\langle D(t)\rangle = D_{\mathrm{AmPu}}(t) + X_\gamma D_x(t) + \langle B\rangle\left[\langle F\rangle\langle X\rangle + G\left(\frac{\langle X\rangle/F}{\langle X\rangle/F}\right) W(t)\, D_{\mathrm{Sr}}(t)\right]. \tag{A5}$$

Variability in $\langle D(t)\rangle$ thus arises from uniform variability in F and G (taken to be 100% rank-correlated) and from lognormal variability in both $\langle R\rangle$ and H (see text). Uncertainty in population-average dose $\overline{D(t)}$ was characterized by evaluating

$$\overline{D(t)} = D_{\mathrm{AmPu}}(t) + X_\gamma D_x(t) + BF\left[\bar{X} + G\left(\frac{X'}{\langle F\rangle}\right) W(t)\, D_{\mathrm{Sr}}(t)\right], \tag{A6}$$

in which the prime symbol denotes an independent random sample from the subscripted variate (for reasons discussed in the text). Uncertainty in eqn (A6) arises from the uniform and lognormal uncertainties assumed for $\bar{F}$ and B, respectively (see text), in addition to uncertainty associated with the variate $\bar{X}$ arising from X defined in eqn (A3). Let the subscript p on a variate denote a value pertaining to a particular individual in the exposed population, such that $X_p = X|\{R = R_p, H = H_p\}$ and $(X_p|\beta)$ is the sum of a presumed large number of identical independently distributed random variates. From the Lindeberg and Central Limit theorems, it follows that $(X_p|\beta)$ is approximately normally distributed with mean and variance given by

$$\langle X_p|\beta\rangle = ct\langle R_p\rangle\langle S_p|\beta\rangle \quad \text{and}$$

$$\sigma^2_{X_p|\beta} = c^2t\langle R_p\rangle^2[(1 + \gamma_R^2)\langle S_p^2|\beta\rangle - \langle S_p|\beta\rangle^2],$$

respectively, in which

$$\gamma_R = \langle R\rangle^{-1}\left(\sum_{j=1}^{11}\langle R_j\rangle^2\gamma^2_{R_{ij}}n_j^{-1}\right)^{1/2} = 0.039 \tag{A7}$$

is the CV for uncertainty in any individual's modeled lifetime, time-weighted average ^{137}Cs intake, based on the assumptions stated in the text and the food-type-specific CV values listed in Table 2. Assuming the exposed population size is sufficiently large to ensure that differences between first and second sample moments with respect to variability and their corresponding population moments are negligible, it follows from the definition of variability expectation that uncertainty in $\overline{X|\beta}$ is approximately normally distributed with mean and variance given by

$$\langle X|\beta\rangle = \frac{1}{N}\sum_{p=1}^{N}\langle X_p|\beta\rangle \approx ct\overline{\langle R\rangle}\,\overline{\langle S|\beta\rangle} \quad \text{and} \tag{A8}$$

$$\begin{aligned}\sigma^2_{\overline{X|\beta}} &= \frac{1}{N^2}\sum_{p=1}^{N}\sigma^2_{X_p|\beta} \\ &\approx c^2t\overline{\langle R\rangle}^2(1+g^2_{\mathrm{R}})[(1+\gamma^2_{\mathrm{R}})\overline{\langle S^2\beta\rangle}-\overline{\langle S\beta\rangle}^2,\end{aligned} \tag{A9}$$

respectively, where

$$\begin{aligned}\langle S|\beta\rangle &= [(\beta K+\lambda)t]^{-1}[(1-e^{-\lambda t})\lambda^{-1} \\ &\quad -(e^{-(\beta K+\lambda)t}-e^{-\lambda t})(\beta K)^{-1}], \quad \text{and} \\ \langle S^2|\beta\rangle &= (\beta K+\lambda)^{-2}t^{-1}\{(2\lambda)^{-1} \\ &\quad + e^{-\lambda t}[(1-2e^{-\beta Kt})(2\beta Kt)^{-1} \\ &\quad + 2(e^{-(\beta K-\lambda)t}-1)(\beta K-\lambda)^{-1}-(2\lambda)^{-1}]\}.\end{aligned}$$

The averages $\overline{\langle S|\beta\rangle}$ and $\overline{\langle S^2|\beta\rangle}$ with respect to H were each evaluated numerically for different β values equally spaced over the range of β. Following this procedure, it turns out that $\sigma_{\overline{X|\beta}}t^{-1/2}$ is for each given t, $0 < t \leq 70$ y, a virtually linear function of $\overline{\langle X|\beta\rangle}t^{-1}$ over a β- and t-dependent range of the latter, and that corresponding $\overline{\langle X|\beta\rangle}t^{-1}$ values are virtually uniformly distributed over these linear ranges (Bogen et al. 1995). The linear coefficients $\{a,b\}|t$ and corresponding $\overline{\langle X|\beta\rangle}t^{-1}$-range boundaries $\{x_{\mathrm{lo}}, x_{\mathrm{hi}}\}|t$ were therefore determined for representative values of t, and this information was then used to evaluate uncertainty in $\bar{X}$, for $\bar{X}$ modeled as a compound normal distribution with mean $= Ut$ and SD $= t^{1/2}(a + bU)$, where U is uniformly distributed between x_{lo} and x_{hi}.

Except where the use of 100% rank-correlated variates was indicated, all variate simulations were conducted using 10 sets of virtually uncorrelated vectors of 2,000 values for each variate involved, generated using systematic Latin-Hypercube sampling procedures. Each ith output fractile (and the first moment) was estimated as the mean of 10 ith ordered values (and first moments) of the 10 corresponding sets of 2,000 evaluations of eqn (A5) or (A6), for i = 1, 2,. . . , 2000. Corresponding Monte-Carlo sampling errors, defined for each estimate as the coefficient of variation of the mean (CVM, equal to the standard error of the mean divided by the mean). Calculations were done on a PowerPC™[†] workstation using the programs *Mathematica*™ 2.2.2 (Wolfram 1991) and *RiskQ* (Bogen 1992). Analyses of quantile convergence indicate that fractile estimates obtained are generally accurate to within ⟨2% (see Figs. 2 and 3), and that mean values obtained are accurate to within <0.2%.

■ ■

[†] Power PC, Apple Computers, Inc., Capistino, CA

ASSESSMENT OF PLUTONIUM EXPOSURE IN THE ENEWETAK POPULATION BY URINALYSIS

L. C. Sun, C. B. Meinhold, A. R. Moorthy, E. Kaplan, and J. W. Baum*

Abstract—**Since 1980, the inhabitants of Enewetak Atoll have been monitored periodically by scientists from Brookhaven National Laboratory for internally deposited radioactive material. In 1989, the establishment of fission track analysis and of a protocol for shipboard collection of 24-h urine samples significantly improved our ability to assess the internal uptake of plutonium. The purpose of this report is to show the distribution of plutonium concentrations in urine collected in 1989 and 1991, and to assess the associated committed effective doses for the Enewetak population based on a long-term chronic uptake of low-level plutonium. To estimate dose, we derived the plutonium dose-per-unit-uptake coefficients based on the dosimetric system of the International Commission on Radiological Protection. Assuming a continuous uptake, an integrated Jones's plutonium urine excretion function was developed to interpret the Enewetak urine data. The Appendix shows how these values were derived. The committed effective doses were 0.2 mSv, calculated from the 1991 average plutonium content in 69 urine samples.**

Health Phys. 73(1):127–132; 1997

Key words: Marshall Islands; plutonium; excretion, urinary; dose assessment

INTRODUCTION

Enewetak Atoll, in the Republic of the Marshall Islands (RMI), lies within the former Pacific Proving Grounds and was chosen as the site for nuclear testing from 1948 to 1951 because of its remoteness location and its geological features. In December 1947, the United States relocated all 136 residents of Enewetak to Ujeland Atoll before starting a program of nuclear-weapons tests. Forty-three tests were conducted between 1948 and 1951 resulting in radiological contamination of the atoll. Plutonium activities measured in the top 2 cm of the soil ranged from 0.4 to 17 mBq g^{-1} with a median of 4.4 on Enewetak Island (Wilson et al. 1975). From 1972 to 1978, major efforts were made to remove the top 30 cm of soil from the Island; then, the soil was buried on Runit Island, located at the northern Enewetak Atoll. The cleanup guidelines were (1) the soil should be removed if the plutonium concentration exceeded 15 Bq g^{-1} (400 pCi g^{-1}); (2) soil could be left in place if the concentration was less than 1.5 Bq g^{-1} (40 pCi g^{-1}); and (3) for concentrations ranging between 1.5–15 Bq g^{-1}, a decision should be made on a case-by-case basis (DNA 1981). Repatriation of the Enewetak population was begun immediately after the cleanup programs. Now, the largest inventory of plutonium on Enewetak Atoll remains in the sediments of the lagoon (Wilson et al. 1975; Nevissi and Schell 1975; Robison et al. 1978, 1980, 1987).

Since 1957, members of the Marshall Islands Program at Brookhaven National Laboratory (BNL) have routinely visited RMI to assess the acceptability of the Enewetak population living on the island by determining their internally deposited radionuclides using whole-body counting and urinalysis methods (Greenhouse et al. 1980; Miltenberger et al. 1981; Lessard et al. 1984; Conard 1992; Sun et al. 1992, 1995). The purposes of this report are to describe the new protocol established for collecting urine samples in 1989 and 1991, to show the distribution of plutonium concentrations using fission track analysis (FTA) urinalysis, and to assess the associated committed effective doses for people of Enewetak, based on a continuous, long-term chronic uptake of plutonium. The FTA method was developed at BNL for analyzing low levels of plutonium in urine (Moorthy et al. 1988). All plutonium data discussed in this paper were analyzed by the FTA method at BNL.

MATERIALS AND METHODS

Methods for interpreting urine data and estimating plutonium dose

The International Commission on Radiological Protection (ICRP) Publication 56 (1990) provides the age-dependent dose-coefficient factors (DCF) for computing internal dose (Leggett 1984, 1985). Due to the long half-life of ^{239}Pu and its lengthy retention in the body, the age-dependent ingestion dose-coefficients after 1 y to adulthood show only small variation. They can be rounded to about 1.0×10^{-6} Sv Bq^{-1}, with a gastrointestinal tract absorption f_1 value of 10^{-3}. The calculated uptake dose coefficient is 1 mSv Bq^{-1} (10^{-6} Sv $Bq^{-1} \div f_1$).

Table 1 shows the calculated committed effective dose-coefficients due to uptake based on recommenda-

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Table 1. Comparison of the ICRP recommended plutonium dose coefficients (mSv Bq^{-1}) for uptake.

Age-specific groups	ICRP Publication 56 (1990)	ICRP Publication 67 (1993)	Constant ratio ICRP 67 ÷ ICRP 56
3 mo	1.4	0.84	0.60
1 y	1.4	0.84	0.60
5 y	1.1	0.66	0.60
10 y	1.0	0.54	0.54
15 y	0.98	0.50	0.51
Adult (18 y and older)	0.97	0.50	0.52

tions in ICRP Publications 56 (1990) and 67 (1993), for calculating dose. The results were obtained by using the individual ingestion pathway dose coefficients divided by the recommended f_1 values. ICRP revised its recommendations for calculating plutonium dose from those given in Publication 56 to new values in Publication 67 because of (1) the f_1 value (age 1 y to 70 y) was reduced by a factor of two (from 1×10^{-3} to 5×10^{-4}), and (2) the tissue weighing factor (w_T) of the bone surface was reduced by a factor of three (from 0.03 to 0.01) in ICRP Publication 60 (1991). The last column of Table 1 shows the ratio of the values from Publication 67 over those of Publication 56; it indicates that the plutonium hazard in the body may be overestimated, and the revised age-specific dose-coefficients from the latest ICRP recommendations are just above one half of the committed effective dose values given in Publication 56.

To interpret 24-h urine data, both Durbin's (1972) and Jones's (1985) plutonium urinary excretion function are the ones most accepted (ICRP 1988; Lessard et al. 1987). Durbin's predicted elimination rate is much faster than that of Jones. By using a model with a fast elimination rate like that of Durbin, an enormous overestimation of plutonium body content can result from long-term post-exposure urine measurements. Therefore, the Jones function is chosen for this study; its predicted values (fraction per unit single acute uptake) for a 100-d and 10,000-d post-uptake are $\sim10^{-4}$ and $\sim10^{-5}$, respectively. Therefore, detection of 1 μBq of ^{239}Pu can be interpreted as a committed effective dose as low as 10 μSv via a 24-h urine sample collected 100 d after an acute uptake (i.e., 1 mSv Bq^{-1} × 1 μBq d^{-1} ÷ 10^{-4} d^{-1}). Similarly, detection of 1 μBq of ^{239}Pu also can be interpreted as a committed effective dose of 0.1 mSv to age 70 y after 10,000 d ($\sim$30 y) of such an uptake (i.e., 1 mSv Bq^{-1} × 1 μBq d^{-1} ÷ 10^{-5} d^{-1}). However, the accuracy of assessment of the dose would be best if the plutonium entered in the body by an injection, the physical size of the particles was 1 activity median aerodynamic diameter (AMAD), and its chemical solubility was in Lung-Class Y (ICRP 1984).

Method of calculating dose from Enewetak urine samples

Since the people of Enewetak were repatriated in May 1980, we assumed for this study that all plutonium intake occurred after they returned to live in their Enewetak homeland. Urine samples were collected in June 1989 and February 1991. Therefore, the ten years from 1980 to 1990 gave us a convenient number for assessing the fraction of the total plutonium uptake over this period that would be eliminated by the last day of the period. Only a few methods are available for interpreting plutonium urine data due to chronic exposure (Butler 1972; Ramsdem et al. 1990). In general, methods of solving convolution integrals of an excretion function were suggested for assessing internal uptake resulting from recurrent or prolonged exposure (ICRP 1969).

Based on Jones's (1985) urinary functions, an integrated procedure was developed for interpreting 24-h urine elimination to assess plutonium body burdens under conditions of constant, continuous, chronic uptake. Both Jones's (1985) function and the integrated arithmetics are described in the Appendix. The calculated integrated elimination rate of plutonium in a 24-h urine sample after a 10-y constant chronic uptake is 2.4×10^{-5}. This constant means that the measured plutonium activity as a 24-h total represents 0.0024% of that in the body. Similarly, the calculated 24-h urine elimination rates of plutonium at the end of 9 and 11 y are 2.5×10^{-5} and 2.3×10^{-5}, respectively, under the same conditions of uptake. Because of the slow rate of elimination of plutonium from the body, the 9-y, 10-y, and 11-y urinary elimination fractions into a 24-h urine sample do not differ by more than 5% within an interval of 1 y. Therefore, when a DCF of 1 mSv Bq^{-1} is used, each 1 μBq d^{-1} of ^{239}Pu indicates a 0.04 mSv committed effective dose (i.e., 1 mSv Bq^{-1} × 1 μBq d^{-1} ÷ 2.4×10^{-5} d^{-1}) to age 70 y for the people of Enewetak.

Urine sample collection protocol

Before 1989, urine bottles (Nalgene™,[†] 2-L high-density polyethylene) were distributed directly to volunteers who collected the samples at home and then placed their bottles in collection boxes at the seashore to be picked up the next day. This protocol gave no assurance that dust and sand was kept out of the bottles, nor was there any guarantee that the urine in the bottle was from the donor named on the outside; further, there was no provision for insuring that the sample represented a 24-h elimination.

In 1989, a shipboard 24-h urine sample collection protocol was developed for the Marshallese (Sun et al. 1993). This protocol was designed to minimize the unwanted contamination and to assure the quality of all 24-h urine samples on ships. The following steps were instituted: (1) all collection bottles were controlled and handled on board by registered nurses and authorized staff; (2) all the Marshallese participants showered and changed into clean clothes provided by BNL staff and stayed on board for the entire interval; (3) a collection log (e.g., name, date of birth, sex, photo ID, urine volume, and elimination time) was properly completed; and (4) all samples were acidified at the end of the 24-h

[†] Nagle Nunc International, 75 Panorama Creek Drive, Rochester, NY 14602

collection to minimize plutonium plating on the inner surface of the collection bottle. All samples were collected under uniform, controlled and monitored environments to reduce unwanted contamination and to insure a full 24-h collection.

Table 2 compares the plutonium contents determined from 24-h eliminations of 32 Marshallese (in Column 1) for whom samples had been obtained under both the old on-shore and the 1989 shipboard protocols. Column two shows the range of ^{239}Pu activity in 24-h urine, from 10 to 297 μBq. These samples were collected between 1981 and 1984 using the on-shore collection protocol described above. Column three shows that only 2 samples (from Subject No. 1 and No. 3) were just above the MDL (defined at 99% confidence level) of 2 μBq of ^{239}Pu using the shipboard protocol in 1989. The difference in the paired plutonium contents between Column 2 and Column 3 can only be explained as due to external contamination of the samples during on-shore collections. Hence, Table 2 shows the benefit of the shipboard protocol and the superior quality of the 1989 urine samples. A disadvantage of the shipboard protocol is that it requires an overnight stay on the ship, and, therefore, participation is limited to those people who do not have pressing domestic responsibilities; this group generally consists of people between 8–18 y old.

Table 2. Comparison of ^{239}Pu content (μBq) in the urine of 32 Marshallese under two collection protocols.

Subject No.	On-shore protocol (1981–1984)	Shipboard protocol (1989)
1	297	2.75
2	175	<2
3	127	2.75
4	125	<2
5	125	<2
6	125	<2
7	119	<2
8	119	<2
9	99.5	<2
10	99.5	<2
11	89.7	<2
12	86.4	<2
13	85.0	<2
14	77.3	<2
15	71.7	<2
16	68.6	<2
17	61.5	<2
18	60.3	<2
19	53.7	<2
20	51.3	<2
21	48.4	<2
22	47.9	<2
23	42.6	<2
24	42.4	<2
25	39.0	<2
26	23.6	<2
27	20.3	<2
28	16.6	<2
29	16.6	<2
30	12.3	<2
31	11.7	<2
32	10.4	<2

Information on 1989 and 1991 urine samples

Due to limited facilities on the ship (e.g., beds, toilets and shower rooms) it was inconvenient to collect urine from more than 10–12 volunteers per day. Therefore, groups of males or females participated on alternate days. On each trip there was a maximum of 80 people tested because we were also limited by the amount of food and tap-water available on the vessel. Seventy-two and sixty-nine FTA were determined for the people from Enewetak in 1989 and 1991, respectively. In 1989, there were 39 male and 33 female volunteers; most of them were teenagers. The average urine volumes of these males and females were 830 and 820 mL, respectively. In the past, we found that the range of the 24-h urine volume from the Marshallese collected using shipboard protocol was 50 to 3,500 mL (Sun et al. 1993). For dose assessment, we decided to use data only for individuals with volumes greater than 300 mL because smaller samples might not constitute a normal 24-h excretion.

URINE RESULTS

Table 3 shows the distribution of plutonium contents in the 24-h urine samples. The ^{239}Pu values in the samples were arbitrarily subdivided into eight groups, ranging from less than 1 μBq to greater than 37 μBq (Column 1). The MDL associated with these samples was 2 and 3 μBq, for 1989 and 1991, respectively (Sun et al. 1995). The statistical parameters shown at the bottom of Table 3 are the total number of samples (n), the samples' mean ($\bar{x}$), and the samples' standard deviation (s). The calculated $\bar{x}$ and s values were based on the net activities, even though some were negative or measured zero.

1989 FTA results

In Column 2 of Table 3, data from 72 people show that ~90% of the 24-h samples had below 3 μBq d^{-1}, and none of them was equal to or higher than 7 μBq d^{-1}. The committed effective dose to age 70 y for a 7 μBq 24-h urine sample was estimated to be about 0.3 mSv.

Table 3. Distribution of ^{239}Pu activity (μBq d^{-1}) and the corresponding values of statistical parameters (n, $\bar{x}$, s) for the people of Enewetak.

^{239}Pu activity in 24-h urine sample (μBq)	1989	1991
	Frequency distribution	
$x < 1$	41	17
$1 \leq x < 3$	23	23
$3 \leq x < 5$	5	18
$5 \leq x < 7$	3	4
$7 \leq x < 9$	0	5
$9 \leq x < 11$	0	1
$11 \leq x < 37$	0	0
$x \geq 37$	0	1[a]
$n =$	72	69
$\bar{x}$ (μBq) =	1.0	4.7
s (μBq) =	1.7	17

[a] This individual value was 146 μBq.

The $\bar{x}$ and s were 1.0 and 1.7 μBq, respectively. The CV value was 170%, where CV (%) = 100 × ($s/\bar{x}$). Therefore, the calculated effective dose to age 70 y due to ^{239}Pu is 0.04 mSv (i.e., 1 mSv Bq^{-1}×1 μBq d^{-1} ÷ 2.4×10^{-5} d^{-1}) for an average person living on Enewetak.

1991 FTA results

In Column 3 of Table 3, values from 69 people show that ~40% were above the MDL value of 3 μBq. The $\bar{x}$ and s of the 1991 samples were 4.7 μBq d^{-1} and 17 μBq d^{-1}, respectively. The committed effective dose was about 0.2 mSv (i.e., 1 mSv Bq^{-1} × 4.7 μBq d^{-1} ÷ 2.4×10^{-5} d^{-1}). The large standard deviation value is due to the 146 μBq in the data set. The $\bar{x}$ and s recalculated without this value are 2.6 and 2.2, respectively, and the CV values fall from 362% to 85%. In this case, the estimated effective dose is ~ 0.1 mSv. Individual urinary excretion data can be highly variable (Clemente and Delle Site 1982; ICRP 1988), and presently it is difficult to identify the cause of the higher ^{239}Pu average in the 1991 results. More urine samples are to be collected from the individuals to evaluate this suspect issue.

DISCUSSION AND CONCLUSION

In Publication 54 (1988), the ICRP indicated that monitoring urine for intakes of plutonium, especially for low levels, can present difficulties in making the measurements and in interpretation. The ICRP recommended using a series of excretion measurements to evaluate an individual intake (ICRP 1988). For monitoring or measuring low-level plutonium in an individual, a repetitive series of urine measurements is required. Furthermore, for the Enewetak population, environmental measurements, analyses of environment pathways, and dietary studies also can be used to estimate intake and corroborate the results of urine bioassay to enhance reliability of the dose assessment.

The algorithm described in the Appendix was specifically developed to interpret urine data for assessing plutonium uptake in the people of Enewetak. The main limitation of this method is the requirement that the intake rate is a constant steady state during the integrated time interval. If the recurrent intake rates were unevenly distributed over this period, then the dose will be underestimated if more plutonium was taken up within the early half of the integrated time. On the other hand, the dose will be overestimated if such intakes were greater within the later half (recent) of the time. In either case, the uncertainty is within a factor of 2.4 (i.e., 2.4×10^{-5} ÷ 1.0×10^{-5}), estimated from the Appendix.

Based on both the Jones (1985) urine excretion function and the ICRP Publication 56 (1990) systemic retention model for plutonium, and also upon the average ^{239}Pu content in the 1991 urine samples, we calculate an average ^{239}Pu uptake of 4.7 Bq and a committed effective dose of 0.2 mSv to age 70 y for an average adult. This calculation assumed a constant chronic intake and included the 146 μBq d^{-1} datum point; its inclusion is appropriately conservative. The estimated average dose for the people of Enewetak would be reduced by about one half if the DCFs of ICRP Publication 67 (1993) were used.

Again, the dose assessed is a population average, and the uncertainty, in percent, can be measured from the mean associated CV. More samples were collected after 1991 by BNL staff for plutonium urinalysis to establish individual plutonium exposure records after 1991. Although the committed effective dose to the Enewetak inhabitants from plutonium is low, plutonium is perceived by Enewetak people as being the element of utmost concern in their environment.

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APPENDIX

This procedure is used to interpret the significance of levels of plutonium found in a urine sample obtained after a constant, continuous, chronic uptake. Let *I(t)* be the uptake rate in day *t*, and *J(t)* be the urine fraction in *t* day using Jones's (1985) plutonium urine excretion function, as in the following:

$$J(t) = 0.00475e^{-0.558t} + 0.000239e^{-0.0442t} + 0.0000855e^{-0.00380t} + 0.0000142e^{\;0.0000284t}, \qquad (A1)$$

where all the eigenvalues associated with exponential terms have a unit of reciprocal days. Then, the fraction of plutonium excreted after the first 24-h of uptake is

$$P(1) = I(1) \times J(1).$$

Similarly, plutonium excreted after each 24-h (day) is

$$P(2) = I(1) \times J(2) + I(2) \times J(1); \qquad (A2)$$

$$P(3) = I(1) \times J(3) + I(2) \times J(2) + I(3) \times J(1); \qquad (A3)$$

$$P(4) = I(1) \times J(4) + I(2) \times J(3) + I(3) \times J(2) + I(4) \times J(1); \quad \text{and so forth.} \qquad (A4)$$

Therefore,

$$P(n) = I(1) \times J(n) + I(2) \times J(n-1) + \ldots + I(n) \times J(1). \qquad (A5)$$

If

$$I = I(1) = I(2) = I(3) = I(4) = \ldots = I(n) \quad \text{is a constant continuous uptake, then} \qquad (A6)$$

$$P(n) = I \times [J(1) + J(2) + J(3) + \ldots + J(n-1) + J(n)] = I \times \sum_{i=1}^{n} J_i(t) = I \times n \times \frac{\int_0^n J(t)\,dt}{n}, \qquad (A7)$$

where *P(n)* is the n^{th} day plutonium excretion in 24-h and "*I*×*n*" is the sum of total uptakes from days 1 to *n*.

Hence,

$$\eta(n) = \frac{P(n)}{I \times n} = \frac{\int_0^n J(t)\,dt}{n}. \quad \text{(A8)}$$

So, $\eta(n)$ is the fraction of the total uptake of plutonium to be excreted in the n^{th} day 24-h urine sample that equals the integration sum of Jones's function from 0 to n days and divided by n. Using Jones's plutonium urine excretion function, we calculate $\eta(3{,}650) = 2.4 \times 10^{-5}$.

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A COMPARISON OF INDEPENDENTLY CONDUCTED DOSE ASSESSMENTS TO DETERMINE COMPLIANCE AND RESETTLEMENT OPTIONS FOR THE PEOPLE OF RONGELAP ATOLL

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Abstract—**Rongelap Island was the home of Marshallese people numbering less than 120 in 1954; 67 were on the island and severely exposed to radioactive fallout from an atomic weapons test in March of that year. Those resident on Rongelap were evacuated 50 h after the test, returned 3 y later, then voluntarily left their home island in 1985 due to their ongoing fear of radiation exposure from residual radioactive contamination. Following international negotiations in 1991, a Memorandum of Understanding (MOU) was signed in early 1992 between the Republic of the Marshall Islands Government, the Rongelap Atoll Local Government, the U.S. Department of Energy, and the U.S. Department of the Interior. In this MOU it was agreed that the Republic of the Marshall Islands, with the aid of the U.S. Department of Energy, would carry out independent dose assessments for the purpose of assisting and advising the Rongelap community on radiological issues related to a safe resettlement of Rongelap. The MOU enacted two action levels which were agreed to be used to establish whether mitigation should be considered as a condition for resettlement of Rongelap Island: (1) no individual should receive an annual dose in the future of 1 mSv or more, above that from natural background radiation, assuming that his/her diet consists of only locally produced foods, and (2) the total surface soil concentration of plutonium and other transuranic elements must be less than 629 Bq kg^{-1} (averaged over the top 5 cm). Environmental radiological data and dietary information were collected over two years (1992–1993) for the purpose of predicting future potential doses to Rongelapese who might resettle. In 1994, four independent assessments were reported, including one from each of the following entities: Marshall Islands Nationwide Radiological Study; Lawrence Livermore National Laboratory; an independent advisor from the United Kingdom (MCT); and a committee of the National Research Council. All four assessments concluded that possibly more than 25% of the adult population could exceed the 1 mSv y^{-1} dose level based on strict utilization of a local food diet. The purpose of this report is to summarize the methodology, assumptions, and findings from each of four assessments; to summarize the recommendations related to mitigation and resettlement options; to discuss unique programmatic aspects of the study; and to consider the implications of the findings to the future of the Rongelap people.**

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Key words: Marshall Islands; fallout; dose assessment; weapons

INTRODUCTION

DURING THE years 1946 through 1958, nuclear weapons testing was conducted by the U.S. on Bikini and Enewetak Atolls in the Marshall Islands. Bikini Atoll was the site of 23 of 66 underwater, ground level, and above ground nuclear tests conducted in the Marshall Islands; Enewetak was the site of 42 nuclear tests. Prior to 1954, the Atomic Energy Commission (AEC) believed that any danger from fallout radioactivity was restricted to the test site atolls (Eisenbud 1990). Moreover, because of the predominant east to west direction of the tradewinds in the mid-Pacific, there seemed little danger to locations to the east of Bikini. Rongelap Atoll, about 200 km east of Bikini Atoll, was the home of 115 Marshallese at the beginning of the nuclear weapons program. During the early years of the testing program, the Rongelap people were allowed to maintain residence on their home atoll as well as on two other nearby food gathering atolls, Ailinginae and Rongerik.

On 1 March 1954 (Pacific date, 28 February GCT), Castle BRAVO, the largest test of the entire U.S. weapon testing program, was detonated at Bikini Atoll. BRAVO, the United States second experimental thermonuclear

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bomb, delivered an explosive yield of 15 MT equivalent TNT. On 3 March 1954, the evacuation of atolls east of Bikini became necessary due to unexpected radioactive fallout from BRAVO tested 2 d earlier. Permanent residents of Rongelap and temporary residents of Ailinginae were evacuated 50 h after the test (Eisenbud 1990; Eisenbud 1997). An account of the immediate days following the exposure incident is in Sharp and Chapman (1957).

As a consequence of the high levels of radioactive fallout and delays in completing a rapid evacuation, 67 Marshallese on Rongelap (including 3 *in utero*), 18 on Ailinginae Atoll, 167 on Utrik Atoll, and 26 U.S. weather observers on Rongerik Atoll were exposed to substantial doses of external radiation and internal radioactive contamination. The doses to the persons on Rongelap Island were estimated to be about 1.9 Gy whole body and between 12 and 52 Gy to the thyroid, depending on age at exposure (Lessard et al. 1985). Exposures on Ailinginae were estimated to be about 30% of those on Rongelap.

Three main factors contributed to the exposure of the Marshallese: (1) the energy yield of BRAVO was three times the most probable predicted value and twice the predicted upper limit (DNA 1954), (2) the winds, which normally blow east to west in the mid-Pacific, blew in roughly the opposite direction on the day of the test, and (3) a substantial delay in evacuating the people from the islands.

Medical surveillance of the Rongelap people was begun following their evacuation and was maintained over the succeeding years. Medical findings have been published in a series of reports from Brookhaven National Laboratory beginning with Bond et al. (1955) and Cronkite et al. (1955). Environmental surveillance of Rongelap by the AEC Health and Safety Laboratory (see Breslin and Cassidy 1955) and the University of Washington's Applied Fisheries Laboratory (see Donaldson 1955) also began immediately after the accident.

In June 1957, the Rongelap community was returned to Rongelap. In 1978, Rongelap Atoll was one of eleven northern atolls monitored in a U.S. Department of Energy (DOE) sponsored aerial survey (see Tipton and Meibaum 1981). Findings from that program were explained to the Marshallese audience in a bilingual report issued by the DOE in 1982 (Bair et al. 1982). The levels of radioactivity contamination on Rongelap Atoll, however, had not been previously known to the Marshallese living there, thus considerable fear resulted among the community. As a result of their apprehension, the Rongelap people moved in May of 1985 from Rongelap Island to Mejatto,** a small island in Kwajalein Atoll, about 200 km south of their homeland. Because Mejatto was not a suitable replacement island, discussions on the safety of their home atoll began within two years' time.

In 1987, the RMI contracted Dr. Henry Kohn, previous chairman of the Bikini Atoll Rehabilitation Committee, to review the 1982 DOE report for the purpose of determining the validity of its conclusions. As part of that process, Kohn reviewed an updated LLNL dose assessment report for Rongelap Island that was based on extensive data developed from samples collected in missions to Rongelap Island in 1985, 1986, 1987, and 1988.

In March 1989, the Rongelap Reassessment Project, chaired by Kohn, issued a final report (Kohn 1989) indicating that Rongelap Island was generally safe for habitation assuming a mixed food diet (locally grown food plus imported food), though the potential radiation doses to infants and children were still of concern and should be studied further. Further negotiations ensued and in February 1992, a Memorandum of Understanding (MOU 1992) was signed between the RMI Government, the Rongelap Atoll Local Government, the U.S. DOE (Office of Environment, Safety and Health) and the U.S. Department of Interior (DOI, Office of Territorial and International Affairs). As part of the agreement, the Department of Interior provided $1.6 M to the Rongelap Local Government for the purpose of funding scientific studies previously outlined and presented to the House Appropriations Committee. The study plan and budget allowed for Rongelap community participation in the conduct of those studies. Funding for a similar but separate evaluation of Rongelap by DOE laboratories was provided for within the DOE annual budget.

The Rongelap Local Government (RALGOV) subsequently established the Rongelap Resettlement Project (RRP††) and contracted a scientific management team to carry out studies designed to determine the expected exposure of a returning population. An international technical oversight body to review the quality of the scientific work was also assembled as well as an administrative body (see Appendix for membership lists). Similarly, the Lawrence Livermore Laboratory (LLNL) embarked on an expanded sample collection of Rongelap and an updated assessment on behalf of the U.S. DOE. The DOE similarly established an independent review board through the National Research Council (NRC, see Appendix for membership list).

The objective of this report is to present a description of the combined activities of the Marshall Islands Rongelap Resettlement Project and those of the Department of Energy for the reevaluation of the safety of Rongelap. These various activities included detailed radiological monitoring and sample analysis and collection of human behavioral data, which ultimately led to four independent dose assessments and recommendations for limited remediation programs as well as resettlement options. The unique aspects of multiple independent assessments and community involvement will also be discussed.

[**] Mejatto Island in Kwajalein Atoll should not be confused with Mejatto island in northern Rongelap Atoll.

[††] The Rongelap Resettlement Project (1992–1994), the subject of this paper, was a separate study from the Rongelap Reassessment Project (1987–1988, see Kohn 1989) despite similar names. RRP refers exclusively to the former.

OBJECTIVES, DATA, AND METHODOLOGY

Objectives as outlined by Memorandum of Understanding

The Memorandum of Understanding (MOU) enacted two primary conditions to determine whether resettlement should be considered without a requirement for mitigative action. These conditions were generally considered by the Marshallese as "limits" that required an absolute determination of compliance; thus, in the end, some misunderstandings resulted. The conditions as specified in the MOU applied exclusively to the southern half of Rongelap Atoll (see Fig. 1), though considerable emphasis was given to Rongelap Island because of its comparatively large size and history as the residence island of the main community. The two conditions as stated in the MOU and that were the responsibility of the RRP to determine are set out below.

1. "The primary condition of a determination to initiate resettlement. . . is that the calculated whole-body radiation dose equivalent to the maximally exposed resident shall not exceed 100 millirem per year above natural background, based upon a local food only diet. . . The 'local food only diet' declaration is meant to constitute a traditional Rongelapese diet consisting of local food taken, grown and/or gathered from the southern islands of Rongelap Atoll and the immediately surrounding waters. . . for comparison purposes a more 'realistic diet' shall be more precisely determined and quantified. . . in consultation with the Rongelap community. In its determination of what constitutes a 'local food only diet', the Rongelap Atoll Local Government Council may at its discretion include imported foods that are staples of the diet, e.g., rice."
2. "An additional condition of mitigation is the extent of transuranic contamination, especially plutonium contamination of the soil. . . . utilizing as an action limit, the screening level of the U.S. Environmental Protection Agency of 0.2 microcuries per square meter, which has been translated by the DOE/ES&H into an activity concentration of 17 picocuries/gram of transuranics averaged in the top 5 cm of soil."[‡‡]

Diet information: Importance and data collection

Cesium-137 is readily transferred from soil to plants in the terrestrial ecosystem of coral atolls because of the absence of clay material to bind the cesium and because the soil is inherently potassium deficient (Robison and Stone 1992). Plant uptake of cesium is enhanced in this environment because of the metabolic needs of plants for potassium and the chemical similarity of cesium to potassium. Agriculture is not a common practice in the RMI aside from occasional planting of sweet potatoes and watermelon. Generally, native fruits including coconut, breadfruit, *Pandanus*, papaya and arrowroot are collected as staples of the traditional island diet. Aside from fruits, seafood, including shallow water dwelling "reef" fish, pelagic fish, crabs including the land dwelling "coconut crab," lobster and giant clams, compose the traditional Marshallese diet. The inclusion of rice in the day-to-day diet is now universally accepted among Marshallese and forms a staple along with canned meats and several variations of bread or cakes made from imported flour.

Foremost of all the dietary components that result in the intake of ^{137}Cs by Marshallese is the coconut. The coconut fruit is used at all stages of growth and provides liquid replenishment at the young "drinking stage," a semi-solid or solid 'meat' (depending on the age of the coconut) which is added to various cooked dishes, and juice which may be fermented into a consumable alcoholic drink. Because there is no freshwater on the atolls except for that collected from rainfall, coconut liquid of the young fruits is widely consumed and is, therefore, a primary contributor of cesium to the diet of Marshallese resettling contaminated lands. A reasonable estimate of the intake of coconut food products is important for assessing radiation dose to Marshallese.

The primary endpoint of the scientific studies was to be a prediction of possible doses to Rongelapese upon resettling Rongelap Island. Because the preponderance of the total radiation dose that would be experienced by Rongelapese today would be from ingestion of locally grown foods containing ^{137}Cs (Robison et al. 1980, 1982a, 1982b, 1987; Robison 1983), the composition of any assumed dietary model was the principal determinant of predicted doses.

The precise dietary intake at any atoll has been difficult to determine despite the review of numerous historical reports and documents. Over a dozen such historical documents describing food habits among Marshallese were reviewed by the NRC (1994), including a National Nutrition Survey conducted in 1991 by the RMI Ministry of Health. However, few useful data could be extracted from any of these to quantitatively describe the variation of dietary intakes which are needed for sex-, age- and atoll-specific dose assessments. For the four dose assessments reported here, two sources of dietary information were used, though several possible variations were considered. One survey conducted by the Micronesian Legal Services Corporation (MLSC) on Ujelang Atoll in 1978 with the assistance of a Marshallese school teacher and reported by Robison et al. (1980, 1993, 1994) was used in the LLNL assessment and ultimately was the basis for the NRC assessment and review. A second survey was conducted for the purposes of the RRP and was reported by Dignan et al. (1994) and summarized by Franke (1994). Because of the implicit importance of these diet studies to the dosimetry endpoint, a summary of both diet surveys is presented here.

LLNL diet model. A summary of the MLSC diet has been provided in Robison et al. (1980). The data were obtained from a survey of 34 adult females and 36 adult males, as well as teenagers and children on Ujelang

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[‡‡] Through the remainder of this publication, the two conditions to be determined as outlined in the MOU will be expressed in SI units, i.e., 1 mSv y^{-1} and 629 Bq kg^{-1}.

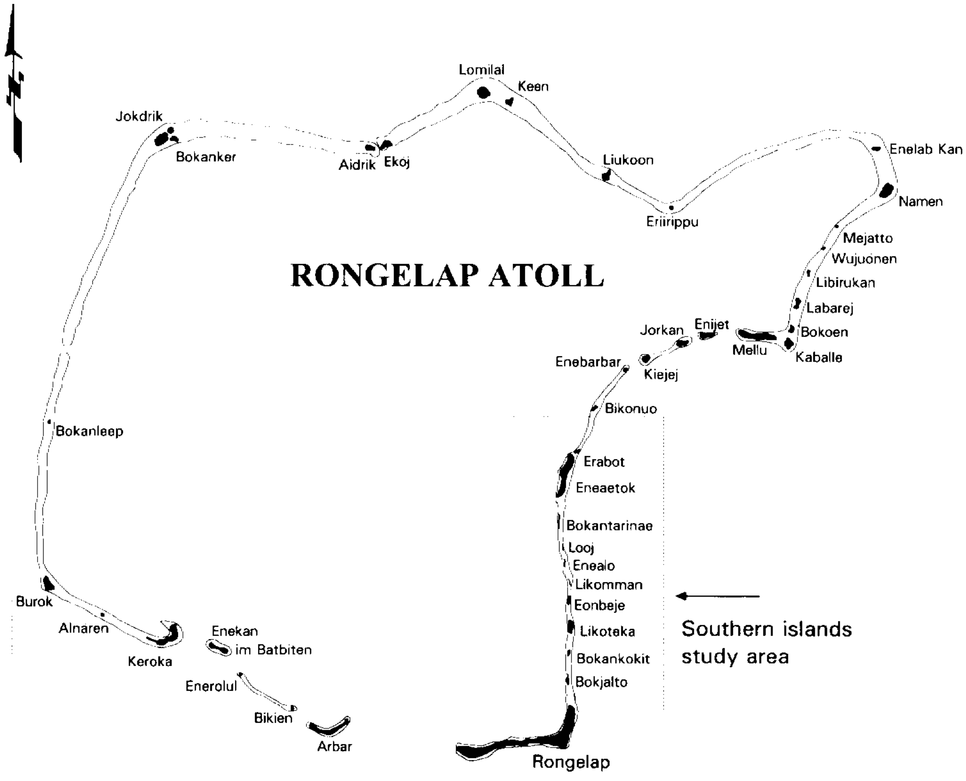

Fig. 1. Map of southern island study area in Rongelap Atoll (map courtesy of Nationwide Radiological Study).

Atoll. Adult intake exceeded that of teenagers and children, and the intake of local food was about 20% greater for women than for men. The higher intake attributed to women is unexplained and certainly questionable. Those unexpected results are indicative of the acknowledged uncertainty in dietary estimates. Rather than attempt further speculative refinement of the diet, the MLSC diet was used by LLNL as a basis for estimating dietary intake. The caloric intake rate (kcal d^{-1}) was 1,392 for the case of imports unavailable (i.e., local food only) and 3,208 for the case of imports available and was specified as the average adult intake for the northern Marshall Islands. The caloric intake rate is relatively low for the imports unavailable case and relatively high for the imports available case. For example, kcal d^{-1} intake for adults living in the U.S. are reported between 1,850 (Yang and Nelson 1986) and 1,925 (Abraham et al. 1979). NRC (1994) in their review of the MLSC diet commented that the caloric intake for the local food only diet resulted in an energy deficit that would normally result in a weight loss of about 1.8 kg per week. Though there are no historical accounts of weight loss, the NRC commented that the Ujelang diet survey is as good as many major diet studies in the U.S. and "was the logical and appropriate choice... to use to estimate exposure...".

Considerable effort to validate various diet models has been made by comparing the predicted body burdens of ^{137}Cs from these diets with ^{137}Cs body burdens measured directly from whole-body counting (Robison and Sun 1996). The LLNL diet model consisting of both local and imported foods predicts very well the actual measured body burdens at Rongelap Island between 1977 and 1984. The use of other diet models to calculate ^{137}Cs body burdens at Rongelap and Utrik Atoll considerably overestimate the observed results (Robison and Sun 1996, 1997). Consequently, the LLNL diet model that contains both local and imported foods was used to calculate a realistic average population dose that reflects current dietary practices in the Marshall Islands.

To comply with the MOU, a diet consisting of only local foods had to be used for calculating a maximum individual dose. The local-food-only diet from the MLSC survey indicated a low caloric intake of 1,392 kcal d^{-1}. That diet may have had relevance during periods when imported foods were unavailable, which happened prior to the atolls having runways for airplane service and when the local population was dependent on field ships. Marshallese in three different atoll communities have referred to the diet as a "famine" diet. This term indicated a lack of food supply and perhaps the caloric intake was low during those periods. Nonetheless, the caloric intake for the LLNL local foods only diet was doubled to 2,784 kcal d^{-1} on recommendations of the NRC review committee. This was accomplished by doubling the intake of all local foods listed for the local-foods-only diet; this action also led to a doubling of the intake of ^{137}Cs for dose assessment purposes.

The MLSC diet model includes all forms of seafood, chicken (locally raised), pigs (locally raised), native fruits including some cultivated varieties, rainwater and well water. The imported food component, which included canned meat, potatoes, rice, canned fruit juice and vegetables, etc., was assumed not to contribute any manmade radioactivity. The intake of coconut products was approximately 99 mL d^{-1} of fluid, 84 g d^{-1} of various forms of the copra and sprouting coconuts, and 32 g d^{-1} of the soft drinking coconut meat.

NRC diet modifications. The report of the NRC (1994) considered the diet model used by LLNL and proposed several modifications. Two of those variations, (1) "Local only" diet and (2) "Coconut collector's diet", were specifically applicable to the conditions set forth in the MOU. The NRC "local only" diet was an adjustment of the MLSC "local-food-only" diet to 3,208 kcal d^{-1} (2.305× the MLSC local food only value), equal in energy intake to the MLSC "local-and-imported-food" diet. The NRC committee felt that this intake value would produce a sustainable body weight. The second variation, the "coconut collectors diet," was also derived from the MLSC "local-food-only" diet; however, the energy intake for this variation was 2,018 kcal d^{-1}. In this case, the energy intake was increased by increasing the intake of fish (2×), coconut juice (5×), drinking coconut meat (5×) and sprouted coconut (5×), though the intake of turtle eggs and water was reduced (90 and 300 g, respectively) so that total intake remained reasonable.

RRP diet model. The sources of dietary information used in the RRP assessments were the results of a 24-hour recall survey of the Rongelap community now residing on the island of Mejatto in Kwajalein Atoll. The Mejatto dietary survey was conducted in May 1993 for the RRP by a nutritionist from the South Pacific Commission who was assisted by Rongelap community members and one of the authors (BF). Before the conduct of this study, the RRP acknowledged that acquiring empirical data on a local-food-only diet in the RMI did not appear possible since there are no longer any atoll communities which subsist for long periods of time solely on a diet of locally grown food. Given the inherent limitations, the study was designed to collect two types of data: (1) the range of caloric intakes today among the resident population, and (2) a determination, by personal inquiry, of the preferred "local foods" which if available would be consumed in replacement of imported foods. Data were collected on 319 residents with a repeat data collection from 48 women several days later.

The strength of this dietary survey was that the population under assessment was examined for their own eating habits, thus ensuring a degree of credibility with the population. The proven validity of the diet as a description of present or future eating habits was less of a concern than was an overt acceptance by the community that the diet adequately described their lifestyle. The RRP diet also met reasonable expectations for energy consumption and expenditure.

Data obtained in the survey of Mejatto residents indicated that, on average, only 18% of their food originated with local produce. The poor supply of locally grown food on Mejatto island was the primary weakness to an empirical determination of the local food component, although the findings were not surprising since the bulk of the Mejatto diet was known to consist of USDA imports.

The observed mean energy intake (EI) for men and women was 1.6 times the estimated mean basal metabolic requirement (BMR_{est}), a value consistent with sedentary-light activity. As anticipated, however, the spread of the distribution of EI BMR_{est}^{-1} was over-disperse with a small number of individuals reporting energy intakes below a reasonable metabolic rate and a few reporting maximum energy intake equivalent to unrealistically high physical activity levels. Since reasonable annual mean values were needed for the dose assessment, the standard deviation of the EI BMR^{-1} distribution was adjusted to reflect a reasonable spread of intakes. The 1st percentile was set equivalent to EI BMR^{-1} of 1.0; the 99th percentile was set equal to 2.3 for males and 2.0 for females.

The findings of the Mejatto diet survey reported by Dignan et al. (1994) indicated caloric intake-rates of approximately 1,960 ± 105 (1 SE) and 2,750 ± 146 (1 SE) kcal d^{-1} for women and men, respectively. The primary "local food diet" was eventually accepted by the Rongelap community to include a 25% caloric contribution from rice. This diet was termed "Mejatto scaled diet with rice."

The variety of local foods that eventually was substituted for calories consumed from imported foods was not as varied as in the MLSC diet. However, the differences in cesium content between most types of seafood are small, as is the variation among most vegetables and among most fruits (with an exception of *Pandanus*). The intake of coconut products for males in the "Mejatto scaled diet with rice" was approximately 104 g d^{-1} of fluid, 23 g d^{-1} of the soft drinking coconut meat ('mede' in Marshallese), and 372 g d^{-1} combined of solid coconut cream, diluted coconut milk, coconut embryo ("iu", pronounced "you") and hard coconut ("waini"). The intake of coconut products for females in the "Mejatto scaled diet with rice" was approximately 151 g d^{-1} of fluid, 1.6 g d^{-1} of the soft drinking coconut meat, and 395 g d^{-1} combined of solid coconut cream, diluted coconut milk, coconut embryo and hard coconut. The liquid and soft coconut meat components were close in value to the MLSC diet.

In all, five dietary variations were evaluated by the RRP although three are of primary interest here: (1) Mejatto observed (18% local food); (2) Mejatto scaled without rice (100% local food); (3) Mejatto scaled with rice (75% local food). The principal dietary model for determination of compliance with the guidelines of the MOU was diet (3), "Mejatto scaled with rice."

External gamma-exposure

LLNL. External gamma measurements of ^{137}Cs were obtained in 1978 by EG&G from an aerial survey using helicopter-mounted NaI detectors (Tipton and Meibaum 1981) and from LLNL ground measurements made on a 100-m grid on Rongelap Island in 1992. The resolution of the EG&G measurements was about 100 m. Exposure contours were developed from those data, and the island average exposure for the interior of the island (non-village area) was determined by weighting each contour by the encompassed ground area.

These decay corrected EG&G data and extensive *in situ* gamma measurements made by LLNL in 1988 inside houses and buildings, outside of the houses, and in the village area were used in conjunction with assumed times that people spend in and around their houses, in the village area, in the island interior, and on the beaches and lagoon to determine the external exposure (Robison et al. 1994).

RRP. Ground contamination measurements and soil samples were collected by the Marshall Islands Nationwide Radiological Study (NWRS) under a contract with the RRP. Four sampling missions were conducted: November 1991, April 1992, September 1992, and April 1993. The sampling missions for the RRP received substantial logistical support from DOE programs in the conduct of their own investigations.

In situ gamma spectrometry measurements using high purity germanium (HPGe) detectors were made by the NWRS on a systematic grid of 200 m spacing over the entire southern half of Rongelap Atoll including the primary residence island (Rongelap)(Fig. 2). There were 63 measurement sites on the 200 m grid of Rongelap Island. In addition, four of the primary grid cells (200 × 200 m each) were chosen for systematic measurements on a 40-m scale (i.e., 25 measurements per grid cell). Thus, the primary set of ground-contamination data for Rongelap Island was 163 *in situ* gamma spectrometry measurements. The *in situ* count rate data from ^{60}Co, ^{137}Cs, and ^{241}Am were interpreted using calibrations determined by theoretical considerations using the relaxation length concept (Beck et al. 1972; Helfer and Miller 1988) and using empirical data collected from over 200 soil profiles around the Marshall Islands to determine a best estimate of the calibration factor, Bq m^{-2} per count s^{-1}. The ground contamination estimates were used to derive external exposure rates by the use of kerma factors (Jacob and Paretzke 1986).

Because Marshallese generally move about the island on foot to collect food, it can be reasonably assumed that their annual exposure would depend on which specific locations of the island were routinely visited. Thus, the average contamination over areas large enough for food collecting might best predict the average external exposure. The determination of the size of the area used for food gathering requires some understanding of traditional Marshallese customs. For example, land ownership is generally specified by *watos* or relatively narrow strips of land that run from the lagoon side of the island to the ocean side. *Watos* may be as narrow as a few hundred meters. Thus, food collection for individuals (or families) might be limited to particular areas or *watos* of the island. Such considerations led to the decision to determine the range of external exposures that might be received among the population depending on the location on the island where an individual resided and by considering various sized areas over which to average the contamination data.

Food radioactivity data

LLNL. Collection of food and soil samples from Rongelap by LLNL began in 1978 as part of the U.S. DOE sponsored Northern Marshall Islands Radiological Survey (NMIRS). A series of reports from the NMIRS provided external gamma measurement data and soil, plant, animal, cistern water, groundwater, and marine species radionuclide concentration data (Tipton and Meibaum 1981; Robison et al. 1981a, 1981b; Noshkin et al. 1981). A dose assessment was made for Rongelap Island as part of the NMIRS (Robison et al. 1982a). LLNL collected hundreds of additional samples of soil and locally grown fruits from 1985 through 1989. More samples were collected during collaborative sampling

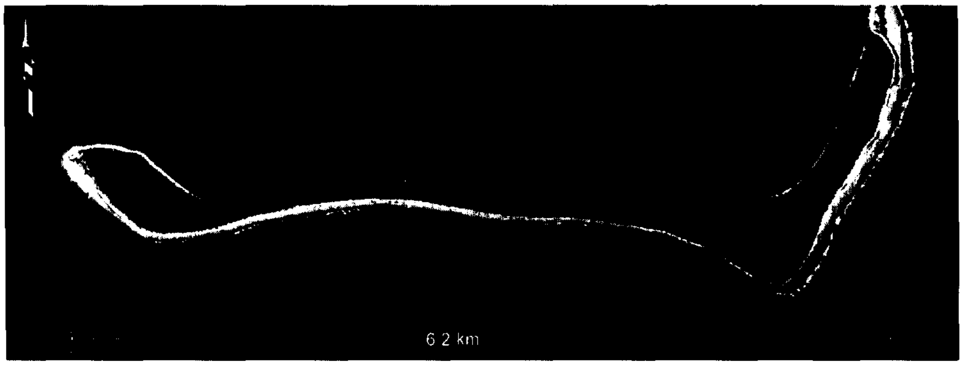

Fig. 2. Reproduction of photograph of Rongelap Island from U.S. DOE sponsored aerial survey (see Tipton and Meibaum 1981; photo courtesy of LLNL).

missions with the NWRS during 1991 to 1993; LLNL collected soil and vegetation samples on a 100-m grid across all of Rongelap Island. The number of samples analyzed over the years from Rongelap by LLNL is extensive (see Robison et al. 1994) numbering, for example, over 400 for drinking coconuts and nearly all *Pandanus* and all breadfruit on the island. Few samples of other fruits such as banana, arrowroot, and limes are available because of the scarcity of these trees on the island.

RRP. The NWRS also collected fruits during sampling missions conducted from 1991 through 1993; types of fruits collected included coconuts (at various stages of growth), *Pandanus*, breadfruit, and arrowroot, as well as five different plant species consumed in traditional Marshallese medicine (for the latter topic, see Duffy 1994).

The capacity of the NWRS for analyzing samples was much less than that of LLNL; however, the objectives of the study included comparing data between the two institutions for the purposes of corroboration, leading eventually to sharing of data. Because the data on radionuclide concentrations in food crops and soil obtained by the NWRS were essentially the same as those from the LLNL database, plant concentrations and plant: soil concentration factors from the more extensive LLNL database were used by the NWRS in their dose assessment. The following section describes the process of data intercomparison.

Quality control programs

Interlaboratory comparison. Interlaboratory comparison was an important part of the quality control program of the combined Rongelap studies. It also served to minimize excessive redundancy in sample collection and analysis. Several different interlaboratory comparisons were made in the course of the combined Rongelap activities. Findings are summarized here but are described in greater detail in Graham and Simon (1994) and Kehl et al. (1995).

Both LLNL and the NWRS laboratory participated in international laboratory intercomparisons through the International Atomic Energy Agency (IAEA). LLNL has had an ongoing intercalibration program with the IAEA for 25 y, which included yearly sample analysis. An extensive intercalibration and split-sample analysis program with several contractor laboratories, universities, and other laboratories around the world are conducted by LLNL. In addition, the NWRS conducted an independent interlaboratory comparison with LLNL and three other institutions,[§§] and numerous types of samples were collected and split for analysis and data comparison directly with LLNL.

Peer review. Both the RRP and the LLNL assessment programs utilized independent and separate peer review as a quality control measure. Some differences were apparent in the implementation of peer review for the two programs. The RRP program established a six-person review board after submitting a roster of names and credentials to the Rongelap Local Government for review. The RRP Technical Oversight Group, which was subsequently assembled, assisted in guiding the RRP study by reviewing study plans before implementation. In particular, one member provided a protocol that was accepted for utilizing dietary information and calculating possible doses to future residents (see Thorne 1994a). In addition, the RRP Oversight Group reviewed final study findings. The U.S. DOE established a Committee on Radiological Safety in the Marshall Islands by contract through the National Research Council. The charges to that committee included a review of the applicability of international dose standards to contaminated areas of the Marshall Islands, evaluation of analytical techniques and dosimetry methods used by DOE contractor laboratories, evaluation of the implications of various dietary regimens, and review and evaluation of methods to reduce future exposure of Marshallese, in particular those persons that might resettle Rongelap Atoll. The findings of the NRC were published in 1994 (NRC 1994).

Dose assessment methodology

Because of the independence of the four groups, there were some differences in assessment methodology. Due to space limitations, only the primary assumptions and types of models are briefly described in this paper.

LLNL. The LLNL dose assessment was designed to calculate realistic population average annual and time integrated doses based on a diet model consisting of both local and imported foods to people returning to live at Rongelap Island. In addition, a dose estimate was made for the conditions outlined in the MOU for a maximum individual dose based on a diet model that assumed the consumption of only locally grown food for a lifetime.

The effective dose to a returning population was determined by a summation of the external exposure from ^{137}Cs, the skin beta dose from ^{137}Cs, and internal exposure from ^{137}Cs, ^{90}Sr, and transuranic radionuclides ($^{239+240}$Pu, ^{241}Am). The detailed methodology is described in Robison et al. (1994).

Calculations of external exposure from gamma radiation used data collected by aerial survey in 1978, supplemented with ground level measurements collected in 1988. The primary assumptions to account for variations in shielding and ground contamination were 9 h d^{-1} indoors, 6 h d^{-1} around the house and village, 7 h d^{-1} in the interior of the island, and 2 h d^{-1} on the beach or lagoon with exposure-rates of 6.0×10^{-14} C kg^{-1} s^{-1} (0.83 R h^{-1}), 1.4×10^{-13} C kg^{-1} s^{-1} (2.0 R h^{-1}), 2.2×10^{-13} C kg^{-1} s^{-1} (3 R h^{-1}), and 6.4×10^{-15} C kg^{-1} s^{-1} (0.089 R h^{-1}), respectively. Skin dose from beta

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[§§] GSF Institut fur Strahlenschutz (Munich, FRG), National Radiation Laboratory of New Zealand (Christchurch, NZ), Colorado State University (Ft. Collins, CO, USA).

radiation was determined to be extremely small and could be neglected.

Internal dose from ^{137}Cs was calculated using methods described in ICRP Publications 30 (1979), 56 (1990), and 61 (1991) to determine the dose factor. The biological half-life was determined as a function of age (i.e., body mass). Internal dose from ^{90}Sr used the model by Leggett et al. (1982) which has three compartments, two within the bone volume and one for the bone surface.

Dose from transuranic radioactivity included contributions from ingestion and inhalation. The methods used to calculate ingestion dose were from ICRP Publications 30 (1979), 48 (1986), and 56 (1990). The gut-to-blood transfer factor, f_1, was assumed as 10^{-3} for plutonium and americium in vegetation and 10^{-4} and 10^{-3}, respectively, for the radionuclides ingested in soil. Forty-five percent of the plutonium and americium in blood was assumed to be transferred to bone and 45% to the liver. The biological half-life was set at 50 y in bone and 20 y in liver. A quality factor of 20 was used for both radionuclides.

Inhalation dose modeling for the transuranic radionuclides used various data collected in resuspension experiments at Enewetak and Bikini Atoll (Shinn et al. 1989, 1996). Mass loading in air was determined for various earthmoving and wind conditions. Assumptions were made on the length of time an individual might spend in those extreme conditions as well as in routine activities of various types (non-occupational, resting, etc.). Methodology from ICRP 30 (1979), 48 (1986), and 56 (1990) was used for the dosimetric models. The activity median aerodynamic diameter assumed in those calculations was 1 μm which provides a slightly conservative dose calculation in that results from the resuspension studies show a medium diameter close to 2.5 μm.

For comparison, the dose from ^{210}Po and ^{210}Pb in seafood was evaluated (Noshkin et al. 1994). The effective doses from ingestion of ^{210}Po and ^{210}Pb were also considered in the LLNL assessment mainly as a means to provide a perspective of the fallout related dose.

Both deterministic and Monte Carlo type calculations were reported. An estimated maximum annual dose was defined as the dose-rate in the year immediately following resettlement when the sum of the external and internal gamma dose are maximum. The input data for those calculations were the LLNL diet model (average values) and environmental radionuclide concentrations in food crops (also average values) as previously described. The uncertainty and inter-individual variability in the population average and maximum individual estimated doses were calculated by methods described in Bogen et al. (1997). Some of the original estimates for Rongelap by Robison et al. (1982a) were revised in Robison et al. (1994). The inter-individual variability in the maximum individual dose was calculated under the assumption of double the caloric intake of the LLNL local food only diet model. Using Monte Carlo techniques to model the variations among individuals (intake-rates, biological half-life, etc.), a distribution of the variation of doses that could occur was also provided.

NRC. The charge to the NRC review committee (1994) was to evaluate the quality of the scientific programs sponsored by the DOE rather than to perform a dose assessment. Consequently, the NRC report made no attempt to collect new data, develop new dose assessment methodologies, or perform independent assessment calculations. In the process of critiquing DOE programs, however, the NRC committee did consider alternative diets and, in doing so, they made estimates of potential exposures under various dietary scenarios. They considered ingestion and inhalation for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Rather than reproduce the probabilistic methods used by DOE or the RRP groups, the NRC used average dietary intake values for each scenario plus the land and food contamination values given by Robison (1994) to determine if compliance with the dose condition was met.

RRP. The dose assessment calculations were carried out at two separate locations (Majuro, RMI and Sussex, UK) according to the same protocol (see Thorne 1994a), but with entirely independent programming and some small differences in approach. Duplicate calculations were made to ensure that the final result contained no artifacts of programming or misinterpretations of the primary data. Because of the difficulties in defining the maximally exposed individual, the approach adopted by the RRP was to assess the distribution of likely doses that might be received by both external and internal exposure. The objectives of the RRP to assess dose were not as broad as that of LLNL, i.e., all pathways and radionuclides were not considered. This decision resulted from considerable evidence showing that ^{137}Cs contributes 99% of the external exposure and close to 90% of the internal dose (Robison et al. 1982a, 1982b, 1987, 1994; Robison 1983). The approach was to calculate first only the contribution from ^{137}Cs. Depending upon the outcome relative to the MOU compliance values, further sensitivity analyses were to be made and evaluations of other radionuclides and pathways would be performed. The methodology adopted by the RRP for dose assessment had as its objectives to compute (1) the probability density function (pdf)[||] of the population distribution for internal dose, (2) the probability density function (pdf) for external exposure and (3) the pdf for the combined external and internal effective doses.

Distributions of dose-rate among members of the population were separately computed for men and women (i.e., using the diet and body weight variation among the community of men or women, not the uncertainty for individuals). Dose to children was examined by

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[||] Probability density function (see any standard statistical text, e.g., Mendenhall et al. 1986) refers to the statistical distribution of the set of computed doses. The probabilities of discrete dose values occurring within the population were derived from the relative frequency of occurrence of each value.

comparison of energy intakes in relation to body masses. Population dose distributions were derived using Monte Carlo techniques to draw at random from the distributions of soil concentrations, body mass, and energy intake. In the calculations by Simon (1994a; also see Simon and Graham 1996), distributions of plant:soil concentration ratios were input as well.

The external component of dose-rate depends on the extent to which an individual moves around the island, particularly if the count rate varies markedly from one part of the island to another. A relatively immobile individual will be subject to an exposure rate typical of the locality in which he or she spends most of their time whereas a mobile individual will approximate to the average exposure rate for the island. This "mobility" factor was allowed for by assuming various sized "radii of utilization" and by spatially averaging ground contamination over these areas. Although data were originally collected on a grid (200 m square) of coarse size relative to the movements of people, soil contamination data were estimated on a finer grid by an optimal interpolation method known as kriging (for an extensive review of kriging methods, see Cressie 1991). These calculations were completed and reported by Diggle et al. (1994, 1997). The interpolated data were then spatially averaged over different radii of utilization.

The distribution of possible doses among the population depends on the variation of yearly averaged food intake-rates and the areas of the island used for food gathering. Environmental contamination data were used differently in the calculations by Simon (1994a) and Thorne (1994b). In the first case, the empirical ground contamination data were used directly, considering each measured value to be representative of the entire 200 m grid cell. Ingestion-rates, as determined by survey, were then matched at random by computer Monte Carlo techniques with the set of environmental concentrations. The second method used the spatially averaged values matched at random with the set of ingestion rates.

Both the external and internal dose rates depend on body mass. In the external case, dose rate was derived from exposure rate using ICRP 51 (1989) conversion factors. For internal exposure, dose rate depends upon food (mass) intake, dietary composition, and body mass. A diet survey of the inhabitants of Mejatto Island was used to assess the contribution of local foods to the present diet and to assess the distribution of energy intakes. The fractions of time spent in different activities were based on previous DOE assumptions. In determining the pdf of the total ^{137}Cs dose, a perfect correlation was assumed between external and internal components, the rationale being that those areas of the island with high (or low) ground contamination would in general result in high (or low) external exposure as well as high (or low) concentrations in food plants.

SUMMARY OF SELECTED DATA

A comprehensive report of all the data collected in these studies cannot be reported here. Data important to the project resulted from a comprehensive and detailed radiological survey of Rongelap Island and other islands (see Tipton and Meibaum 1981; Robison et al. 1982b, 1994; Simon and Graham 1994), findings from a diet survey of the Mejatto community (Dignan et al. 1994; Franke 1994) and the Enewetak community (Robison et al. 1982a, 1994), extensive fruit and soil sampling (Robison 1994) and quality control studies (Graham and Simon 1994; Kehl et al. 1995).

Land contamination

The levels of ^{137}Cs and transuranic radioactivity in soil cover a range of about five for most soil samples obtained from Rongelap Island; however, the lowest measurements (generally by the beaches) and the highest (generally in the interior of the island) can cover a range of nearly 80. Measurements in this context could refer to *in situ*, aerial, or laboratory gamma spectrometry. The ground contamination is characterized by four areas of highest activity: interior of the east end of island, an area midway in the isthmus, and two interior areas on the west end of the island.

The average areal inventory of ^{137}Cs determined by LLNL (summed to 60 cm depth) was 52 kBq m^{-2} (Robison et al. 1994). Concentrations in the top 5 cm of soil for the transuranic radionuclides were 96 Bq kg^{-1} for ^{241}Am and 132 Bq kg^{-1} for $^{239+240}$Pu in the interior of the island and 15 Bq kg^{-1} for ^{241}Am and 19 Bq kg^{-1} for $^{239+240}$Pu in the village and housing area (Robison et al. 1994).

Values of land contamination determined by the NWRS were similar. The average areal inventory of ^{137}Cs (to 30 cm depth) was 35 kBq m^{-2} (Simon and Graham 1994). The island average concentrations in the top 5 cm of soil were 0.48 Bq kg^{-1} for ^{60}Co, 65 Bq kg^{-1} for ^{241}Am, and 133 Bq kg^{-1} for $^{239+240}$Pu (Simon and Graham 1994).

Local foods

A comprehensive summary of radioactivity concentrations in locally produced foods as determined by LLNL is reported in Robison et al. (1994); measurements made by the NWRS for the RRP are reported in Simon and Graham (1994).

The average concentrations of ^{137}Cs in locally grown foods as determined by LLNL were 71 Bq kg^{-1} (wet weight) in drinking coconut meat, 32 Bq kg^{-1} in drinking coconut fluid, 120 Bq kg^{-1} in copra (mature coconut), 250 Bq kg^{-1} in *Pandanus*, and 130 Bq kg^{-1} in breadfruit (Robison et al. 1994).

Measurements of ^{137}Cs from the NWRS, based on a much smaller sample size, were 185 Bq kg^{-1} (dry weight) for drinking coconut meat, 24 Bq L^{-1} for drinking coconut fluid, 903 Bq kg^{-1} (dry weight) in Polynesian arrowroot (Simon and Graham 1994), and between 300 and 700 Bq kg^{-1} in five species of plants whose leaves are used for preparing traditional medicinal remedies (Duffy 1994).

Quality control studies

Though the Marshall Islands Nationwide Radiological Study (NWRS) and LLNL have participated in a variety of international laboratory comparison activities, only those programs between the two laboratories for the purpose of the combined Rongelap study are discussed here. In all, six different laboratory comparisons were made including (1) a five laboratory intercomparison conducted by the NWRS of soil samples containing ^{60}Co, ^{137}Cs, ^{207}Bi, $^{239+240}$Pu, and ^{241}Am; (2) soil profiles from Rongelap Island sampled independently by the NWRS and LLNL; (3) split soil profile samples from Rongelap Atoll; (4) surface soil samples (0–5 cm) collected independently by the two laboratories from within the *in situ* measurement grid; (5) split plant samples; and (6) a comparison of exposure-rates and soil inventory measurements between NWRS data (collected 1991–1993) and an aerial survey conducted by EG&G for the U.S. DOE in 1978. The results of these intercomparisons are summarized here.

1. Three soil samples were submitted by the NWRS to five laboratories, including its own and LLNL. The ^{137}Cs activity of the three samples covered a range nearly 100 fold; the $^{239+240}$Pu activity covered a range of over 600 fold. Little variation among the laboratories was noted from the analysis of three soil samples; the average coefficients of variation among the four laboratories reporting were 8.3% and 10.8% for ^{137}Cs and $^{239+240}$Pu, respectively.
2. Twelve pits were dug on Rongelap Island at roughly equidistant intervals along the 6-km-long island. Soil profiles were individually sampled by the two laboratories from the pits with each using their own sampling and analysis protocol. The topmost three layers, each of 5 cm depth, were analyzed for ^{137}Cs and compared. In general, the measurements of the NWRS were 20% to 30% lower, with the difference in sample preparation accounting for the differences. The LLNL routinely analyzed the soil after removing particles >2 mm in size whereas the NWRS included such particles after crushing them to a uniform size distribution and remixing the sample. Thus, the RMI methodology which included the larger particles resulted in some dilution of the sample relative to the methodology of LLNL.
3. Another group of 77 samples was taken from profiles collected from the entirety of Rongelap Atoll. Each sample was mixed in the field and split for the two laboratories. The NWRS analyzed the soil profiles with and without the particles >2 mm in size. In the topmost increment (0–5 cm depth), the median ratio between the data from the two laboratories (NWRS/LLNL) was 0.97 without the particles >2 mm.
4. Surface soil samples (0–5 cm) were obtained from the *in situ* measurement grid with each laboratory using its own individual sampling protocol. In this comparison, the median and mean ratio of the data (RMI/LLNL) were 0.83 and 1.2, respectively. A higher variability in this type of sample resulted because the soil was not mixed and split but collected by each lab within the near vicinity of the *in situ* gamma spectrometry measurement site.
5. Measurements of ^{137}Cs in split plant samples were also compared by the two laboratories. Thirty-one plant samples including three *Pandanus* fruits, four leaf samples of specified species, and twenty-four coconut samples were included. The median ratio of concentrations from the two laboratories (RMI/LLNL) was 1.0; the minimum and maximum ratios were 0.83 and 1.57, respectively.
6. Finally, a comparison was made between the soil inventory and exposure-rate estimates reported by EG&G from the 1978 aerial survey (Tipton and Meibaum 1981) and those acquired by the NWRS ground survey of Rongelap Island in 1991–1993 that used *in situ* gamma spectrometry. The two sets of data were decay corrected to the same date, and ratios of the data for identical locations were determined. The median ratio (NWRS/LLNL) of exposure rates for 283 locations on 27 islands in Rongelap Atoll was 1.07.

There was excellent agreement between the NWRS and LLNL intercalibration analyses as well as with the EG&G external gamma aerial survey. Because of the high level of agreement, the extensive LLNL database on plant:soil concentration factors was used by one author (SLS) in the dose assessment calculations. Moreover, as a result of the comparison exercises, the credibility of the extensive LLNL data was enhanced to the Rongelap community.

STUDY FINDINGS AND DISCUSSION

Dose assessment

Multiple, semi-independent assessments that were based on shared data but independent calculations were eventually reported by three organizations (NWRS: Simon 1994a; LLNL: Robison et al. 1994; NRC: 1994) and one individual (Thorne 1994b). A summary of those findings are presented here.

RRP. Independent dose calculations were reported by Simon (1994a) and Thorne (1994b) on behalf of the RRP. Findings for specified percentiles of the population are presented for three diets in Table 1: the observed Mejatto diet (18% local food), the "Mejatto scaled without rice" diet, (100% local food) and the "Mejatto scaled with rice" diet (75% local food).

The calculations of Simon (1994a) were based on the empirical distribution of areal inventory values of ^{137}Cs and used probability distributions for the plant:soil transfer factors for different plants. The calculations of Thorne (1994b) were based on the ground contamination data that were spatial averages of interpolated values over a 500 m radius. The latter calculations also used a single value of the plant:soil concentration ratio (= 0.2). As anticipated, the calculations by Thorne had a narrower dispersion due to the use of the spatial averaged data and a single plant:soil transfer factor. Conversely,

Table 1. Percentiles of the calculated population distribution of potential annual effective dose (mSv y^{-1}) from ^{137}Cs (external + internal) to male Rongelap residents in 1995 assuming three diet variations (Simon 1994a; Thorne 1994b). For more detail, see Figs. 3 and 4.

	Annual effective dose (mSv y^{-1})					
	NWRS (Simon 1994a)			Thorne (1994b)		
Percentile	Diet 1[a]	Diet 2[b]	Diet 3[c]	Diet 1[a]	Diet 2[b]	Diet 3[c]
5	0.089	0.40	0.32	0.18	0.55	0.44
25	0.20	0.86	0.67	0.21	0.68	0.54
50	0.28	1.25	0.95	0.23	0.79	0.62
75	0.37	1.68	1.22	0.26	0.92	0.72
95	0.53	2.81	1.74	0.30	1.15	0.89

[a] Observed Mejatto diet.
[b] 100% local food diet.
[c] 75% local foods, 25% rice.

the calculations by Simon were broader due to the greater dispersion of the measured ground contamination data and to the inclusion of uncertainty in the plant:soil ratios which were characterized by lognormal distributions.

The results of the Monte Carlo calculations for the three diets are shown as the cumulative probability for male members of the population having an annual effective dose less than the abcissa value (Figs. 3 and 4). This cumulative probability was interpreted to be equal to the proportion of the population who might receive a dose less than the abcissa value.

External exposure due to ^{60}Co and ^{241}Am would only increase the external dose component by about 1%. ^{90}Sr may add a further 2% to the internal dose. Actinides, due to their very limited uptake into the plants, contribute only a few percent or less to internal dose. For example, the amount of transuranic radioactivity in bone of deceased former residents of Rongelap residents was determined following exhumation; a contribution of about 0.01 mSv y^{-1} was estimated for those individuals (Franke et al. 1995).

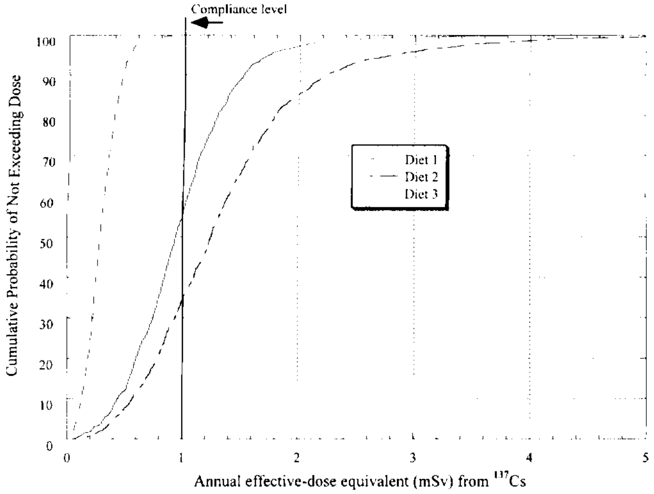

Fig. 3. Cumulative probability of predicted annual effective dose (Simon 1994a) from ^{137}Cs (external + internal) for adult men on Rongelap Island in 1995. Probability is interpreted as the fraction of the population not exceeding the abcissa dose value. Diet models were (1) diet of 18% local food as observed on Mejatto (Dignan 1994), (2) local food only diet (Franke 1994), and (3) local food only diet including 25% caloric contribution from rice.

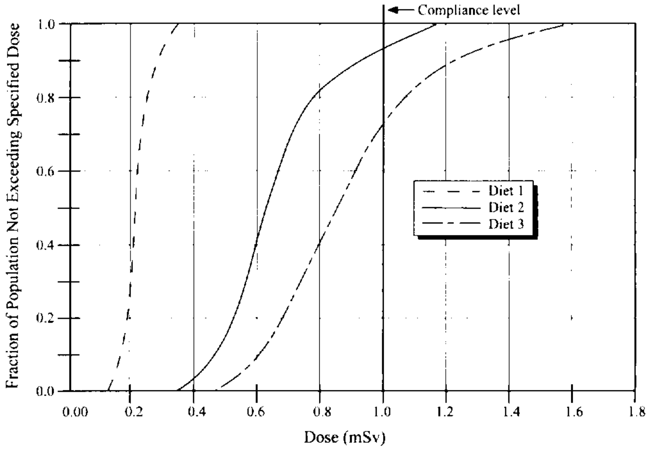

Fig. 4. Cumulative probability of predicted effective dose (Thorne 1994b) from ^{137}Cs (external + internal) for adult men on Rongelap Island in 1995. Probability is interpreted as the fraction of the population not exceeding the abcissa dose value. Diet models were (1) diet of 18% local food as observed on Mejatto (Dignan 1994), (2) local food only diet (Franke 1994), and (3) local food only diet including 25% caloric contribution from rice.

The relative dose to children was examined from the perspective of differences in body mass and energy intake. It can be demonstrated that the dose per unit intake is higher for children aged 6-to-10-years than for adults by a factor 1.4 to 1.5. The energy intake of adults more than compensates such that under identical exposure conditions the ^{137}Cs doses to small children are typically 54% of those to adult males and 74% of the adult female values.

The results indicate that, on the basis of ^{137}Cs exposure alone, between 25% (Fig. 4, Diet 3) and 65% (Fig. 3, Diet 3) of adult male members of the Rongelap community might exceed the compliance limit of 1 mSv y^{-1} while living a traditional outer-island lifestyle and consuming a diet of only locally grown food. If rice is included, between 5% (Fig. 4, Diet 2) and 45% (Fig. 3, Diet 2) of adult males might exceed the compliance limit. The internal dose dominates in all cases.

LLNL. The assessment findings by Robison et al. (1994) are summarized in Table 2. The estimated population average annual effective dose when both local and imported foods are available is 0.26 mSv y^{-1}. An uncertainty analysis indicates that no individual would be expected to exceed 1 mSv y^{-1} at 99% confidence. The estimated 50-y integral dose[¶¶] is 8.2 mSv for this scenario.

If only local foods are consumed, the average annual effective dose to the population in the first year when the environmental concentrations are greatest is estimated to be 0.85 mSv. About 13% of this estimated dose is from external gamma exposure and 87% is from internal exposure, most from ^{137}Cs ingested via intake of local foods. An uncertainty analysis indicates that about 25% of the population might receive a dose greater than 1 mSv y^{-1} on high calorie local food only diet (Fig. 5, light line). The 50-y integral effective dose for a local foods only diet is 15 mSv.

For a case where only local foods are consumed (i.e., no imported foods) and the island is treated with potassium, the average annual effective dose to the population is estimated to be 0.18 mSv. An uncertainty analysis indicates no person would be expected to have an annual dose above 1 mSv at 99% confidence. The 50-y integral dose for the local foods only diet plus potassium treatment of the soil is 5.1 mSv.

A dose assessment for children was based on dietary data for children of various ages obtained through the Bikini Atoll Rehabilitation Committee and originating from Peace Corps volunteers in the Marshall Islands. Those calculations indicated that due to differences in dietary intake, the children's doses were generally less than that of adults (Robison and Phillips 1989). Consequently, the estimated doses for adults living on the atolls are conservative estimates of dose for intake beginning at any other age.

NRC. The assessment findings presented by NRC were summarized by estimated average doses for six different diet variations (see NRC 1994, Table 5-4). Three of the variations were specifically applicable to the MOU: (1) a local food only diet with an energy intake equal to the MLSC diet with imported food; (2) a coconut collectors diet; and (3) same as variation (1) above except including treatment of the soil with KCl. Based on the information available to the NRC committee, it was estimated that a sizable fraction of the persons on a purely native diet, or any other diet that includes a large intake of coconuts, could exceed the 1 mSv annual effective dose above background as specified in the MOU. Using a scenario approach, the committee estimated that the average individual consuming a local-foods-only diet could receive an annual whole-body dose of 0.92 to 1.06 mSv y^{-1} (92 to 106 mrem y^{-1}), depending on the choice of diet. Their Executive Summary concluded: "Based on the available information. . . the committee estimates that a sizable fraction of the persons on a purely native diet, or any other diet that includes a large intake of coconuts, could exceed the 100 mrem, above normal background, annual dose equivalent limit specified in the MOU." The proportion of the population that might exceed the agreed limit was not determined; however, the assumption that a significant proportion of the population would exceed the average member in terms of intake-rate and consequent dose is reasonable. Table 3 provides detail on the NRC committee's findings.

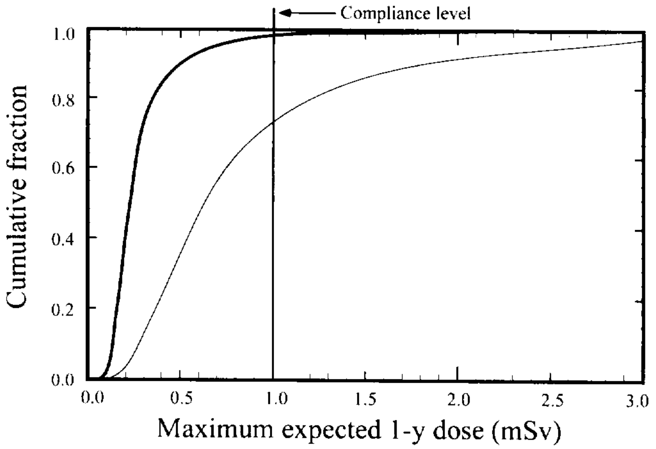

Fig. 5. Cumulative fraction of population not exceeding effective total dose (i.e., all radionuclides and pathways as discussed in text; Robison et al. 1994) shown on abcissa. Calculations consider inter-individual variability and are based either on MLSC imports-available diet (bold line) or a local foods only diet model (light curve) with twice the caloric intake of Table 20 in Robison et al. (1994).

Compliance with the screening level for transuranic radionuclide concentrations in soil

The determination of compliance with any environmental standard for radionuclide concentration in soil, as determined by soil sampling, is a difficult process; the success or failure of determination of compliance is dependent on the sampling methodology, statistical methodology, and the level of statistical significance considered appropriate. The MOU, however, did not include any details regarding the ground area (1 ha, 0.5 ha, etc.) over which the transuranic radionuclide concentration should be averaged for comparison with the selected guideline or the level of sampling required within such an area. Thus, a simplistic methodology was adopted by both groups in which the island was sampled to a degree determined by budgetary constraints. Indi-

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[¶¶] Integral dose is the actual dose received during the period of integration as a result of all intakes. A 50-y period of integration is used because the assessment applies to members of the population who would be adults at the time of resettlement.

Table 2. Deterministic estimates of the population average annual effective dose and the 50-y integral effective dose for the LLNL diet models when imported foods are available and when only local foods are consumed. Diet models are applied to both the current island conditions and after treatment of the island with potassium. (See Fig. 5 for results of LLNL uncertainty analysis.)

	Average annual effective dose (mSv y^{-1})			Integral effective dose over 50 y (mSv)		
	Local plus imported food (3,802 kcal d^{-1})	Local food only (2,784 kcal d^{-1})	Local food only with soil K treatment	Local plus imported foods (3,802 kcal d^{-1})	Local food only (2,784 kcal d^{-1})	Local foods only with soil K treatment
External	0.11	0.11	0.11	3.3	3.3	3.3
Ingestion						
^{137}Cs	n/a			4.5	11.0	1.1
^{90}Sr	n/a			0.13	0.4	0.4
$^{239+240}$Pu	n/a			0.033	0.13	0.13
^{241}Am	n/a			0.033	0.06	0.06
Ingestion (subtotal)	0.15	0.74	0.07	8.0	11.6	1.7
Inhalation						
$^{239+240}$Pu	n/a			0.070	0.070	0.070
^{241}Am	n/a			0.045	0.045	0.045
Inhalation (subtotal)	~0.0016	~0.0016	0.0016	0.115	0.115	0.115
TOTAL	0.26	0.85	0.18	8.2	15	5.1

vidual samples or general areas of the island were compared against the compliance limit. The determination of soil transuranic contamination[##] as written in the MOU was viewed by all parties as secondary in importance to the primary determination of dose to individual community members. Only two of the four groups reporting dose assessments involved laboratory programs (NWRS and LLNL); a summary of their findings on transuranic radionuclide contamination in soil follows.

Surface soil samples were collected by the NWRS and LLNL according to their individual protocols. Surface soil samples were collected by the NWRS at each *in situ* gamma spectrometry measurement site. Each sample was a composite of three 15 × 15 × 5 cm deep samples, collected at random within a radius of approximately 15 m of the gamma spectrometer. The samples were obtained from the 63 sites on the 200-m grid, plus 100 additional sites at 40-m spacing within the four grid cells selected for more detailed study. In total, 170 surface soil samples on Rongelap Island, 5 on Burok Island[***] (Burokku), 10 on Keroka Island (Tufa), 4 on Enekan im Batbien Island (Eniran), 5 on Litoteka Island (Busch), and 19 on Eneaetok Island (Eniaetok) were analyzed by the NWRS for $^{239+240}$Pu and ^{241}Am.

The median concentration of total transuranic radioactivity was 200 Bq kg^{-1} on Rongelap Island although samples ranged from 17 Bq kg^{-1} to 836 Bq kg^{-1}. The proportion of samples exceeding the transuranic radionuclide screening level of 629 Bq kg^{-1} varied according to island. Only 1.2% of the total surface soil samples collected by the NWRS from Rongelap Island exceeded the guideline (Simon 1994b). Other islands exceeded the guideline to a greater degree: 20% for Burok, 10% for Keroka, and 21% for Eneaetok. The possible error of the percentage exceeding the guideline is greater for those islands with few samples. The higher contamination level on Eneaetok was expected because of its closer proximity to the northern side of Rongelap Atoll where contamination is known to be significantly greater.

Surface soil samples 20 cm × 20 cm × 5 cm deep were collected by LLNL on a 100-m grid across the entire island. The 0–5 cm increment was taken as one of 6 increments of a 60-cm-deep soil profile. In addition, soil samples were collected at other sites over the island associated with various experiments. An extensive sampling of surface soils was also carried out in the housing and village area of the island. These samples were collected around and between houses and community buildings and in the ball field area, etc., rather than on a uniform grid pattern. Uniform sample collection in these areas was generally prevented by various small buildings, pig pens, and bedrock emerging at the surface. Consequently, the samples were taken in the area where surface soil was previously available for contact by the residing population.

The LLNL data indicated that the concentrations of $^{239+240}$Pu and ^{241}Am in soil in the housing and village area are, on average, about 15% of the concentration found in soil in the interior of the island. Consequently, in the housing and village area where people spend most of their time, the combined activity concentration of $^{239+240}$Pu and ^{241}Am from the 77 samples analyzed never exceeded the MOU guideline of 629 Bq kg^{-1}. About 170 samples distributed over the rest of the island have been analyzed for both $^{239+240}$Pu and ^{241}Am, and less than 5% exceeded the MOU screening level.

Inhalation is the major exposure pathway for the transuranic radionuclides. To realistically assess the an-

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[##] Total transuranic activity was defined to the sum of ^{241}Am and $^{239+240}$Pu. Because the environmental concentrations of ^{238}Pu at Rongelap were near the limit of detectability by alpha spectrometry, determination of compliance was not substantially affected by ignoring the radionuclide.

[***] Considerable variation of the spelling of Marshallese names exist. The names used on Figure 1 and in this section are accepted Rongelapese names. Names in parentheses are also commonly used; their spellings date from pre-WWII Japanese navigation charts.

Table 3. Calculated population average annual effective dose (mSv y^{-1}) in 1995 to Rongelap residents as determined by NRC committee (summary of Tables 3-1 and 5-4, see NRC 1994).

	Ujelang local and imported diet	Ujelang local food diet	Local food diet calories adjusted	Coconut collectors' diet	Local food only diet (w/adjusted caloric intake) following KCl soil treatment
Energy intake (kcal d^{-1})	3,208	1,392	3,208	2,018	3,208
Annual effective dose (mSv y^{-1}) from:					
^{137}Cs	0.16	0.40	0.92	0.78	0.17
Other radionuclides	0.13	0.14	0.14	0.14	0.14
Total annual dose (mSv y^{-1})^{a}	0.29	0.54	1.06	0.92	0.31

[a] Total dose is sum of external, ingestion and inhalation.

nual dose from transuranics, the concentration of $^{239+240}$Pu and ^{241}Am in the surface soil should be averaged over an area relevant to the various activities in which persons are engaged during the course of a year. The source of material resuspended and available for inhalation during a variety of activities is derived from an area on the order of 0.5 to 1.0 hectare (Shinn and Gouveia 1992). When the $^{239+240}$Pu plus ^{241}Am activity concentration is averaged over data points contained in areas of 0.5 to 1.0 hectare, no area at Rongelap Island exceeds the 629 Bq kg^{-1} MOU screening guideline.

Interpretation

The annual effective dose to the population of 0.18 mSv, calculated by LLNL when only local foods are consumed and the island is treated with potasium, can be compared with the Marshall Island background dose of 2.4 mSv (Noshkin and Robison 1994). Under this condition the combined natural background dose and dose from regional fallout is 2.6 mSv, which is comparable to the world wide average background dose of 2.4 mSv y^{-1} (UNSCEAR 1988) and is less than the U.S. average background dose of 3.0 mSv (NCRP 1987). Similarly, the 50-y integral effective dose after potasium treatment is 5.1 mSv. It is clear that treatment with potasium reduces the doses to very low levels. Consequently, any remedial action of Rongelap Island beyond the treatment with potasium would appear unwarranted.

Although a small percentage of surface soil samples exceeded the transuranic concentration guideline, this situation was not viewed as a serious impediment to resettlement. The philosophy of the original EPA (1990) guideline was not as an absolute standard to indicate the necessity of mitigation: "Such a screening level is not intended to be interpreted as a derived intervention level or as a soil cleanup standard to which all sites of transuranic contamination must be decontaminated; instead, when properly applied, it would identify land areas where no additional monitoring is required. . . " (EPA 1990).

The MOU recognized the possibility that measurements in excess of the guideline might be encountered. Article II, Section 4(b) and 4(c) of the MOU noted: "If. . . it is determined that soil concentrations exceed the prescribe action limit, then recommendations as to the need for remedial activity and/or clean-up shall be included as part of the report pursuant to the Rongelap Work Plan. . . To the extent that transuranic contamination exists in excess of the 'action limit' but is limited in nature, controllable, and does not impact designated dwelling, food gathering, food growing, and/or recreational areas, then resettlement may ensue while mitigative measures are considered and/or undertaken." However, any mitigation should be reviewed in the context of the dose that is received by the population from the transuranic radionuclides in the soil. These doses are very low and expenditure of resources to reduce an extremely low dose would seem unwarranted.

The 50-y integral effective dose estimate from exposure to $^{239+240}$Pu and ^{241}Am via ingestion and inhalation is listed in Table 2 and totals 0.18 mSv. This is compared to a 50-y integral dose estimate of 8.2 mSv for all radionuclides. Consequently, $^{239+240}$Pu and ^{241}Am from both ingestion and inhalation exposure pathways contribute less than 2% of the estimated dose over 50 y. The plutonium dose estimates based on environmental data and models are consistent with those calculated by Brookhaven National Laboratory (BNL) from direct measurements of plutonium in urine of the Rongelap people. For example, the population average effective dose equivalent to age 70 y (also a 50-y integral dose) was about 0.2 mSv for data from 1981 through 1991 (Sun et al. 1995).

The average annual dose from plutonium and americium calculated from the LLNL 50-y integral dose is about 0.004 mSv y^{-1}; the dose would be lower in early years and higher in the last several years. This simple analysis can be used for comparison with results from autopsy bone sample analyses for $^{239+240}$Pu from Rongelap residents. The bone samples were acquired from deceased former residents who resided on Rongelap most of their life since 1954 and some who grew up there as children. The results showed no difference in the concentration of $^{239+240}$Pu in bone of the Rongelap group compared with $^{239+240}$Pu concentration in bone samples from European residents (Franke et al. 1995). The estimated effective dose equivalent was stated to be less than 0.01 mSv y^{-1}, a value consistent with the calculated average annual dose of 0.004 mSv y^{-1} as discussed above. For perspective, these numbers can be compared with the average annual background dose in the Marshall Islands of 2.4 mSv y^{-1}.

Recommendations

Recommendations from the various research and advisory groups were oriented towards minimizing future radiation exposure and the subsequent risk following resettlement of Rongelap Island in the near future. The various groups were also mindful of preventing further damage to the environment, which could result from some types of remedial actions. The primary recommendations were designed to mitigate radiation dose from ingestion via the food chain, to reduce the availability of transuranic radioactivity, particularly to children, and to take actions to ensure that the Rongelap community remained comfortable with the assessed safety of their islands. A summary of possible remedial actions and some recommendations that were issued are presented here.

LLNL. Recommendations in Robison et al. (1994) for mitigative actions at Rongelap Atoll were the same as those made previously to the Enewetak people (Robison et al. 1980) and to the Bikini people over the last 10 y. They list five possible actions that could result in significant dose reductions to future settlers of Rongelap. These actions included removing 30 cm of surface soil from the village area for 10 to 15 m around each housing site to minimize external gamma (^{137}Cs), alpha ($^{239+240}$Pu and ^{241}Am), and beta exposure (^{90}Sr, ^{137}Cs); placing a 10-cm layer of crushed coral around each house in a 5- to 10-m radius, which would result in a small reduction in external gamma exposure and a small reduction in internal exposure from reduction in plutonium and americium intake via soil; treating the entire agricultural area of the island with potassium chloride (KCl) to reduce ^{137}Cs uptake into plants; providing water catchment systems so that during dry periods the use of contaminated ground water would be avoided; and excavation of the top 30 to 40 cm of soil over the whole island, which is very effective in removing the radionuclides but carries a heavy environmental impact.

NRC. Several possible remedial actions were discussed by NRC (1994) although they noted that their recommendations were not only provided to meet the MOU action level, but also to increase the physical and psychological well being of the Rongelap people. Although an evaluation of the northern islands of Rongelap or those of Rongerik were not within the charge of the NRC group, their first recommendation was to restrict food gathering from those islands such that a local food diet would be limited to food collected from Rongelap Island and the other southern islands of Rongelap Atoll. Second, NRC recommended restrictions on the consumption of some local foods; this could be more easily accomplished by maintaining a modest supplementary (imported) food program. Third, NRC agreed with the suggestion of Robison et al. (1994) to remove the top soil layer around the homes and to add a layer of crushed coral in the village area. Fourth, the application of KCl was recommended as it had been demonstrated to be effective in suppressing uptake of ^{137}Cs by Robison and Stone (1992). Finally, the option of removing the top 30–40 cm of soil from throughout the island was not advised because it would cause excessive damage to the environment and ecology of the island.

NRC additionally recommended an annual whole-body counting program, establishing pre- and post-resettlement measurements of plutonium in urine, establishing a central repository for medical and dosimetry records, and continuing a program of medical surveillance.

RRP. The findings of the RRP assessments (i.e., Simon 1994a; Thorne 1994b) were summarized by Baverstock et al. (1994). Although the assessment calculations indicated that the terms and conditions of the MOU regarding dose-rate and soil concentration of actinides were out of compliance on Rongelap Island and the neighboring islands, it was noted that compliance could be met by relatively simple remedial actions. Among the various options available to mitigate dose, the research team of the RRP advocated (1) measures to reduce the level of cesium in the local food diet including support to eliminate the need to gather food from the more contaminated islands in the atoll, (2) measures to reduce the availability of actinides for incorporation into the body, and (3) measures to ensure that the Rongelap community was comfortable with the determinations of safety of their islands as a future home. As stated (Baverstock et al. 1994), "The need to offset the loss of well-being incurred by past uncertainties concerning the radiological status of their homelands should be given a high priority when exploring with the Rongelap community solutions to redress the radiological status of their islands."

In particular, emphasis was given to the usefulness of reducing the internal component of radiation dose by treating food-growing areas with potassium fertilizer. Recommendations included measures to ensure adequate water and food supplies on Rongelap Island that would diminish the need to visit and collect from the more contaminated islands of the north part of the atoll. Programs could be implemented for ground or ocean water purification and for ensuring the capability to refrigerate and store protein foods. The consumption of imported foods was noted to further reduce doses.

Rongelap Island soil exceeded the soil contamination limit only slightly, though the other southern islands were much further from compliant. Accordingly, the use of radiologically clean coral to provide actinide free surfaces around houses and in community areas was endorsed to reduce the possibility of intakes by young children who might ingest soil. Finally, the scientific management team stated that public concern for health detriment, real or imagined, is in itself a health detriment when health is viewed in its widest sense—that is, including loss of well-being. Thus, measures that reduce the likelihood that community members would exceed the compliance limit would serve to minimize the detriment caused by undue concern for their health.

SUMMARY AND CONCLUSIONS

The Rongelap people were unique among Marshallese in that they were highly exposed to external and internal radiation from weapons testing fallout. The responsibility accepted by the research groups in this study was to prevent additional future exposure that could possibly add to their cumulative risk. The importance of ensuring low exposures during the coming years was underscored by the possible consequences of failing to determine the appropriate risks.

Although variations in diet models and other parameters were promoted by different groups, all groups agreed that, under the conditions of the MOU, it was likely that a significant proportion of the population (25% or more) might exceed the agreed upon dose limit. Recommendations to diminish dose to individuals resulting from ingestion of ^{137}Cs in locally grown foods were universally supported. Similarly, programs to minimize potential ingestion of ^{137}Cs, ^{90}Sr, and transuranic radionuclides were supported with the caveat that environmental destruction (e.g., complete soil removal) was not warranted to avert the small doses from transuranics that may be on the order of 10 μSv y^{-1}. All groups also accepted the fact that most returning Rongelapese will not choose to exist on a local food only diet; thus, the future doses will likely be significantly less than those based on a diet of only locally grown foods.

The strength of the study described here was based on several principles: (1) cooperation between study groups and sharing of data as useful or necessary; (2) thorough and continual external peer review; (3) use of multiple, independent assessments; and (4) participation by Rongelap community members.

The process of community participation was one of the most important elements of the combined projects because of its positive impact within the community toward accepting the scientific findings. Community participation included attending scientific and administrative meetings, assisting in collection of environmental samples, receiving training and taking responsibility for routine sample analysis in the laboratory of the NWRS, and attending a series of presentations by RRP scientists, representatives of the U.S. Government and the NRC advisory group.

It often occurs that assessments of potential or real radiation exposure of the public suffer from a lack of public credibility because of the perceived interests of the sponsor of the investigation. Involvement of the community can serve to alleviate this problem. Although the layman cannot easily participate in the calculation of radiation dose or statistical risk, it was shown in this study that members of the community can participate in sample and data gathering, laboratory analysis, and that financial resources to allow community members to attend and observe scientific planning and review meetings can enhance the level of trust between the public and the investigators.

The process of conducting and comparing multiple, independent dose assessments was also a unique aspect of the study. Although data were readily shared between the research groups, conducting independent assessments best served the Rongelap community by providing a means under which consensus could be demonstrated among scientists with different institutional affiliations.

The most important facet of these combined studies was that the objectives of the investigations and the process of conducting the assessments were all directed to determining the potential safety of resettling Rongelap Island. This overall goal was of the greatest importance to the people of Rongelap and was fulfilled by a program that involved not only thorough investigations but also multiple levels of independent review and extensive cooperation among research groups. The primary outcome was that the resettlement of Rongelap Island was viewed as a viable and safe option. Radiation risk should not prevent resettlement to those who desire to return to the island. The safety of the population can be ensured even further by implementing the recommendations discussed herein.

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APPENDIX

The Scientific Management Team of the Rongelap Resettlement Project was composed of K. F. Baverstock, B. Franke and S. L. Simon.

The Technical Oversight Group of the Marshall Islands Rongelap Resettlement Project was composed of U. Boikat, A. C. McEwan, K. Shimaoka, I. Schmitz-Feuerhake, M. C. Thorne and R. E. Novick (temporary member).

Administration of the Rongelap Resettlement Project was provided by J. Matayoshi, J. Anjain (deceased), J. Riklong, B. Edmond, C. Bigler, P. Oliver, D. Capelle, J. Jilej.

The assessments conducted by the LLNL for the U.S. DOE were performed by W. L. Robison, C. L. Conrado and K. T. Bogen. Staff of LLNL that assisted in the collection and analysis of samples and data from Rongelap included M. Stuart, H. Jones, J. Rehder, S. Kehl, C. Stoker, M. Mount, K. Wong and others.

The National Research Council (NRC) Committee on Radiological Safety in the Marshall Islands was composed of J. V. Neel (Chairman), S. C. Finch, B. B. Boecker, L. M. Carucci, J. M. Cleveland, P. M. Dixon, J. L. Greger, W. C. Hanson, N. S. Nelson, R. V. Osborne, C. E. Roessler and J. C. Shoolar.

NRC administration was conducted by the Board on Radiation Effects Research, John Zimbrick, Director and Study Directors D. L. Mahlum and L. H. Toburen.

The U.S. Department of Energy's Project Officer for the NRC grant was R. T. Bell.

Glossary of acronyms and abbreviations:

- AEC: U.S. Atomic Energy Commission;
- BNL: Brookhaven National Laboratory;
- BMR_{est}: estimated basal metabolic rate (kcal d^{-1});
- DNA: Defense Nuclear Agency;
- DOE: U.S. Department of Energy;
- DOE/ES&H: Environment, Safety and Health Division of the U.S. Department of Energy;
- DOI: U.S. Department of the Interior;
- EI: energy intake (kcal d^{-1});
- EPA: U.S. Environmental Protection Agency;
- HPGe: high purity germanium (detectors);
- IAEA: International Atomic Energy Agency;
- ICRP: International Commission on Radiation Protection;
- LLNL: Lawrence Livermore National Laboratory;
- MLSC: Micronesian Legal Services Commission;
- MOU: Memorandum of Understanding;
- NaI: Sodium iodide (detectors);
- NMIRS: Northern Marshall Islands Radiological Survey (sponsored by the U.S. DOE);
- NRC: National Research Council;
- NWRS: Nationwide Radiological Study (sponsored by the Republic of the Marshall Islands);
- pdf: probability density function;
- RALGOV: Rongelap Local Government;
- RMI: Republic of the Marshall Islands;
- RRP: Rongelap Resettlement Project;
- USDA: U.S. Department of Agriculture.

■■

THE USE OF COMPARATIVE ^{137}Cs BODY BURDEN ESTIMATES FROM ENVIRONMENTAL DATA/MODELS AND WHOLE BODY COUNTING TO EVALUATE DIET MODELS FOR THE INGESTION PATHWAY

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Abstract—Rongelap and Utirik Atolls were contaminated on 1 March 1954, by a U.S. nuclear test at Bikini Atoll code named BRAVO. The people at both atolls were removed from their atolls in the first few days after the detonation and were returned to their atolls at different times. Detailed studies have been carried out over the years by Lawrence Livermore National Laboratory (LLNL) to determine the radiological conditions at the atolls and estimate the doses to the populations. The contribution of each exposure pathway and radionuclide have been evaluated. All dose assessments show that the major potential contribution to the estimated dose is ^{137}Cs uptake via the terrestrial food chain. Brookhaven National Laboratory (BNL) has carried out an extensive whole body counting program at both atolls over several years to directly measure the ^{137}Cs body burden. Here we compare the estimates of the body burdens from the LLNL environmental method with body burdens measured by the BNL whole body counting method. The combination of the results from both methods is used to evaluate proposed diet models to establish more realistic dose assessments. Very good agreement is achieved between the two methods with a diet model that includes both local and imported foods. Other diet models greatly overestimate the body burdens (i.e., dose) observed by whole body counting. The upper 95% confidence limit of interindividual variability around the population mean value based on the environmental method is similar to that calculated from direct measurement by whole body counting. Moreover, the uncertainty in the population mean value based on the environmental method is in very good agreement with the whole body counting data. This provides additional confidence in extrapolating the estimated doses calculated by the environmental method to other islands and atolls.

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Key words: Marshall Islands; ^{137}Cs; dose; diet

INTRODUCTION

RONGELAP AND Utirik Atolls were contaminated on 1 March 1954, by a U.S. nuclear test at Bikini Atoll code named BRAVO. The location of the atolls in the Marshall Islands is shown in Fig. 1. A photo montage of each atoll is shown in Figs. 2 and 3. The people living on Rongelap at the time of the BRAVO test were removed from the atoll by the U.S. military about 48 h after the start of the fallout. The Rongelap community was returned to their atoll in June of 1957, and the people resided on Rongelap until May 1985 when they decided to move to an island in the northern part of Kwajalein Atoll. Resettlement plans for Rongelap Island are currently being developed, and are based in large part on dose estimates to the returning population that are based on measured radionuclide concentrations in the soil and vegetation on the island, and dose models that include estimates of intake of locally grown foods (Robison et al. 1994). The Utirik people were also relocated in the first few days after the BRAVO test, and they were returned to their atoll about 3 mo later and continue to reside there today. Their resettlement occurred more rapidly because the dose at Utirik was much lower than at Rongelap.

The exposure pathways at the contaminated atolls are external gamma, inhalation, and ingestion. The potential uptake through a wound is so minor that it is not included. The ingestion pathway includes intake of terrestrial foods, marine foods, and cistern and groundwater. Extensive work has been done since the mid 1970's by LLNL to document the radiological conditions at Bikini, Enewetak, Rongelap and Utirik Atolls to provide dose assessments for alternate living patterns for people wishing to resettle their islands. Detailed studies have been carried out to evaluate the contribution of each exposure pathway. These studies show that the radionuclides remaining today that contribute in any significant way to the estimated dose are ^{137}Cs ^{90}Sr, $^{239+240}$Pu, and ^{241}Am.

All the dose assessments for the various atolls show that the major potential contribution to the estimated dose is ^{137}Cs uptake into terrestrial foods, and the subsequent consumption of these foods by the people.

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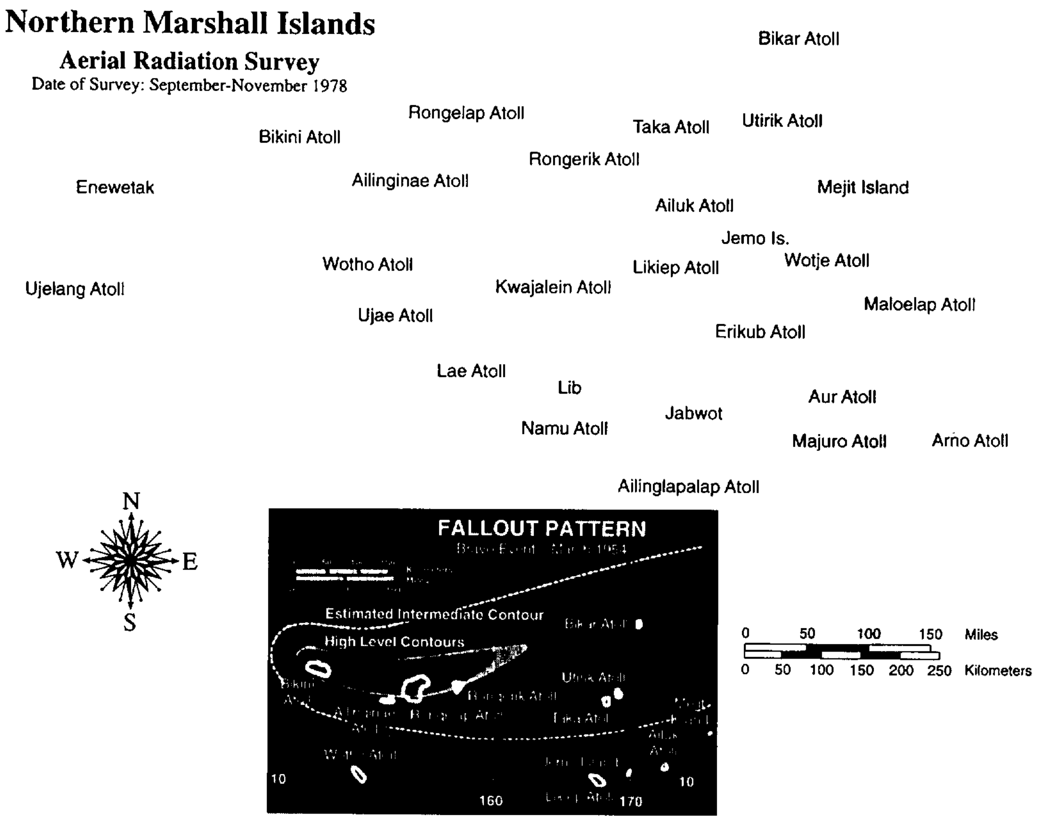

Fig. 1. A photographic montage of the Marshall Islands showing the location of Rongelap and Utirik Atolls.

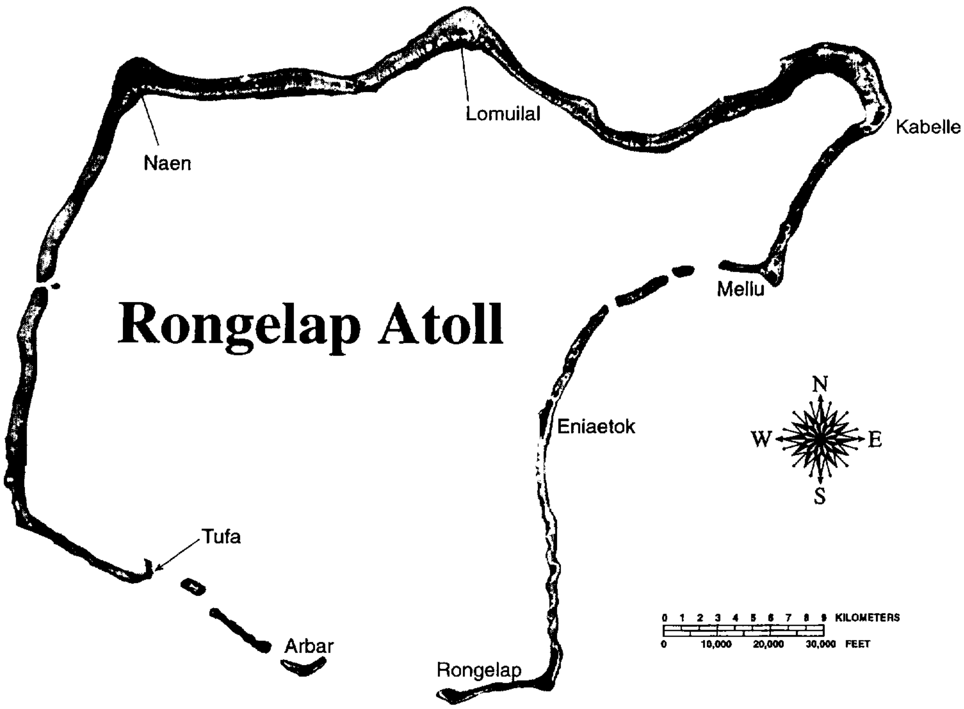

Fig. 2. A photographic montage of Rongelap Atoll showing the location of Rongelap Island which is the main residence island.

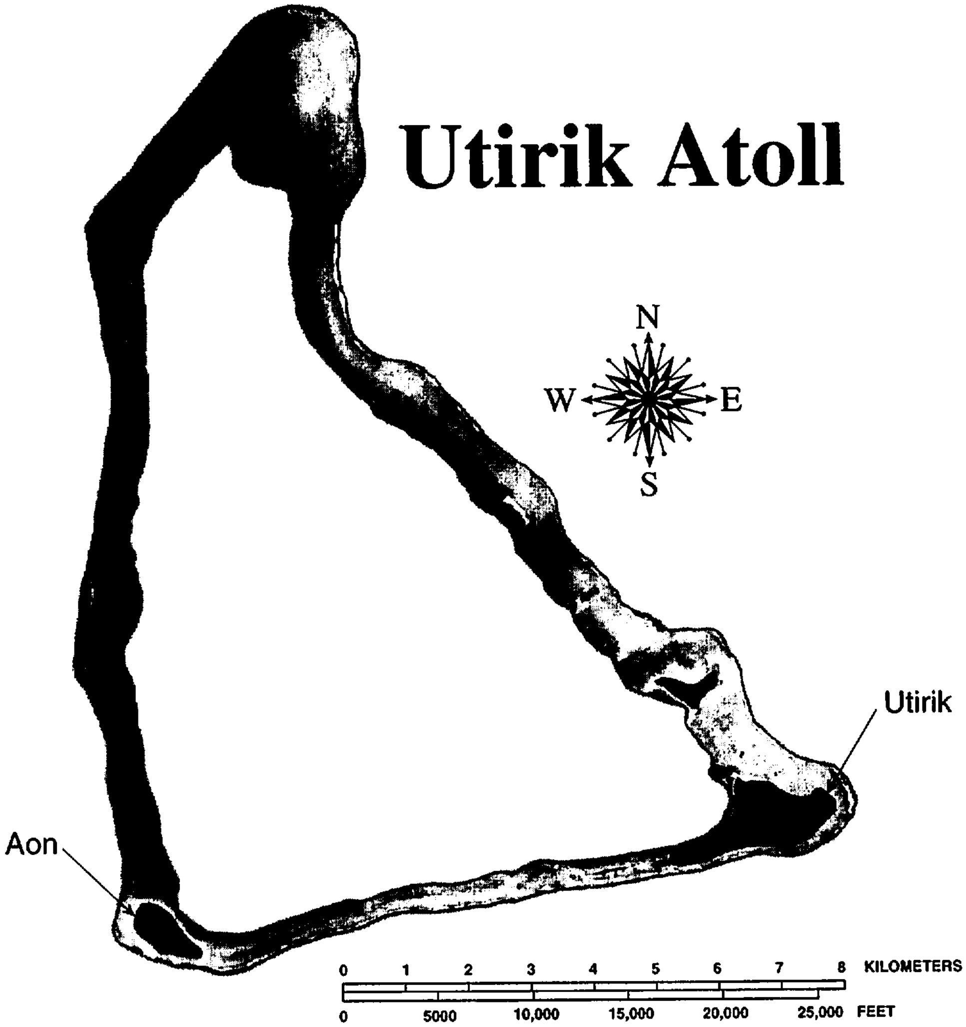

Fig. 3. A photographic montage of Utirik Atoll showing the location of Utirik Island which is the main residence island.

^{137}Cs in the terrestrial food chain accounts for about 90% of the dose at the atolls (Robison et al. 1997).

The Brookhaven National Laboratory (BNL) between 1970 and 1984, has performed many whole body counting field missions to monitor the ^{137}Cs body burdens of the Rongelap and Utirik people while they were living on their respective islands (Greenhouse et al. 1977; Miltenberger et al. 1981; Lessard et al. 1980a, 1984). These whole-body count data provide a direct measure of the ^{137}Cs body burdens for comparison with predicted body burdens based on the environmental data and models. BNL's program also included whole body measurements of the Bikini people who resettled Bikini between 1970 and 1978, and the Enewetak community after their return to the southern half of Enewetak Atoll in 1980 (Lessard et al. 1980b; Miltenberger et al. 1980; Greenhouse et al. 1980).

Before 1985, the Rongelap population lived primarily on Rongelap Island, which is a narrow island about 120 ha in size (Fig. 4), and consumed local foods from the island. Some coconut and *Pandanus* were collected from Arbar Island next to Rongelap Island, and some people lived on Arbar for extended periods of time; however, this does not change the dose estimates because the radionuclide concentration in the soil and vegetation are the same as on Rongelap Island (Robison and Conrado 1996). The relatively small island area, well defined by bordering ocean and lagoon, makes it possible to thoroughly determine the radionuclide concentration in local food crops and the associated ranges and distributions. It was also possible to access the adult population so that many adults were analyzed by BNL by whole body ^{137}Cs measurements over a period of several years. The situation at Utirik Atoll is very similar, although the main residence island is somewhat smaller (Fig. 5).

Another important feature of both Rongelap and Utirik is that the populations resided on their islands continually (with, of course, occasional trips off-island) from 1957 through May of 1985 for Rongelap, and June of 1954 to the present day for Utirik, so that a steady state

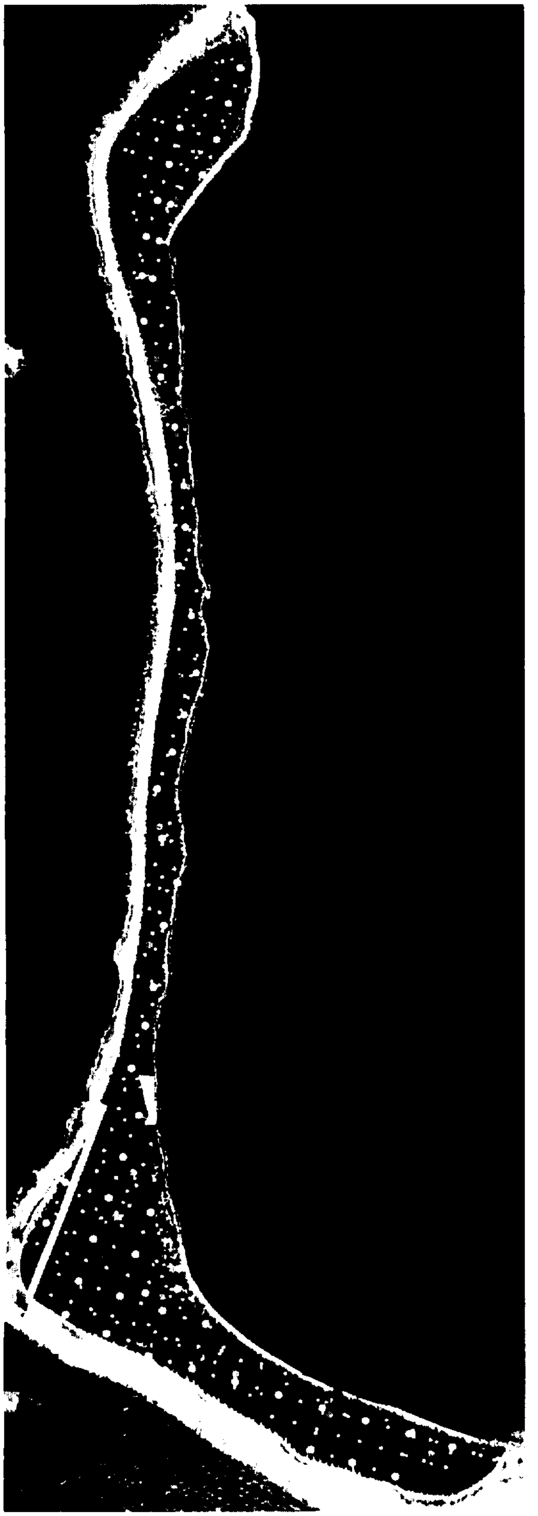

Fig. 4. An aerial photograph of Rongelap Island with soil, vegetation, and gamma spectrometry sampling sites superimposed.

condition existed for the ^{137}Cs body burdens averaged over time periods of a year. Seasonal variations in the dietary intake of local foods can and do occur due to the seasonal production of breadfruit and *Pandanus* fruit.

The average annual body burden estimated from the environmental data and models (hereafter referred to as the "environmental method") are based on the measured concentrations of radionuclides in foods (Robison et al. 1994, 1997), the average dietary intake of the various local foods (Robison et al. 1994, 1997), and the ^{137}Cs dose model (Leggett 1986; ICRP 1979, 1990, 1991). BNL whole body measurements of the adult population were made annually (occasionally biannually), and at different times of the year so that over a period of time any seasonal dependence would be averaged out. Moreover, some variations would be expected in the BNL average population body burden from year to year because the same people at each atoll were not always measured every year; each year the population group analyzed was essentially a random sample dictated by who volunteered to be measured on a given trip.

The dietary intake of local foods is a very important part of the LLNL environmental method used to generate the estimated body burdens and dose. Unfortunately, the exact dietary intake of local foods often is not well known. When it is not well known, various diet models are proposed, and sometimes insisted upon, by people, groups, or government agencies that lead to radionuclide intakes that can range over an order of magnitude.

In this paper we compare the estimates of the body burdens at Rongelap and Utirik Atolls from the LLNL environmental method with the body burdens measured by the BNL whole body counting method. The data base for the radionuclide concentrations in local foods is very extensive (Robison et al. 1994); also, the biokinetic model for ^{137}Cs uptake, transport, and distribution in the human body is well documented (Leggett 1986; ICRP 1979, 1990). Consequently, we can, in conjunction with the whole body measurements, demonstrate the usefulness of the environmental method to help define realistic dietary intakes of locally contaminated food at the northern atolls of the Republic of the Marshall Islands that are crucial to realistic dose assessments.

METHODS

Environmental data and dietary models

Samples of soil, vegetation (food crops and natural species), marine species, animals, fowl, and ground and cistern water were collected at the atolls, frozen aboard ship, and returned to LLNL for processing. Each individual sample was double bagged and sealed to prevent any contamination from other samples. Water samples were collected in individual 5- or 15-gallon containers for shipment to the laboratory.

Vegetation, food crops, animal, fish and other marine species, and fowl samples were freeze dried upon return to the laboratory and subsequently ground to uniform consistency and packed in steel tuna cans 8 cm in diameter and 4.0 cm in depth for gamma spectroscopy. Additional aliquots of the sample were sometimes sent for radiochemistry analysis of ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Some samples were ashed prior to chemical

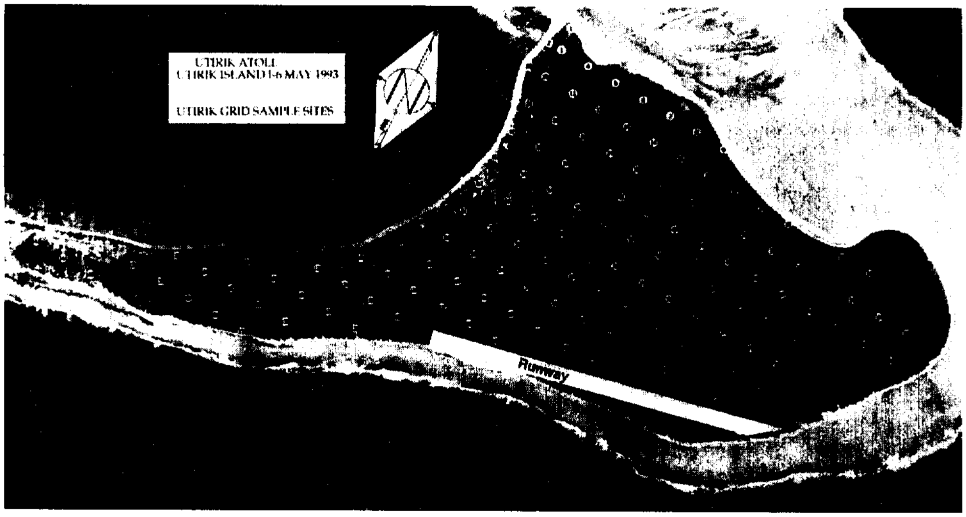

Fig. 5. An aerial photograph of Utirik Island with soil, vegetation, and gamma spectrometry sampling sites superimposed.

separation in preparation for wet chemistry analysis (Wong et al. 1994). The LLNL radiochemistry facility has a multitude of analytical equipment that includes alpha spectrometers with surface barrier detectors for analyzing $^{239+240}$Pu, ^{238}Pu, and ^{241}Am, and beta spectrometers for ^{90}Sr analysis. A summary of our radiochemistry procedures for processing samples, separating radionuclides, and analyzing for several radionuclides and elements is available in a recently updated report (Wong et al. 1994).

Soil samples were oven dried to constant weight, ball milled to a fine talcum powder consistency and canned for gamma spectroscopy in the same geometry as the vegetation samples. Again, aliquots were sometimes sent for radiochemistry analysis. Sample processing of soil for wet chemistry radionuclide analysis is described in Wong et al. (1994).

The LLNL gamma-spectroscopy facility consists of 22 high-resolution, solid-state gamma detectors with associated electronics. Details of the facility design, internal calibration procedures, and general operation can be found in recent updated reports (Brunk 1995a, b).

Both the gamma-spectroscopy and radiochemistry facilities have their own "internal" quality control procedures (Wong et al. 1994; Brunk 1995a, 1995b) and an extensive "external" quality control program that has been in place for years. Standard and duplicate samples that are blind to the analysts are submitted with each group of 50 samples submitted to either our own facilities or an outside contractor. The LLNL acceptance protocols are as follows: (1) the standard samples must be within 10% of the known value or the entire set of samples is rejected and must be reanalyzed; and (2) the duplicate samples must also be within 10% of each other for most samples; the error allowed does increase as the total activity in the samples decreases, especially for $^{239+240}$Pu and ^{241}Am analyses (Kehl et al. 1995).

Additional quality assurance is provided through multiple intercalibration exercises every year with the International Atomic Energy Agency (IAEA), National Institute on Standards and Technology (NIST), and other organizations. The IAEA intercalibration exercises cross-calibrate the LLNL analytical results with other participating laboratories around the world. Another important part of our quality control program is the use of "split samples" with other laboratories. For example, in many cases the soil and vegetation samples are collected by LLNL and other participants, split in the field, and subsequently analyzed by both parties. In other cases the samples are homogenized in the laboratory then split and sent to us from other laboratories, or sent by us to other labs, for analysis. A recent updated report details our quality control procedures and results (Kehl et al. 1995).

The estimated average intake of local and imported foods used in the dose assessment is a very important parameter; radiological dose (or body burden) will scale directly with the total intake of ^{137}Cs, which is proportional to the quantity of locally grown foods that are consumed. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. LLNL and its independent committees, in concert with local government authorities, with the legal representatives of the people, with Peace Corps representatives, and anthropologists have endeavored to establish and document pertinent trends, cultural influences, and economic realities—with the hope that the estimates of intake rates for local foods are objective and realistic.

The LLNL preferred diet model, the so called "imported food available" (IA) diet model, used to estimate the dose from ^{137}Cs at the atolls is listed in Table 1 for Rongelap Island and includes consumption of both local and imported foods. A diet consisting entirely of consumption of local foods, "imports unavailable" diet (IUA), for Rongelap Island is listed in Table 2. The diet

Table 1. Diet model—Rongelap Island. Local and imported foods available for adults greater than 18 y.

Local food	g d^{-1}	kcal g$^{-1\,a,b}$	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.)				Bq d^{-1}			
				^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
Reef fish^{d}	24.2	1.40	33.8	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.6×10^{-2}	5.9×10^{-4}	3.0×10^{-4}	3.3×10^{-5}
Tuna	13.9	1.40	19.4	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6e}	8.4×10^{-3}	3.4×10^{-4}	4.1×10^{-6}	1.9×10^{-5}
Mahi Mahi	3.56	1.10	3.92	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6e}	2.1×10^{-3}	8.7×10^{-5}	1.1×10^{-6}	4.9×10^{-6}
Marine crabs^{f}	1.68	0.90	1.51	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.5×10^{-4}	8.3×10^{-5}	6.0×10^{-5}	6.8×10^{-6}
Lobster^{f}	3.88	0.90	3.49	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	1.3×10^{-3}	1.9×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Clams^{c,d,g}	4.56	0.80	3.65	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.9×10^{-4}	6.0×10^{-4}	1.8×10^{-3}	5.4×10^{-4}
Trochus^{c,d,g}	0.10	0.80	0.08	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.2×10^{-6}	1.3×10^{-5}	3.9×10^{-5}	1.2×10^{-5}
Tridacna muscle^{c,d,g}	1.67	1.28	2.14	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	7.1×10^{-5}	2.2×10^{-4}	6.4×10^{-4}	2.0×10^{-4}
Jedrul^{c,d,g}	3.08	0.80	2.46	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.3×10^{-4}	4.1×10^{-4}	1.2×10^{-3}	3.7×10^{-4}
Coconut crabs^{c,h}	3.13	0.70	2.19	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	2.8×10^{-1}	1.2×10^{-1}	2.3×10^{-4}	7.2×10^{-5}
Land crabs^{c,i}	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	4.51	1.00	4.51	4.3×10^{-4j}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	1.9×10^{-3}	1.1×10^{-4}	5.6×10^{-5}	6.2×10^{-6}
Turtle	4.34	0.89	3.86	6.6×10^{-5k}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	2.9×10^{-4}	1.1×10^{-4}	5.4×10^{-5}	6.0×10^{-6}
Chicken muscle	8.36	1.70	14.2	1.3×10^{-1l}	1.3×10^{-4c}	2.5×10^{-6m}	3.3×10^{-6m}	1.1×10^{0}	1.1×10^{-3}	2.1×10^{-5}	2.8×10^{-5}
Chicken liver	4.50	1.64	7.38	8.8×10^{-2l}	2.9×10^{-4c}	1.5×10^{-5m}	3.1×10^{-5m}	4.0×10^{-1}	1.3×10^{-3}	6.8×10^{-5}	1.4×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2c}	3.2×10^{-4c}	9.6×10^{-6m}	1.0×10^{-5m}	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	5.67	4.50	25.5	4.9×10^{-1l}	9.0×10^{-5c}	1.3×10^{-6c}	9.1×10^{-7c}	2.8×10^{0}	5.1×10^{-4}	7.6×10^{-6}	5.2×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1l}	1.5×10^{-4c}	1.3×10^{-5m}	2.4×10^{-5m}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	2.60	2.41	6.27	2.0×10^{-1l}	1.5×10^{-4n}	3.4×10^{-5m}	1.3×10^{-5m}	5.3×10^{-1}	3.9×10^{-4}	8.8×10^{-5}	3.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1l}	9.0×10^{-5o}	1.3×10^{-6o}	9.1×10^{-7o}	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle^{e}	2.71	1.70	4.61	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.8×10^{-3}	6.6×10^{-5}	3.4×10^{-5}	3.8×10^{-6}
Bird eggs	1.54	1.50	2.31	1.7×10^{-4p}	3.7×10^{-5p}	1.2×10^{-5e}	1.4×10^{-6e}	2.7×10^{-4}	5.7×10^{-5}	1.9×10^{-5}	2.1×10^{-6}
Chicken eggs^{q}	7.25	1.63	11.8	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	9.4×10^{-1}	9.7×10^{-4}	1.8×10^{-5}	2.4×10^{-5}
Turtle eggs	9.36	1.50	14.0	6.6×10^{-5r}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	6.2×10^{-4}	2.3×10^{-4}	1.2×10^{-4}	1.3×10^{-5}
Pandanus fruit^{l}	8.66	0.60	5.20	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.1×10^{0}	1.3×10^{-1}	1.4×10^{-5}	7.0×10^{-6}
Pandanus nuts^{s}	0.50	2.66	1.33	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	1.2×10^{-1}	7.3×10^{-3}	8.2×10^{-7}	4.0×10^{-7}
Breadfruit^{l}	27.2	1.30	35.3	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	3.5×10^{0}	5.5×10^{-2}	1.6×10^{-5}	2.0×10^{-5}
Coconut juice^{l}	99.1	0.11	10.9	3.2×10^{-2}	3.7×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	3.2×10^{0}	3.6×10^{-3}	9.8×10^{-5}	9.2×10^{-5}
Coconut milk^{t}	51.9	3.46	179	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	6.3×10^{0}	2.7×10^{-2}	8.6×10^{-5}	1.1×10^{-4}
Tuba/Jekero^{t}	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat^{l}	31.7	1.02	32.3	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	2.3×10^{0}	1.0×10^{-2}	3.9×10^{-5}	4.4×10^{-5}
Copra meat^{l}	12.2	4.14	50.3	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.5×10^{0}	6.3×10^{-3}	2.0×10^{-5}	2.5×10^{-5}
Sprout. coco^{t}	7.79	0.80	6.23	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	9.4×10^{-1}	4.0×10^{-3}	1.3×10^{-5}	1.6×10^{-5}
Marsh. cake^{t}	11.7	3.36	39.2	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.4×10^{0}	6.0×10^{-3}	1.9×10^{-5}	2.4×10^{-5}
Papaya	6.59	0.39	2.57	4.3×10^{-1u}	6.7×10^{-3v}	4.7×10^{-6w}	4.9×10^{-6u}	2.8×10^{0}	4.4×10^{-2}	3.1×10^{-5}	3.2×10^{-5}
Squash	NR	0.47	0.00	2.1×10^{-1l}	2.8×10^{-3v}	6.3×10^{-7v}	6.5×10^{-7w}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin^{x}	1.24	0.30	0.37	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	2.6×10^{-1}	3.5×10^{-3}	7.8×10^{-7}	8.1×10^{-7}
Banana	0.02	0.88	0.02	1.2×10^{-2l}	1.1×10^{-3u}	4.7×10^{-6y}	4.9×10^{-6y}	2.5×10^{-4}	2.3×10^{-5}	9.4×10^{-8}	9.8×10^{-8}
Arrowroot^{l}	3.93	3.46	13.6	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	8.0×10^{-1}	1.0×10^{-2}	1.0×10^{-4}	5.2×10^{-5}
Citrus	0.10	0.49	0.05	5.7×10^{-2l}	2.0×10^{-3z}	6.0×10^{-7z}	7.4×10^{-7z}	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater^{aa}	313	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.6×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater^{aa}	207	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.5×10^{-3}	1.3×10^{-2}	9.8×10^{-5}	5.8×10^{-5}
Malolo^{bb}	199	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.3×10^{-3}	1.1×10^{-3}	2.2×10^{-5}	1.5×10^{-6}
Coffee/Tea^{bb}	228	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.6×10^{-3}	1.3×10^{-3}	2.5×10^{-5}	1.7×10^{-6}
Soil^{l,cc,dd}	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1,322		547					31	0.47	0.012	0.0071
Fluids	1,046		11								
Solids	276		536								

Imported food	g d^{-1}	kcal g^{-1} [a,b]	kcal d^{-1}
Baked bread	30.3	2.75	83.3
Fried bread	72.0	4.25	306
Pancakes	59.5	2.18	130
Cake	2.64	3.27	8.63
Rice	234	1.10	257
Instant mashed potatoes	127	0.90	114
Sugar	65.2	3.85	251
Canned chicken	13.0	1.98	25.7
Corned beef	78.7	2.16	170
Spam	55.0	2.28	125
Canned mackerel	44.0	1.83	80.5
Canned sardines	42.5	2.14	91.0
Canned tuna	59.0	1.98	117
Canned salmon	NR	2.03	0.00
Other canned fish	NR	2.00	0.00
Other meat, fish, or poultry	NR	2.00	0.00
Carbonated drinks	338	0.40	135
Orange juice	188	0.44	82.6
Tomato juice	99.5	0.19	18.9
Pineapple juice	178	0.55	97.6
Other canned juice	25.4	0.50	12.7
Evaporated milk	201	1.37	276
Powdered milk	72.9	1.37	99.9
Whole milk	0.00	0.68	0.00
Canned butter	0.00	7.16	0.00
Onion	0.00	0.45	0.00
Canned vegetables	NR	0.80	0.00
Baby food	NR	1.00	0.00
Cocoa	178	0.97	173
Ramen noodles	6.07	1.25	7.6
Candy	NR	4.00	0.00
Total Imported	2,168		2,661
Fluids	1,280		895
Solids	888		1,766
Total Local and Imported	3,490		3,208
Fluids	2,326		906
Solids	1,164		2,302

NOTE: NR stands for no response.

[a] Data from Murai et al. (1958).

[b] Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).

[c] Specific activity from Robison et al. (1982).

[d] Specific activity from Noshkin et al. (1981a); Robison et al. (1981).

[e] Specific activity used is that of reef fish.

[f] Specific activity calculated using the ratio (Bq g^{-1} shellfish tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).

[g] Data used is from *Hippopus hippopus* and *Tridacna squamosa*.

[h] Data used is from coconut crabs from Arbar Island on Rongelap Atoll.

[i] Specific activity used is that of coconut crab.

[j] Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).

[k] Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).

[l] Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.

[m] Specific activity is unpublished data from the 1978 NMIRS.
[n] Specific activity used is that of pork kidney.
[o] Specific activity used is that of pork muscle.
[p] Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight vs. Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al. 1988).
[q] Specific activity used is that of chicken muscle.
[r] Specific activity used is that of turtle.
[s] Specific activity used is that of *Pandanus* fruit.
[t] Specific activity used is that of copra meat. Tuba is made from the sap that normally would support coconut development.
[u] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight vs. Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.
[v] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight vs. Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.
[w] Specific activity used is calculated using the same concentration ratio for $^{239+240}$Pu and ^{241}Am when no data is available and assuming $^{239+240}$Pu and ^{241}Am are the same.
[x] Specific activity used is that of squash.
[y] Specific activity used is that of papaya.
[z] Specific activity used is that of breadfruit.
[aa] Specific activity from Noshkin et al. (1981b).
[bb] Specific activity used is that of rainwater.
[cc] Specific activity is in Bq g^{-1} dry weight.
[dd] Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area vs. 7 h d^{-1} in the interior of Rongelap Island.

model for the food intake rate (g d^{-1}) of local foods is the same for Utirik Island, and only the radioactivity intake rate (Bq d^{-1}) changes because of the lower concentration of ^{137}Cs in the soil and vegetation at Utirik relative to Rongelap. The basis of these diet models was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and a Marshallese school teacher on Ujelang (Robison et al. 1980, 1987, 1994). The survey results were presented for adults (women and men), teenagers, and children. Adult intake exceeded that of teenagers and children, and the intake of local food was about 20% greater for women than for men. The higher intake attributed to women is unexplained and certainly questionable. It is indicative of the acknowledged uncertainty in dietary estimates. Nevertheless, we believe that the MLSC survey provides a reasonable basis for estimating the current dietary intake. Pending the availability of empirical data, we have chosen to use the higher (female) diet from the survey as our diet model rather than attempt further speculative refinement.

Detailed descriptions of LLNL dietary model and a review of other dietary data from the Marshall Islands are given by Robison et al. (1987, 1994). Also, these reports provide a detailed analysis of the caloric content of the diet model compared with United States and Japanese diets. The LLNL IA diet model (Table 1) has a daily calorie intake of about 3,208 calories, which is greater than the U.S. population average value, ranging from 1,853 calories to 1,925 calories (Yang and Nelson 1986; Abraham et al. 1979)

The idea that people will return to the historical lifestyle and consume only local foods without any imported foods continues to surface, although it is almost certain this type of lifestyle will not occur again in the Marshall Islands. Nonetheless, we have calculated the doses for such a diet scenario. The IUA diet data listed in Table 2 are those derived from the results of the Ujelang survey. However, as part of a National Academy of Sciences review in 1993 of the LLNL program, it was recommended that the calorie intake of the IUA diet as it came from the survey be doubled because the calorie intake was low and could not sustain a population for a long period of time (NRC 1994). We accomplished this by doubling the intake of all dietary items listed in Table 2. Consequently, the gram per day intake, the daily ^{137}Cs intake, and the calorie intake are double the values in Table 2 for the dose calculations for the local food only diet (IUA) and are reflected in the tables by the symbol IUA*2. Other diet models have been proposed by people associated with Marshall Islands projects and will be used for comparison (Naidu et al. 1980; Simon and Graham 1995).

The age-dependent biokinetic model for ^{137}Cs is that developed by Leggett (1986) and adopted by the ICRP (1990, 1991). It is a two compartment, exponential model with 10% of the ingested ^{137}Cs activity going to a short-term compartment with a biological half-life of 2 d and 90% going to a long-term compartment with a

Table 2. Diet model—Rongelap Island. Original imported foods unavailable (local foods only) diet for adults greater than 18 y.

Local food	g d^{-1}	kcal g$^{-1\,a,b}$	kcal d^{-1}	Specific activity in 1995 (Bq g^{-1} wet wt.)				Bq d^{-1}			
				^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am
Reef fish^{d}	43.4	1.40	60.7	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	2.9×10^{-2}	1.1×10^{-3}	5.4×10^{-4}	6.0×10^{-5}
Tuna	36.0	1.40	50.4	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6c}	2.2×10^{-2}	8.8×10^{-4}	1.1×10^{-5}	5.0×10^{-5}
Mahi Mahi	10.7	1.10	11.8	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6c}	6.5×10^{-3}	2.6×10^{-4}	3.2×10^{-6}	1.5×10^{-5}
Marine crabs^{f}	9.75	0.90	8.78	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	3.2×10^{-3}	4.8×10^{-4}	3.5×10^{-4}	4.0×10^{-5}
Lobster^{f}	17.6	0.90	15.8	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.7×10^{-3}	8.7×10^{-4}	6.3×10^{-4}	7.2×10^{-5}
Clams^{c,d,g}	29.1	0.80	23.2	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.2×10^{-3}	3.8×10^{-3}	1.1×10^{-2}	3.4×10^{-3}
Trochus^{c,d,g}	0.12	0.80	0.10	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	5.1×10^{-6}	1.6×10^{-5}	4.6×10^{-5}	1.4×10^{-5}
Tridacna muscle^{c,d,g}	5.72	1.28	7.32	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	2.4×10^{-4}	7.6×10^{-4}	2.2×10^{-3}	6.8×10^{-4}
Jedrul^{c,d,g}	9.69	0.90	8.72	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-3}	3.7×10^{-3}	1.1×10^{-3}
Coconut crabs^{c,h}	12.5	0.70	8.73	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	1.1×10^{0}	4.8×10^{-1}	9.0×10^{-4}	2.9×10^{-4}
Land crabs^{c,i}	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	24.5	1.00	24.5	4.3×10^{-4j}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6c}	1.1×10^{-2}	6.0×10^{-4}	3.1×10^{-4}	3.4×10^{-5}
Turtle	8.88	0.89	7.90	6.6×10^{-5k}	2.4×10^{-5c}	1.2×10^{-5c}	1.4×10^{-6c}	5.9×10^{-4}	2.2×10^{-4}	1.1×10^{-4}	1.2×10^{-5}
Chicken muscle	15.6	1.70	26.5	1.3×10^{-1l}	1.3×10^{-4c}	2.5×10^{-6m}	3.3×10^{-6m}	2.0×10^{0}	2.1×10^{-3}	3.9×10^{-5}	5.2×10^{-5}
Chicken liver	8.84	1.64	14.5	8.8×10^{-2l}	2.9×10^{-4c}	1.5×10^{-5m}	3.1×10^{-5m}	7.8×10^{-1}	2.5×10^{-3}	1.3×10^{-4}	2.7×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2c}	3.2×10^{-4c}	9.6×10^{-6m}	1.0×10^{-5m}	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	6.96	4.50	31.3	4.9×10^{-1l}	9.0×10^{-5c}	1.3×10^{-6c}	9.1×10^{-7c}	3.4×10^{0}	6.3×10^{-4}	9.3×10^{-6}	6.3×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1l}	1.5×10^{-4c}	1.3×10^{-5m}	2.4×10^{-5m}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	3.35	2.41	8.07	2.0×10^{-1l}	1.5×10^{-4n}	3.4×10^{-5m}	1.3×10^{-5m}	6.8×10^{-1}	5.0×10^{-4}	1.1×10^{-4}	4.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1l}	9.0×10^{-5o}	1.3×10^{-6o}	9.1×10^{-7o}	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle^{e}	13.2	1.70	22.4	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	8.8×10^{-3}	3.2×10^{-4}	1.6×10^{-4}	1.8×10^{-5}
Bird eggs	11.4	1.50	17.1	1.7×10^{-4p}	3.7×10^{-5p}	1.2×10^{-5e}	1.4×10^{-6c}	2.0×10^{-3}	4.2×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Chicken eggs^{q}	20.6	1.63	33.6	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	2.7×10^{0}	2.7×10^{-3}	5.2×10^{-5}	6.8×10^{-5}
Turtle eggs	117	1.50	176	6.6×10^{-5r}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	7.7×10^{-3}	2.9×10^{-3}	1.5×10^{-3}	1.6×10^{-4}
Pandanus fruit^{l}	31.5	0.60	18.9	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	7.8×10^{0}	4.6×10^{-1}	5.1×10^{-5}	2.5×10^{-5}
Pandanus nuts^{s}	1.00	2.66	2.66	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}
Breadfruit^{l}	93.1	1.30	121	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	1.2×10^{1}	1.9×10^{-1}	5.6×10^{-5}	6.9×10^{-5}
Coconut juice^{l}	167	0.11	18.3	3.2×10^{-2}	3.6×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	5.4×10^{0}	6.1×10^{-3}	1.6×10^{-4}	1.6×10^{-4}
Coconut milk^{t}	60.9	3.46	211	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.2×10^{-4}
Tuba/Jekero^{t}	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat^{l}	90.4	1.02	92.2	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	6.4×10^{0}	3.0×10^{-2}	1.1×10^{-4}	1.3×10^{-4}
Copra meat^{l}	35.7	4.14	148	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	4.3×10^{0}	1.8×10^{-2}	5.9×10^{-5}	7.3×10^{-5}
Sprout. coco^{t}	61.2	0.80	48.9	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.3×10^{-4}
Marsh. cake^{t}	0.00	0.76	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Papaya	13.5	0.39	5.26	4.3×10^{-1u}	6.7×10^{-3v}	4.7×10^{-6w}	4.9×10^{-6u}	5.7×10^{0}	9.1×10^{-2}	6.3×10^{-5}	6.6×10^{-5}
Squash	NR	0.47	0.00	2.1×10^{-1l}	2.8×10^{-3v}	6.3×10^{-7v}	6.5×10^{-7w}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin^{x}	2.72	0.30	0.82	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	5.7×10^{-1}	7.7×10^{-3}	1.7×10^{-6}	1.8×10^{-6}
Banana	0.29	0.88	0.26	1.2×10^{-2l}	1.1×10^{-3u}	4.7×10^{-6y}	4.9×10^{-6y}	3.6×10^{-3}	3.3×10^{-4}	1.4×10^{-6}	1.4×10^{-6}
Arrowroot^{l}	47.4	3.46	164	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	9.7×10^{0}	1.2×10^{-1}	1.2×10^{-3}	6.3×10^{-4}
Citrus	0.10	0.49	0.05	5.7×10^{-2}	2.0×10^{-3z}	6.0×10^{-7z}	7.4×10^{-7z}	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater^{aa}	315	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.7×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater^{aa}	215	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.7×10^{-3}	1.3×10^{-2}	1.0×10^{-4}	6.0×10^{-5}
Malolo^{bb}	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Coffee/Tea^{bb}	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Soil^{l,cc,dd}	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1,541		1,392					78	1.5	0.031	0.013
Fluids	696		18								
Solids	845		1,374								

NOTE: NR stands for no response.
[a] Data from Murai et al. (1958).
[b] Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).
[c] Specific activity from Robison et al. (1982).
[d] Specific activity from Noshkin et al. (1981a); Robison et al. (1981).
[e] Specific activity used is that of reef fish.
[f] Specific activity calculated using the ratio (Bq g^{-1} shellfish tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[g] Data used is from *Hippopus hippopus* and *Tridacna squamosa*.
[h] Data used is from coconut crabs from Arbar Island on Rongelap Atoll.
[i] Specific activity used is that of coconut crab.
[j] Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[k] Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[l] Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.
[m] Specific activity is unpublished data from the 1978 NMIRS.
[n] Specific activity used is that of pork kidney.
[o] Specific activity used is that of pork muscle.
[p] Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight vs. Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al. 1988).
[q] Specific activity used is that of chicken muscle.
[r] Specific activity used is that of turtle.
[s] Specific activity used is that of *Pandanus* fruit.
[t] Specific activity used is that of copra meat.
[u] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight vs. Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.
[v] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight vs. Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.
[w] Specific activity used is calculated using the same concentration ratio for $^{239+240}$Pu and ^{241}Am when no data is available and assuming $^{239+240}$Pu and ^{241}Am are the same.
[x] Specific activity used is that of squash.
[y] Specific activity used is that of papaya.
[z] Specific activity used is that of breadfruit.
[aa] Specific activity from Noshkin et al. (1981b).
[bb] Specific activity used is that of rainwater.
[cc] Specific activity is in Bq g^{-1} dry weight.
[dd] Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area vs. 7 h d^{-1} in the interior of Rongelap Island.

biological half-life of 110 d. Data from BNL support the use of the 110 d half-life for the average adult males in the Marshall Islands (Miltenberger et al. 1980, 1981; Lessard et al. 1980a, 1980b, 1984).

In this paper we calculate the average ^{137}Cs body burden only for the adult age group. The estimated dose from ^{137}Cs for adults is a conservative estimate of dose for intake beginning at any other age based on available age-specific dietary information from the Marshall Islands (Robison and Phillips 1989).

Whole body counting system and radiocesium measurements

In vivo WBC is a simple, accurate, and effective method to determine the quantity of gamma emitters in the body, such as ^{40}K, ^{60}Co and ^{137}Cs. Hence, the WBC is an important technique employed in assessing the internally deposited radionuclides in the Marshallese populations since 1957 (Conard 1992). The WBC measurements have been conducted by scientists at BNL (Greenhouse et al. 1980) over the past 20 y; many of the body burden measurements for the Marshallese using the WBC and urinalyses methods are available (Cohn et al. 1956, 1963; Cohn and Gusmano 1965; Greenhouse et al. 1980; Miltenberger et al. 1980, 1981; Lessard et al. 1980a, 1980b, 1984; Sun et al. 1991, 1992).

Whole-body counting was performed in two shadow-shielded chairs, each having a single thallium-doped sodium iodide detector, 20.2 cm (11.5 inches) diameter by 10.2 cm (4 inches) thick, produced by Bicron.[‡] The WBC detector is mounted on a pivoted arm allowing it to be centered across the front of the chair where the people are seated for 15 min during a counting. The WBC system is calibrated with a bottle mannequin absorber (BOMAB) phantom. Isotope identifications are based on four distinct photon energy peaks: 0.622 (^{137}Cs), 1.17 and 1.33 (^{60}Co), and 1.46 MeV (^{40}K). Counting efficiencies are established for four geometries by selecting whole or partial sets of the BOMAB phantom's segments called large, medium, small, and infant. The counting efficiency obtained with the large geometry is used to analyze spectra from persons weighing 60 kg or more, the medium geometry for persons weighing between 40 and 60 kg, the small geometry for youngsters age 3 y or older who weigh less than 40 kg, and the smallest geometry for infants less than about 14 kg. The minimum detectable activities (MDA) of ^{137}Cs and ^{60}Co at the 95% confidence level for an empty chair for the present WBC system are 60 and 52 Bq, respectively (NCRP 1985; Sun et al. 1991).

All measurements were made on volunteers from among the Marshallese who were residing on either Rongelap or Utirik Atolls. It was assumed that measured cesium activity is maintained in the body over 365 d as the result of a series of chronic intakes. Cesium body burdens in Marshallese must be interpreted on the basis of chronic intakes (Lessard et al. 1980a; Sun et al. 1991; Kercher and Robison 1993).

RESULTS AND DISCUSSION

The initial ^{137}Cs intake (kBq mo^{-1}) in 1974 for the various diet models is listed in Table 3. The estimated body burdens based on the environmental method for the years 1977 through 1984 for Rongelap and 1977 through 1993 for Utirik are listed in Table 4 for the various diet models. The body burdens were calculated using the data from food samples collected on Rongelap and Utirik Islands from 1978 through 1993. The data were decay corrected to 1970 to serve as input to the dose model. The body burdens were calculated for a 25 y period (1970 to 1995), and the body burdens were extracted for the appropriate year for comparison with the BNL whole body measurements.

The BNL body burden data for ^{137}Cs in the adult population at both atolls are shown in Table 5. These data represent the mean body burden of the adults (both male and female) who volunteered to be measured on any given trip. The number of people varied each year, as did the actual persons involved. Also listed are the upper 95% confidence limits for the mean body burdens observed on each trip. The 95% confidence limits for each set of BNL body burden measurements for a specific year and island were calculated as follows. The lower bound (LB) = the 2.5th percentile of the data values if $n > 39$, otherwise LB = the minimum data value. The upper bound (UB) = the 97.5th percentile of the data values if $n > 39$, otherwise UB = the maximum data value. The minimum or maximum data values are used when $n < 39$ because the LB and UB cannot be calculated for such a case (i.e., $0.025 \times 39 = 0.98$; less than one individual.

Several other diet models have been suggested for the Marshall Islands for use in dose calculations (Naidu et al. 1980; Simon and Graham 1995). The original reports can be reviewed for detailed intakes of each food product. Rather than list three more very extensive tables, the body burdens calculated using these diets are shown in Figs. 6 and 7, along with the results from the LLNL preferred diet model (IA) and the local foods only diet model (IUA) as described in Tables 1 and 2. For a variety of reasons, politicians, lawyers, some community members, and others have insisted that a diet consisting of consumption of only locally grown foods should be used for dose calculations.

The very good agreement between the estimated ^{137}Cs body burdens from the LLNL environmental

Table 3. The initial intake in 1974 in kBq per month for the various diet models for Rongelap and Utirik Islands

	^{137}Cs intake, kBq mo^{-1}	
	Rongelap Island	Utirik Island
IA	1.54	0.316
IUA*2[a]	7.62	1.43
Naidu A	13.2	2.94
Naidu B	4.37	0.957
Naidu C	4.11	0.918

[a] IUA*2 represent a doubling of the values listed in the original IUA (local food only) diet listed in Table 2 (see text for explanation).

[‡] Bicron, 6801 Cochran Road, Solon, OH 44139.

Table 4. The estimated body burdens in kBq for the populations at Rongelap and Utirik Atolls by the environmental method for various diet models.

	^{137}Cs body burden, kBq					
	Utirik Island					
Diet model	1977	1979	1981	1982	1983	1984
IA	1.41	1.35	1.29	1.26	1.23	1.20
IUA*2[a]	6.22	5.94	5.68	5.55	5.43	5.31
Naidu A	12.8	12.2	11.7	11.4	11.1	10.9
Naidu B	4.16	3.98	3.81	3.72	3.63	3.54
	Rongelap Island					
Diet model	1977	1979	1981	1982	1983	1984
IA	6.89	6.59	6.29	6.15	6.01	5.87
IUA*2[a]	33.1	31.6	30.3	29.5	28.9	28.3
Naidu A	57.4	54.8	52.4	51.3	50.1	48.9
Naidu B	19.0	18.2	17.4	16.9	16.6	16.2

[a] IUA*2 represent a doubling of the values listed in the original IUA (local food only) diet listed in Table 2 (see text for explanation).

Table 5. The BNL mean whole body measurements in kBq for populations at Rongelap and Utirik Islands for 1977 through 1993.

	Body Burdens, kBq								
	1977	1979	1981	1982	1983	1984	1989	1991	1993
Rongelap									
Mean	9.3	6.3	6.8	9.2	8.3	3.7			
Upper 95% confidence	18.5	17.0	17.4	13.0	20.8	11.2			
	(51)[a]	(35)	(66)	(47)	(52)	(78)			
Utirik									
Mean	3.8	2.0	3.1	—	2.1	1.0	0.8	1.1	0.4
Upper 95% confidence	7.4	3.7	6.9		4.4	2.6	3.0	2.9	1.5
	(48)	(36)	(126)	—	(168)	(165)	(143)	(153)	(103)

[a] Number in parentheses is the number of people measured.

method using the preferred diet model (IA) and the BNL whole body counting method provide a basis for evaluating proposed diet models in the Marshall Islands. As can be seen in Fig. 6, the LLNL diet model that provides for both local foods and imported foods in the diet reflects very well the results observed in the whole body counting of the people at Rongelap Island over a 7-y period. The IUA scenario, and other proposed diet models, significantly over predict actual observation by WBC at Rongelap Island.

The results from Utirik Atoll (Fig. 7) span a range of 16 y (1977 to 1993) and provide a slightly different picture of dietary intake in the years from 1977 to 1983. In 1977 to 1981 and 1982 the intake of local foods was significantly higher than predicted by the LLNL IA diet model. In 1979 and 1983, the whole body measurements indicate that the local food intake was slightly above model predictions. From 1984 through 1993, the environmental method and WBC are in excellent agreement as was the case for Rongelap Atoll. The higher intake of local foods at Utirik Atoll relative to Rongelap Atoll from 1977 through 1983 could reflect the more constant supply of imported foods from the U.S. to Rongelap Atoll via the Trust Territory and Republic of the Marshall Islands Government (RMI) because of the higher level of contamination at Rongelap. When the air strips were established on the outer atolls in the early 1980's, service

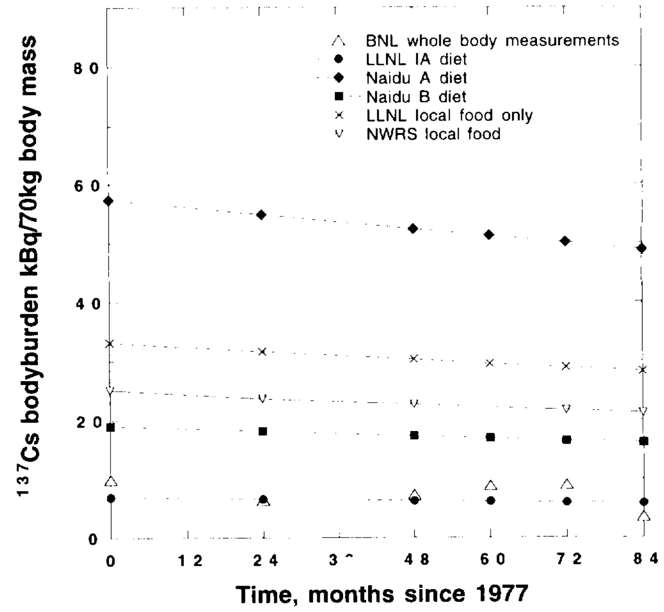

Fig. 6. The estimated body burdens for Rongelap Island for various diet models from the environmental method compared with the WBC method.

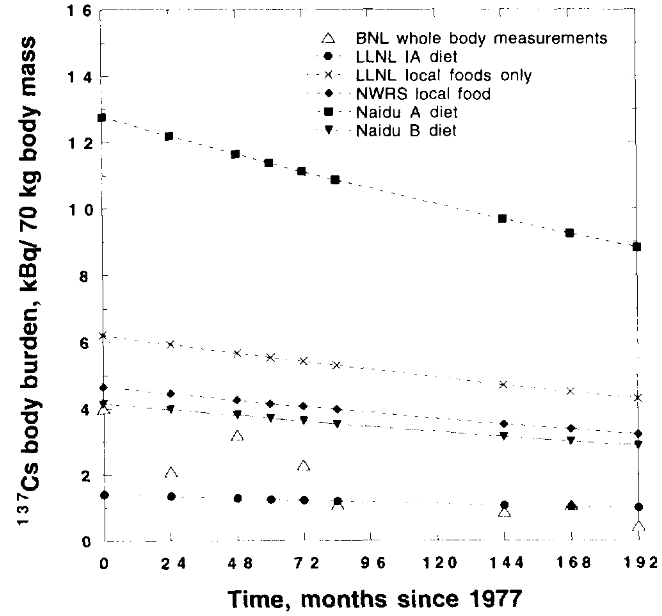

Fig. 7. The estimated body burdens for Utirik Island for various diet models from the environmental method compared with the WBC method.

became much more regular and imported foods could be delivered routinely to nearly all outer atolls. Ship service to the outer atolls has also improved under the RMI. Consequently, the combined diet of local and imported is obviously the preferred, and now standard, diet of the northern Marshall Island atolls, and the measured body burdens over the past 10 y are in excellent agreement with model predictions at both atolls.

General observation of the lifestyle in the Marshall Islands, with weekly airplane service, boat support periodically, trade with the outside world, government programs to ensure availability of imported foods, and a population that now enjoys and expects imported foods, indicates that the average diet in the Marshall Islands will more closely resemble the combined diet of imported and local foods than a diet of only local foods or other suggested diet models. This is particularly true for the most affected atolls of Bikini, Enewetak, Rongelap and Utirik, two for which we have direct data, and the other two which have very similar lifestyles to the other two atolls.

Resettlement of the atolls in order to live at "home" is very important to many of the people. The fact that the people are not currently living on the atolls precludes any direct whole body measurements. Consequently, decisions on resettlement are made based on dose estimates from the environmental method. Therefore, realistic dose assessments should be made so that people are not excluded *a priori* from going home because of unrealistic, over-conservative dose calculations. In the Marshall Islands, this necessarily translates into realistic diet models for estimating the intake of local foods because of the importance of ^{137}Cs uptake into terrestrial foods that subsequently provides a majority of the estimated dose. It is very clear from the comparative data shown in Figs. 6 and 7 that proposed diets consisting of consumption of only locally grown food stuffs simply do not represent the current diet in the Marshall Islands. This is very evident at both Rongelap and Utirik Atolls. The same is also true for the other diet models that have been proposed that are shown in Figs. 6 and 7. Consequently, based on these direct comparative data at two atolls, and general observations on current dietary habits in the Marshall Islands, a combined diet of imported and local foods should be used to provide realistic dose assessments.

Another very important part of any dose assessment is the uncertainty that surrounds the population average values. A detailed uncertainty analysis of these environmental-method dose estimates (i.e., body burdens) has been made for Rongelap Island (Robison et al. 1994). The method can be reviewed in the associated paper in this issue that describes the uncertainty analysis methods for the Bikini Island dose assessment (Bogen et al. 1997).

The results of the uncertainty analysis for the environmental method are shown in Fig. 8 where the upper 95% confidence limits for individual variability in the population average dose are shown by the solid circles connected by a solid line. For comparison, 95% confidence limits based on directly measured body burdens from BNL for each year at Rongelap and Utirik Atolls are shown by open diamonds for Rongelap and by open triangles for Utirik.

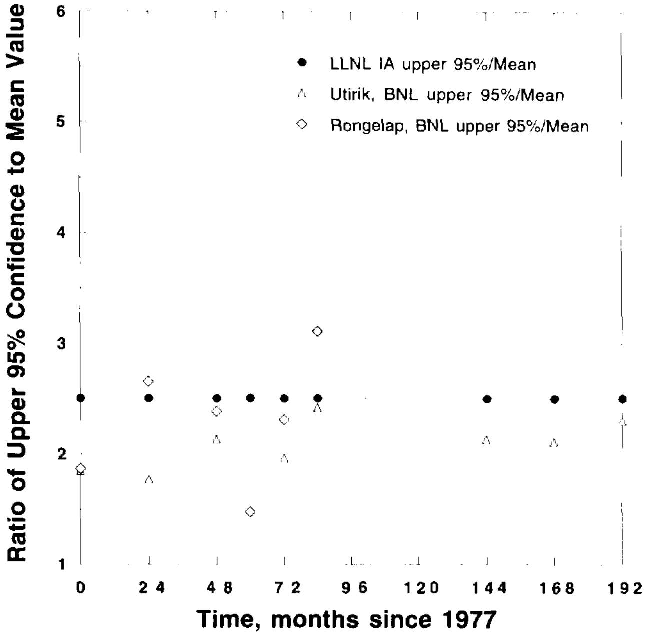

Fig. 8. The comparison of the 95% confidence limits for interindividual variabiltiy from the environmental method with the 95% confidence limits from experimental data by WBC for both Rongelap and Utirik Islands.

The upper 95% confidence limits from the direct measurement of both populations for all the years are within the modeled upper 95% confidence limits with the one exception in 1984 (84 mo. since 1977) at Rongelap. The model estimates of the interindividual variability around the population's mean predict very well actual observations and thus provide assurance about the environmental dose estimates and interindividual variability when applied to other atolls and islands.

Moreover, the modeled 95% confidence limits in uncertainty in the population average dose are a factor of 2 above and below the calculated mean value. The upper 95% confidence limits based on the population average observed by BNL at the two atolls over the years are 1.6 for Rongelap and 2.1 for Utirik, a result once again in good agreement with the environmental method uncertainty of 2.0. This provides additional confidence in applying the predictive LLNL environmental method to other atolls and islands where people do not currently reside, but where resettlement is likely or assumed.

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GASTROINTESTINAL ABSORPTION OF PLUTONIUM BY THE MARSHALL ISLANDERS

L. C. Sun and C. B. Meinhold*

Abstract—**The gastrointestinal absorption constant (f_1) is a critical parameter in assessing systemic uptake following the ingestion of a radioactive material and in monitoring such intakes. This study addresses the latter, particularly for plutonium, and from environmental measurements derives an f_1 value of 4×10^{-4} for the Marshallese population. The uncertainty associated with the methodology and measurements used in this f_1 value assessment is evaluated. This evaluation takes into account the results from 24-h urine samples and the particular lifestyle of the Marshallese. Plutonium intake resulting from soil consumption is a primary parameter in this evaluation; for this study, it was assumed to be 500 mg d^{-1}. The f_1 value determined here is consistent with the values in ICRP Publication 67 of 5×10^{-4} for ages 1 to adult, and is the same as that suggested by the NRPB.**

Health Phys. 73(1):167–175; 1997

Key words: gastrointestinal tract; Marshall Islands; plutonium; soil

INTRODUCTION

THE INTAKE of radioactive material can occur principally through three major pathways: inhalation, ingestion, and absorption through open wounds. Uptake is the fraction of the intake that reaches the systemic system of the body through any of these pathways. In this study, the quantity of plutonium entering the gastrointestinal (GI) tract is limited to ingestion, and since the uptake is considered to be proportional to the fraction of the ingested plutonium that is absorbed through the gut wall into the blood stream, it can be expressed as a constant: the gastrointestinal absorption coefficient (f_1). Therefore, for ingestion, the systemic uptake via the GI tract is the product of the intake and the f_1 value.

The International Commission on Radiological Protection (ICRP) in Publication 30 (1978) introduced the annual limit on intake (ALI) and provided dose per unit intake coefficients for controlling occupational exposure to internally deposited radionuclides. In that publication, the intake of one ALI, either from inhalation or ingestion, was taken to result in a committed effective dose of 50 mSv in the 50-y interval following an intake. Inherent in calculating ALIs by ingestion is the f_1 value. In ICRP Publication 48 (1986) f_1 value of 10^{-3} was recommended for adults for unknown or mixed compounds with the intention of providing "an adequate margin of safety for radiological protection purposes" (ICRP 1987). However, they suggested a value of 10^{-2} for infants for the first year of life. Similar values of 10^{-2} for infants and 10^{-3} for adults were also used in Publication 56 for plutonium in the diet (ICRP 1989). Both ICRP Publication 67 (1993) and the U.K. National Radiological Protection Board Gut Transfer Report (NRPB 1990) gave values of 5×10^{-3} for infants and 5×10^{-4} for adults.

As Kocher and Ryan (1983) indicated, these values are intended to be used for dose limitation. Durbin (1975) indicated the plutonium absorption from the GI tract, wound sites, or the lung decreases in the following order: soluble complexes > hydrolyzable salts > insoluble compounds of plutonium. It is important to remember, however, as stated in ICRP Publication 48 (ICRP 1986) "the use of the cautious value of 10^{-3} may not be considered appropriate in all situations where a best estimate of absorption is required, either for a critical group or in estimating a population dose." Underestimating the f_1 value would increase the estimate of the intake as interpreted from urinalysis. It is for this reason that we undertook an examination of the most appropriate f_1 value for the Marshallese people.

Other studies

There have been numerous studies on the behavior of plutonium in human and animal biological systems. In a study in which plutonium was fed chronically to rats, Weeks et al. (1956) determined an f_1 value of about 3×10^{-3}. On the other hand, an f_1 value of $\sim10^{-5}$ has been cited by Priest and Tasker (1990). Pinder et al. (1990) suggested f_1 values of 10^{-3} and 10^{-5} for the ingestion of plutonium from plants which incorporated plutonium via roots from contaminated soil and from plants with surface contamination, respectively. Bhattacharyya et al. (1992) used Pu(+4) and found that GI absorption values were similar in mice, baboons, and humans and they suggested an f_1 value of 1×10^{-4}. From their investigation of plutonium levels in urine from people whose diet included shellfish, Hunt et al. (1990)

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proposed an f_1 value of 2×10^{-4} from Cumbrian winkles. Another similar study based on the ingestion of plutonium incorporated in reindeer meat concluded that the f_1 value is about 8×10^{-4} (Mussalo-Rauhamaa et al. 1984). Between April 1945 and July 1947, Pu(+4) and Pu(+6) citrate solutions were selected and injected in ill men to study plutonium toxicity in humans (Russell 1946; Russell and Nickson 1946; Langham et al. 1980). Also, Popplewell et al. (1994) carried out experiments with ^{244}Pu(+4) in volunteers and suggested an f_1 value between 2×10^{-4} and 9×10^{-4} for their human biokinetics modeling of plutonium. Later, Langham's results (Langham et al. 1980) were thoroughly reviewed and the data extrapolated in the development of biokinetic models for dose calculations and for interpretation of bioassay data (Beach and Dolphin 1964; Durbin 1975; Rundo et al. 1976; Parkinson and Henley 1981; Leggett 1984; Jones 1985; Kathren and McInroy 1991; McInroy et al. 1991; Voelz and Lawrence 1991; Moss and Eckhardt 1995).

Taylor (1989) suggested that the f_1 value for plutonium and other actinides and transuranium elements could vary by three orders of magnitude depending upon the mass ingested, the specific compounds ingested, and the individual's dietary habits and physiology. Smith et al. (1975) indicated that smaller particle sizes give lower f_1 values due to the greater retention time in the GI tract. On the other hand, Sullivan (1980a, b) indicated that smaller particle sizes give larger f_1 values due to easier digestion in the GI tract. Larsen et al. (1977, 1983) suggested a f_1 value for plutonium between 10^{-3} and 2×10^{-1} based on the chemistry of plutonium in chlorinated drinking water. However, animal studies have not produced convincing evidence that either the oxidation state of the ingested compound or individual biology influence the f_1 value (NEA 1988). Uptake is proportional to plutonium intake, and each individual's intake differs, as do living habits. Therefore, a proper and correct f_1 value must take into account an individual's living habits, such as foods consumed (and their preparation) (McKay and Fox 1991; ICRP 1989).

In a study on plutonium retention in the intestinal wall of rats, the f_1 value for older animals was found to be about 10% of that for younger animals (NRPB 1990; Harrison and Fritsch 1992). This finding is consistent with the ICRP Publication 67 (ICRP 1993) recommended f_1 values of 5×10^{-3} for 3-mo-old infants and 5×10^{-4} for those aged 1 y and older. Therefore, it is more likely that the f_1 value remains nearly constant for variables except age, and perhaps gender, and it is variable intake which leads to differences in excretion. Moreover, the current plutonium retention-excretion models and biokinetics parameter values (ICRP 1989, 1993) allow for age-dependent changes in bone physiology, which are reflected in changes in urine excretion as a function of age. Therefore, the uncertainty of an assessed f_1 value for Marshallese populations using urine data may be overlooked.

MATERIALS AND METHODS

Data obtained through urine measurements

On the morning of 1 March 1954, a device code named Bravo was detonated at Namu Island, Bikini Atoll, the Republic of Marshall Islands (RMI). An unexpectedly large yield resulted in radioactive fallout inadvertently contaminating two inhabited atolls, Rongelap and Utirik (U.S. Committee on Interior and Insular Affairs 1989; U.S. Committee on Energy and Natural Resources 1991; National Research Council 1994; U.S. Committee on Natural Resources 1994). The current work is limited primarily to the Rongelap population.

The Bravo test released plutonium isotopes that were transported to Rongelap and Utirik in fallout. All 64 Rongelap residents were evacuated 2 d after the Bravo detonation. These residents, therefore, were exposed to acute radiation from early fallout both before and during their evacuation. In June 1957, the whole population was allowed to return to Rongelap Atoll. However, in May 1985, the entire community was evacuated again due to fear of exposure to fallout radiation. At present, no one lives in the Rongelap Atoll. Thus, from June 1957 to May 1985, the original 64 inhabitants and their descendants were chronically exposed to low-level plutonium contamination while living on the Atoll. In the summer of 1989, a BNL mission conducted whole-body counting and collected urine samples from 34 Rongelapese living at Mejatto Island (Sun et al. 1992, 1995). The estimated number of Rongelap people living at Mejatto then was 200–250, with half being children under the age of 10 y. After May 1985, while living on Mejatto, the Rongelap people were unlikely to ingest any plutonium as evidenced by the low levels of radiocesium activity detected there. Our interpretation of the urine data is based on these chronological events, and, therefore, assumes that no intake of plutonium occurred before March 1954 nor after May 1985.

In 1989, the fission track analysis (FTA) method was fully implemented (Moorthy et al. 1988) and a protocol established for a 24-h shipboard urine collection that led to a set of reliable data on ^{239}Pu excretion in urine (Sun et al. 1993a). For example, the average plutonium body content obtained from 24-h urine samples is in good agreement with that from analyses of bone samples of deceased Rongelap residents (Franke et al. 1995).

Calculation method and measurements

Table 1 shows the ages, sex, and the time of residence on the Rongelap atoll of the 34 people, together with their individual FTA results. The results are indicated as gross and net plutonium contents (μBq) in 24-h urine samples. The average total background from reagent urine blanks and systematic background is about 1.6 μBq [36 fission tracks with each fission track equivalent to 0.044 μBq (Sun et al. 1995)]. In order to obtain a positive result of plutonium in the body, the gross plutonium content in the sample must be no less

Table 1. Estimates of ^{139}Pu activity in 24-h urine samples and total days lived on Rongelap Island from 34 Rongelap people.

ID	Age[a]	Sex	^{239}Pu gross activity in 24-h urine (μBq)	^{239}Pu net activity in 24-h urine (μBq)	Exposure days[b]
1	19	M	4.5	2.9	5,475
2	14	M	3.4	1.8	3,650
3	12	M	2.9	1.3	2,920
4	14	M	3.2	1.6	3,650
5	16	M	3.4	1.8	4,380
6	16	M	3.4	1.8	4,380
7	15	M	3.0	1.4	4,015
8	12	M	2.3	0.7	2,920
9	14	M	2.2	0.6	3,650
10	16	M	2.2	0.6	4,380
11	14	M	1.9	0.3	3,650
12	10	M	1.7	0.1	2,190
13	19	M	1.7	0.1	5,475
14	10	F	3.0	1.4	2,190
15	15	F	3.2	1.6	4,015
16	11	F	2.4	0.8	2,555
17	10	F	2.3	0.7	2,190
18	11	F	2.3	0.7	2,555
19	15	F	2.7	1.1	4,015
20	85	F	4.5	2.9	10,220
21	16	F	2.3	0.7	4,380
22	13	F	1.9	0.3	3,285
23	15	F	2.0	0.4	4,015
24	10	F	1.7	0.1	2,190
25	12	F	1.6	0	2,920
26	17	F	1.6	0	4,745
27	33	F	1.1	−0.5	10,220
28	14	F	0.8	−0.8	3,650
29	14	F	1.4	−0.2	3,650
30	14	F	1.5	−0.1	3,650
31	16	F	1.2	−0.4	4,380
32	12	F	1.3	−0.3	2,920
33	13	F	1.2	−0.4	3,285
34	66	F	1.1	−0.5	10,220
Total			76.4	22.5	141,985

[a] The age during the year of sample collection.

[b] Days calculated between 16 June 1957 and 15 May 1985.

than 1.6 μBq. However, 8 of the 34 individuals' sample results were shown below 1.6 μBq and resulted net plutonium contents in a negative value. Clearly, a negative plutonium content in the urine is not possible, nor is a negative f_1 value, as might be suggested from these 8 individual negative net plutonium results. To avoid nonsensical statistical biases, 22.5 μBq plutonium was obtained from the sum of the 34 FTA gross results (76.4 μBq) then subtracted by total background of the 34 FTA analyses (1.6 μBq × 34 = 53.9 μBq). Similarly, 141,985 days were simply summed from the same 34 people who lived in the Rongelap Islands between June 1957 and May 1985. These two totals are shown on the bottom line of Table 1.

The population examined in Table 1 has an age range between 10 and 85 y. Since the plutonium elimination rate is faster in older individuals, the fractional daily excretion might be expected to differ between individuals in this population. Priest and Birchall (1989) reported that the ICRP age-specific model for bone-surface seeking radionuclides in humans is relatively insensitive to the age of the individuals, and the plutonium urine excretion model applied to the adult age group still provides sufficient accuracy for estimation of intake for all ages except infants. Therefore, the variation of plutonium excretion rates between age 10 to 85 y is small as suggested by the ICRP (1989, 1993) human bone model, and translocation parameter values among bone, blood, urinary tract tissue, and urine compartments are small as well. Hence, based on Jones's plutonium excretion model (1985), a predicted fractional elimination of 1.4×10^{-5} of an original single acute uptake can be applied for the following 4 y. Therefore, a total plutonium uptake of 1.61 Bq (i.e., 22.5 μBq ÷ 1.4×10^{-5}) would be interpreted as the average plutonium body content of the 34 people in May 1985 when they left Rongelap Island. Further, based on the suggestion in ICRP Publication 67 (1993) that about 80% of the plutonium uptake absorbed in the systemic whole-body is available for a rapid elimination, the total uptake (systemic burden) of ^{239}Pu is about 2.01 Bq (i.e., 1.61 Bq ÷ 0.8). Therefore, the average rate of plutonium uptake for these 34 individuals from both the inhalation and ingestion pathways was about 14.2 μBq d^{-1} (i.e., 2.01 Bq ÷ 141,985 d).

An alternative calculation can be made using nonparametric statistics. For FTA data generated during 1989, the minimum detection level (MDL) was 2 μBq (99% confidence level). It is seen in Table 1 that a large number of results were below this value. As reported by Helsel (1990), there are several statistical procedures for handling values reported as less-than MDLs, such as substituting zero for such values, or one-half the MDL, or even the MDL itself. However, each method introduces bias when estimates of means and variances for the population are made. An alternative is to use percentiles (e.g., medians, interquartile range), which are robust parameter estimators for entire population data sets. Using all 34 net plutonium results in column 5, Table 1, the median value is 0.6 μBq (e.g., compared to the mean value, 0.66 μBq). This translates into an intake of 12.8 μBq d^{-1}, which is only 10% below the previous calculation.

Estimation of plutonium inhalation uptake per day

Lawrence Livermore National Laboratory (LLNL) has been monitoring the exposure of the Marshallese through environmental methods (Noshkin et al. 1979, 1981, 1988, 1994; Robison et al. 1980, 1982, 1987, 1988; Robison 1983; Robison and Stone 1992). The LLNL group analyzed plutonium concentrations in air, soil, water, and food. These data, combined with the observed dietary patterns in the Northern RMI, are then used to estimate plutonium intake and committed doses. On the other hand, the BNL group analyzed plutonium concentration in 24-h urine samples to estimate plutonium uptake and committed dose (Lessard et al. 1984; Sun et al. 1993a, 1995). An intake model developed and used by the LLNL group for assessing plutonium dose via inhalation pathway for Marshallese based on their environmental and the life style conditions estimated a total activity intake of about 180 μBq d^{-1} for both ^{239}Pu and ^{240}Pu. This is based on the product of 22 m^3 d^{-1} breathing rate and the $^{239+240}$Pu concentration 8 μBq m^{-3} in the air breathing zone (Robison et al. 1987, 1982, 1989). A similar value was also reported by Kohn (1989) for assessing potential inhalation intake of plutonium for the people of Rongelap.

Because ^{240}Pu is not measured by the FTA method, the relative proportions of ^{239}Pu to ^{240}Pu must be estimated if the FTA measurement results are to be compared with the LLNL results. Oak Ridge National Laboratory reported a ^{239}Pu to ^{240}Pu activity ratio of 20:27 for another thermonuclear device detonated on Enewetak in 1952, code name Ivy Mike (Holleman et al. 1987). Since the plutonium compositions produced by the Bravo and Ivy Mike devices were similar, the present work applies the Ivy Mike ratio to obtain the LLNL inhalation value of 77 μBq d^{-1} for ^{239}Pu.

ICRP Publication 48 (1986) reported a range of pulmonary clearance rate of 0.0002 to 0.0010 d^{-1} for all $^{239}PuO_2$ and $^{239}PuO_2$:UO_2 depending upon the particles' sizes and solubility in body fluids. ICRP Publication 48 also indicates that the rate of lung clearance could be even slower than 0.0002 d^{-1} for plutonium compounds fired at high temperatures (i.e., over 1,000°C). This is a valid concern in estimating the plutonium burdens in the Marshallese, since the plutonium remaining on the islands primarily is an insoluble, high-fired oxide (Schell and Walters 1975; Noshkin et al. 1981). A recent study on pulmonary clearance for workers with chronic exposure to Class Y uranium indicated that the rate of the lung clearance is about 0.0001 d^{-1} (Dang et al. 1994). For various oxide forms of Type S (corresponding to "Class Y") plutonium particles (assume 1–5 μm-AMAD), the ICRP's Human Respiratory Tract Model (HRTM) (1994) indicated that about 10% of inhaled particles cannot be exhaled. The activity associated with these 10% particles is eventually deposited in the alveolar-interstitial (AI) compartment, the pulmonary region of the lung. About 10% of the AI-deposited plutonium reaches the blood. The HRTM (ICRP 1994) also indicates that 0.1% of the AI deposited plutonium can be rapidly absorbed to blood and affects the interpretation of urine measurements.

Using both the estimates of 77 μBq d^{-1} inhalation intake rate for ^{239}Pu and the HRTM default value 10% for inhaled activity deposited to the pulmonary region of lung, the calculated deep lung deposition rate is 7.7 μBq d^{-1}. Because of both 0.1% of instantaneously rapid absorption and 1% of the cumulative absorption from AI compartment to systemic blood, the estimated total plutonium uptake via lung (inhalation pathway) is 0.077 μBq d^{-1} [i.e., 7.7 μBq d^{-1} × (0.001+0.01)]. This contribution is small and can be negligible relative to the total intake at 14.2 μBq d^{-1}. Hence, the uptake contribution due to the potential inhalation pathway is not considered further.

Estimation of plutonium ingestion intake per day

Although the dietary pattern is important when estimating ingestion uptake, particularly for populations such as the Marshallese, other aspects of their life style also must be considered. For example, sleeping on the floor, preparing food outdoors, and eating in their often dusty environments increases the possibility that deposited plutonium will enter the body through ingestion (Lessard et al. 1985; Simon 1994; Baverstock et al. 1995). Table 2 is an abridged version of the LLNL dietary pattern for the Rongelap Islands [all dietary items contributing less than 37 μBq d^{-1} have been omitted (Robison et al. 1989)]. Based on Table 2, the total dietary intake of ^{239}Pu and ^{240}Pu is about 5 mBq d^{-1} (Robison et al. 1989). Using the Ivy Mike ratio of 20:27 for ^{239}Pu:^{240}Pu, the dietary intake of ^{239}Pu alone would be about 20 mBq d^{-1}. Since the plutonium (both ^{239}Pu and ^{240}Pu) concentration in Rongelap soil is reported (Robison et al. 1989) to be 150 mBq g^{-1} (4 pCi g^{-1}), about 64 mBq g^{-1} would be ^{239}Pu. Similarly, Baverstock et al. (1995) indicates the average and standard deviation of $^{239+240}$Pu concentration in 0–5 cm topsoil (8 samples) at the Rongelap Island were 198±140 mBq g^{-1} with a

Table 2. An abridged version of the model Marshallese diet from Robison et al. (1989). All dietary items contributing less than 37 μBq d^{-1} have been omitted.

Local food	Ingestion rate g d^{-1}	Intake rate Bq d^{-1} (^{239,240}Pu)
Reef fish	24.20	2.1×10^{-4}
Tuna	13.90	1.2×10^{-4}
Marine crabs	1.68	6.7×10^{-5}
Lobster	3.88	1.6×10^{-4}
Clams	4.56	1.7×10^{-3}
Trochu[a]	0.10	3.7×10^{-5}
Tridacna Muscle[a]	1.67	6.3×10^{-5}
Jedrul[a]	3.08	1.2×10^{-3}
Coconut crabs	3.13	2.3×10^{-4}
Octopus	4.51	4.4×10^{-5}
Chicken liver	4.50	5.6×10^{-5}
Pork liver	2.60	8.9×10^{-5}
Coconut juice	99.10	9.6×10^{-5}
Coconut milk	51.90	8.5×10^{-5}
Drinking coco meat	31.70	4.1×10^{-5}
Arrowroot	3.93	1.0×10^{-4}
Well water	207.00	1.0×10^{-4}

[a] Clam or shellfish-related species.

median value of 155 mBq g^{-1}. The uncertainty of Rongelap's soil measurement is estimated to be about 0.7 at 67% confidence level.

Estimation of plutonium intake from soil consumption

Harrison et al. (1989) and Haywood and Smith (1990) reported an average soil intake of 10,000 mg d^{-1} in dose assessments for the Emu and Maralinga nuclear weapons testing sites in Australia. As a result of resuspension, soil dust can be deposited on plants and in food during preparation. Hence, it may be ingested directly. A soil ingestion rate of 100 mg d^{-1} as a default was chosen for a pathway analysis for the U.S. population (Yu et al. 1993). The assessments included inhaling suspended dust, drinking water, and ingesting food contaminated with deposited dust. Haywood and Smith specifically discussed the effects of lifestyle on plutonium ingestion for the Australian aboriginal people; an average soil intake of 1,000 mg d^{-1} was established from the fecal samples of the investigators who made field trips to the affected areas. Therefore, the 1,000 mg d^{-1} soil intake is regarded by Haywood and Smith as the lowest limit on soil intake for the aboriginal people, and it is in general agreement with populations exhibiting habitual pica (the deliberate ingestion of soil) (Schaum 1984; LaGoy 1987). A health risk impact study of the U.S. population also suggested that children who eat soil can ingest as much as 5,000 mg d^{-1} directly without exhibiting ill effects (Cleverly 1987).

It is difficult to quantitatively compare the amount of soil ingested by the Marshall Islanders and the Aboriginal people because of their different lifestyles. However, both societies live in close contact with their natural environment, although the Australian aboriginal people are nomadic, while the Marshallese have a lifestyle more nearly like to that of industrial nations. LaGoy (1987) reported a maximum intake of 500 mg d^{-1} for adults in developed nations who do not exhibit habitual pica. This value, then, was taken to be a reasonably conservative average for the Marshallese people. Therefore, this work adopts 500 mg d^{-1} as the average life-time intake of soil by the Marshallese (Table 3).

RESULTS AND DISCUSSION

Derivation of f_1 value for Marshallese

Since the fraction of the ingested plutonium absorbed that is reaching the systemic system is the f_1 value, we can estimate f_1 by dividing the daily uptake to blood of 14.2 μBq d^{-1} by the total intake rate. Using the 500 mg d^{-1} soil ingestion rate value, the ^{239}Pu intake is estimated to be 0.032 Bq d^{-1}. Combining this with an estimate of dietary intake of 0.002 Bq d^{-1} gives a total intake of 0.034 Bq d^{-1}. The estimated f_1 value is

$$f_1 = \frac{14.2 \times 10^{-6}}{0.034} \approx 4.2 \times 10^{-4}. \qquad (1)$$

This f_1 value is about the same as we presented earlier (Sun et al. 1993b). Outlines of the calculation and parameter values used are summarized in Table 4. Using the median value of 0.6 μBq d^{-1} for uptake, an f_1 value of 3.8×10^{-4} is calculated instead. Sensitivity analyses between f_1 values vs. soil ingestion rates were performed, with results tabulated in Table 5. The maximum estimated f_1 value could be as high as about 7×10^{-3}. Also, the plutonium intake rate from ingested soil would equal that of dietary sources at about 30 mg d^{-1} soil ingestion rate. Above this value, plutonium intake from soils exceeds that from dietary intake.

Among the 34 participants whose urine results were used in this study, two are among the original 64 inhabitants who evacuated Rongelap in 1954. Unlike the others, these two individuals both observed the fallout, went through the 3 y of exile, and then lived a full 31 y on Rongelap Island after returning. However, both had less than 3.7 μBq in their 24-h urine samples or a committed effective dose about 0.37 mSv to age 70 y (Sun et al. 1995). This suggests that the impact on internal exposure of plutonium during the direct fallout in March 1954 was not significant. A similar conclusion

Table 3. Estimates of soil ingestion rates.

Study year	Estimate (mg d^{-1})		Applicable population
Schaum (1984)	100	Avg.	2–6 y, U.S.
	5,000	Max.	2–6 y, U.S., Habitual pica
LaGoy (1987)	500	Max.	Adult, U.S.
	5,000	Max.	Adult, U.S., Habitual pica
Haywood and Smith (1990)	1,000	Avg.	Adult, Aborigine
Robison et al. (1989)	10	Avg.	Adult, Marshallese Based on dietary intake
This work	500	Avg.	A lifetime average, Marshallese

Table 4. Outline of the f_1 value calculation with assumptions and related parameter values.

	The ^{239}Pu and ^{240}Pu activity ratio in the Bravo dust was taken to be 20:27.
Intake estimates	
A: Inhalation pathway	= 77 μBq d^{-1} (The products of 22 m^3 d^{-1} breathing rate times the plutonium concentration of 8 μBq m^{-3} times the ^{239}Pu and ^{240}Pu activity ratio). 10% of the inhaled plutonium particles are assumed to be deposited in the pulmonary region (AI). Hence, the deposited ^{239}Pu in lung is 7.7 μBq d^{-1}.
B: Ingestion pathway	
1. Via dietary intake	= 0.002 Bq d^{-1} (The products of 5 μBq d^{-1} diet intake rate times the $^{239+240}$Pu concentration of 8 μBq m^{-3} times the ^{239}Pu and ^{240}Pu activity ratio.)
2. Via ingested soil	= 0.032 Bq d^{-1} (The products of 500 mg d^{-1} intake rate times the soil concentration of 150 mBq g^{-1} times the ^{239}Pu and ^{240}Pu activity ratio.)
Uptake Estimates	
A: Via inhalation pathway	= (7.7 μBq d^{-1}) × (0.001 + 0.01) = 0.077 μBq d^{-1}, the fractional transferred to blood for Type S particles are 0.1% and 1% for instantaneously and cumulative absorptions, respectively (ICRP 1994).
B: Via ingestion pathway	= [(0.032 + 0.002) Bq d^{-1}] × f_1[a] (dietary plus ingested estimate given above).
C: Via 24-h FTA urinalysis	= 14.2 μBq d^{-1}.

[a] f_1 = urinalysis result − the uptake to blood via inhalation divided by the total ingestion activity. Therefore, f_1 = (14.2–0.077) μBq d^{-1} ÷ [(0.032 + 0.002) Bq d^{-1}] = 4.2 × 10^{-4}.

Table 5. Sensitivity analysis for f_1 value due to various soil ingestion rates for Marshallese.

Soil intake rate (mg d^{-1})	Plutonium intake from soil (Bq d^{-1})	Plutonium intake from diet (Bq d^{-1})	Total intake (Bq d^{-1})	f_1 Value
0		2.0×10^{-3}	2.0×10^{-3}	7.1×10^{-3}
10	6.4×10^{-4}	2.0×10^{-3}	2.6×10^{-3}	5.4×10^{-3}
30	1.9×10^{-3}	2.0×10^{-3}	3.9×10^{-3}	3.6×10^{-3}
50	3.2×10^{-3}	2.0×10^{-3}	5.2×10^{-3}	2.7×10^{-3}
100	6.4×10^{-3}	2.0×10^{-3}	8.4×10^{-3}	1.7×10^{-3}
200	1.3×10^{-2}	2.0×10^{-3}	1.5×10^{-2}	9.6×10^{-4}
300	1.9×10^{-2}	2.0×10^{-3}	2.1×10^{-2}	6.7×10^{-4}
500	3.2×10^{-2}	2.0×10^{-3}	3.4×10^{-2}	4.2×10^{-4}
1,000	6.4×10^{-2}	2.0×10^{-3}	6.6×10^{-2}	2.2×10^{-4}

was drawn from a study of bone samples of deceased Rongelap peoples who were on Rongelap Island (Franke et al. 1995). Therefore, all the estimated f_1 values presented in this study represent chronic exposure of the people of Rongelap to a plutonium-contaminated environment.

Influence of factors other than soil ingestion on estimates of f_1 values

Although the major assumption in this paper is that increasing the assumed soil ingestion rate thereby reduces the deduced f_1 value, other parameters which might also reduce the estimated uptake have been conservatively evaluated.

First, there was no allowance for the assumption that the specific activity associated with airborne plutonium is 2.5 times greater than that for the soil (Shinn et al. 1980); however, the top layer of soil can be expected to reflect the specific activity of that in the air. Then, it might be assumed that the ingested soil has a specific activity 2.5 times that of the soil averaged over 5 cm depth; such an assumption would lower the f_1 value by a factor of about 2. Second, there was no allowance for plutonium transfer during embryonic development following intake by the mother, which also would somewhat lower estimates of the value (~10%) (Morgan et al. 1992; Stather et al. 1992). Third, no allowance was made for a large f_1 value (about 10 times higher) during infancy. Since this enhanced uptake occurs over a relatively short period of life, the effect would be to lower the estimated f_1 value by a factor of 1.5. Fourth, there also was no allowance for intake through open skin cuts and wounds (Geiger and Sanders 1956; Piechowski et al. 1989). Such intakes could enhance uptake, thereby reducing the estimate of the f_1 value.

Marshall Islands soil was created from coral reef. Hence, the basic topsoil components in the Rongelap Atoll consist of sand, small fragments of marine shells, and hard corals. Therefore, plutonium in the soil samples from the Marshall Islands exists with lime enriched compounds.) Laboratory experimentation shows that bulk soil from the Marshall Islands can be easily dissolved in weak acids similar to those encountered during digestion (Simon[†]). It is likely that the f_1 value is governed both by the oxidation states of the plutonium and the compounds it binds with during digestion. This may explain why the f_1 value calculated for the people of Rongelap Island from plutonium oxide is about double the ICRP (1995) recommended value (f_1 = 10^{-5}).

CONCLUSIONS

The objectives of this study were to provide a method using urine data for assessing GI tract absorption constant and to determine an appropriate value for the Marshallese populations. All values for critical parameters for estimating the f_1 value for the Marshallese are based on environmental concentrations of plutonium in the Rongelap Islands and in low-level plutonium urinal-

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[†] Simon, S. L. Private communication, National Academy of Sciences, 2101 Constitution Ave, N. W., Washington, DC 20418 1995.

yses. In addition to the uncertainty associated with the methodology and measurements used in this assessment, there are other parameters that could influence the determination of the f_1 value. Because of both the Marshallese life style and the levels of plutonium present in the topsoil, we must emphasize the importance of estimating the most realistic soil ingestion intake rate for assessing the f_1 value. Overestimating the rate of intake could result in a fivefold overestimation of total intake for some individuals. Table 5 also shows that the most sensitive factor for estimating f_1 value is the soil ingestion rate (i.e., more important than dust resuspension, embryo uptake from the mother, and open skin absorption). The 500 mg d^{-1} soil ingestion rate is an assumed single value. Increasing the soil ingestion rate will decrease the f_1 value, and visa versa. Using both parametric and non-parametric statistics, 4×10^{-4} is found as a realistic f_1 value for the Marshallese.

The f_1 value of 4×10^{-4} calculated for adults is applicable to children as well. This value is in substantial agreement with studies in which plutonium was chronically fed to young animals (NRPB 1990) and with the values recommended for children ages 1 y and older (ICRP 1993). We conclude that the f_1 value of 5×10^{-4} recommended by the ICRP (1993, 1995) is the most appropriate one for assessing plutonium exposure to the Marshall Islands population.

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HISTORICAL EVENTS ASSOCIATED WITH FALLOUT FROM BRAVO SHOT—OPERATION CASTLE AND 25 Y OF MEDICAL FINDINGS

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Abstract—**The events prior to Bravo Shot-Operation Castle that led to a decision not to evacuate the Marshallese prior to testing the thermonuclear bombs are presented as are the actions taken after the fallout incident in evacuating the exposed Marshallese and the military personnel. The initial medical effects (findings during first 6 wk after exposure) are briefly described and are followed by description of long term effects, namely, induction of one case of fatal acute myeloid leukemia and a large number of thyroid tumors (benign and malignant) in addition to hypothyroidism in adults and children and two cases of cretinism. The hypothyroidism and cretinism responded well to administration of oral thyroxine. During the first 25 y, there was also much unrest and political agitation initiated by exposed and unexposed Marshallese who were very unhappy as a result of relocation and inability to return to their homelands and feeling that all illness and deaths were due to the mysterious radiation, which they understandably did not understand. The difficulties in part were ameliorated by financial aid from the U.S. Congress. In view of one of us (EPC), no one agency or person in the U.S. Government was willing to take the responsibility for care of the Marshallese and its financing. The exposed and non-exposed Marshallese had their lifestyle changed, some of their homelands made uninhabitable for several years and could aptly be called "nuclear nomads," an expression coined by others.**

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Key words: Marshall Islands; fallout; thyroid; health effects

INTRODUCTION

THE PURPOSE of this paper is to provide background information on who of the Marshallese were not evacuated prior to Operation Castle, an operation for testing of thermonuclear bombs in the Pacific Proving Grounds. In addition, we outline the response of the Commander Joint Task Force Seven (CJTF7) to the exposure of natives and military personnel to large amounts of fallout radiation and describe how both were evacuated. When the CJTF7 requested the Atomic Energy Commission (AEC) and Department of Defense to send a medical team to study and take care of the exposed Marshallese and military personnel, they turned to the Navy Medical Department and Armed Forces Special Weapons Project (AFSWP) for help since both had been concerned with study of biomedical effects of radiation at bomb test sites in Nevada and the Pacific. The three of us EPC, RAC and VPB had been associated with several atomic weapons tests from the first (Operation Crossroads). There were no plans for biomedical studies in Operation Castle and hence no qualified medical personnel were available within the Joint Task Force-7 (JTF-7) to perform such on the accidental casualties.

Cronkite, Conard and Bond had been actively pursuing radiobiological research at the Naval Medical Research Institute (NMRI) (EPC and RAC) and VPB at the U.S. Naval Radiological Defense Laboratory (USNRDL). All research had been directed toward potential therapy of acute radiation injury in human beings. In addition, EPC had reviewed the reports of the Atomic Bomb Casualty Commission to learn the mechanism of fatal irradiation injury in the Japanese casualties. Accordingly, all three were familiar with the various syndromes that could be produced by exposure to whole body irradiation and had the necessary security clearances for entry into the Pacific Proving Ground.

It is difficult to provide references since data or comments are based on voluminous Commander Joint Task Force operational orders and Radiological Safety Reports that are only available through the Defense Nuclear Agency, Washington, DC. These are listed in part in the references.

Prologue to Bravo Shot of Operation Castle

Joint Task Force Seven (JTF-7) Commander Lt. General Clarkson. During previous atomic tests, natives were protected by temporary relocations. Gordon Dunning, AEC Division Biology and Medicine (DBM) stated "the main objection to evacuation is the high cost and the logistic problems presented in supporting such an operation." CJTF-7 concurred emphasizing the military financial austerity for 1954 and the lack of ships and aircraft. If evacuation became necessary, the security ships of JTF-7 would be required to accomplish this upon request of Commander in chief of Pacific Fleet

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(CINCPACIFLT) who was designated to be responsible for safety of people outside of the designated test area by Commander in chief Pacific (CINCPAC) (Defense Nuclear Agency 1985).

Pretest

The maximum permissible exposure (MPE) for task force personnel was set at 3.9 R accumulating 0.3 R wk^{-1} for 13 wk. All exposure was assumed to be gamma radiation. Key personnel were anticipated to exceed 3.9 R. With the concurrence of the Surgeon Generals (SG) of the Army, Navy, Air Force and the Director, DBM AEC (John Bugher) the MPE for special personnel was set at 20 R, a dose considered *acceptable for the natives* (Defense Nuclear Agency 1985).

CJTF-7 was responsible for safety of Task Force (TF) personnel and was directed to advise CINCPAC about special hazards and danger areas within the purview of CINCPAC and outside of the area for which CJTF-7 was responsible. CINCPAC directed CINCPACFLT (13 January 1954) to assume complete responsibility for safety matters for CINCPAC and to take such actions as necessary to provide for the safety of all units and populated areas of the Pacific except those areas for which JTF-7 was responsible (Command Joint Task Force).

Dosimeters were not placed on the atolls occupied by Marshallese to determine the exposure rate nor were film badges or integrating dosimeters used to determine the total exposure (Defense Nuclear Agency 1985).

Analyses and recommendations made for future tests after Bravo

The BRAVO shot was estimated to explode at 6±2 MT. It detonated at 15±2 MT (Defense Nuclear Agency 1985). It was fired on land in Bikini atoll near NAMU.

The bulk of the native populations within 500 nautical miles (NM) resided in the southeast quadrant out of fallout area. The clouds with radioactive particles passed over Ailinginae, Rongelap, Utirik, and Ailuk depositing fallout and irradiating the persons below from the radioactive cloud (cloud shine).

The evacuation after Bravo was considered sound by the Task Force, was well executed, and could serve as a model for future tests.

The following features would enhance any future evacuation:

1. Provide ship captains that may be involved in evacuation with detailed maps of all Northern Atolls;
2. Inform native populations of upcoming tests so they would be prepared for unusual phenomena (intense light, noise, and shock wave and fallout);
3. Advise natives to return promptly to home islands if any unusual phenomena are observed so that all will be concentrated in one place for prompt evacuation; and
4. Provide dosimeters recording dose rate and integrating (film) for inhabited areas so that the dose from fallout and from cloud shine will be known.

The reasons for not evacuating natives were:

1. Economy imposed by reduction in military budget for FY 1954;
2. The notion that fallout would not be a problem was based on Operation Ivy experience (first thermonuclear explosions); and
3. Inadequate ships and aircraft to relocate Marshallese to safe areas.

The "Bravo" accident

A serious fallout accident occurred following the first test, "Bravo," a thermonuclear device at Bikini Atoll on 1 March 1954. In spite of some uncertainty about the weather, the device was detonated at 6 a.m. An unexpected shift in winds resulted in fallout on Marshallese on Rongelap, Ailinginae, Utirik and Ailuk Atolls, American servicemen on Rongerik Atoll, and Japanese fishermen on The Lucky Dragon. Several naval vessels, 30 miles east of Bikini, unexpectedly encountered fallout with white flakes falling on the decks of the ships. Flank speed retreat was ordered; the automatic wash down systems removed substantial amounts of fallout. Crews remained below deck minimizing exposure. Later several sailors developed mild radiation burns of the skin (Defense Nuclear Agency 1985).

The extensiveness and amount of the fallout emerged slowly because of confusing and overlapping events. Difficulties were encountered with the cloud-tracking planes. There was confusion about the radiological situation on Rongerik atoll. The men on Rongerik saw a mist 4 h after the blast. Seven hours later, the needle of a radiation-measuring instrument went off scale at 100 mR h^{-1}. The next day a radiological safety officer arrived by air. Due to the high levels of radiation, he evacuated personnel and recommended immediate surveys of Rongelap and Utirik. Radiation levels on Rongelap and Utirik resulted in evacuation of the people. Ailuk Atoll had measurable levels, but it was decided not to evacuate the 400 people on that atoll (Defense Nuclear Agency 1985).

The *Fukuru Maru* (Lucky Dragon), with a crew of 23 men, was about 80 miles east of Bikini. The fishermen saw the detonation from their ship. Soon a snow-like fallout covered the deck and stuck to the exposed portions of their bodies. The crew experienced nausea and vomiting for 24 h. The ship's captain decided to return to Japan, arriving 2 wk later. By this time, skin burns were developing and the crew was put into hospitals.

The Marshallese inhabitants of Rongelap saw the flash of the detonation describing it as "like the sun rising in the west" followed minutes later by a blast wave. In early morning a snowlike material fell for several hours covering the ground and adhering to the body. Water in the cisterns was said to turn yellowish. The health aide advised against drinking water but many people did. During the first two days several became nauseated, a few vomited and had diarrhea. On 3 March, the people on

Rongelap and Ailinginae were evacuated by plane and ship to Kwajalein (Defense Nuclear Agency 1985).

The 159 people on Utirik Atoll saw the flash of the detonation in the west and felt the blast wave. Fallout was not seen on Utirik. It was estimated that the fallout began at about 4:00 a.m. on 2 March (about 22 h after the detonation) and continued for about 4–5 h. The Utirik people did not have any cutaneous or GI symptoms. On 4 March, the Utirik people were evacuated by Navy destroyer to Kwajalein (Defense Nuclear Agency 1985).

Establishment of the initial medical program

On or about 4 March, one of us (EPC) was ordered to report immediately to the Navy Surgeon General's Office, Washington, DC. Already present were Shields Warren, M.D.,[†] past Director of DBM-AEC; John Bugher, M.D.,[†] the present Director, DBM-AEC; Charles Dunham, M.D.,[†] Director Medical Program and later Director of DBM; representatives of Armed Forces Special Weapons Program (AFSWP) and others.

The CJTF-7 had requested the Department of Defense and the AEC to organize a medical team to take care of the exposed natives and military personnel and to study the effects. The assistance of the Medical Department of the USN was requested and given promptly by Surgeon General Lamont-Pugh. The situation was described. EPC was given verbal orders to organize a team in conjunction with AFSWP and to be ready to depart within 48 h with necessary laboratory equipment. The services of V.P. Bond, M.D., Ph.D., USNRDL, were requested as were the services of R.A. Conard, Cdr. MC USN, two other Medical Officers and two Medical Service Corp Officers. Several enlisted personnel from NMRI and U.S. Naval Radiological Defense Lab (USNRDL) with appropriate security clearance were assigned to the team. A total of 25 persons was airlifted to Kwajalein (Conard et al. 1955).

It was believed that the dose to the Marshallese was sublethal (Cronkite et al. 1955). However, in addition to the medical team, second echelon help was identified. For example, a preventative medicine unit of the CINCPACFLT was alerted for possible bacteriological studies along with additional clinicians and nurses in case their services were needed. Rear Admiral Bartholomew Hogan, MC USN PACFLT Medical Officer, met with the medical team on landing at Oahu and promised support of medical facilities of the Pacific Fleet. With the preceding planning and backup, it was felt that medical problems that arose could be handled at Kwajalein.

En route Oahu to Kwajalein the physicians of the medical team discussed management of the exposed persons. They unanimously decided that we'd listen to estimates of the exposure dose of radiation but management of the casualties would be guided solely by developing signs and symptoms.

The medical team arrived at Kwajalein on 8 March 1954. The Commander U.S. Naval Station Kwajalein gave immediate support and within 24 h a functioning laboratory and clinic were available adjacent to housing for the natives.

On arrival at Kwajalein, a "letter of instruction" was given to EPC from Col. Gilbert, USAF establishing project 4.1 with EPC as project officer and requiring that all requests for support beyond that locally available be directed to Commander Task Group 7.1 Attn Commander Task Unit 13 placing a line officer between the medical team, the SG's and DBM AEC. Project 4.1 was classified Secret Restricted Data.

Summary of clinical observations

Full descriptions are published (Cronkite et al. 1955, 1956).

Nature of the event and exposed groups

The fallout consisted of fission products and included radioactivity adherent to flakes of CaO that fell on the inhabited islands of Rongelap, Ailinginae, and Rongerik. CaO was formed by incineration of coral (largely $CaCO_3$) (Cronkite et al. 1956). The flakes resembled snow on Rongelap, mist on Rongerik, and was invisible on Utirik. The flakes of CaO adhered to the skin, hair, trees, and buildings. The exposure of the individuals was from material adherent to the skin, the radioactive material on the ground, trees, and buildings. There was also an unknown increment of gamma radiation from the radioactive cloud as it passed by (cloud shine). The material adherent to skin and hair irradiated the skin and hair follicles with an unknown amount of mixed beta and gamma irradiation. The military personnel aware of the hazard, changed clothes, bathed and stayed inside the building, thus receiving a lesser dose to skin and deep tissues.

The Marshallese and Servicemen had been evacuated by air and ship to Kwajalein where the radioactive contamination of skin and clothes was still evident despite shipboard decontamination. Repeated washing of skin and hair was continued. Decontamination of hair of females was particularly difficult because of the heavy coconut oil hair dressing they used. On nearby Ailuk Atoll, about 400 natives with about same or lesser dose as Utirik were not evacuated.

Whole body gamma dose

Dose rate was determined at 3 ft above ground on Rongelap, Ailinginae and Rongerik several days after evacuation. Making assumptions about arrival time of radioactive cloud the doses were calculated for Rongelap and Ailinginae (Cronkite et al. 1956). On Rongerik the

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[†] Logistic support was complex—organization of medical teams, shipment of medical supplies and equipment, travel arrangements, setting up examination facilities on Rongelap and Utirik Islands, etc. Travel in the islands in the early years was by U.S. Navy and Trust Territory cargo ships. Later, a small ship with examination facilities was acquired. The U.S. presence in the islands brought in money and jobs, and since many people from Rongelap and Utirik migrated to the district centers at Ebeye and Majuro, additional examining facilities had to be set up in these centers.

arrival time was documented by a recording dosimeter. The dose rate was diminished by the decay of the short-lived isotopes. The dose from the cloud shine remains unknown; however, the consistency of the calculated doses with the doses that were measured by film in refrigerators on Rongerik increases the reliability of the dose to personnel on the atolls.

The external doses are listed in Table 1.

Characteristics of the gamma radiation and tissue dose distribution

The fallout on the ground constituted a large planar source. Spectrometric data of the mixed fission products and the degradation by Compton scattering in air resulted in a radiation field with maxima at 100, 700 and 1,500 keV. The total exposure is the sum of partial doses from each energy region. This, plus the planar source (radiation coming from all directions), resulted in a relatively high dose to the first 1–3 cm of tissue equivalent material, perhaps 8 times the midline dose. The absorbed dose throughout the rest of a tissue equivalent phantom man was quite constant (Cronkite et al. 1956).

The fallout occurred in a cigar-shaped pattern. In the easterly direction the 8 Gy isodose curve extended about 140 miles, 5 Gy about 160 miles, 3 Gy about 190 miles, and 2 Gy about 220 miles. The north-south distance for 2 Gy was roughly 40 miles with shorter distances for the higher isodose curves. A few miles north of the 2 Gy line might have been lethal. These doses are estimates of what would have accumulated over a 48-h period without shielding (Cronkite et al. 1956).

Clinical observations and management

Twenty eight percent of the Rongelapese, 20% of the Ailinginaeans and 5% of the military personnel experienced itching and burning of the skin. The natives on Utirik had no cutaneous symptoms.

During exposure there was burning of the skin, eyes and lacrimation that subsided (Cronkite et al. 1956). About 2 wk after exposure, itching, burning and pain became evident in areas of skin not protected by clothing. There were no constitutional symptoms associated with developing skin lesions. The sequence of signs and symptoms were subsidence of early symptoms, development of black pigmented areas, and increase in size of the lesions. Desquamation of the epithelium resulted in large depigmented areas. In some lesions ulcers developed and some became infected. Epilation, spotty in nature, occurred in some individuals. Hair regrew with normal color and texture. In one older man it regrew somewhat sparsely. Biopsies of lesions showed the typical appearance of radiation injury. The lesions healed. After healing, depigmented scars, particularly on the feet, were evident. The infected ulcers were treated successfully with antibiotic ointments. Details of skin lesions with color photographs are published (Cronkite et al. 1956).

The skin lesions were minimized in the military personnel who bathed, changed clothes and took shelter in aluminum buildings. Children who went wading had fewer and less severe burns of the feet. A single layer of cotton clothing gave almost complete protection. The legs and feet also received additional exposure from beta radiation from fallout on the ground.

Early constitutional symptoms

About two-thirds of Rongelap group were nauseated for 2 d. About one-tenth vomited and had diarrhea. These symptoms suggested significant radiation exposure (Cronkite et al. 1956).

There were no GI symptoms in military personnel or the natives from Utirik.

Hematologic observations

Blood counts (neutrophil, platelet and lymphocytes) are sensitive indicators of marrow suppression. Extensive simple hematologic studies were performed. Since there were no prior hematologic studies on the exposed Marshallese or any comparable group, it was necessary to establish a control group of non-exposed Marshallese of same age and sex distribution for comparative purposes.

Neutrophil count

The absolute count of all age groups fell during the second week to about 70–80% of the comparison population (Cronkite et al. 1956). Following this initial depression, the counts fluctuated around the comparison group until 30 d after exposure and then progressively decreased with minima being reached at 45 d after

Table 1. Doses to the exposed personnel and Marshallese.

	Total exposed	Arrival time fallout hours	Evacuation hours	Dose rate	Total gamma dose in air (Gy)
Rongelap	67	4–6	50–51	375 mR h^{-1} at 7 d	1.9
Ailinginae	18	4–6	58	100 mR h^{-1} at 9 d	1.1
Rongerik U.S. Personnel	28	6.8	28.5–34	280 mR h^{-1} at 9 d	0.78
Utirik	167	22	55–78	40 mR h^{-1} at 8 d	0.11
Marshallese Control	117				
American Control	105				

exposure. The depression of neutrophils was greater in children less than 5 y of age than in older children and adults (Cronkite et al. 1956). At 6 mo and 1 y after exposure, the neutrophil counts were close to the control population.

Further clinical observations and blood counts

Between 33 and 43 d after exposure the absolute neutrophil counts of Rongelapese were less than 1,000 mm^{-3}. The lowest count was 700 mm^{-3}. During this interval the question of prophylactic antibiotics was considered. The administration of antibiotics was not commenced because

- Individuals were seen daily. Temperatures were taken. If an infection were to develop, it would be discovered early and therapy commenced.
- Premature administration of antibiotics might obscure infectious processes and might lead to development of drug resistant commensal bacteria in individuals with lowered resistance to infection.
- There was no useful knowledge in 1954 of the number of granulocytes below which infections from commensal organisms might develop.

The clinical picture of the Rongelapese was significantly different from the Japanese exposed to atomic bombs. In Japan, the radiation was delivered in a short burst. The Marshallese were exposed over several hours with a decaying dose rate. Their granulocyte counts decreased slowly to about one-fourth of the normal values. Immature granulocytes were observed in the peripheral blood suggesting regeneration of the bone marrow. In the Japanese whose neutrophil counts fell precipitously to low levels, infections with septicemia developed with a high mortality.

During the fourth and fifth week after exposure, an epidemic of upper respiratory infections (URI) occurred in all Marshallese with fever and a purulent nasal and tracheal discharge for about 10 d. A similar URI occurred in the control population and Medical Team (Cronkite et al. 1956).

Platelet counts and hemorrhagic diathesis

In 11 individuals the platelets fell between 35,000 to 65,000 mm^{-3}. Individuals with platelets less than 100,000 mm^{-3} were examined daily for retinal bleeding, cutaneous petechiae, hematuria (microscopic), and women were questioned about excessive menstruation. At the nadir of platelet counts, two women had excessive bleeding. It subsided spontaneously (Cronkite et al. 1956).

The platelet counts were very slow (several years) in reaching the average of the control population (Conard 1992; Cronkite et al. 1956).

Pregnancy

Four Rongelapese were pregnant; two in first trimester, one in second, and one in third. In the Ailinginae group, one woman was in second trimester. The pregnant women had a significant thrombopenia. There was no vaginal bleeding. One baby was born dead; the others were normal. Whether irradiation was responsible for the stillbirth is unknown.

Lymphocyte counts

By 3 d after exposure, the lymphocyte counts were 50% of the comparison group. The decrease observed in children less than 5 y of age was more pronounced. The lymphopenia persisted through the initial observation and was still present at 6 mo, 12 mo, and for several years after exposure (Conard 1992; Cronkite et al. 1995).

Platelets

The maximum depression in platelet counts occurred at 28 to 30 d after exposure. The children less than 10 y of age had a greater percentage drop. The platelet levels commenced to recover 30 d after exposure, attaining a maximum on day 45 with a secondary drop and leveling off for the remainder of the post exposure period. There was a very slow recovery in average platelet counts to that of the control population (Conard 1992; Cronkite et al. 1995).

Internal deposition of radioactive materials: Early observations

The amount of internal exposure was derived by radiochemical urinalyses carried out beginning at about 2 wk after exposure. Only radioactive strontium (^{90}Sr) and iodine (^{131}I) were near the maximum permissible levels. No effects of any of these absorbed elements, except for radioiodine have been detected in the Marshallese people. The details of early internal contamination are published (Cronkite et al. 1956).

Since thyroid tumors developed and there was evidence of hypothyroidism, reevaluation of the thyroid dose was needed. It was based on the distribution of the iodine family of radioisotopes in fission products, their decay rates, arrival of fallout, time on the contaminated atolls, thyroid size as a function of age, the excretion of ^{131}I in 24-h urine samples at 17 d, the biological half-life and the measured ^{131}I in air samples. The major route of radioisotopes into the body was via ingestion. Inhalation was of minor importance. Details have been published by Lessard et al. (1985). The doses are shown in Table 2 for age and island groups.

Post Bravo care and responsibility for fallout casualties

CJTF-7 was responsible for temporary care and disposition. It was decided by higher authority to transfer the military personnel to Tripler General Hospital in Hawaii, and then they were returned to duty without any follow-up studies planned. CINCPACFLT was assigned responsibility for restoration of atolls with AEC assistance and for return of inhabitants at proper time and the Trust Territory Hi Com (Department of Interior) for routine welfare and medical care.

Table 2. Dose estimates (Gy) to the thyroid (Lessard et al. 1985).

Group	Age	External dose	Thyroid dose (ave–max) (Gy)
Rongelap (67 people)	1 y	1.9	50–200
	9 y	1.9	2–8
	Adult		1–4
Ailinginae (18 people)	1 y	1.1	13–52
	9 y	1.1	5.4–22
	Adult		2.8–11.2
Utirik (167 people)	1 y	0.1	6.7–27
	9 y	0.1	3.0–12.0
	Adult	0.1	1.5–6.0

On 24 April 1954, the project 4.1 medical team made detailed recommendations for life long observations to CJTF-7. The project 4.1 team did not visualize the development of thyroid problems. In 1954 there was no clear cut evidence of susceptibility of the thyroid to radiation effects other than ablation by high doses.

On 12–13 July 1954, a conference on "Long Term Surveys and Studies of Marshall Islands" was convened at USAEC, Washington, DC, at offices of John Bugher, Director DBM for planning future studies on the possible hazards of living on the contaminated atolls and care of the exposed Marshallese. The conference was classified Secret Restricted Data. It was chaired by John Bugher, M.D., Director DBM-AEC. In his opening statement Bugher emphasized that the U.S. holds the Pacific Islands Trust Territory (TT) including the Marshall Islands's in trust. The mandate was administered by a trusteeship under the Department of Interior. The U.S. held the right to withdraw such land as might be necessary for strategic and security purposes but beyond that *"to administer the whole area for the benefit of the people concerned"*.

Bugher expressed his pleasure at the apparent recovery of the exposed Marshallese but had reservation in respect to possible development of carcinoma in the beta burns of skin. It was concluded that there should be regular examinations of the Marshallese for 1) cancer, 2) cataracts, 3) growth and development, 4) general health, and 5) study of flora and fauna for radioactivity, uptake into food chain, and that the medical studies should be separate from the studies on flora and fauna. Bugher, in a prelude to development of plans and identification of personnel emphasized that 1) *there are groups with authority without capability and other groups with capability without authority*; 2) the Marshallese are not U.S. citizens; and 3) the Marshallese reside in a place that is not American territory. The U.S. under the UN Trusteeship is the Governing Authority (GA). The U.S. does not have sovereignty.

The GA delegated the Department of Interior as the administrative body with whom the Marshallese would deal through the Hi Com TT. The Hi Com did not have the scientific staff or the logistic resources to do the things that must be done.

The AEC accepted the responsibility for the continuing studies and care of the *exposed* Marshallese. The AEC has in part the scientific resources but does not have the necessary logistic support in the Pacific area.

Bugher clearly perceived the problems then present and that would emerge in the future with clairvoyance. No one organization in the U.S. had the responsibility, the authority, and the capability to do what the U.S. was mandated to do by the Trusteeship and was morally obligated to do. As time went on no one organization seemed to wish to see that the U.S. lived up to their obligations.

Bugher hoped that the same individuals and institutions involved with the initial event would be able to continue over the succeeding years, namely personnel at NMRI and USNRDL recognizing that personnel would change with time.

In a letter to Admiral Pugh (SG USN), Bugher solicited help and outlined the requirements for the continuing observations on the exposed Marshallese and their control population. At unspecified but regular intervals, physical exams, interval history, hematologic studies, search for cancer and leukemia, cataracts, growth of children, health of newborn and studies on internal deposition of radioisotopes in the exposed persons should be performed.

Financial responsibility would be assumed by DBM-AEC. The SG USN concurred and CINCPAC gave unreserved backing. The TT was happy with this relationship.

It was agreed that V. P. Bond of USNRDL would take a team of his selection for a 6-mo survey and that E. P. Cronkite would do the same for a 12-mo survey from NMRI in March 1955.

Long term plans were made for continuing medical surveys involving USNRDL, NMRI, USA, and USAF personnel. These plans were altered by the acceptance of Cronkite's request for resignation from the USN and employment in the Medical Department, Brookhaven National Laboratory, effective 1 October 1954. Bond also relocated from USNRDL to BNL in December 1954. DBM-AEC then decided to transfer responsibility for organizing continued studies to the Medical Department, BNL, in a letter from Bugher to AUI Trustees. He requested that Medical Department, BNL, assume the responsibility for the continuing medical surveillance of the Marshallese.

The 6- and 12-mo surveys showed the Marshallese to be in good general health. There was scarring from the beta burns in some individuals. There was no evidence of cutaneous cancer or hyperkeratosis.

In 1955, R. A. Conard's resignation from the USN was accepted and he accepted an appointment in Medical Department, BNL, with responsibility for directing the continuing medical surveillance of the exposed Marshallese and their comparison population. The responsibility for general medical care of other Marshallese was that of the TT (Department of Interior).

In 1956 July, an unclassified account of the effects of radiation on the Marshallese was published by the US Government Printing Office (Cronkite et al. 1956). It was preceded by publication of a short report in the Journal of American Medical Association (JAMA) (Cronkite et al. 1955).

Events Connected with Evacuation of Marshallese

Bishop Feeney S-J said "the people on Likiep were greatly excited by the light and the blast wave which arrived about 30 min after the light flash. Church attendance was greatly stimulated on the day of the test." (Defense Nuclear Agency 1985)

As a result of a high dose rate (375 mR h^{-1}) on Rongelap Island, evacuation was considered necessary. After a TT official requested evacuation it was accomplished by air and sea. Sixteen sick and elderly were removed by air and the remainder by ship. Decontamination by bathing and laundering was pursued aboard ship.

The ship proceeded to Ailinginae and picked up 18 Marshallese. Searches were made of other islands to be certain no Marshallese were left behind.

The *U.S.S. Phillip* arrived at Kwajalein on 4 March at 8:30 a.m., and the Marshallese were disembarked and taken to the USN Dispensary.

Evacuation of Utirik

Orders received by USS Renshaw on 3 March 1954 at dawn while on patrol north of Enewetak. Set course and speed to arrive at Utirik daylight of 4 March. Arrived at 6:30 a.m. on 4 March 1954. Fortunately the weather was good with light wind and moderate swells. At 7:30 a.m., the ship hove to about 500 yards south of Utirik Island on which all the natives were reported to live. TT officials had not arrived. The CO proceeded to organize the evacuation awaiting arrival of TT officials and interpreters.

At 7:40 a.m., the gig (26 ft MWB) was launched with beach party aboard. This team was to get ashore, organize the natives for evacuation and locate the best place and means for evacuation.

The team surveyed the village and collected water samples from wells. The water had low radiation levels probably due to roofs over each reservoir. The radiation levels varied from 100 mR to 160 mR h^{-}.

The TT representative arrived by plane. After being apprised of the situation, it was decided to evacuate the natives but to leave the livestock. A life raft was brought in to shuttle people from shore over the reef to a MWB waiting outside the reef. Women, children, and the elderly were first shuttled out to the MWB's, with men last. The skill of the natives and their willingness to help proved invaluable in getting across the reef. All natives were aboard and in their assigned quarters by 12:00 p.m. There were 47 men, 55 women and 52 children under 16 (26 boys and 26 girls). At 1:00 p.m., ship was secured and course was set for Kwajalein. The natives were monitored as they came aboard and had an average of about 7 mR h^{-1}, substantially less than the average of 20 mR h^{-1} on the beach. Transit through the surf apparently washed off a substantial amount of radioactivity.

Natives on Ailuk (about 400) were not evacuated for reasons discussed earlier.

Long-term follow up

Following the initial examinations, the exposed people of Rongelap including the Control population were examined at Majuro Atoll by a medical team from BNL headed by Conard who continued studies until his retirement 25 y later in 1979.

Examination schedules

The lack of significant findings during the first 2 y was encouraging. However, in view of studies of the Japanese exposed to the atomic bombs at Hiroshima and Nagasaki and of other irradiated populations, the exposed Marshallese were at greater than normal risk of late effects, such as leukemia and cancer. Therefore, it was recommended that annual examinations of the Rongelap people be continued indefinitely. In view of the small radiation exposure of the Utirik population, it was considered that examinations every 3 y would be adequate. The AEC approved and, with the concurrence of the TT, asked BNL to continue the examinations jointly with the TT.

Conard at BNL was asked to head up the program. It was understood that the Trust Territory would be responsible for the general health care, whereas the AEC mandate limited the medical team to the diagnosis and treatment of radiation effects in the exposed population along with the control population.

It was soon apparent that the general health care was not satisfactory. Therefore, the medical team, within its capability and time limits, expanded efforts to include many other conditions. Later, at the requests of the inhabitants of Rongelap and Utirik, the entire population on the islands was examined. When thyroid nodules developed on Utirik, annual examinations commenced.

Beginning in 1971 for about 10 y, a physician from BNL was stationed in the islands to monitor the thyroid treatment program and assist in follow-up care of the exposed Marshallese.

Conard retired in 1979. The surveys of 1980–1981 were headed by Cronkite and Pratt. From 1981–1990, the program was headed by Adams and since 1990 by Howard.

The examinations have continued on an annual (later semi-annual) basis. By 1957, radiological surveys indicated that Rongelap was safe for habitation. A new village was built and the people returned. Examinations were conducted there until 1985 when local politicians decided the island was not safe and the people were again evacuated to a small island in Kwajalein Atoll and the examinations have continued there since then.

Outstanding physicians in many specialties and subspecialties and technicians from the United States participated in the examinations, including endocrinologists specializing in thyroid problems. They provided extremely important diagnostic, therapeutic, and technical capabilities. Equally important has been the participation of a large number of medical personnel (practitioners, technicians, health aides, and nurses) from the Health Services of the Marshall Islands who contributed in carrying out the examinations, obtaining medical histories, and in acting as interpreters.

Problems associated with the examinations

Before presenting the late medical findings, some of the problems affecting the examinations are pertinent.

Carrying out the examinations in these distant islands was a complex undertaking and could not have succeeded without the support of many government agencies, e.g., Department of Energy, Department of Interior, Department of Defense and authorities in the Marshall Islands.[†]

The medical teams were faced with the medical care of people with different backgrounds, lifestyles, customs and language. The language barrier made it difficult to communicate with people even with the Marshallese interpreters. Efforts to help the people understand the need for and results of the examinations and the effects of radiation exposure were disappointing. They were afraid of this unseen, unfelt, "poisonous powder" and its effect, and this became a strong psychological factor. They continued to believe that every ailment and every death was somehow related to radiation exposure.

It is understandable that with the disruption of their lives, the development of radiation effects, and the contamination of their islands, there was increasing bitterness towards the United States about the accident and, justifiably, increasing demands for compensation.

Unexpectedly in the 1970's, local politicians and lawyers representing the people and certain Japanese groups instigated actions that concerned the medical team. In 1972 the medical team after arrival at Rongelap had to cancel the examinations due to political interference.[‡]

Following this difficult period, it was encouraging that there ensued a marked improvement in attitude toward the program. There were several possible reasons for this: the favorable report of the medical observers to the Congress of Micronesia on the conduct of the examinations; efforts to increase communication with the people about the effects of radiation and the objectives of the program, increased efforts to expand primary health care and, last but not least, the increased response of the United States in compensation settlements.[§]

Miscellaneous late findings

Examinations of the exposed Rongelap people at 6 mo showed that they largely had recovered from the acute effects and were generally in good health. No deaths were attributable to radiation exposure. There was further recovery of the blood elements, though they were not yet up to normal levels.

Stillbirths and miscarriages

During the first decade after the accident, there were few findings that could definitely be associated with radiation exposure. There was an increase in miscarriages and stillbirths in the exposed Rongelap women, but the numbers were small and it is uncertain if this increase was related to radiation effects (Conard et al. 1980). Based on birth rate, fertility has been about the same in the exposed and in the unexposed groups (Conard et al. 1980).

Eye examinations

Regular examinations of the eyes, including slit-lamp studies for cataracts, have not revealed any radiation-induced effects.

Growth and Development

Anthropometric measurements (height, weight, osseous maturation, etc.) in exposed Rongelap children and matched unexposed children revealed that beginning a few years after exposure some of the exposed children, particularly boys less than 10 y of age, lagged in growth. Growth deficiencies were result of hypothyroidism and were corrected by thyroxin therapy (Cronkite et al. 1995).

Late effects on skin

Examination of the skin showed slight scarring and pigment changes in areas of the lesions, and a few benign nevi developed in areas of neck burns in a few people. One skin cancer was found recently in an area of former lesion.

[‡] The criticisms increased and the years 1972 to about 1977 were troublesome. Unexpectedly, the Japanese anti-A and H-bomb groups became involved with the Marshallese politicians in criticizing the way the fallout victims were being handled. These groups were very active in Japan and created much publicity concerning the fallout exposure of the Japanese fishermen on the *Lucky Dragon*. The Marshallese politicians were greatly angered when the Trust Territory Government refused to allow a Japanese group that they had invited to visit Rongelap to examine the exposed people and the group had to return to Japan. This action precipitated a cascade of events: the abortion of the 1972 medical examinations after the team had arrived at Rongelap due to political interference; the formation of a special investigative committee on Rongelap and Utirik by the Congress of Micronesia with arrangements for medical observers to accompany the examinations.

[§] In 1966, $950,000 were granted the Rongelap (about $11,000 per person). In 1974 a "Survivor's Fallout Bill" furnished travel and per diem funds for persons requiring hospitalization. In 1978 compensation was paid to Rongelap individuals with radiation injuries. In 1986, the new Republic of the Marshall Islands and the United States agreed to a "Compact of Free Association" to last for 15 y. The United States provided $750 million for fiscal support, $150 million of which was for claim, including injuries related to nuclear testing. Based on a list of possible radiation-related illnesses, a local Nuclear Claims Tribunal has received numerous claims from individuals throughout the Marshalls.

Possible genetic effects

Examination of children born to exposed parent or parents, based on the incidence of gross anomalies, has not revealed evidence of genetically inherited defects. Neel was unable to demonstrate any inherited genetic effects in blood samples from the Marshallese (Conard et al. 1980).

Lisco and Conard (1967) found a number of two break chromosomal aberrations (dicentrics, translocations and a ring form) in cultured lymphocytes in the exposed Rongelap at 10 y after exposure.

Degenerative diseases

The incidence of degenerative disease (cardiovascular, arthritis, nephrosclerosis) is not greater in the exposed Marshallese as of 25 y after exposure (Conard et al. 1980). Studies of aging, using a battery of nonspecific tests did not reveal evidence of radiation-induced premature aging (Conard et al. 1966).

Thyroid dysfunction

Diverse thyroid abnormalities were the major late effects. First nodules appeared in a 12-y-old girl 9 y after exposure. About one-third of exposed Rongelap developed thyroid abnormalities, the largest incidence was in children exposed when less than 10 y of age whose small thyroids had a higher dose from same amount of radioactive iodine ingested or inhaled (Lessard et al. 1985).

The relationship of growth retardation in children to hypothyroidism was not appreciated at first since the Marshallese have a high level of iodinated protein in their blood (Robbins et al. 1967). When radioimmuno assays for thyroid hormones became available, the depressed thyroid hormone was detected and replacement therapy commenced with success. Details of thyroid function in the Marshallese adults and children are described in Conard et al. (1980).

In 1966, on the advise of a panel of thyroid experts, the exposed Rongelapese (later the Ailinginae group) were put on lifetime thyroxine replacement therapy in the hope of reducing the development of thyroid tumors. Compliance with the program by the people has not always been satisfactory. The thyroxine treatment has not been completely successful. Some people on therapy developed tumors. The treatment has been most rewarding in promoting normal growth in the children that showed growth retardation.

Surgical removal of the thyroid nodules in both the exposed and control populations was carried out usually in hospitals in the United States. (In a few cases because of age or health, surgery was not done). Metastases to the lymph nodes in the neck had occurred in some cases but distant metastasis was not noted. Recovery from surgery was uncomplicated and no fatalities have occurred related to thyroid cancers.

Hypothyroidism. Hypothyroidism and cretinism were observed. Two infants exposed on Rongelap had estimated doses of 50 to 200 Gy (Lessard et al. 1985). The real dose is more likely close to 50 Gy. When treated with thyroxin, normal growth ensued (Conard et al. 1966; Robbins et al. 1967; Sutow and Conard 1969; Conard et al. 1970).

Two Rongelap children exposed *in utero* later developed benign thyroid tumors suggesting that radioiodine from the mother may have been partly responsible for the thyroid tumors (Conard et al. 1980).

Thyroid adenomata and cancer. The revised thyroid doses are published in detail (Lessard et al. 1985). Adenomata commenced appearance about 10 y after exposure. The incidence peaked at between 12 and 14 y and declined thereafter to a low incidence. The higher doses also resulted in a shorter latency before appearance. The early adenomata appeared in individuals who had thyroid exposures in range of 0.02–50 Gy whereas later appearing adenomata occurred in people whose thyroid had 2 to 20 Gy. Thyroid cancer occurred in individuals whose thyroid had 2.5–30 Gy. No cancers observed in individuals when thyroids received more than 30 Gy.

Benign adenomata increased in incidence from exposure to 2.5 Gy or more radiation. Hypothyroidism was observed in individuals whose thyroid received in excess of 54 Gy. There are simply not enough cases to draw any conclusion in respect to a dose effect relationship.

Leukemia

One case of acute myeloblastic leukemia developed in a boy age 19 y, exposed to 1.9 Gy at 1 y of age. This leukemia was probably due to exposure to radiation. One case of leukemia also occurred in the control population in a male age 63 y.

Longevity

Survival curves for the people exposed on Rongelap, Ailinginae, Utirik and Rongelap unexposed people show there is no significant difference. Actually of those exposed on Rongelap and Ailinginae, there was a slightly higher fraction alive in 1986 (Conard et al. 1992).

Internal deposition of radioactive materials

The amount of internal exposure was derived by radiochemical urinalyses carried out beginning at about 2 wk after exposure. Only radioactive strontium (^{90}Sr) and iodine (^{131}I) were near the maximum permissible levels. Based on later studies, plutonium, a long-lived element, was present in small amounts and well within the federal guidelines. By 6 mo, there was barely detectable radioactivity in the urine of the Rongelap people. Table 3 shows the early mean body burden of the Rongelap group for isotopes other than radioiodine.

In view of the extensive later development of thyroid abnormalities (largely from radioiodine exposure), it became apparent that the original doses estimated to this organ were too low; and re-evaluation of the doses received by the Marshallese is shown in Table 2. The dose from the iodine family of radioisotopes is discussed in detail by Lessard et al. (1985).

Table 3. Mean body burden of Rongelapese in early period after exposure.

Radioisotope	μCi at 82 d	USNRDL μCi at 1 d	LASL μCi at 1 d
^{90}Sr	0.19	1.6	2.2
^{140}Ba	0.021	2.7	0.34
Rare earth group	0.03	1.9	—
^{103}Ru	—	—	0.013
^{45}Ca	0	0	0.016 (μg)

Internal deposition of radioisotopes

In addition to the medical studies, the BNL Medical Team assumed responsibility for personnel monitoring of the Rongelap and Utirik people and the Bikini people who returned to their home island in 1969. In 1978, environmental and personnel monitoring were transferred to the Safety and Environmental Protection Division of BNL.

During the first few years after the Bikini people returned to their islands, the levels of exposure were low. However, by 1978, due to availability of plant foods, there was a sudden increase in whole body levels of ^{137}Cs and ^{90}Sr, and the people were evacuated again.

At the time of return of the Rongelap and Utirik people, radioactive elements of concern were cesium (^{137}Cs, a gamma emitter with a half-life of 30 y), strontium (^{90}Sr, a beta emitter with a half-life of 28 y), and zinc ^{65}Zn, a gamma emitter with a half-life of 247 d). Small amounts of other radioactive elements, such as cobalt (^{60}Co) and iron (^{55}Fe) were of less concern. The radioactive iodines decayed. The other radioactive elements, cesium and strontium, were found in low amounts mainly in the pandanus, coconuts, breadfruit, and arrowroot plants grown on the islands. Unexpectedly high levels of radioactive cesium and strontium were found in the coconut crab, a great delicacy to the Marshallese (n Rongelap they were temporarily banned from the diet). The doses from the above radioisotopes were not much different from the doses received by U.S. citizens (Conard et al. 1992).

A whole body counter of several tons was built and shipped to the Marshall Islands for determination of body burden of gamma emitters. In 1957, the Rongelap people were returned to Rongelap. Their body burden of ^{137}Cs on return was negligible. One year later the body burden was 25,000 Bq, remaining at this level for about 2,500 d and then decreasing so that at 8,000 d after rehabitation it was 5,000 Bq. By 9,800 d the level was about 500 Bq.

EPILOGUE

There is a long, sad and tangled story of confusing top level management in the U.S. Government in which no one person or agency seemed willing to take the responsibility, finance, or assign authority for getting the job done. Most everything that Bugher had described in 1954 July resulted in confusion and failure to assign responsibility and arrange long term financing of the Marshallese programs for which the U.S. was responsible.

After the initial examinations were completed, the AEC decided to move the Utirik people back to their home island since the low residual radiation levels were considered safe for habitation. In 1954, they were returned and provided with supplementary food. However, surveys of Rongelap Island showed that radiation levels were too high to permit the people to return. Therefore, they were moved to temporary quarters set up for them on a small island (Ejet) at Majuro Atoll several hundred miles south of Kwajalein. Following our initial examinations of the American servicemen, they were taken to Tripler Army Hospital in Honolulu for further examination by Army physicians. Lifetime studies were not initiated as recommended to the CJTF-7 and was suggested in the JTF Radiological Safety Volume 1 (Defense Nuclear Agency 1985).

The Utirik people also developed a few thyroid tumors. It is unclear whether this is a characteristic of the Pacific Islanders or was due to radioiodines. Studies continue on body burdens of radioisotopes considered in other presentations in this issue of *Health Physics*.

The displacement of the Bikinians resulted in a major change in lifestyle, diet, etc., which may have contributed to diabetes, its deleterious effects on health, etc., whereas the Bikinians and residents of other atolls have probably not been exposed to harmful levels of radiation. They have been subjected to major psychological trauma from repetitive relocation and are aptly called "nuclear nomads" by Weisgall (1994).

In 1985, the Rongelapese were removed from Rongelap to Kwajalein because they believed all of their health problems were due to radiation.

With transfer of responsibility for internal contamination the Medical Team was no longer responsible for the measurements of radioactivity in foodstuffs or body burdens.

Summary

1. The exposure of the Marshallese and the military personnel showed that fallout from a nuclear explosion may have major health effects.
2. In the case of Bravo short term effects were:
   a. Nonfatal depression of blood cell production in Marshallese and Americans;
   b. Skin burns from beta emitting fission products;
   c. Measurable internal contamination of several fission products;
3. Longer term effects:
   a. One case of acute myeloid leukemia;
   b. Unexpected serious effects of radioiodine family on thyroid function.
      1. Hypothyroidism children and adults
      2. Cretinism: two boys
      3. Thyroid tumors (benign and malignant)

Lifetime observation of Marshallese and military personnel was recommended. Military personnel were not followed for reasons not clear to us.

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Paper

MORTALITY OF VETERAN PARTICIPANTS IN THE CROSSROADS NUCLEAR TEST[†]

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Abstract—**Operation CROSSROADS, conducted at Bikini Atoll in 1946, was the first post World War II test of nuclear weapons. Mortality experience of 40,000 military veteran participants in CROSSROADS was compared to that of a similar cohort of nonparticipating veterans. All-cause mortality of the participants was slightly increased over nonparticipants by 5% ($p < .001$). Smaller increases in participant mortality for all malignancies (1.4%, $p = 0.26$) or leukemia (2.0%, $p = 0.9$) were not statistically significant. These results do not support a hypothesis that radiation had increased participant cancer mortality over that of nonparticipants.**

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Key words: Marshall Islands; health effects; radiation, low-level; mortality

INTRODUCTION

In November 1983, the Congress of the United States passed Public Law 98-160 that directed the Veterans Administration (VA) to provide for the conduct of epidemiological studies of the long-term adverse health effects of exposure to ionizing radiation from detonation of nuclear devices. In response, the Medical Follow-up Agency (MFUA), then in the Commission on Life Sciences, National Academy of Sciences (NAS), proposed to compare the mortality experience of veteran participants in the CROSSROADS nuclear test to a similar group of nonparticipants. Operation CROSSROADS involved approximately 40,000 military personnel, mostly Navy, and occurred in July of 1946 at Bikini Atoll in the Marshall Islands.

The VA convened an *ad hoc* scientific committee to review the NAS proposal, which recommended that it be funded[‡] to "enlarge the growing body of information relating to the effects of low levels of radiation on human populations." The study was begun in September 1986, and, in 1988, a committee of the Institute of Medicine was organized to provide guidance and advice to the MFUA staff on the conduct of the study. The study was interrupted by the untimely death of the principal investigator, Dennis Robinette, in 1992. In 1994, the study was resumed culminating in the October 1996 publication of the report (Johnson et al. 1996).

MATERIALS AND METHODS

Mortality experience was evaluated for the approximately 40,000 U.S. Navy personnel who participated in Operation CROSSROADS, a 1946 atmospheric nuclear test series that took place at Bikini Atoll in the Marshall Islands (DNA 1984). To judge whether that mortality experience was influenced by CROSSROADS participation, those personnel were compared to a control group assembled to be similar to the participants in all ways (age, paygrade, military service, time of service, location of service) possible except for Operation CROSSROADS participation.

A roster of CROSSROADS participants was assembled and provided to the Medical Follow-up Agency (MFUA) by the Nuclear Test Personnel Review (NTPR) program of the Defense Nuclear Agency.[§] A validation study by MFUA examining other sources of information regarding participant status[||] found that the final roster captured between 93 and 99% of the military personnel who participated in Operation CROSSROADS. The

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[§] In June 1996, the Defense Nuclear Agency became the Defense Special Weapons Agency.

[||] Comparisons were made with a roster of CROSSROADS participants from the National Association of Atomic Veterans and a roster compiled from direct solicitation of information from veterans by MFUA.

mortality data gathered from Department of Veterans Affairs (VA) records were validated by sample comparisons with other national data sources.[¶] By the study cut-off date, 31 December 1992, 31.3% of the participants and 30.8% of the comparison cohort were known to have died. Cause of death was available for 86.3% of the participants and 89.3% of the controls.

Adjusting for remaining differences between the cohorts in distributions of age and paygrade, we compared, using proportional hazards analysis, the survival times of the two groups (SAS Institute 1992). Because available dosimetry data were not considered suitable for epidemiologic analysis (IOM 1995), we based this study on exposure surrogate groups. We looked at three principal causes of mortality: all-cause, all-cancer, and leukemia, hypothesizing that increases in the latter two could result from radiation exposure. For descriptive purposes, we also compared mortality for participants and the comparison group for 44 other disease categories.

RESULTS

Among Navy personnel, the primary analysis group for this study, we found that participants at the CROSSROADS nuclear test experienced higher mortality than a comparable group of nonparticipating military controls. The increase in all-cause mortality was 4.6% [relative risk (RR) = 1.046, 95% confidence interval, 1.020–1.074] and was statistically significant ($p < 0.001$). For malignancies, the elevation of mortality was lower—RR = 1.014 (0.96–1.068)—and was not statistically significant ($p = 0.26$). Similarly, leukemia mortality RR was elevated to 1.020 (0.75–1.39), but not significantly ($p = 0.90$) and by less than all-cause mortality. The increase in all-cause mortality did not appear to concentrate in any of the disease groups we considered. Of the 44 other specific cancers and disease categories we examined, there were no statistically significant increases in mortality. The overall elevation of mortality rate ratios for malignancies and leukemias in the participants were not statistically significant and, in fact, were lower than for many other causes of death.

Navy mortality due to all malignancies and leukemia did not vary substantially among our exposure surrogate groups (i.e., those who boarded target ships after a detonation vs. those who did not, and those enlisted personnel who had an Engineering & Hull occupational specialty vs. those in other specialties).

Participants who boarded target ships were thought to be more highly exposed than the rest of the participant group. Relative to the controls (nonparticipating comparison group), boarding participants experienced a 5.7% increase in all-cause mortality, RR equal to 1.057 (1.014–1.10), $p = 0.0093$, whereas the nonboarders (less exposed participant group) experienced a 4.3% increase [RR = 1.043 (1.015–1.073), $p = 0.0028$]. Aside from all-cause mortality, risks for boarding participants did not significantly exceed those for controls for any of the disease categories, and risks relative to controls were similar for boarding and nonboarding participants. The increase in risk for all-malignancies among the participants was 2.6% [RR = 1.026 (0.94–1.12), $p = 0.55$] for boarders and 1% [RR = 1.010 (0.95–1.068), $p = 0.73$] for nonboarders. For leukemia, the increase in mortality risk for boarders was 0.7% [RR = 1.007 (0.61–1.66), $p = 0.98$] and for nonboarders 2.4% [RR = 1.024 (0.737–1.422), $p = 0.89$]. In all cases the 95% confidence intervals overlap, suggesting the difference between boarders and nonboarders could well be due to chance.

Those Navy participants holding an Engineering & Hull (E&H) occupational specialty were thought to be more highly exposed to radiation than their non-E&H counterparts. However, the E&H participants had essentially the same risk of mortality from all causes as non-E&H participants [RR = 0.99 (0.95–1.038), $p = .81$]. For all malignancies and leukemias, the rate ratios were somewhat higher, 1.051 (0.97–1.14) and 1.51 (0.94–2.44), respectively, but both could be attributed to chance ($p = 0.25$ and 0.088, respectively). Risk ratios for leukemia and malignancies among E&H controls showed a similar elevation relative to non-E&H controls, suggesting that a factor specifically associated with CROSSROADS was not likely to have been the cause.

DISCUSSION AND CONCLUSIONS

These findings do not support a hypothesis that exposure to ionizing radiation was the cause of increased mortality among CROSSROADS participants. Had radiation been a significant contributor to increased risk of mortality, we should have seen significantly increased mortality due to malignancies, particularly leukemia, in participants thought to have received higher radiation doses relative to participants with lower doses and to unexposed controls. We did not observe any such effects. We note, however, that this study was neither intended nor designed to be an investigation of low-level radiation effects, *per se*, and it should not be interpreted as such.

In comparing the findings and methods employed in this study with those of other investigations of atomic veteran mortality (Robinette et al. 1985; Darby et al. 1988, 1993; Watanabe et al. 1995), we have identified a possible self-selection bias in the participant cohort: participants who died of a disease (particularly cancer) may have been more likely than healthy participants to have identified themselves to the NTPR, and hence become a part of this study. Such a bias would have resulted in an apparent increase in death rates among the participants. We do not have data with which to make a good quantitative estimate of this potential bias. However, the roster of participants is nearly complete, and mortality from all malignancies and leukemia was lower, not higher, than the increase in all-cause mortality. These factors suggest that a self-selection bias was not entirely

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[¶] We used data from the Health Care Financing Administration and the National Death Index, National Center for Health Statistics. All statistical tests are two-sided.

responsible for the finding of increased all-cause mortality in study participants.

The elevated risk of all-cause mortality in CROSSROADS participants relative to a comparable military comparison group is probably the result of two factors. The first is an unidentified factor, other than radiation, associated with participation in, or presence at, the CROSSROADS test. The second is a self-selection bias within the participant roster. However, the relative contributions of these two explanations could not be accurately determined.

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THYROID DISEASE AMONG THE RONGELAP AND UTIRIK POPULATION—AN UPDATE

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Abstract—**In 1954, 253 Marshallese were accidentally exposed to fallout radiation from the hydrogen bomb, BRAVO. The Marshall Islands Medical Program (MIMP) was established by the Department of Energy in 1955 to monitor and treat radiation-related disease pursuant to this accident. Medical teams from Brookhaven National Laboratory, a federal institution, regularly visit the Marshall Islands to give medical care to the exposed population. The most significant complication of the exposure has been found to be thyroid disease due to the ingestion of radioactive iodides from the fallout. In 1963 the first thyroid nodules were found in Rongelap subjects and in 1969 in Utirik. Non-neoplastic adenomatous nodules were associated with higher doses of radiation and neoplastic nodules developed in individuals receiving lower doses of radiation. Women were more susceptible to the development of palpable thyroid nodules than men. In 1994 the MIMP initiated examination of the thyroid by ultrasound to supplement the clinical examination. One hundred and sixty-four patients were evaluated. No significant differences were found in the incidence of thyroid nodules or the mean nodule count between the three groups of Rongelap and Utirik exposed and a comparison patient population. There was no significant difference in the incidence of thyroid nodules in males vs. females. Five exposed patients were referred for surgical excision of a nodule detected only by ultrasound. These ultrasound findings are unexpected in that females are known to have a higher incidence of thyroid disease than males and we expected that the incidence of ultrasound nodules would be higher in the exposed population.**

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Key words: thyroid; radiation effects; fallout; Marshall Islands

INTRODUCTION

THE MARSHALL Islands are located in the eastern part of Micronesia just north of the equator. They became the site of post-World War II testing of nuclear devices from 1946 until 1958. On 1 March 1954, a thermonuclear device, BRAVO, was detonated on Bikini atoll. An unexpected change in the wind direction resulted in the distribution of fallout over the inhabited atolls of Rongelap and Utirik as well as American military personnel and Japanese fishermen on board a vessel, The Lucky Dragon. Details of the accident and its acute effect on the Marshallese were published by Cronkite et al. (1955). The exposed Marshallese population originally was comprised of 64 persons on Rongelap Atoll who received on the average an estimated 190 cGy (1 cGy = 1 rad) of whole body external gamma radiation, 18 on nearby Ailingnae Atoll who each received 110 cGy, and 159 on Utirik Atoll who each received 11 cGy. Three women on Rongelap, one on Ailingnae, and eight on Utirik were pregnant at the time of exposure. Fallout material settled in the area, particularly on thatched roofs, open water cisterns and food. It contained significant quantities of radioactive iodides, which were ingested by the population. Therefore, the dose to the thyroid gland was much greater than the whole body dose, the magnitude of which was a function of age and gender as well as island (Lessard et al. 1985). Rongelap Atoll was maximally exposed and the estimated average dose to the thyroid was as high as 5,200 cGy in a 1-y-old child and as high as 1,300 cGy in an adult female. As a consequence, thyroid disease is the main complication of the exposure to the fallout.

The Marshallese were initially examined and treated by physicians of the U.S. Navy. The following year in 1955, the Marshall Islands Medical Program (MIMP) was established at Brookhaven National Laboratory (BNL). Its purpose is to monitor and treat the exposed Marshallese for radiation-related illness. In 1957, a comparison group (defined below) was selected on an age- and sex-matched basis (Conard et al. 1958).

Recently in the program, clinical examination of the thyroid has been supplemented by thyroid ultrasound and many more thyroid nodules have been detected in the Marshallese population by this modality. The analysis of the results of both methodologies of examination is presented below.

MATERIALS AND METHODS

Since the inception of the program, patients have been given a comprehensive physical examination on an annual basis[†] and a follow-up examination as indicated at 6-mo intervals following the guidelines of the American

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[†] Utirik patients were initially examined less frequently.

Cancer Society for cancer surveillance. Between 1964 and 1990, all palpable thyroid nodules were surgically resected.

For this study three subject groups have been defined: Rongelap (comprised of Rongelap and Alingnae), Utirik, and comparison. The Rongelap and Utirik groups consist of those individuals living on Rongelap and Utirik, respectively, at the time of the accident and therefore exposed to fallout. There were in 1954, 86 Rongelap exposed individuals and 167 Utirik exposed individuals thus making a total of 253 exposed individuals. The comparison population is comprised of Rongelap individuals who were not living on Rongelap at the time of the accident and therefore were not exposed to fallout. This group was originally selected principally from Rita on Majuro Atoll in 1954 and consisted of 115 Marshallese originally from Rongelap (Conard et al. 1980). They were age- and sex-matched for the exposed population. By 1957, attrition by emigration required the addition of other unexposed Rongelap Marshallese to provide an adequate number of patients for this comparison population. The total comparison population eventually under examination comprised 227 individuals. The Rongelap exposed individuals as well as the comparison group were repatriated back to Rongelap three years after the accident. In 1985 they were relocated again off Rongelap. The Utirik group was repatriated back to Utirik 3 mo after the accident and has remained on Utirik.

In 1965, 2 y after thyroid nodules were first detected in the Rongelap exposed population, administration of thyroxine for the purpose of suppression of the development of thyroid nodules in this group was begun. Subsequently, this therapy was extended to the Ailingnae exposed population. Utirik patients to date are not routinely managed with thyroxine suppression. Use of thyroxine in these individuals and in the comparison population is by clinical indication only. Compliance with the regimen has been variable.

At the beginning of 1994 there were remaining of these three patient populations 54 Rongelap exposed individuals, 86 Utirik exposed individuals, and 109 comparison individuals. That year (1994) thyroid ultrasound was initiated as part of the examination procedure. An experienced endocrinologist, who was unaware at the time of examination of any ultrasound results, performed the clinical examination of the thyroid. All exposed patients who presented themselves for examination underwent thyroid ultrasound in the spring 1994 mission. For the fall 1994 mission this selection criteria was expanded to include the comparison population as well. That year ultrasound was performed on 47 Rongelap exposed persons, 70 Utirik exposed persons, and 47 unexposed comparison patients for a total 164 patients, including surviving surgical patients. These patients had undergone a partial thyroidectomy for benign disease or usually a total thyroidectomy for malignant disease. Thus, the percent of the available population who underwent ultrasound was 87% of Rongelap exposed, 81% of Utirik exposed, and 43% of the comparison unexposed. The mean age of this examined exposed population in 1954 was 11.3 y, standard deviation (SD) 11.3. Thus, the mean age of this population at the time of their ultrasound was approximately 51 y. Ultrasound examinations were performed with the subject's neck in an extended or neutral position with a General Electric[‡] RT 3200 Advantage II in real time using a 7.5 MHz linear array transducer.

Based on the criteria discussed with Jacob Robbins of the National Institutes of Health, who has been a consultant to the MIMP (Jacob Robbins, personal communication), any patient having a nodule with the greatest dimension at least 1 cm, or at least 0.5 cm when features sometimes associated with malignancy such as hypoechegenicity or solid appearance are noted (James et al. 1991), was considered for fine needle aspiration (FNA). FNAs were performed under ultrasound guidance using local anesthesia with a 22–25 gauge needle, depending upon the preferences of the operator. The slides were spotted with the aspirate material and spread using a second slide and then immediately fixed in methanol. At least one slide was stained with a modified Wright stain the day of the procedure for review by the endocrinologist. All slides were sent to MetPath[‖] for formal reading by its pathologist.

Thyroid stimulating hormone (TSH) assays were performed using the IMx Ultrasensitive hTSH method of Abbott Laboratories.[§] Thyroglobin levels were performed by MetPath.[‖]

The histopathologic classification of thyroid nodules surgically removed through 1989 (as a result of clinical palpation) is based on the diagnostic categories of the World Health Organization (Hedinger et al. 1974) as modified by Donald Paglia of the University of California Los Angeles in association with an expert panel of pathologists (unpublished work). The histologic classification of nodules surgically removed as a result of detection by ultrasound in 1994 was performed by the surgical pathology group of the Straub Clinic and Hospital in Hawaii. FNA cytology was evaluated by the surgical pathology group of MetPath.

Statistics were performed using standard non-paired *t*-test and regression analysis.

RESULTS

Thyroid nodules—Clinical examination from 1955 to 1994

In 1963, two twelve-year-old Rongelap females were found to have thyroid nodules on physical examination. Both of them underwent surgery the following year for removal of the nodules. Final pathologic results revealed adenomatous hyperplasia. In 1969 the first Utirik inhabitant, an adult female, developed a thyroid

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[§] Abbott Laboratories, Diagnostics Division, Abbott Park Illinois 60064.

[‖] MetPath, 1 Malcolm Avenue, Teterboro, NJ 07608-1070.

Table 1. Thyroid nodules diagnosed at surgery through 1990. Not included are the following unoperated (and therefore unconfirmed) nodules: Rongelap—1; Ailingnae—1; Utirik—1; Comparison—5. Included are all consensus diagnoses of a panel of consultant pathologists: two different lesions were detected in one person from Rongelap, one from Ailingnae, and two from Utirik.

	Adenomatous nodules	Adenomas	Papillary cancers	Follicular cancers	Occult cancers
Rongelap (67)[a]	17	2	5	—	—
Ailingnae (19)[a]	4	—	—	—	1[d]
Utirik (167)[a]	10	5	4	1[c]	6[d]
Comparison (227)[b]	4	1	2	—	2[d]

[a] Number of persons (including those *in utero* at the time of exposure) who were originally exposed.

[b] This number includes all persons who have been in the comparison group since 1957. Some have not been seen for many years; others were added as recently as 1976. No thyroid surgeries have been performed on this group since 1985.

[c] Equally divided opinion in one case; follicular carcinoma vs. atypical adenoma.

[d] Majority opinion in one case; occult papillary carcinoma vs. follicular carcinoma. The same patient had lymphocytic thyroiditis.

nodule; final pathologic diagnosis was follicular carcinoma. The last time that a clinically palpable nodule was detected in a Rongelap patient was in 1980 and by 1989 only one additional thyroid nodule had been detected in a Utirik patient (a male *in utero* at the time of exposure). From 1989–1994 there was a hiatus in the detection of thyroid nodules by clinical examination. In 1994, one nodule was detected in a Utirik exposed patient 5 y old at the time of the fallout. An FNA performed on this patient revealed benign cytology. She was not included in the following tables and figures because she did not undergo thyroid surgery.

Table 1 shows the thyroid surgery findings from 1964–1990 on these clinically palpable nodules. The numbers and types of nodules in the comparison group are also listed in this table. The sponsored program for surgical exploration of palpated nodules in this group was concluded in 1985. However, this group is the comparison group and continues to be examined on a regular basis (see Materials and Methods) and has the same level of examinations in the Marshall Islands as do the exposed population. One patient in this group developed a clinically palpable nodule in 1990. This was a male age 60 y at that time. This nodule decreased in size under the influence of suppressive Synthroid therapy and is currently barely palpable.

Fig. 1a shows the incidence by year of surgically removed, clinically palpable thyroid nodules in the exposed patients. Note the delayed onset and late occurrence of thyroid nodules in the Utirik patients. Fig. 1b shows the same cases expressed as a percent of the population that remain susceptible to new nodule formation. The mean time between exposure and surgery was 16 ± 6 y for Rongelap patients and for Utirik patients was 25 ± 5 y ($p < 0.0001$). The development of thyroid nodules in the comparison population was similar to the spontaneous occurrence of thyroid nodules reported in nonexposed subjects (Maxon et al. 1977).

Mean total dose to the thyroid as reported by Lessard et al. (1985) vs. the histologic type of nodule was examined in 52 exposed patients who developed palpable thyroid nodules between 1963 and 1990. In the Rongelap group the mean total dose to the thyroid in subjects with benign vs. malignant disease was 2,563 ± 163 cGy and 1,630 ± 498 cGy, respectively (p = .03). In the Utirik subjects the same comparison of mean dose in benign vs.

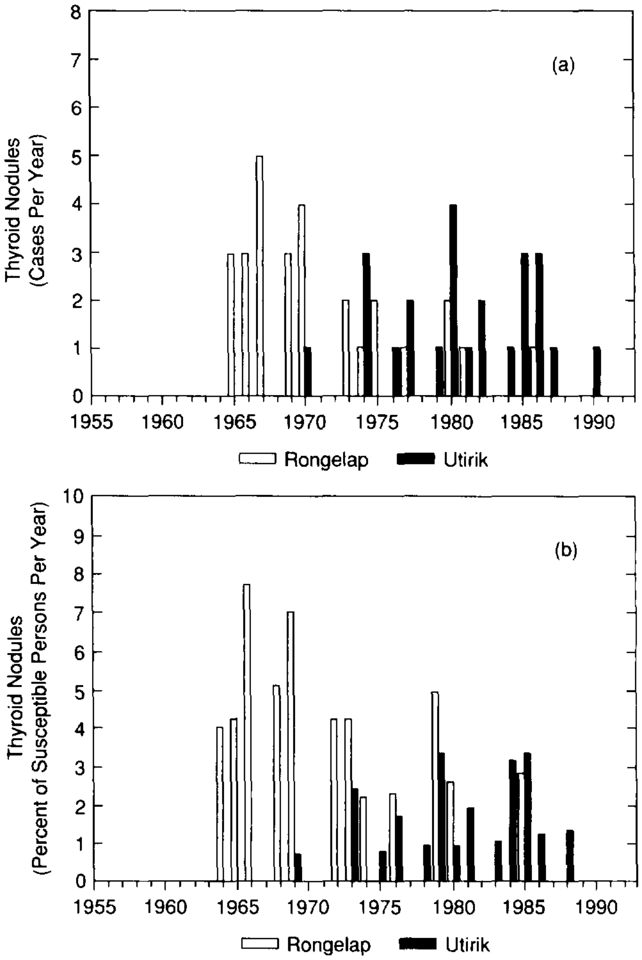

Fig. 1. Surgically confirmed thyroid nodules, Rongelap and Utirik exposed populations. (a) Surgical cases per year; (b) surgical cases per year expressed as percent of the remaining susceptible population (remaining individuals at risk to develop their first nodule).

Table 2. Thyroid nodules types,[a] mean total thyroid-absorbed dose, and time from exposure (1954) to time of surgery in 52 patients, grouped by age.[b]

Exposure group by age (total of surgical subjects)	Type of nodule (n)		Ratio total benign/[c] cancer	Mean thyroid dose ± SD in cGy	Mean years to surgery ± SD
Rong <10 y	Adenomatous nodules	(17)		3,116 ± 1,470	14 ± 4
(*n* = 19)	Other benign[d]	(1)	18:1	710	26
	Cancer	(1)		2,490	15
Rong ≥10 y	Adenomatous nodules	(3)		697 ± 514	19 ± 7
(*n* = 9)	Other benign[d]	(2)	1.25:1	1,595 ± 1,690	19 ± 1
	Cancer	(4)		1,415 ± 150	20 ± 9
Utirik <10 y	Adenomatous nodules	(3)		478 ± 158	28 ± 3
(*n* = 9)	Other benign[d]	(4)	3.5:1	383 ± 160	31 ± 3
	Cancer	(2)		526 ± 50	26 ± 6
Utirik ≥10 y	Adenomatous nodules	(6)		171 ± 0	21 ± 4
(*n* = 15)	Other benign[d]	(6)	4:1	234 ± 35	25 ± 4
	Cancer	(3)		216 ± 78	26 ± 6

[a] If two thyroid nodules occurred in the same individual only the "higher grade" histologic classification was used in compiling this table.

[b] Ten years of age is used as cut-off for the younger group because Rongelap children below this age received a mean thyroid-absorbed dose of >2000 cGy and thereby sustained extensive thyroid injury, a factor that influenced nodule type. All others received lower doses. Two in Utero Rongelap children who received <2000 cGy are not included in the table.

[c] Sum of adenomatous and other benign nodules.

[d] "Other benign" nodules includes adenomas, and occult papillary carcinomas.

malignant was 278 ± 150 cGy and 371 ± 187 cGy, respectively (p = .4); the difference is not statistically significant. Table 2 tabulates the breakdown of the histologic type of nodule vs. the age at the time of exposure, the mean thyroid dose (Lessard et al. 1985) and the number of years between exposure and surgery in the 52 patients. The data suggests that the highest doses of radiation resulted in the formation of adenomatous-type nodules in the Rongelap subjects. The radiation risk to the thyroid was summarized in an earlier paper (Robbins and Adams 1989). The authors concluded that the risk coefficient for thyroid nodules, adjusted for their occurrence in the comparison population, was 8.3×10^{6} persons per cGy y^{-1}. The risk coefficient for thyroid cancer was 1.5×10^{6} persons per cGy y^{-1}.

As shown in Table 3 there was a higher incidence in females for all categories of nodules ($p < 0.05$). The strong correlation between total absorbed dose and earlier nodule development as shown in Fig. 2 was independent of gender.

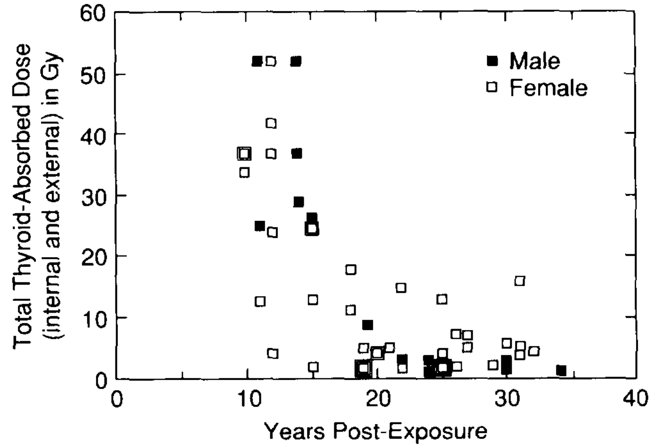

Fig. 2. Relation of thyroid-absorbed dose to time of development of surgically confirmed nodules, according to sex.

Thyroid ultrasound

The initiation of thyroid ultrasound resulted in the detection of many occult nodules. None of the occult nodules detected by thyroid ultrasound were palpable by the endocrinologist; however, there was one patient (discussed above) who did not have an ultrasound on whom a nodule was detected by clinical examination. Table 4 shows the percentage of individuals in each exposed group with thyroid nodules. A lower percent of Rongelap patients developed thyroid nodules than either the exposed Utirik patients and the comparison group. The difference between the Rongelap and Utirik group was statistically significant (p = .0089). There were otherwise no significant differences between the groups. However, when the subset of patients who had had thyroid surgery prior to 1990 was removed there were no longer any differences among the three groups. Table 5 shows the same analysis only for nodules greater than 10 mm in diameter showing again no difference among the

Table 3. Distribution of thyroid nodule type by sex.[a]

	Male (%)	Female (%)	Total
Adenomatous nodules	8 (25)	24 (75)	32[b]
Adenomas	2 (29)	5 (71)	7[b]
Occult papillary carcinomas	2 (29)	5 (71)	7[b]
Carcinomas	1 (10)	9 (90)	10[b]
Total	13 (23)	43 (77)	56[b]

[a] Nodules detected by palpation prior to 1990.

[b] The total number of nodules exceeds the number of surgeries because four female patients had two categories of nodules (see Table 2 for details of the 52 surgical patients).

Table 4. Percentage of subjects in each patient group with thyroid nodules.[a]

	All patients		Non-surgical patients[b]	
	N	Percent	*N*	Percent
Rongelap	47	12.8	23	21.7
Utirik	70	32.8	55	30.9
Comparison	47	25.5	39	28.2
Total	164	25.0	117	28.2

[a] Nodules detected only by ultrasound.

[b] Patients not subjected to thyroid surgery prior to 1990.

Table 5. Percent of subjects who had nodules ≥10 mm in diameter.[a]

	All patients		Non-surgical patients	
	N	Percent	*N*	Percent
Rongelap	47	6.4	23	8.7
Utirik	70	12.9	55	14.5
Comparison	47	10.6	39	12.8
Total	164	10.4	117	12.8

[a] Nodules detected only by ultrasound.

three groups. Table 6 shows the mean nodule count (the sum of the number of nodules in the group divided by the number of subjects in the group) in all groups, analyzing the total number of patients as well as the group with the surgical patients removed, showing that there were no significant differences in the mean nodule count. Table 7 shows that regardless of whether the subjects were comparison or exposed, the mean nodule count in those subjects who had nodules greater than 10 mm was the same. Table 8 shows all the above analyses in men vs. women for the combined three groups showing that there was no statistically significant sex difference.

The relation of the TSH to the nodule count in the patients was evaluated in all patients who underwent thyroid ultrasound. The results can be expressed by the equation: nodule count = .382 − .00296 × TSH (r = .05). Removing from the analysis patients who had had surgical excision of their nodules on or prior to 1990 the same equation is expressed as nodule count = .43965 − .00886 × TSH (r = .01). The mean TSH on the 157 subjects was 4.25 ± 12.32 μIU mL^{-1} (the normal range being 0.32–5). Eighty subjects had been placed on L-thyroxine (Synthroid therapy); however, compliance with the medication regimen was variable and some subjects were clearly hypothyroid accounting for the upper normal mean as well as the large standard deviation. Sixteen patients had a TSH level greater than five; two of those patients (12.5%) had ultrasound detectable nodules.

Radiation dose (Lessard et al. 1985) vs. nodule count was also examined, again with and without the above surgical group included. For all patients the nodule count equaled .32075 + .00005 × the radiation dose in cGy (r = .08). With the surgical patients removed the nodule count equaled 3111 + .00018 × the radiation dose (r =.22, p =.02).

Fine needle aspiration

A total of 18 patients—5 Rongelap exposed, 10 Utirik exposed, and 3 comparison patients—underwent a total of 23 FNAs for nodules that were greater than 1 cm in diameter or that had ultrasound characteristics associated with malignancy. Twenty FNA procedures were performed for evaluation of nodules which were greater than 10 mm in diameter. Three procedures were performed for smaller nodules based on the criteria described in Materials and Methods. In 20 procedures the cytology results were of an insufficient quantity for interpretation. Of the remaining 3 procedures, 1 cytology result was indeterminant and called a follicular neoplasm; 1 cytology report was benign; and the other was felt to be malignant by the interpreting pathologist.

The criteria for surgical removal of a nodule included a size greater than 10 mm in diameter or a nodule

Table 6. Mean nodule count in all patient groups.[a]

	All patients			Non-surgical patients		
	N	Mean ± SD		*N*	Mean ± SD	
Rongelap	47	.277	.877	23	.478	1.16
Utirik	70	.457	.736	55	.454	.765
Comparison	47	.298	.548	39	.307	.521

[a] Nodules detected only by ultrasound.

Table 7. Mean count of nodules ≥10 mm in diameter only in patients who had nodules than greater than 10 mm in diameter.[a]

	All patients			Non-surgical patients		
	N	Mean ± SD		*N*	Mean ± SD	
Rongelap	3	1.00	5.77	2	1.01	7.07
Utirik	9	1.22	.441	8	1.25	.463
Comparison	5	1.00	.332	5	1.00	4.47

[a] Nodules detected only by ultrasound.

Table 8. Percent of patients who had nodules of any size,[a] percent of patients with nodules ≥10 mm in diameter, in all patients, and with the surgical patients removed, comparing women vs. men.

	N	All patients	
		All nodules	Nodules ≥10
Women	92	20.7	8.70
Men	72	30.6	12.5
		Non-surgicalpatients	
Women	60	23.3	10.0
Men	57	33.3	15.8

[a] Nodules detected only by ultrasound.

less than 10 mm in diameter that had characteristics suspicious for malignancy or multiple unsuccessful FNA outcomes. On the basis of this criteria, six of these patients underwent thyroid surgery. FNA cytology results were inadequate in four of these patients; one result was indeterminant (follicular neoplasm); the remaining patient had cytology results interpreted as being malignant. One of the six patients underwent surgical exploration for a nodule less than 10 mm in diameter, and this was the patient who had the indeterminant FNA result. Final histologic diagnosis on the six patients were one with a hemorrhagic cyst, two with adenomatous goiters (including the one with the pre-surgical diagnosis of malignancy), two with follicular adenomas (including the one with the indeterminant cytology), and one with adenomatous hyperplasia with an occult papillary carcinoma. The thyroglobulin on this last patient was within normal limits. Of the five patients who had thyroid tissue found at surgery, four were Utirik patients and one was a Rongelap patient.

DISCUSSION

The occurrence of clinically palpable thyroid disease in the radiation exposed population of our study is in agreement with other published data (Sugenoya et al. 1995; Nagataki 1994; Williams 1994; Kazakov et al. 1992; Baverstock et al. 1992; Souchkevitch and Repacholi 1994), although there is one study of the Chernobyl population (Mettler et al. 1992) that suggests that the prevalence of thyroid nodules was the same in population samples from highly contaminated and control settlements and was similar to the results of unexposed populations in other countries. The development of palpable thyroid nodules in the comparison population is similar to the spontaneous thyroid nodule incidence reported elsewhere (Maxon et al. 1977). The ratio of benign to malignant disease as shown in Table 2 is comparable to that presented by DeGroot et al. (1983) who found a ratio of benign to malignant lesions of approximately 3:1 in an irradiated population. The Utirik population had ratios of 3.5:1 and 6.5:1 in age groups < 10 y and > 10 y, respectively (at the time of exposure). Of note, the Rongelap patients over the age of 10 y at the time of exposure had a ratio of benign nodules to malignant nodules of only 1.25:1. These patients received a mid-range thyroid radiation dose. By contrast, the Rongelap patients who were less than 10 y at the time of exposure had a very high ratio of benign to malignant nodules of 18:1. This suggests there was a relatively low probability of malignancy in persons whose dose exceeded 2,000 cGy. This is consistent with the concept that with high radiation doses to the thyroid the incidence of carcinoma is decreased due to extensive cell death which leaves few cells capable of becoming neoplastic (National Research Council 1990).

The mean time of development of benign nodules compared to the time to development of thyroid cancer between radiation exposure and surgery for the specified groups was remarkably similar. This similarity was independent of age or the use of thyroxine suppression and suggests benign lesions and malignant ones evolve simultaneously. Ron et al. (1989) also noted this similarity in time from radiation exposure to development of nodules regardless of histologic type.

Our findings show that sex was a factor in the development of palpable nodular thyroid disease. Table 3 showed a female preponderance for all histologic categories of nodules. These findings are similar to those of Shore et al. (1985) who found that the risk of development of both benign and malignant thyroid disease was increased for females. Mettler et al. (1992) also found an increased incidence of thyroid disease in the females of the Chernobyl population although that group did not find an overall increased incidence of thyroid disease in the contaminated settlement vs. the control settlement.

Thyroid ultrasound has become an increasingly utilized modality for the evaluation of thyroid disease (Rojeski and Gharib 1985; Brander et al. 1989; Brander et al. 1991; Watters et al. 1992; Gooding 1993). Ultrasound guided fine needle aspiration of the thyroid gland is also being increasingly utilized (Sanchez et al. 1994; Cochand-Priollet et al. 1994). In our study we found a correlation between radiation exposure and the potential for presence of nodules only on the non-operated subjects. Since age directly affected the radiation dose to the thyroid (younger patients received higher doses of radiation than older patients), it was not possible to independently evaluate the effect of age on nodule formation. By contrast, in our analysis of the three subject groups we did not detect a significant difference between the exposed population of Rongelap and Utirik and the comparison population in the incidence of thyroid nodules nor we did detect a difference in the mean nodule counts among the three groups. That the incidence of thyroid nodules greater than 10 mm is equal in all three groups is a finding of significance in that larger nodules are felt to have a greater potential of being clinically significant. None of these nodules were clinically palpable by an endocrinologist who was unaware of the results of the ultrasound examination. Our patient population was examined by ultrasound for the first time 40 y after the exposure to radiation. Mettler et al. (1992) examined the Chernobyl population approximately 4 y after the time of exposure and did not detect an increased incidence of either palpable or ultrasound detected nodules in the contaminated population vs. the control settlement. By comparison, Nagataki et al. (1994), who examined Nagasaki atomic bomb survivors 42 y after exposure, found an increased incidence of thyroid nodules both benign and malignant. However, it is unclear from their analysis whether the increased incidence was a function of clinically palpable nodules or ultrasound detectable only nodules or both. They also did not state the percent of clinically detectable nodules of the total number of all nodules (by ultrasound and palpation). Souchkevitch and Repacholi (1994) also report an increased incidence of thyroid nodules in the Chernobyl population. Their patients were evaluated both by clinical palpation and by thyroid ultrasound. Again, it is unclear from their report which significant lesions were detected by ultrasound only vs. which ones were in addition clinically palpable.

Our overall percent of patients who had ultrasound detectable thyroid nodules (with the surgical patients prior to 1989 removed from evaluation) was 28.2%. This finding is in agreement with the findings of Brander et al. (1991). Mettler et al. (1992), by contrast, determined a lower percentage of detectable nodules by thyroid ultrasound in the Chernobyl population, the incidence of the contaminated vs. the control settlement being 17.9% and 19%, respectively. An even lower percent of thyroid nodules (13.4%) incidentally detected by ultrasound was reported by Carroll (1982). By contrast, an autopsy study by Mortensen et al. (1954) demonstrated nodules in 50% of subjects studied.

Both Brander et al. (1991) and Mettler et al. (1992) found an increased incidence of ultrasound-detected thyroid nodules in women compared to men in contradistinction to our finding where the incidence of nodules in women was actually slightly less than that of men and the difference was not statistically significant. Brander et al. in a separate publication (1989) found that the incidence of thyroid nodules in a random screen of a female population to be 35.6%.

The role of thyroxine suppression in the prevention of nodular thyroid disease is not clear (Rojeski and Gharib 1985). We found no difference in the TSH and the nodule formation in our patient population. However, most of our TSH values were either normal or only mildly elevated. Also, thyroxine suppression was initiated 10 y after exposure. One could speculate that if more of our patients had had markedly elevated TSH values, or if suppression had been initiated at exposure, the results might have been different.

Of interest is the findings of the Rongelap exposed population. This group of individuals had a lower incidence of ultrasound-detected thyroid nodules overall. Once the patients who had undergone thyroid surgery prior to 1990 were removed from the analysis, the incidence of thyroid nodules was not statistically significantly different from that of the other two patient groups. This suggests that removal of the thyroid gland reduces the risk of development of recurrent thyroid nodules. This is consistent with the findings of Fogelfield et al. (1989) who found that the risk of recurrence correlated inversely with the amount of thyroid tissue removed. After 1989, only one patient developed a clinically palpable thyroid nodule (in 1994) and this was benign. This tendency is consistent with the observations of Fig. 1b, from which it can be predicted that approximately 2% of the Utirik population at risk would develop thyroid nodules by 1994. Thus it appears that the development of clinically palpable thyroid nodules is diminishing with time although it is not altogether zero.

FNA of non-palpable nodules that were detected by ultrasound was performed 23 times. Our experience was that most of the time (in 20 cases) the FNA yielded insufficient quantity for interpretation. This is contradistinction to the experience of Rosen et al. (1993) and Cochand-Priollet et al. (1994) and Sanchez et al. (1994), all of whom had a rate of yield of adequate material for diagnosis ranging from 60–96.2%. However, it should be noted that the conditions under which the ultrasound FNA's of this study are conducted are in a suboptimal clinical setting.

Of the six patients who underwent surgery after ultrasound nodule detection, only one was found to have a malignancy and this was occult. The thyroglobulin was not a useful predictor of the presence of carcinoma in this patient. This patient was one of the 20 who had inadequate FNA cytology. The surgery was performed on the basis of a thyroid nodule that was a complex, cystic mass increasing in size. The one patient who had a diagnosis of malignancy by FNA was found to have an adenomatous goiter. The patient who had a diagnosis of a follicular neoplasm had a follicular adenoma.

McHenry et al. (1993) retrospectively reviewed 411 patients with palpable nodular thyroid disease and concluded that persistent nondiagnostic cytology was a limitation of FNA. They suggested that patients' FNA's should be repeated and that surgical treatment of persistent nondiagnostic cytologies in a dominant nodule was indicated for the male patient or in the situation of radiation-associated thyroid disease or failure of 6 mo of thyroxine suppression. It should be emphasized that this was for palpable nodules. However, in our patient population all the ultrasound detected nodules which underwent FNA were nonpalpable. Thus we cannot necessarily make a correlation between our results and future clinical management in our patients and those of McHenry et al. We feel that in our patient population, our experience with FNA of ultrasound detected nodules is too limited to draw conclusions at this time.

In one study occult thyroid carcinoma was found in 2.8% of routine autopsies (Mortensen et al. 1954). Fifty-five percent were low grade papillary carcinoma, which generally has a benign course. Another study showed an even higher autopsy incidence of occult papillary carcinoma of 30% (Harach et al. 1985). Therefore, the clinical implications of having found a surgically determined occult papillary carcinoma by thyroid ultrasound is unclear.

There has been no mortality in our Marshallese patients due to thyroid carcinoma. Papillary carcinoma, the histologic type of thyroid carcinoma associated with radiation, is considered to have a relatively benign course. Schneider (1990) and Schneider et al. (1986) conclude that the course of radiation-induced thyroid cancer is the same as that of thyroid cancer found in other clinical settings. He therefore recommends conservative management of small nodules that are either barely palpable or not palpable and detected only by scintigraphy or ultrasonography. However, since thyroid nodules and thyroid cancers continue to develop in this clinical setting he recommends periodic examination of the thyroid, especially in an older population in which thyroid cancer is felt to be more aggressive. He is in the process of evaluating the role of thyroid ultrasound in the continuing surveillance of the irradiated patient.

In conclusion, the incidence of palpable thyroid nodules was increased in a Marshallese population whose thyroid glands were exposed to radiation. The thyroid gland of the women was more susceptible to radiation induced palpable nodules than men. By contrast, there was no difference in thyroid nodularity as evaluated by ultrasound in radiation exposed groups vs. a comparison population; nor was there any difference between males vs. females examined by ultrasound. The regression analysis, being more sensitive, may have detected more subtle differences in nodularity vs. radiation dose. However, this analysis is affected by the inseparable variable of subject age at exposure. Perhaps the age of our population resulted in a "levelling out" of the incidence of thyroid nodules in the exposed vs. the comparison population and women vs. men. If thyroid ultrasound had been available and been performed in the Marshallese shortly after the accident, the incidence and distribution of thyroid nodules might have been different. However, since there were no deaths in this population related to thyroid cancer, early detection by ultrasound could not have altered that outcome. The implications of these findings are unclear. Therefore, although none of our patients who underwent surgery as a result of thyroid ultrasound had overt malignancy, we will continue to assess the efficacy of thyroid ultrasound as an adjunct to the physical examination and the ongoing evaluation of thyroid disease in the increasingly aging Marshallese population.

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AN INVESTIGATION INTO THE PREVALENCE OF THYROID DISEASE ON KWAJALEIN ATOLL, MARSHALL ISLANDS

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Abstract—The prevalence of thyroid nodules and thyroid cancer was studied in the indigenous population residing on Ebeye Island, Kwajalein Atoll, in the Republic of the Marshall Islands. This island, centrally located in the nation, is home to about 25% of the nation's population, many who have migrated there from other atolls. The objective of the study was to obtain thyroid disease rate statistics on as much of the population as possible that was alive during the years of nuclear testing and to test the hypothesis that described a linearly decreasing prevalence of palpable nodules with increasing distance from the Bikini test site. 1,322 Marshallese born before 1965 were given a thyroid examination using neck palpation, fine needle aspiration biopsy, and high resolution ultrasound imaging. Approximately 40% of the total population living on this island who are at risk from exposure to radioactive fallout during the years 1946–1958 were screened. Of that group, 815 were alive at the time of the BRAVO test on 1 March 1954. Two hundred sixty-six people with thyroid nodules were found (32.6%): 132 were palpable nodules (16.2%), and 134 were nodules that could be diagnosed with ultrasound only (15.7%). Prevalence of palpable nodules was particularly high in men and women older than 60 y, in men who were 6 to 15 y of age at the time of the BRAVO test, and in women 1 to 10 y of age at the time of the BRAVO test. In 22 people, the clinical diagnosis was most likely cancer though histopathological evidence was only available from 11 operated cases. Of the 11 operated cases, 10 were cancer. Cancer prevalence was particularly high in those women born between 1944 and 1953 (7/220 = 3.2%), i.e., who were children during the early years of nuclear testing. The Ebeye data showed a marginally significant correlation between palpable nodule prevalence among women and distance to Bikini ($r = -0.44$, $p = 0.06$). This report summarizes the clinical findings of the thyroid examinations, the age distributions for nodular disease and cancer, and examines the relationship between prevalence of nodules and present day levels of ^{137}Cs in the environment of each atoll.

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Key words: Marshall Islands; thyroid; cancer; health effects

INTRODUCTION

THE U.S. atomic weapons testing program in the Pacific conducted between 1946 and 1958 resulted in contamination of a number of atolls in the Marshall Islands to various degrees (Simon and Graham 1997). The most serious radiation exposures were caused by early radioactive fallout from the test, Castle BRAVO, a hydrogen bomb detonated on Bikini Atoll on 1 March 1954. The radioactive fallout was intense on the inhabited atoll of Rongelap (175 km to the E of Bikini) resulting in thyroid exposures estimated between 10 and 40 Gy for an adult and between 50 and 200 Gy for a 1-y-old child (Lessard et al. 1985). Lower exposures were received on the atolls of Ailinginae (about 30% of the value at Rongelap) and Utrik (about 10% of the value at Rongelap). The exposed communities on these three atolls were evacuated, treated for acute radiation illness, and provided with follow-up medical care and cancer surveillance over the decades since (Conard 1984; Adams et al. 1989). The most significant long-term health effect in the exposed population was an increased frequency of thyroid nodular disease including thyroid cancer, which has been attributed to intake of short-lived radioiodines immediately following the BRAVO detonation.

There is historical evidence to indicate that residents of other atolls may have been exposed to radioactivity in local fallout from the BRAVO test as well as from other explosions. In particular, fallout data were collected on Kwajalein Atoll (located about 400 km SE of Bikini) using gummed film as part of the worldwide fallout monitoring network of the AEC Health and Safety Laboratory. Gummed film data (measurements of beta activity collected within successive 24-h periods) during the years 1954 through 1958 (Harley et al. 1960) show that all eighteen of the large Marshall Islands tests (those >1 MT explosive yield) were detected at Kwajalein at about 100 × the background radiation level (Simon and Graham 1996). Presumably, other mid-latitude atolls in the Marshall Islands received similar amounts of early fallout as did Kwajalein.

The contamination on all of the atolls, consisting of mainly ^{137}Cs, has recently been assessed by the Marshall Islands Nationwide Radiological Study and reported (Simon and Graham 1994, 1997) including calculations of external exposure-rates and ingestion doses under

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various dietary scenarios. The radiological data indicate that 10 of the 24 inhabited atolls or separate reef islands have environmental levels of ^{137}Cs enhanced over the level of global fallout received in the mid-Pacific region. Many of these locations are only minimally enhanced in ^{137}Cs, which has not contributed any dangerous exposure over recent decades. However, the extent of exposure of the Marshall Islands population to radioiodine during the testing years has never been assessed. Moreover, little information exists about health consequences among residents of the many atolls other than Rongelap and Utrik.

Only a single health effects study prior to this one examined Marshallese at numerous locations from around the Marshall Islands. In a report by Hamilton et al. (1987) it was suggested that thyroid nodular disease, as diagnosed by palpation of the neck, was frequent in residents of many atolls from throughout the Marshall Islands. In that study, an increased prevalence was noted at distances closer to the Bikini test site with a linear decrease in prevalence with increasing distance. The Nationwide Radiological Study (Simon and Graham 1996) and a Marshall Islands Government appointed Advisory Panel (McEwan et al. 1997) recommended to the Marshall Islands Government in 1990 that an independent thyroid screening study should take place and that the hypothesis of Hamilton be independently tested. Subsequently, a nationwide thyroid disease screening program was initiated to gather data useful for such an evaluation and also for the purposes of advising the Marshall Islands government on the current health situation with respect to thyroid disease. Of all the conditions for which claims for damages are made to the Marshall Islands Government, thyroid disease is the most common and for that reason it is of interest to the Ministry of Health.

The specific objectives of the thyroid disease screening program were (1) to examine and gather data on the frequency of thyroid disease (both nodular and cancerous conditions) and information about the subjects residence history in as large of proportion as possible of those Marshallese alive at the time of the BRAVO test and during the years of atomic testing, (2) to advise the Government of the Marshall Islands on the findings from the medical screening program, and (3) to test the hypothesis of Hamilton. The long term goals of the investigators also include estimating thyroid radiation exposures using historical and contemporary data, though those analyses are still underway and are beyond the scope of this report. The objective of this paper is to report a summary of the medical findings from examinations conducted on Kwajalein Atoll from January to March 1993 and during follow-up examinations in 1996 and the results of statistical hypothesis testing of the Hamilton hypothesis using the thyroid screening data.

METHODS

Location and study population

Most of the thyroid examinations were conducted in the Ebeye Hospital, located on Ebeye Island in Kwajalein Atoll. Kwajalein, the largest atoll in the world, is centrally located in the Marshall Islands about 400 km SE of Bikini Atoll and is used as an U.S. Army missile test range. Ebeye Island is located about 15 km N of the Army base, which is the southern most island in the atoll. Ebeye is home to over 12,000 Marshallese, about one fourth of the total Marshall Islands population today. The population of Ebeye is known from national census data to be a mixture of former residents of atolls that are located over the entire geographic range of the Marshall Islands. Many of the people examined in Ebeye also lived there at the time of the BRAVO test. The remaining persons lived on 20 other atolls. Because Ebeye has jobs, goods and services not existent on more remote atolls, many Marshallese have migrated there for semi-permanent or permanent residence. The population of Ebeye includes Marshallese from a variety of locations throughout the chain of atolls; therefore, it provided an excellent location for the first phase of thyroid examinations.[§]

The main source of exposure of Marshallese is believed by many to have been the BRAVO test; hence, those Marshallese alive at the time of the test are usually considered most at risk for radiogenic disease. In the original design of this study, consideration was given to using Marshallese born within 10 y after the testing era as control subjects. They would be the only population available that had been screened for thyroid disease and were genetically and culturally similar to the exposed population. Though not a perfect control group because of differences in age, subjects who were born up through the 10-y period following the testing era, i.e., with dates of birth before 1968, were originally invited for examination. Although we sought persons in the age range described, we did not reject anyone requesting a thyroid examination.

After the original study design was implemented, historic deposition data were located that influenced our choice of primary study cohort. The gummed film data collected during the Castle and Ivy series (1954–1958) indicated there had been deposition of regional fallout on Kwajalein from other large tests in the Marshall Islands, thereby suggesting that Marshallese might have been exposed from events other than BRAVO. Consequently, all Marshallese who had already been examined and who were *in-utero* or alive any time during the weapons testing years, i.e., before the last test on 11 August 1958, were considered at risk. The primary analysis reported here, however, is for the cohort alive at the time of the BRAVO test (termed as the Ebeye "BRAVO cohort") so that a comparison can be made with the study by Hamilton et al. (1987). We have defined a group of secondary interest as all those Marshallese who were born before 1 March 1959. We have termed this group the "End of testing" cohort or EOT cohort. Finally, those

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[§] A second phase of thyroid examinations were held in 1994 in Majuro, the capital city, however, those data are not reported here. The second phase of examinations should not be confused with the follow-up examinations of the Ebeye population in 1996 which are discussed in this paper.

individuals who presented themselves for examination but who were born between 1 March 1959 and 31 December 1964, were termed the Ebeye "After testing" cohort or AT cohort.

It was of interest in this study to attempt to determine if there was a relationship between prevalence among residents of each atoll at the time of the testing and the location of residences. Because the testing period lasted for 12 y, long enough to allow families to move among locations, the issue of residence and exposure is complex and requires a complete residence history and dose reconstruction for each subject. Although such work is in progress, in this report only the residence at the time of the BRAVO test is examined and all analyses are conducted with respect to that residence location. The rationale behind this methodology is to make this comparison as consistent as possible with the methods of Hamilton et al. (1987). In that study, residence location was used as proxy variable for exposure to short-lived radioiodines.

Examinations

The thyroid screening investigation was composed of two components: a personal interview and a clinical examination. The interview was conducted by Marshallese assistants in their native language. The most important data collected in the interviews were a complete residence history from birth until the examination date, a brief health history, a fertility history for women, and brief data on food and diet preferences. The residential history data were collected with the intent of later using them in calculations to determine radiation exposure.

Each study subject was examined sequentially by two endocrine surgeons highly trained in the use of ultrasound and palpation. Each physician administered either a palpation or ultrasound exam, and each was initially blinded to the findings of the other as well as to the interview findings. Physicians alternated in their assignment to perform ultrasound or palpation.

The physical examination performed by one of the two doctors included a brief medical interview (with the help of a translator), blood pressure measurement, and a careful palpation of the neck. The second doctor performed the ultrasound examination of the neck.[||] An initial diagnosis was made in real-time. In addition, a minimum of four pictures of the echograms of each participant were recorded. When thyroid nodules were found, additional pictures were taken and the size of each nodule was measured in three dimensions. Our definition of a nodule as imaged by ultrasound included all focal abnormalities of the echo pattern that were larger than 2 mm in diameter though the minimum nodule size that could be reliably detected was 4 mm.

The involvement of two physicians sometimes resulted in differences between the clinical and ultrasound findings. When such differences occurred, it was the policy of the study for the doctors to discuss their findings and to re-examine the neck of the patient again in an effort to reach a consensus diagnosis.

Every participant who had a palpable thyroid nodule was told in the Marshallese language that he or she had a nodule and that a fine needle aspiration (FNA) biopsy was recommended to determine its nature. In the biopsies performed, only one puncture was made for each nodule using a disposable 21G needle with a 12 mL syringe. Because many subjects feared the pain from the puncture, it was determined early in the study that multiple punctures would likely reduce community participation. For this reason, the biopsy was limited to a single puncture. The aspirated material was divided onto four slides and smeared. Two slides were stained with a modified Papanicolau method and the other two slides were stained with a modified Giemsa method. Staining was performed in Ebeye within 72 h after the biopsy. All slides were examined by (N. Kimura) in the Department of Pathology of Tohoku University (Sendai, Japan).

In January 1996, three years after the first examinations, a scheduled follow-up program was conducted in Ebeye. Every person who was diagnosed in 1993 with a palpable or non-palpable thyroid nodule was personally invited by letter and by local radio announcement to attend the follow-up clinic. Three goals were integral to the follow-up study: (1) to provide reassurance to those persons previously diagnosed of an abnormality that they were not left without proper surveillance and medical care; (2) to determine the progression or regression of thyroid nodules with an emphasis of examining the long-term behavior of non-palpable nodules; and (3) to verify the 1993 clinical findings to the degree possible, knowing that some nodules might have regressed while new ones might have appeared.

The follow-up examinations began with an interview by one of the investigators (KRT) using a Marshallese interpreter. Special emphasis was placed on the questions concerning the subject's residence history. The interview was followed by a clinical examination by two of the doctors from the 1993 exams (TT and NN) who are authors of this report.

All clinical techniques in 1996 were the same as in 1993, except for a modification of the policy with respect to FNA punctures. About 30% of the FNA biopsies in 1993 had not been successful because of insufficient cellular material. In 1996, a temporary cytology laboratory was set up in the examination room for the purposes of improving the rate of successful FNA biopsies. An experienced cytologist checked the quality of the FNA biopsy while the patient was still in the clinic and notified the physicians when it was not successful so that a second puncture could be made.

Statistical methodology

The crude and age-adjusted prevalence of all nodular goiters (nodular goiter and nodules are equivalent), and palpable nodules only, was estimated for each atoll based on the 1954 residence location of each study subject (see Table 1 for data from the Ebeye BRAVO cohort). Two standardization methods were used to

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[||] Equipment used was an ALOKA echo camera SSD-121™ with a 7.5 MHz mechanical sector probe.

correct for differences in age-distribution between the groups: the direct and indirect methods. The estimates obtained by the direct method reflect the prevalence of nodular goiter in the index population when this index population has the same age distribution as the standard population. The age distribution of the entire population on the Marshall Islands, as taken from the national census (RMI 1989) was used as a standard. With indirect standardization, the age-specific prevalence rates of the standard population are applied on the age distribution of the index population. Since no external source was available, we took all the people born before 1 March 1954 and residing on those atolls southwards from Jabwat in 1954 as the reference population. These atolls were selected because the exposure of residents to radioactive fallout was likely the lowest there of all the atolls.

With the direct method, the number of people in each age group at each atoll of residence was often very small with the result that the age-specific prevalence rates were subject to large fluctuations. The use of the indirect standardization method also had its shortcomings because of the lack of a large reference population. In spite of that, we chose to use the indirect method because the age-adjusted prevalence rates showed less fluctuation in comparison to the crude prevalence rates.

Various hypotheses were tested using the results of both the screening data and the age-adjusted data. The null hypothesis of no difference in crude prevalence among the atolls (other than Rongelap and Utrik) was tested by a Chi-square test. In an examination of possible relationships between the age-adjusted rates and location of residence in 1954, the prevalence data were plotted against the distance between Bikini and the residence atolls. Correlations between prevalence and distance were examined. Because the population size in 1954 varied dramatically among the atolls, the reliability of the prevalence estimates also varied. Consequently, we weighted the prevalence estimates by the inverse of the group variance.

To examine the occurrence of nodular goiter in more detail, a logistic regression analysis was conducted using several variables as predictors: the distance from Bikini to the residence atoll, the variable θ—defined as the angle measured clockwise between a W to E line drawn through Bikini and a line from Bikini to the center of the residence atoll—sex, age and the interaction term defined by the product of distance and θ. The dependent variable was the presence or absence of nodular goiter in the individual. The data of distance and θ are given in Table 2.

We also examined the relationship between the age-adjusted prevalence and current data of the radiological conditions at each atoll. For this purpose, we used measurements of ^{137}Cs in the environment that were obtained during the years 1989 through 1994 by the Marshall Islands Nationwide Radiological Study (NWRS). These measurements were conducted on all islands of the nation at least 500 m in length in all of the 29 atolls as well as the 5 separate reef islands. The measurements included over 1,200 *in-situ* gamma spectrometry measurements, collection and laboratory analysis of more than 800 surface soil samples and more than 200 deep soil profiles. The results of the measurements were compared with the levels of global fallout estimated for mid-Pacific locations from published data on islands nearby to the Marshall Islands. This comparison provided a measure of the degree of ^{137}Cs contamination

Table 1. Summary of prevalence data of Ebeye BRAVO cohort grouped by atoll of residence in 1954.

Residence in 1954	Number of people	Mean age, y	Female %	Benign solitary nodules	Benign multiple nodules	Malignant goitre	Thyroid-ectomy	Crude %, all nodules	Age-adjusted %, all nodules	Crude %, palpable nodules only	Age-adjusted %, palpable nodules only
Wotho	7	55.7	57.1	2	0	0	0	28.6	24.3	14.3	12.8
Rongelap	11	52.9	54.5	1	0	0	4	45.5	40	36.4	31.4
Ujae	30	47.8	50	6	0	1	1	26.7	26.4	13.3	11.3
Lae	23	50	52.2	7	2	0	1	43.5	46.6	26.1	24.5
Kwajalein	346	53.3	57.8	89	26	10	4	37.3	34.5	18.5	18.9
Likiep	52	50.8	55.8	9	2	0	0	21.6	20.7	13.5	13.8
Namu	17	50.7	58.8	3	0	0	0	17.6	17.9	5.9	5.7
Utrik	14	48.2	64.3	4	1	0	1	42.9	44.7	35.7	39
Ailuk	14	48.2	64.3	3	0	0	0	21.4	22.2	7.1	6.1
Wotje	17	51.7	88.2	5	1	0	0	35.3	32.4	17.6	16.9
Ailinglaplap	77	50.3	58.4	21	2	0	1	31.2	29.8	13	12.9
Mejit	20	50.2	55	6	0	0	0	30	28.3	5	4.7
Maloelap	15	50.5	46.7	1	1	0	0	13.3	13.5	6.7	7.3
Namorik	17	46.1	52.9	0	1	0	0	5.9	6.6	5.9	6.2
Aur	10	47.2	40	0	0	0	0	0	0	0	0
Jaluit	47	48.5	68.1	5	5	1	1	25.5	27.8	12.8	14.5
Kili	1	43	100	1	0	0	0	100	n/a	0	0
Majuro	55	50.9	61.8	21	4	2	1	50.9	46.8	20	19.2
Arno	10	44.8	40	2	0	0	0	20	19.9	0	0
Ebon	28	45.3	64.3	5	0	1	1	25	27.3	14.3	14.4
Mili	4	44.8	75	0	0	0	0	0	0	0	0
Total	815	51.11	58.5	191	45	15	15	32.6	n/a	16.2	n/a

Table 2. Atolls of residence in 1954 for subjects in Ebeye BRAVO cohort and Hamilton study and related information used in hypothesis testing and Figs. 1 and 4.

Number	Atolls represented in Ebeye study	Atolls in Hamilton study	Distance from Bikini (km)	Angle θ (°)	Ratio total ^{137}Cs:global fallout ^{137}Cs
1	Ailinglaplap		574	51	1.25
2	Ailuk	✓	505	15	8.15
3	Arno		833	35	1.6
4	Aur		731	29	1.3
5	Bikini		0	0	1235
6	Ebon	✓	855	64	1.1
7	Enewetak		350	177	295/975
8	Jaluit	✓	769	52	1.2
9	Kili		770	57	1.2
10	Kwajalein	✓	401	49	2.0[a]
11	Lae	✓	305	74	1.65
12	Likiep	✓	453	24	5.8
13	Majuro		813	38	1.2
14	Maloelap	✓	683	25	1.4
15	Mejit	✓	609	12	7.35
16	Mili	✓	918	39	1.65
17	Namorik		722	65	1
18	Namu		463	54	1.4
19	Rongelap	✓	175	10	210[b]
20	Ujae	✓	262	85	1.15
21	Ujelang		537	157	2.55
22	Utrik	✓	472	3	16
23	Wotho	✓	162	70	2.25
24	Wotje	✓	568	24	2.85

[a] North Kwajalein 2.1–4.3, South Kwajalein 1.0–2.0; value of 2.0 taken because of population distribution.

[b] Value derived from measurements of South Rongelap.

above that expected from global fallout that originated from nuclear weapons' tests in other nations, e.g., Nevada (USA), Russia, China, French Polynesia, and Australia, as well as the Marshall Islands. The ratio of the ^{137}Cs deposited on the atolls from regional fallout (i.e., radioactive deposition that moved directly from Bikini and Enewetak Atolls without global circulation) to that from global fallout is given in Table 2 (as adapted from Simon and Graham 1994).

The ratio of regional to global fallout deposition was specified in Simon and Graham (1994) as a range because of spatial variation and measurement and estimation uncertainty. We used the mean value of the reported range as an independent variable to investigate relationships with the occurrence of nodular disease. The mean value of the ratio should be understood to only be a measure of the long-lived radioactive component that is in excess of that expected from global sources. Because the exposure from ^{137}Cs and other long-lived radionuclides is not specific to the thyroid gland, this measure of radioactive contamination can only be used as a proxy variable to the short-lived radioiodines; however, it may be more relevant than distance from Bikini.

Two different associations were examined using the ^{137}Cs data: (1) the relationship between the excess ^{137}Cs deposition and the distance from Bikini Atoll; and (2) the prevalence of both total number of nodules and of palpable nodules and the mean excess ^{137}Cs ratio for each atoll in which study participants lived in 1954.

Assumptions for the various statistical tests were examined to determine the reliability of test results. These inspections included use of the Shapiro-Wilks' test to examine normality of variables used to determine correlations. In some cases, the Spearman correlation coefficient, a non-parametric equivalent of the Pearson correlation coefficient, was also estimated. Assumptions necessary for reliable regression were also examined including inspection that the prediction error was unrelated to the predicted value.

RESULTS

Population and summary disease data

Between 15 January and 5 March 1993, 1,368 persons were examined; among those were 1,129 born before 1965. In the follow-up examinations held in Ebeye in early 1996, an additional 193 Marshallese born before 1965 were examined. Of the Marshallese examined in Ebeye in 1993 and 1996, 815 were born before the BRAVO test on 1 March 1954. These 815 persons defined the Ebeye BRAVO cohort and prevalence data derived from that group were used to test the Hamilton hypothesis. Of the Marshallese examined in Ebeye, there were 1,062 born before the end of nuclear testing in the Marshall Islands; that group defined the EOT cohort. There were an additional 260 individuals born after the end of nuclear testing and they defined the AT cohort. Table 3 summarizes the disease statistics for the three cohorts although only statistical hypothesis test results for the BRAVO cohort are reported in this paper.

Of the 815 who fit the age criteria for the Ebeye BRAVO cohort, there were 338 males and 477 females; the ratio of male to female was 0.71:1. The minimum age by definition for inclusion into the Ebeye BRAVO cohort was 38 y; the mean age of the participants was 51.1 ± 10.4 y.

In the Ebeye BRAVO cohort, there were 191 (23.4%) persons diagnosed as having a benign solitary nodular goiter and 45 (5.5%) as having a benign multiple nodular goiter (see Table 3). In addition, 15 persons (1.8%) had thyroid cancer. The prevalence of nodular goiter for the entire population was 32.6%.

In the Ebeye EOT cohort, there were 230 (21.7%) persons diagnosed as having a benign solitary nodular goiter and 53 (5.0%) as having benign multiple nodular goiter (Table 3). In addition, 16 persons (1.5%) had thyroid cancer. The prevalence of nodular goiter among the entire cohort was 29.8%. In the Ebeye EOT cohort, the number of disease cases was larger than in the BRAVO cohort presumably due to the additional persons who qualified for inclusion in the EOT cohort. The prevalence in this cohort, however, was slightly lower than in the BRAVO cohort. The prevalence of nodular disease in the AT cohort was very much lower although the crude prevalence of cancer was not greatly different for women. Because the number of people examined in the AT cohort was significantly less, there were correspondingly less cases and, consequently, the disease rates are more uncertain.

Table 3. Diagnostic results of Ebeye BRAVO cohort, Ebeye EOT cohort and Ebeye AT cohort. Absolute numbers and prevalence rates (%).

	Males (%)	Females (%)	Total (%)
BRAVO cohort			
Benign solitary nodular goiter	62 (18.3)	129 (27.0)	191 (23.4)
Benign multiple nodular goiter	12 (3.6)	33 (6.9)	45 (5.5)
Thyroid cancer	5 (1.5)	10 (2.1)	15 (1.8)
Previous thyroidectomy	3 (0.9)	12 (2.5)	15 (1.8)
[w/cancer]	[0]	[3]	[3]
Total nodular goiter	82 (24.3)	184 (38.6)	266 (32.6)
[palpable nodules only, %]	[38, 11.2%]	[93, 19.5%]	[131, 16.1%]
Total cases of cancer[a]	5 (1.5)	13 (2.7)	18 (2.2)
Size of study population	338	477	815
EOT cohort			
Benign solitary nodular goiter	69 (16.1)	161 (25.4)	230 (21.7)
Benign multiple nodular goiter	12 (2.8)	41 (6.5)	53 (5.0)
Thyroid cancer	5 (1.2)	11 (1.7)	16 (1.5)
Previous thyroidectomy	4 (0.9)	14 (2.2)	18 (1.7)
[w/cancer]	[0]	[3]	[3]
Total nodular goiter	90 (21.0)	227 (35.9)	317 (29.8)
[palpable nodules only, %]	[40, 9.3%]	[112, 17.7%]	152, 14.3%]
Total cases of cancer[a]	5 (1.2)	14 (2.2)	19 (1.8)
Size of study population	429	633	1062
AT cohort			
Benign solitary nodular goiter	4 (4.3)	18 (10.8)	22 (8.5)
Benign multiple nodular goiter	1 (1.1)	4 (2.4)	5 (1.9)
Thyroid cancer	—	4 (2.4)	4 (1.5)
Previous thyroidectomy	—	1 (0.6)	1 (0.4)
[w/cancer]		[0]	[0]
Total nodular goiter	5 (5.4%)	27 (16.2)	32 (12.3)
[palpable nodules only, %]	[0]	[11, 6.6%]	[11, 4.2%]
Total cases of cancer[a]	—	4 (2.4)	4 (1.5)
Size of study population	93	167	260

[a] Total cases of cancer = number of diagnosed cancers + cancers in previous thyroidectomies.

Palpable nodules

In the 1993 phase of the study, there were 1,275 Marshallese examined who were born before 1968. Of that group, 68 individuals had palpable nodules upon the first physical examination. However, 8 of those were not confirmed by ultrasound performed immediately after the physical examination. Conversely, after determining the presence and location of a nodule by ultrasound, a second palpation of the patient (supine position with hyperextended neck) revealed an additional 63 palpable nodules. Thus, the total number of palpable nodules was determined as 68 − 8 + 63 = 123 (123/1275 = 9.7%). The number of cases of nodules identified only by ultrasound (i.e., not-palpable even after a second physical exam) was 151 (11.8%). The ratio of non-palpable to palpable nodules was 1.24:1, and the total number of nodule cases was 274 (21.5%). The crude prevalence of palpable and non-palpable nodules by year of birth for participants in the Ebeye study is summarized in Table 4.

Of the 123 subjects with palpable nodules, 121 had a FNA biopsy; two refused. The success rate of FNA slides was 70%, disappointingly low. In most cases, failure was due to insufficient material aspirated during the single pass through the thyroid, however, in some cases, the quality of the staining was also to blame.

At the follow-up examination in 1996, we sought to re-examine all of the 274 nodule cases identified in 1993. However, in the intervening 3 y, 16 persons of that group had died (in no case was thyroid disease an obvious factor contributing to death), 11 had moved out of the Marshall Islands, and 20 had moved to other atolls and, therefore, had no opportunity to attend the follow-up clinic. Of the remaining 226 people with a nodule diagnosis, we re-examined 192 (85% of those remaining, 70% of the original group).

The same methods and equipment were used as in 1993 except for the improvement in obtaining FNAs. Using the on-site cytologist at the follow-up exams, we performed 84 FNA biopsies of previously assayed patients and achieved a 96% success rate for satisfactory slides.

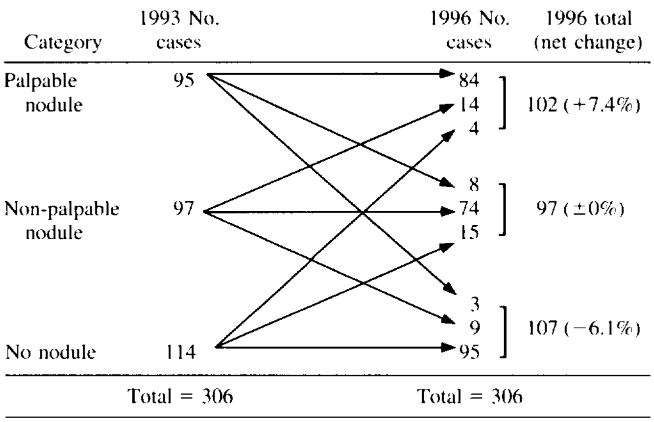
Two of the goals of the re-examinations—confirming the 1993 findings and a study of the progression or regression of thyroid nodules—were viewed as closely

Table 4. Prevalence of palpable and non-palpable nodules and of suspected thyroid cancer in different birth cohorts.

Year of birth	Number of subjects	Non-palpable nodules (%)	Palpable nodules (%)	Suspected cancers (%)
Males				
<1923	36	14 (38.9)	6 (16.7)	2 (5.6)
1923–1928	20	3 (15.0)	1 (5.0)	0
1929–1933	28	2 (7.1)	3 (10.7)	0
1934–1938	20	1 (5.0)	2 (10.0)	1 (5.0)
1939–1943	33	1 (3.0)	7 (21.2)	2 (6.1)
1944–1948	57	3 (5.3)	6 (10.5)	0
1949–1953	97	12 (12.4)	2 (2.1)	1 (1.0)
1954–1958	68	4 (5.9)	2 (2.9)	0
1959–1963	74	3 (4.1)	0	0
1964–1968	73	2 (2.7)	0	0
>1969	20	0	0	0
Males born before 1969	506	0	0	0
Females				
<1923	36	14 (38.9)	6 (16.7)	3 (8.3)
1923–1928	32	6 (18.8)	7 (21.9)	0
1929–1933	38	6 (15.8)	11 (28.9)	0
1934–1938	47	10 (21.3)	7 (14.9)	0
1939–1943	46	12 (26.1)	4 (8.7)	0
1944–1948	99	15 (15.2)	12 (12.1)	2 (2.0)
1949–1953	121	10 (8.3)	22 (18.2)	5 (4.1)
1954–1958	133	21 (15.8)	13 (9.8)	1 (0.8)
1959–1963	114	10 (8.8)	6 (5.3)	2 (1.8)
1964–1968	103	2 (1.9)	6 (5.8)	3 (2.9)
>1969	62	0	0	0
Females born before 1969	769	0	0	0
Total <1969	1275	151 (11.8)	123 (9.7)	22 (1.7)

related. By comparing the 1993 and 1996 examination findings for at least a subset of the study participants, data could be collected for both purposes. Upon re-examination in 1996, some changes in diagnoses were evident as compared to the 1993 findings, though, in general, the original diagnoses were confirmed. We believe that the different diagnoses in 1996 are evidence of changes in the individual's pathology during the intervening period rather than mistaken diagnoses. Table 5 shows the changes in diagnoses in a group of 306 study subjects who were examined on both occasions. In this subset of the 1993 study population, there were roughly equal numbers in the palpable, non-palpable (only ultrasound detection), and no nodule categories: 95, 97, and 114, respectively.

Table 5. Changes in thyroid nodule diagnoses between first examinations in 1993 and follow-up examinations in 1996.



Category	1993 No. cases	1996 No. cases	1996 total (net change)
Palpable nodule	95	84 14 4	102 (+7.4%)
Non-palpable nodule	97	8 74 15	97 (±0%)
No nodule	114	3 9 95	107 (−6.1%)
	Total = 306	Total = 306	

Of the 95 palpable nodule cases in 1993, 84 (88%) remained palpable in 1996. Three of the 95 cases (3.2%) were not detectable by any means in the follow-up exam, and 9 cases (9.3%) became detectable by ultrasound only. Of the 97 cases with a non-palpable nodule in 1993, 74 (77%) remained non-palpable in 1996; 9 of the 97 cases (9.3%) showed no evidence of a nodule in the follow-up exam; but 14 cases (14.6%) had developed into a palpable lesion. Of the 114 cases who had no nodule in 1993, 15 (13.2%) were found to have a non-palpable nodule in 1996 and 4 (3.5%) were found to have a palpable lesion.

The rates of palpable nodules within all three cohorts are of interest for the purpose of intercomparison as well as for comparison with other studies. Summary of all the Ebeye data (see Table 3) show that nodules were found by palpation of the thyroid gland in 131 persons from the BRAVO cohort (131/815 = 16.1%), 152 persons from the EOT cohort (152/1062 = 14.3%), and 11 persons from the AT cohort (11/260 = 4.2%). The ultrasonography found nodular goiter, which was not palpable in a total number of 134 persons (16.4%) from the BRAVO cohort, 165 persons (15.5%) from the EOT cohort, and 21 persons (8.1%) from the AT cohort.

Cancer diagnoses

Clinical diagnoses of cancer were made, where possible, in all examinations. In 22 study subjects diagnosed with palpable nodules in 1993, the ultrasound image was suggestive of cancer or large follicular adenomas, which by ultrasound imaging are indistinguishable from follicular thyroid cancer. We used the diagnostic criteria published by the Japan Society of Ultrasonics in Medicine (1992) with particular emphasis placed on boundary posterior echo, shape and prethyroid muscle echo (Suzuki et al. 1994).

Twelve of the 22 cases were operated in Majuro although histopathological verification is available in only 11 of the 12 operated cases. Table 6 lists these cases together with the results of the 1993 FNA biopsies or the histopathology where available. Of the eleven operated in 1994, there were 3 follicular carcinoma, 5 papillary carcinoma, 2 micropapillary carcinoma, and 1 adenomatous goiter. One additional case was operated in Honolulu in 1996, and it was also papillary cancer. In view of the precision of the ultrasound diagnoses and the im-

Table 6. Ultrasound findings, FNA results and histopathology of suspected and confirmed cancer cases.

ID	Sex	Age	Cohort	Ultrasound findings	FNA results 1993	FNA results 1996	Histopathology	Clinical status
230	F	24	AT	suspicious of cancer	insufficient	follicular adenoma	—	surgery deferred due to pregnancy, planned for 1996
1067	F	29	AT	suspicious of cancer	papillary cancer	N/A	micropapillary cancer	operated Majuro 1994
273	F	29	AT	suspicious of cancer	papillary cancer	N/A	papillary cancer	operated Majuro 1994
123	F	31	AT	large follicular neoplasm, 60 mm	follicular tumor	N/A	follicular cancer	operated Majuro 1994
885	F	31	AT	suspicious of cancer	insufficient	N/A	follicular cancer	operated Majuro 1994
1273	F	39	BRAVO, EOT	suspicious of cancer	insufficient	N/A	papillary cancer	operated Honolulu 1996
877	F	39	BRAVO, EOT	20 mm follicular neoplasm	follicular neoplasm	follicular adenoma	—	deferred for acute medical problems, planned for 1996
1112	F	40	BRAVO, EOT	suspicious of cancer	papillary cancer	N/A	papillary cancer	operated Majuro 1994
501	F	42	BRAVO, EOT	suspicious of cancer	insufficient	adenomatous goiter	—	inoperable for medical reasons
1201	F	46	BRAVO, EOT	suspicious of cancer	insufficient	N/A	papillary cancer	operated Majuro 1994
510	F	57	BRAVO, EOT	suspicious of cancer	papillary cancer	—	—	surgery deferred, planned for 1996
792	F	66	BRAVO, EOT	30 mm follicular neoplasm	insufficient	follicular adenoma	—	inoperable for medical reasons
293	F	71	BRAVO, EOT	suspicious of cancer	papillary cancer	papillary cancer	—	inoperable for medical reasons
315	F	71	BRAVO, EOT	suspicious of cancer	insufficient	papillary cancer	—	inoperable for medical reasons
221	F	72	BRAVO, EOT	suspicious of cancer	follicular neoplasm	N/A	follicular cancer	operated Majuro 1994
83	F	73	BRAVO, EOT	large follicular neoplasm	insufficient	follicular adenoma	—	growing
756	M	39	BRAVO, EOT	suspicious of cancer	insufficient	N/A	micropapillary cancer	operated Majuro 1994
799	M	40	BRAVO, EOT	large follicular neoplasm	follicular adenoma	N/A	adenomatous goiter	operated Majuro 1994
576	M	53	BRAVO, EOT	suspicious of cancer	adenomatous goiter	N/A	papillary cancer	operated Majuro 1994
609	M	55	BRAVO, EOT	suspicious of cancer	adenomatous goiter	N/A	papillary cancer	operated Majuro 1994
272	M	56	BRAVO, EOT	35 mm follicular	papillary cancer	adenomatous goiter	—	growing despite T4 therapy
995	M	75	BRAVO, EOT	50 mm follicular neoplasm	follicular neoplasm	—	—	died from unrelated cause

proved FNA data of 1996, there is evidence to indicate that the total number of cancers in this study group is about 15 or 1.2% (15/1275) of the Marshallese examined or about 12% (15/123) of all the palpable nodule cases we investigated.

Fifteen study participants in 1993 had a neck scar on their first examination that revealed that they had been previously operated for thyroid disease. Historical records indicated that two of the fifteen were members of the Rongelap community who had been directly exposed on Rongelap to the BRAVO test fallout and who had been operated on for thyroid adenomas more than 25 y earlier.

In order to estimate the total cancer rate in this population, the cancers among those previously operated have to be added to those confirmed in our study. An extensive search for histopathology reports in the medical records in the hospitals of Ebeye and Majuro for the 15 earlier operated cases provided evidence that there were two thyroid cancers and one case of occult papillary cancer in adenomatous goiter. Therefore, for further calculations we assume that the total number of thyroid cancers in our study population ($n = 1{,}322$) is between 15 and 20, i.e., 1.1 to 1.5%. All but 3 occurred in women; thus, the frequency in female Marshallese is approximately 2%. One of the cancer patients we investigated had been exposed to early fallout of the BRAVO test on Rongelap.

Hypothesis testing

A number of statistical tests were conducted specific to the objectives outlined earlier. To test the hypothesis that there was no difference in prevalence of thyroid nodules among the atolls, a Chi-squared test was carried out. All atolls were used with the exception of Rongelap and Utrik and three atolls (Kili, Mili and Wotho) where the number of persons was less than 10. The null hypothesis was not accepted ($\chi^2 = 34.9$, df = 15, $p < 0.003$). The rejection of this hypothesis prompted further examination into the differences between the atolls and to determine whether there was evidence for a functional relationship between prevalence and distance.

The age-adjusted prevalences were plotted against the distance to Bikini for the total number of nodular goiters and for palpable nodules only. This examination was conducted for the data of both sexes pooled as well as the data for men and women separately. The prevalence were weighted as described earlier. The correlations are listed in Table 7.

There were several unexpected results from these analyses. The correlation of age-adjusted prevalence with distance from Bikini for all nodular goiter with both sexes pooled was not significant for the atolls represented in the Ebeye study ($r = -0.29$, $p = 0.12$) but had a higher correlation and attained marginal significance for the atolls used by Hamilton ($r = -0.43$, $p = 0.07$) (see Table 2 for a listing of the atolls used in the Ebeye study and the Hamilton study). Furthermore, the correlation of age-adjusted prevalence with distance from Bikini for all nodular goiter in males was significant ($r = -0.44$, $p = 0.04$) but was not significant for females ($r = -0.18$, $p = 0.25$).

The correlations for palpable nodules differed from the case of all nodular goiter. The relationship with men and women pooled was close to significance for the Ebeye atolls ($r = -0.37$, $p = 0.06$) and the atolls used by Hamilton ($r = -0.43$, $p = 0.08$). Fig. 1 shows a plot of the relationship between palpable nodules and distance from Bikini. The key to the numbered atolls in this figure is provided in Table 2.

In order to examine the occurrence of nodular goiter in more detail, a logistic regression analysis was conducted. As in Hamilton's study, the variable θ was initially included in addition to distance to better define the location of each residence atoll with respect to Bikini (see Table 2). The logistic regression was first run with all prediction terms, thereafter sequentially eliminating those with p-values greater than 0.10. The analysis was carried out for the four combinations of all nodular goiters, palpable nodules only, atolls from the Ebeye study and atolls from the Hamilton study.

In the analyses that we conducted, neither the interaction term between θ and distance or the independent variable θ were statistically significant. In the regression model using data for all nodular goiters, the variable distance was not significant and, therefore, excluded. However, distance maintained significance for the Hamilton atolls. For the analysis of palpable nodules only, distance remained in the model for both the Ebeye atolls and the Hamilton atolls. The variables sex as well as age were both significant predictors of the presence of

Table 7. Correlations between age-adjusted nodule prevalence and distance from Bikini. Correlation coefficients are Pearson's r (weighted) except where noted in brackets [. . .] which are Spearman's r (unweighted). Atolls are either: (1) all the residence atolls in 1954 for subjects in the Ebeye study, or (2) all the residence atolls in 1954 for subjects in Hamilton et al. (1987) study.

Diagnosis	Atolls	Sex	r	p-value
All nodular goiter	those in Ebeye study	M & F	−0.29[−0.34]	0.12[0.14]
All nodular goiter	those in Hamilton study	M & F	−0.43[−0.38]	0.07[0.19]
All nodular goiter	those in Ebeye study	M	−0.44	0.04
All nodular goiter	those in Ebeye study	F	−0.18	0.25
Palpable nodules only	those in Ebeye study	M & F	−0.37[−0.45]	0.06[0.04]
Palpable nodules only	those in Hamilton study	M & F	−0.42[−0.41]	0.08[0.14]
Palpable nodules only	those in Ebeye study	M	−0.14	0.32
Palpable nodules only	those in Ebeye study	F	−0.44	0.06

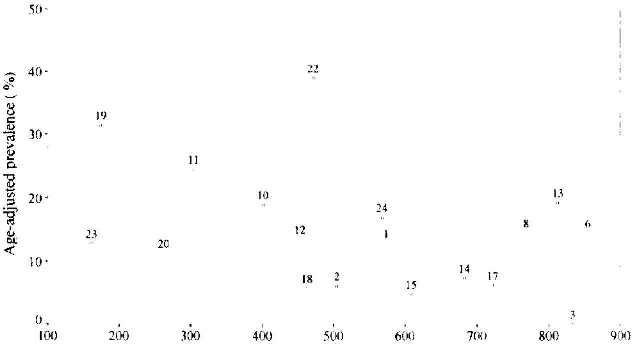


Fig. 1. Age-adjusted prevalence of palpable nodules as a function of distance (km) of residence atolls in 1954 from Bikini Atoll. All atolls of Ebeye study are included. Atoll identification numbers refer to Table 2.

nodular goiter in general and for the presence of palpable nodules. For sex, the odds ratio (female to male) varied from 2.02 to 2.24 within the four variable combinations examined. These findings are summarized in Table 8.

DISCUSSION

Most previous population screening programs to detect nodular thyroid disease, e.g., the follow-up of the exposed Marshallese by medical teams organized by Brookhaven National Laboratory (Conard 1984; Adams et al. 1989) and the study of Hamilton et al. (1987) have used palpation of the neck as the primary criterion of positive findings. The development of high resolution ultrasound equipment permits the additional means for objective and precise thyroid and nodule size determination and the ability to photographically document abnormalities for later study. One of the achievements of this study was establishing the capability and value of using ultrasound in a large scale study and in remote and primitive environments. Some of the examinations in this study were conducted on remote islands without centralized electrical power. Using a portable gasoline powered generator as small as a few kW power, ultrasound was used in the field without any reduction in diagnostic quality. Whereas the advantages of this method are several, there remains the question of the clinical importance of nodules that are not palpable.

Several findings of the clinical examinations were noteworthy. First, non-palpable nodules tended to be smaller than palpable nodules; the median diameter being 7.5 mm for non-palpable compared to 16 mm for palpable. The size distributions of the palpable and non-palpable nodules, however, showed considerable overlap (Fig 2). For example, 20% of palpable nodules were smaller than 10 mm diameter while 20% of non-palpable nodules were larger than 10 mm.

We defined the palpability of thyroid nodules to be the proportion of all nodules detected by ultrasound that were also palpable. The palpability increased only very slowly with increasing size as measured by ultrasound (Fig. 3). Furthermore, in 52 women who had nodules of 9 to 12 mm diameter, 40% of which were palpable, there was no correlation of palpability with a body mass index. In this group, palpability of nodules for obese women (17 of 28 cases) was similar to that for normal and slim size women (15 of 24 cases). Although neck size and the amount of adipose tissue over the thyroid is often speculated to be related to the difficulty in palpating a nodule, those generalizations were not well supported by our observations.

The ease of palpation of a nodule is determined partially, but not exclusively, by the size of the nodule.

Table 8. Results of logistic regression, independent variables with $p < 0.10$.

	Atolls of Ebeye study		Atolls of Hamilton study	
	All nodules	Palpable nodules only	All nodules	Palpable nodules only
Age				
Coefficient β	0.0437	0.0215	0.0422	0.0273
p-value	<0.0000	0.019	<0.000	0.007
Standard error	0.0074	0.0091	0.0084	0.01
95% confidence interval on β	0.029–0.059	0.003–0.04	0.025–0.059	0.007–0.047
Sex				
Coefficient β	0.769	0.702	0.806	0.723
p-value	<0.000	<0.001	<0.000	0.002
Standard error	2.16	2.02	2.24	2.06
95% confidence interval on β	1.56–3.00	1.33–3.07	1.54–3.26	1.29–3.29
Distance				
Coefficient β	ns	−0.001	−0.0012	−0.0014
p-value	ns	0.084	0.04	0.073
Standard error	ns	0.0006	0.0006	0.0008
95% confidence interval on β	ns	−0.002–0.000	−0.002–0.000	−0.003–0.000
Constant				
Coefficient β	−3.464	−2.7068	−2.8632	−2.853
p-value	<0.000	<0.000	<0.000	<0.000
Standard error	0.4228	0.626	0.574	0.7012
95% confidence interval on β	−4.31/−2.618	−3.959/−1.455	−4.011/−1.752	−4.255/−1.451

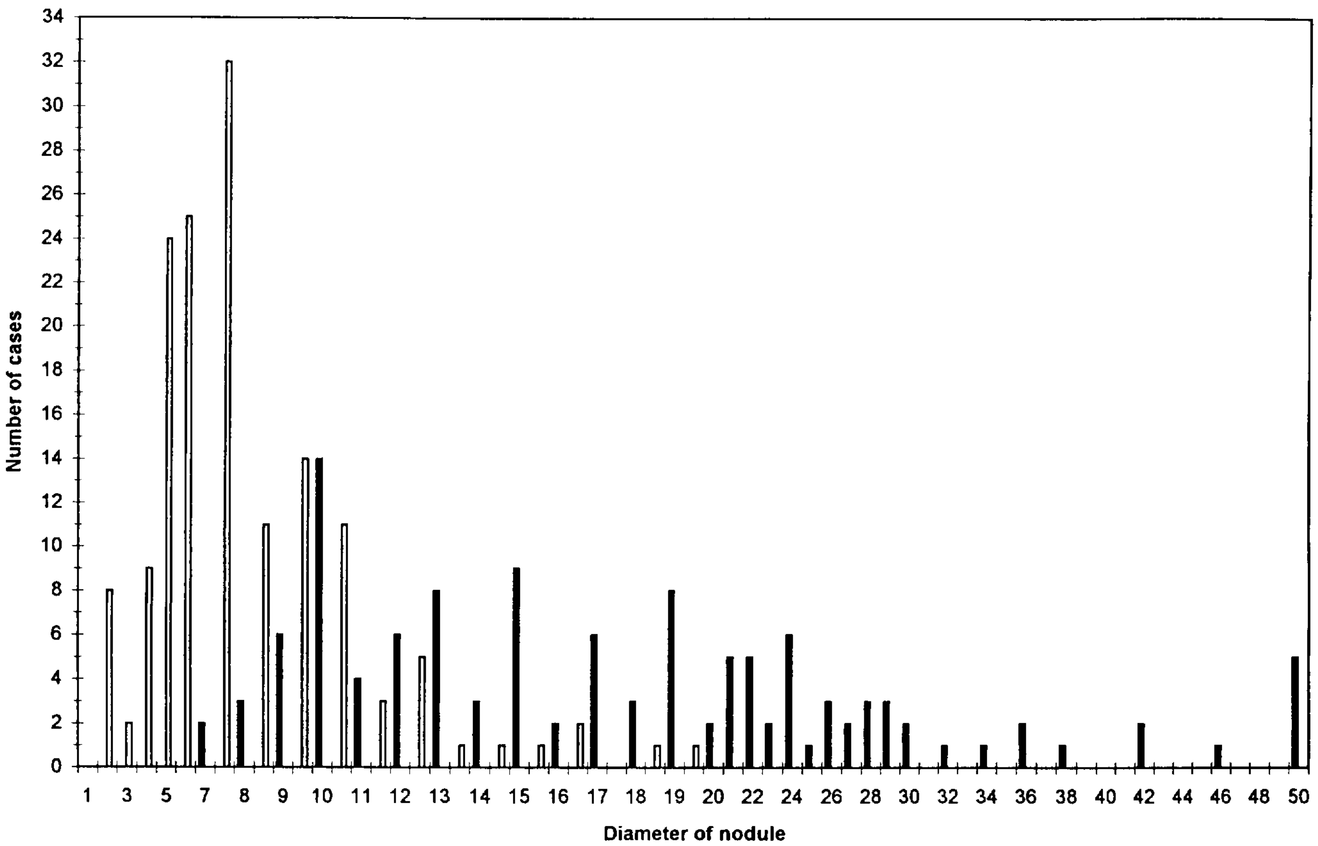


Fig. 2. Size distribution of palpable (closed bars) and non-palpable (open bars) nodules for subjects examined at Ebeye. The diameter is defined as the largest diameter of the largest nodule of a study subject in mm.

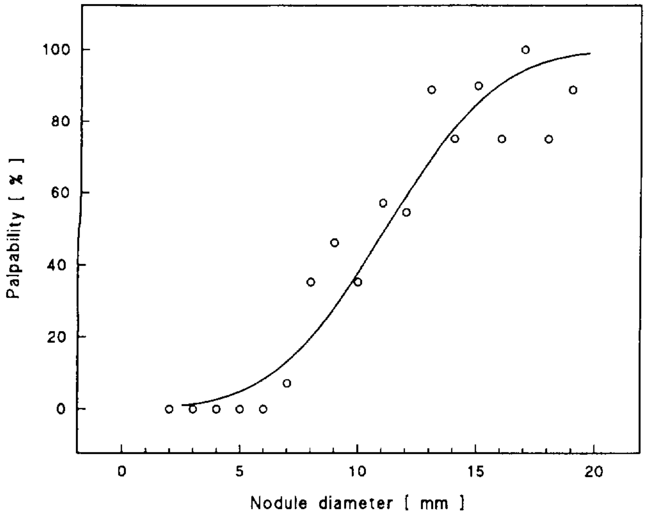


Fig. 3. Palpability of nodules as a function of its largest diameter in mm.

The probability of a successful palpation does increase with nodule size though there are also other important factors including the specific anatomy of each patient's thyroid, neck, and skin as well as the experience and expectations of the examiner. Although the experience of the endocrine surgeons who made the examinations was very extensive, false positive and false negative judgments sometimes occurred. For example, about 12% of nodules palpated during the first examination proved to be non-existent on ultrasound imaging. On the other hand, the number of palpable nodules doubled after the examiner had learned about the presence and approximate location of a nodule from ultrasound. For this reason, we suggest that in addition to clinical investigation and palpation, high resolution ultrasound imaging is an important addition to accurately determine the nodule prevalence rate in a population that is undergoing screening. The size and the structure of a thyroid nodule is probably more important in regard to its clinical impact than its palpability; however, repeated follow-up of this group of patients will be needed to resolve this question.

Comparison of our 1993 and 1996 findings demonstrate that the original diagnoses were generally verified. The number of individuals in the non-palpable category did not change over the 3-y period though there was some cross-over of individuals between categories (see Table 5). During the 3-y interval, the palpable and no nodule category were about equally stable though the change in number of palpable nodules was towards an increase (+7%) while the change in number of cases without any nodule was towards a decrease (−6%). On an individual basis, a non-palpable nodule was most likely to change (24% changed category), a no nodule case was somewhat less likely to change (17% changed category) and a palpable nodule was the most likely to remain the same (only 10% changed category).

Approximately 9% of the non-palpable nodules disappeared during the 3-y interval (usually cystic lesions of less than 6 mm diameter), and about 9% of palpable nodules became non-palpable. Whereas these numbers may give some indication of the potential error range of the findings of screening programs, particularly those conducted over several years time, a more detailed analysis of the echo patterns is required before we can identify structural features that predict progression or regression of palpable or non-palpable nodules.

The prevalence of palpable nodules we observed in Ebeye (16.2%) was about twice that noted by Hamilton et al. (1987) (6.2% crude prevalence rate). Assuming that the population on Ebeye in 1993 represented a similar cross-section of the population of the Marshall Islands as when Hamilton examined the population 8 y earlier, either the prevalence had significantly increased during the elapsed time, or there were significant differences in diagnostic sensitivity of the two studies. The latter explanation is suggested by the high proportion of thyroid nodules that could only be palpated after they had been diagnosed by ultrasound first. This fact alone could explain the differences in numbers of detected nodules between the two screening programs and further emphasizes the usefulness of ultrasound to determining an accurate assessment of palpable nodular disease within a population.

Fine needle aspiration biopsy of palpable nodules remains the gold standard of diagnosis for nodules. However, in this field study, which routinely operated under tropical and sometimes primitive conditions, the rate of insufficient material or insufficient staining was high. On the other hand, even under these difficult conditions, the accuracy of the ultrasound diagnosis of cancer was >90%, remarkably high as judged from the agreement with the histopathological evidence from the operated cases.

In 4 cases in 1993 that were suggestive of cancer by the ultrasound examination but that were not operated, FNA was able to provide a cytological diagnosis in 1996. A strong likelihood of cancer was noted for 2 cases and follicular adenoma in 1 case. In the 4 cases that were diagnosed by ultrasound as follicular adenoma, 3 were diagnosed by FNA as adenoma. In 2 of 42 cases where the ultrasound diagnosis in 1993 was adenomatous goiter, FNA biopsy in 1996 was indicative of cancer.

Taking histological or cytological diagnosis as a criterion, sensitivity of ultrasound diagnosis was 87% and specificity was 96%. Overall, these data demonstrate that in the hands of experienced physicians who make their diagnosis during the conduct of the examination, ultrasound is nearly equivalent to FNA biopsy in its ability to determine the nature of a thyroid nodule.

Comparison with cancer rates elsewhere

The thyroid cancer rate in our study was not dissimilar to that observed in 2,587 atomic bomb survivors in Nagasaki where 21 cancers were reported (0.8%) compared to 1 in 935 (0.1%) unexposed persons (Nagataki et al. 1994). A cancer rate in unexposed adult women screened in Kamaishi, Japan, was 0.6% (Takaya et al. 1982), intermediate to the Nagasaki control and exposed population rates.

Cancer statistics from different countries suggest great differences in thyroid cancer incidence (IARC 1992). In particular, rates are high among island populations (Henderson et al. 1985; Kolonel et al. 1990; IARC 1992) including Hawaii, Iceland and New Zealand. For example, one of the highest reported rates is for Filipinos living in Hawaii (Goodman et al. 1988); thyroid cancer among that group accounted for 2.7% of all non-skin cancers in Hawaii between 1973 and 1977. Native Hawaiians and those of Chinese descent who live in Hawaii have also shown high rates. A similarly high rate was reported to be nearly 2% among female Melanesians over 25 y of age (Ballivet et al. 1995). The thyroid cancer prevalence in female Marshallese is similar to these values.

The likelihood of an enhancement in the nodule and cancer rates in this study, relative to most reported rates, was considered as a result of our intensive screening. That phenomenon was demonstrated by Ron et al. (1992) who reported a 7-fold increase in cancer rates and a 17-fold increase in nodule rates when screening followed public announcements for examinations and publicity concerning the relationship of thyroid disease to head and neck irradiation. Due to our screening efforts, some enhancement of the cancer rate has certainly occurred relative to most nationally reported thyroid cancer statistics. Presently it is not possible to know the extent of this effect among the Marshallese population. Enhancement of the cancer rate is primarily of concern in making comparisons with cancer rates from other countries. The determination of relationships between disease incidence and location within the Marshall Islands should not be effected by this phenomenon.

In our study, 73% (8/11) of the cancers confirmed by histopathology were of the papillary or micropapillary type; the remaining 27% were of the follicular type. This ratio generally agrees with observations in Hawaii during the years 1960 through 1984, where 74% of thyroid cancers were papillary and 17% were follicular (Goodman et al. 1988).

Correlations with environmental radioactivity

Considerable thought has been given to alternative hypotheses that might explain a decreasing relationship between nodular goiter and distance from the Bikini test site. Hamilton assumed that his results indicated that the geographic extent of radioiodine exposure was broader than assumed and that distance served as a proxy variable for past exposure to short-lived radioiodines. To investigate the plausibility of that hypothesis, we examined recently acquired radioactive contamination data of the

Marshall Islands from a radiological monitoring program of the entire nation (Simon and Graham 1997). Accordingly, we plotted the mean ratio of ^{137}Cs (regional:global deposition) against distance from Bikini (Fig. 4). However, that analysis showed no obvious relationship thus casting some doubt on the existence of a decreasing linear dose effect as a function of distance. Furthermore, we plotted age-adjusted prevalence of all nodular goiters and palpable nodules only against the ratio of ^{137}Cs (regional:global deposition) and, similarly, there was no obvious relationship.

It should be noted that the magnitude of environmental ^{137}Cs is not a perfect proxy variable for radioiodine exposure. The primary determinant of radioiodine air concentrations that might lead to individual exposure is the cloud transit time from the point of the explosion to the inhabited location. Secondary parameters that determine the bioavailability of radioiodine include particle size in the atmosphere, the presence or absence of rain, etc. Variations in transit time among different tests would dramatically affect the radioiodine concentration of the cloud but would have little effect on the ^{137}Cs concentration because of the difference in their physical half-lives. Yet, for locations with near equal transit times, the ^{137}Cs should be highly correlated with the past radioiodine deposition, particularly ^{131}I, the longest lived of the short-lived suite.

We did observe, however, a relationship between the excess ^{137}Cs and angle (as measured clockwise from a E-W line); the relationship decreases in a curvilinear fashion from 0° to about 30° where it levels out at a value of approximately 1.0. This indicates that the cloud's direction of travel was not highly correlated with straight line distance in all directions. It is known, for example, that the cloud likely initially moved in the east direction, but then may have veered southerly with lower air concentrations as a result of dilution and decay. The fact, however, that θ was not significant in the logistic regression lends little support to this variable as an explanatory cause for the pattern in thyroid disease.

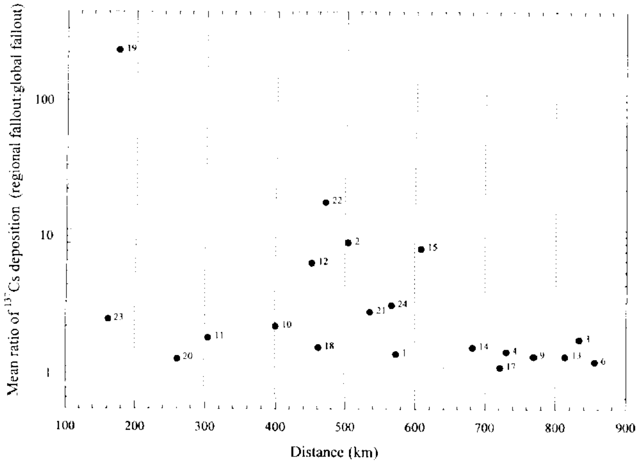


Fig. 4. Mean of regional fallout:global fallout ^{137}Cs deposition in atolls as a function of distance (km) from Bikini Atoll (data from Simon and Graham 1994, 1997).

Diet and other risk factors

A number of risk factors in addition to ionizing radiation may be related to the high cancer rates. There is accumulating evidence that populations resident on island countries, in particular those in the tropical waters of the Pacific, have higher than normal incidence rates for thyroid cancer despite earlier observations of little ethnic difference in rates (Ron and Modan 1982). These observations may be related to diet as well as other factors peculiar to island life.

Diet is considered as a plausible risk factor (Kolonel et al. 1990), in particular, where the consumption of high iodine seafood is common. Seafood based diets have showed positive risk associations to thyroid cancer in a number of studies (Kolonel et al. 1990; Ron et al. 1987; and Preston-Martin reported by Henderson 1990).

SUMMARY AND CONCLUSIONS

The objectives of this study were (1) to examine and gather data on the frequency of thyroid disease (both nodular and cancerous conditions) in as large of proportion as possible of those Marshallese alive during the years of atomic testing, (2) to advise the Government of the Marshall Islands on the findings from the medical screening program, and (3) to test the hypothesis of Hamilton et al. (1987) Goals (1) and (3) are the main subject of this report though several other findings are noteworthy and are also summarized here.

First, non-palpable nodules tended to be smaller than palpable nodules although the size distributions of the palpable and non-palpable nodules show considerable overlap. This finding implies that unassisted palpation may not be successful in finding the smaller nodules, which can be only palpated after directing the physician to the location by ultrasound.

Ultrasound was shown to be a viable technique even in tropical and primitive environments as the devices can be successfully powered by small, portable electrical generators. The advantages of ultrasound are that it can supplement palpation by providing objective measurements of the size of lesions and can photographically record the examination for later review. In the hands of experienced practitioners, ultrasound can nearly equal the reliability of FNA biopsy for predicting a cancerous condition. Comparison of our findings from the 1993 and 1996 examination phases demonstrated that the original diagnoses were generally verified.

The prevalence of palpable nodules was highest in the Ebeye BRAVO cohort (16%), about 20% lower in the EOT cohort, and about 85% lower in the AT cohort. Most of the difference in the AT cohort is undoubtedly due to their younger age, though the difference is dramatic enough to suggest that other factors might be involved. Radiation exposure may be one of several factors involved.

The prevalences of non-palpable nodules were similar among all three age cohorts but were moderately

Table 9. Comparison between study of Ebeye BRAVO cohort and Hamilton et al. (1987). Results are given for palpable nodules only except where noted and for those atolls which were included in each study.

	Ebeye BRAVO cohort	Cohort of Hamilton et al. (1987)
Size of cohort	815	2,273
Location of study	Ebeye Island, Kwajalein Atoll	Present day residence atolls
Proxy variable for radioiodine exposure	Residence in 1954; present day environmental ^{137}Cs measurements	Residence in 1954
Number of residence atolls of study subjects in 1954	21	14
Description of medical examinations	Palpation, ultrasonography, FNA biopsy, histology	Palpation
Definition of thyroid nodule	Visibility on ultrasound, solitary/multiple	solitary, palpable, >1.0 cm diameter
Crude prevalence rate	16.2	6.2
Range of prevalence of palpable nodules exclusive of Rongelap and Utrik (%)	0–36.4	0.9–10.6
Estimate of prevalence in Mili and Ebon Atolls (%)	12.5 (4/32)	2.45 (9/370)
Odds ratio female/male	2.1	3.7
Chi-square test of homogeneity in prevalence among atolls exclusive of Rongelap and Utrik	$\chi^2 = 34.9$; df = 15, $p < 0.003$ (all nodules)	$\chi^2 = 23.45$, df = 11, $p < 0.025$
Pearson correlation coefficient between age-adjusted prevalence (weighted) and distance from Bikini	$r = -0.42$ ($p = 0.08$) for Hamilton atolls; $r = -0.37$ ($p = 0.06$) for all atolls of Ebeye cohort	$r = -0.65$, $p < 0.002$
Statistically significant predictor terms in logistic regression model	Age, sex, distance ($p = 0.07$)	Age, sex, distance, θ, distance θ

different from palpable nodule rates in the EOT and AT group. The rate of non-palpable lesions was virtually the same in the BRAVO cohort (16%) as for palpable nodules, about 10% higher in the EOT cohort, and about twice as high in the AT cohort. This availability of such data is uncommon and is undoubtedly valuable as a description of the progression of thyroid disease with age in an island population.

The prevalence of palpable nodules that we observed in Ebeye (16.2%) was more than twice that noted by Hamilton et al. (1987) (6.2% crude prevalence rate) when averaged over all the atolls of residence in 1954. The use of ultrasound to direct physicians in locating and palpating nodules is the primary explanation for the differences in the two screening programs, aging of the population being a secondary cause.

The results of statistical analysis and hypothesis testing for the population in this study are suggestive of relationships similar to that observed by Hamilton et al (1987). A summary of the results from the Ebeye analysis and the analysis of Hamilton et al. is shown in Table 9. Because of the suggestion that location of residence during the testing era may be related to nodule prevalence, further analysis of the incidence and casual factors of thyroid disease among Marshallese appears to be a worthwhile endeavor.

An examination of the relationship between present day ^{137}Cs concentrations in the environment and distance from the Bikini test site did not shed any light on radioactive contamination as a causal factor. No relationship was obvious between the variables examined although it is understood that only for locations of equal fallout transit time would the radioiodine concentrations be expected to be highly correlated with cesium.

Though we were not able to confirm the Hamilton hypothesis with a high level of statistical significance, there is also no evidence to disprove it. Moreover, our data on nodule prevalence with distance show similar trends to those observed by Hamilton. Our interpretation is different, however, in that we found present levels of ^{137}Cs and distance to show no relationship which is suggestive of radiation exposure as a causal factor. Two possibilities to explain this phenomenon might be considered. The first deserves the most attention because it is the most plausible: (1) even though there is no relationship between cesium levels and distance, there may be a functional relationship between radioiodine exposure and location though it very well might not be a relationship that is linear with distance; or (2) there is another phenomenon that is responsible for induction of thyroid abnormalities, and it is also distance dependent. It is difficult to conceive of plausible risk factors that might be distance dependent though the influence of diet and dietary (stable) iodine intake must be considered. Either iodine deficiency or excess might be responsible for unusual thyroid responses in island inhabitants. If, for example, the intake of seafood differed among the atolls because of differences in fish availability, a deficiency might have been occurred in one group relative to another. In some other atolls, an excess might have occurred for the opposite reasons. Such hypotheses require further study.

Presently, we believe that it is reasonable to proceed with our current plans of reconstruction of exposures to the individuals we have examined for thyroid disease in the Marshall Islands. Such an effort will necessarily rely on residence history data for each individual and historcal monitoring data, which will require both careful interpretation and probably some degree of interpolation to cover all locations and all time periods. Until such detailed examinations are complete, the cause of high rates of thyroid nodules and cancer and their relationship with locations of residence remains without adequate explanation.

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UNIVERSITY OF WASHINGTON'S RADIOECOLOGICAL STUDIES IN THE MARSHALL ISLANDS, 1946–1977

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Abstract—**Since 1946, personnel from the School of Fisheries, University of Washington (Applied Fisheries Laboratory, 1943–1958; Laboratory of Radiation Biology, 1958–1967; and Laboratory of Radiation Ecology, since 1967), have studied the effects of nuclear detonations and the ensuing radioactivity on the marine and terrestrial environments throughout the Central Pacific. A collection of reports and publications about these activities plus a collection of several thousand samples from these periods are kept at the School of Fisheries. General findings from the surveys show that (1) fission products were prevalent in organisms of the terrestrial environment whereas activation products were prevalent in marine organisms; (2) the best biological indicators of fallout radionuclides by environments were (a) terrestrial—coconuts, land crabs; (b) reef—algae, invertebrates; and (c) marine—plankton, fish. Studies of plutonium and americium in Bikini Atoll showed that during 1971–1977 the highest concentrations of ^{241}Am, 2.85 Bq g^{-1} (77 pCi g^{-1}) and ^{239,240}Pu, 4.44 Bq g^{-1} (120 pCi g^{-1}), in surface sediments were found in the northwest part of the lagoon. The concentrations in the bomb craters were substantially lower than these values. Concentrations of soluble and particulate plutonium and americium in surface and deep water samples showed distributions similar to the sediment samples. That is, the highest concentration of these radionuclides in the water column were at locations with highest sediment concentration. Continuous circulation of water in the lagoon and exchange of water with open ocean resulted in removal of 111 G Bq y^{-1} (3 Ci y^{-1}) ^{241}Am and 222 G Bq y^{-1} (6 Ci y^{-1}) ^{239,240}Pu into the North Equatorial Current. A summary of the surveys, findings, and the historical role of the Laboratory in radioecological studies of the Marshall Islands are presented.**

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Key words: Marshall Islands; water; radioactivity, environmental; radionuclide

LABORATORY HISTORY

THE LABORATORY was established at the University of Washington, College of Fisheries, in late 1943. Its first mission was to obtain information about the effects of ionizing radiation upon fish and other aquatic organisms. In July 1946, the Laboratory participated in the first series of nuclear tests in the Marshall Islands, Operation Crossroads, at Bikini Atoll and in the 1947 extensive resurvey. In the 1950's, the Marshall Island studies became the principal focus of the Laboratory's research efforts. The last test of the 66 nuclear detonations in the Marshall Islands was 18 August 1958, at Eniwetok. Since that time there have been a few other resurveys and surveys with other missions.

The name assigned to the Laboratory in 1943 by the U.S. Army Corps of Engineers, Manhattan Project, was "Applied Fisheries Laboratory," and bibliographically identified as UWFL (University of Washington Fisheries Laboratory). In 1957 the name was changed to Laboratory of Radiation Biology (LRB) and in 1966 changed again to Laboratory of Radiation Ecology (LRE). To avoid confusion, the simple term "Laboratory" will be used in this report.

In the planning stages for the Hanford plutonium production plant, there was concern about potential impact of the discharge of reactor cooling water into the Columbia River and its effects upon the plants and animals in the river, especially the very valuable salmon resource. A study of this potential problem was favored by Leslie Groves and Stafford Warren of the U.S. Army Corps of Engineers, the agency responsible for development of the Hanford Project. It was then suggested "that the program be set up outside of the Manhattan District by persons experienced in aquatic biology" (Hines 1962). Lauren R. Donaldson, College of Fisheries, accepted the leadership role for this research study in late summer 1943, about 3 mo after the beginning of construction of the first pile at Hanford. He served as Laboratory Director for 24 y. As a Manhattan District sponsored project, the program was classified until it was transferred to the Atomic Energy Commission in 1947.

Marshall Islands, 1946–1961

The sources of the fallout radionuclides in Marshall Islands samples were from one or more of 66 nuclear detonations: 23 at Bikini and 43 at Eniwetok. The schedule of detonations is given in Table 1.

A detailed and excellent account of the Laboratory's involvement in the Marshall Islands testing program is provided in Hines (1962). He participated in the field programs and was well acquainted with the Laboratory

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Table 1. Schedule of nuclear detonations at Bikini and Eniwetok Atolls 1946–1958[a]

Atoll	Operation code name	Date	No. of detonations B[b]	E[b]	Comments
Bikini	Crossroads	1946 July	2		1 air drop; 1 underwater; yields : 23 KT each
Eniwetok	Sandstone	1948 April–May		3	3-tower yield: 37, 49 & 18 KT
Eniwetok	Greenhouse	1951 April–May		4	4-tower yields: 3–?, 1–47 KT
Eniwetok	Joy	1952 Nov		2	first thermonuclear (MIKE)); surface; 10 MT also, 1 air drop, 500 KT
	Castle	1954			second thermonuclear; surface; 15 MT;
Bikini		March–May	5		also 3 barge, 1 surface at 110 KT; 3–?
Eniwetok		May		1	barge; yield,?
	Redwing	1956			first U.S. airdrop of a thermonuclear; also
Bikini		May–July	6		4 barge, 1 surface; yields (total) 10
Eniwetok		May–July		11	1 airdrop; 2 barge; 2 surface; 2 tower; 4–? yields: 1–40 KT; 10–?
	Hardtack	1958			
Bikini		May–July	10		1; barge; yields: 10–?
Eniwetok		April–August		22	1 balloon NE of Eniwetok; 15 barge; 2 surface, 2 underwater, 3 (?) yields 3–29 MT, total: 18–?
			23	43	
			TOTAL B[b] + E[b]	66	

[a] Selected information form Schultz and Schultz (1994).

[b] B = Bikini Atoll and E = Eniwetok Atoll.

and its people. For this period, he recognized four phases: 1946–1949; 1952; 1954; and 1958.

1946–1949. Operation Crossroads, pre and post test surveys, was the starting point where almost everything was new. Survey and analytical procedures needed to be tested and adapted to the task at hand. The instrument first used for detection and measurement of radiation in the field and in samples brought to the field or home laboratories was a simple Geiger-Mueller counter. The counting rates provided estimates of the relative radioactivity of the samples but no qualitative information. There were pre-Crossroads studies and collections for use in comparison with the post-Crossroads resurveys of 1946 and 1947. For operations Sandstone (1948) and Greenhouse (1951) there were no plans for environmental surveys. A plan for the Laboratory to return to Eniwetok for a post-Sandstone, pre-Greenhouse survey was canceled because of the Korean war.

1952. The first thermonuclear detonation (MIKE) was on 1 November 1952, at Eniwetok Atoll. This much more powerful detonation brought a new dimension to fallout studies. [The islet on which the detonation occurred became a hole in the reef more than 1.85 km (one nautical mile) wide and 60 m (200 feet) deep (Hines 1962).] With thermonuclear detonations, much greater quantities of fallout radionuclides were produced per detonation, and a relatively greater proportion was injected into the stratosphere.

1954. A 15-megaton thermonuclear detonation (BRAVO) at Bikini Atoll on 1 March 1954, had grave consequences. The prevailing wind in this area is the NE trade wind, but at the time of BRAVO the tropospheric fallout was carried to the NE and E of Bikini. There was a heavy fallout of Bravo-produced radionuclides onto a Japanese fishing boat that was 150 km (80 miles) NE of Bikini at the time of the detonation and this incident became of great national concern to the Japanese people. Also, Bravo fallout was carried to Rongelap Atoll, a populated atoll, 185 km (100 miles) east of Bikini. The mean external dose to individuals at Rongelap was calculated to be 1.75 Gy (175 R); they were in the SE corner of the atoll, but had they been in the northern area their calculated dose would have been as great as 8 Gy (800 R). The radioisotope of greatest concern was ^{131}I, which was primarily inhaled by the residents and accumulated in the thyroids. Children were affected most seriously because as they became adults thyroid nodules developed. The Brookhaven National Laboratory had the responsibility for caring for the health of Rongelap people. An account of radiation doses to the people are given by Conard (1992). Our Laboratory began intensive ecological studies at Rongelap soon after the arrival of the 1954 Bravo fallout. The terrestrial ecosystems studies are reported by Walker, Gessel, and Held in another section of this volume.

1954 was also the year of the first ocean survey, the voyage of the Japanese oceanography research vessel "Shunkotsu Maru," and this was followed by six U.S.

surveys—the Taney in 1955, the Walton and Marsh in 1956, and the Rehoboth, Collett and Silverstein in 1958 (Palumbo et al. 1959).

1958. By international agreement, the United States ended the program of nuclear testing in the Marshall Islands in August, 1958.

As the Laboratory's Marshall Island survey studies became less frequent, the knowledge gained from these experiences prepared the staff for expanding the scope of their radioecological studies to Fern Lake, Washington; the Washington State Coast; Amchitka, Alaska; Cape Thompson, Alaska; and elsewhere.

1962–1977. In 1964, six years after the last test series, the Laboratory carried out a survey of Bikini and Eniwetok Atolls to obtain information on the long-term effects of nuclear detonations. The major objectives for the 1964 study were documentation of biological and physical conditions at the atolls; a comparison, wherever possible, of the biological and physical conditions with those existing before and during the testing period; and documentation of the radiological conditions of the atolls. Specifically, during this expedition, the Laboratory had documented the kinds, numbers, and condition of organisms present in 1964, described the physical environment of the lagoon and land areas, identified the radionuclides present, and determined the amount of radioactivity in the biota and in the physical environment. An extensive photographic documentation of plants and the environment in general accompanies the 1964 survey report (Welander 1964).

A study of the concentrations of two long-lived radionuclides ^{239}Pu ($t_{1/2}$ = 24,000 y) and ^{241}Am ($t_{1/2}$ = 458 y) in biota and sediments at Bikini and Eniwetok Atolls was initiated in 1970. The survey for this study, later named the Biogeochemistry of the Transuranic Elements in Bikini and Eniwetok Atolls, was a joint effort of our Laboratory, the Lawrence Livermore National Laboratory, and the Puerto Rico Nuclear Center in 1972. The Laboratory conducted additional field surveys in 1976 and 1977. The purpose of this study was to investigate the concentration and redistribution processes of the long-lived radionuclides ^{239}Pu and ^{241}Am in Bikini Atoll lagoon.

In 1974, the Laboratory's program to determine the concentration of radionuclides in foods, plants, animals, and soils was extended to the Central Pacific atolls and islands. The purpose was to furnish data to other agencies so that they might make an assessment of the dose of fallout radiation received by the people living throughout the Central Pacific. Areas sampled from April 1974 to August 1975 were, in addition to the Marshall Islands, Truk and Ponape in the Caroline Islands, Guam in the Marianas Islands, Christmas Island in the Line Islands, and Koror and Babelthaup in the Palau Islands.

SURVEY FINDINGS

Introduction

The basic field program was the collection of terrestrial, lagoon, and ocean samples that represented the major components of the ecosystem. Initially, a broad spectrum of sample types was collected but later most attention for biological samples was focused on specific radionuclide indicators. With regard to identification and measurement of the radionuclides in the samples, some of this work was done in the field, either in temporary accommodations aboard ships or at the Eniwetok Marine Biology Laboratory. The purpose of the field measurements was to provide guidance to the on-going field program. However, most of the samples were counted in the home laboratory where there were facilities for more sensitive detection and measurement of radionuclides and longer sample counting times could be accommodated.

Both Bikini and Eniwetok atolls were prime collection sites, and Rongelap Atoll became a major study area after the arrival of Bravo fallout from the 1 March 1954 detonation at Bikini Atoll. At the Bikini and Eniwetok sample collection sites, the nuclear detonation impact included thermal, over pressure, prompt radiation and local fallout factors, factors not present at Rongelap Atoll.

The discussions of the "findings" will be grouped by major environments: terrestrial, lagoon, ocean. Greater emphasis will be placed on general findings than on quantitative values for specific radioisotopes that change constantly with time, except when these values may be of relative significance. If more detailed information is sought, see the Archives section of this report for the location and availability of the Laboratory's publications and reports, especially Hines (1962).

Terrestrial

What happens to fallout after it arrives on island soils? Horizontal distribution will be largely by wind, precipitation, run-off and wash-overs; and vertically by percolation and sorption. Biological uptake also will play some role in fallout distribution—for example, the transfer of radionuclides from the ocean to seabirds to island nesting areas.

Bikini and Eniwetok are in the "local" fallout area where "the effects of blast and fire may be of even greater importance than the effects due to ionizing radiation . . ." (Eisenbud 1963). The specific cause of observed effects may be difficult to identify. The estimated relative yields of a nuclear explosion at "ground zero" are as follows: "Approximately 50% of the energy from a nuclear explosion is released in the form of blast effects, 35% as thermal radiation and the remaining 15% as ionizing radiation . . ." " . . .Of the ionizing radiation one third is prompt radiation . . . and the remainder is produced by decaying fission products and induced radionuclides" (Eisenbud 1963). Hence, the "cause-effect" relationship in a "local" fallout area is clouded by uncertainty about the cause(s).

The first thermonuclear detonation was the Mike shot of 1 March 1952 at the northern reef of Eniwetok Atoll. The estimated energy release was 10 MT. The Laboratory conducted both pre-shot and post-shot surveys. For the pre-shot survey, the most radioactive sample types (the residual radioactivity from previous detonations) were algae, aquatic invertebrates, plankton, fish, land plants and land invertebrates. The post-shot collection schedule in terms of days after Mike and of distance from ground zero were as follows: +2 to +4 d, 26–37 km (14–20 miles); +5 to +6 d, 13–22 km (7–12 miles); and +7 d, 3.7–5.6 km (2–3 miles). The order of radioactivity for sample type was the same as for pre-test samples except that post-test land plants ranked third. The ratio of post-shot to pre-shot radioactivity values was about 300 for the aquatic organisms and 1,000 for the land plants and vertebrates (Donaldson 1953).

For the 1959 Rongelap samples, information about what radionuclides were present in what samples was presented in an ecosystem type of chart. See Fig. 1 (Hines 1962). The distribution of fallout isotopes at Bikini and Eniwetok in comparable samples would be expected to be similar to Fig. 1. Although Bikini and Eniwetok were in the "close-in" fallout zone, there was no close-in fallout at Rongelap.

In 1964, a radiobiological study of the islands and reefs of Bikini and Eniwetok atolls was conducted by Welander et al. (1964). They observed that principal damage to the islands was the loss of topsoil on or near the test islands, apparently as a result of blast and heat effects. Similarly, blast and heat damaged the reefs and added greatly to fine silt and turbidity of the reefs and lagoons. ^{60}Co was the dominant radionuclide in the marine samples, whereas ^{137}Cs and ^{90}Sr were dominant in the land environment (Welander et al. 1964).

An extensive radiological survey of plants, animals, and soil at five atolls in the Marshall Islands was reported by Nelson (1979). The results of this survey indicated that ^{90}Sr and ^{137}Cs were dominant in the terrestrial environment and, in addition, ^{241}Am and ^{239,240}Pu were also important long-lived radionuclides in the soil samples from Bikini and Rongelap atolls. ^{60}Co and ^{55}Fe were dominant in the marine environment together with naturally occurring ^{40}K.

The amounts of radioactivity varied between atolls and between islands within an atoll in relation to the distance from the test sites. In the 1974–1975 survey, Bikini Atoll had the greatest amount of fallout radioactivity (^{90}Sr, ^{137}Cs, and ^{239,240}Pu), but the northern islands of Rongelap Atoll had only slightly lower amounts. Rongerik and Ailinginae Atolls and the southern island of Rongelap Atoll had similar amounts of radioisotopes, but were less than similar values for Bikini by factors of 5 to 10 or more. Values at Utirik Atoll were lower still, but were higher than amounts at Wotho and Kwajalein Atolls. Christmas Island in the Line Islands had the least amount of radioactivity of the areas surveyed. It was concluded that radioactivity on Bikini and Rongelap atolls had declined significantly with time and should continue to do so because of physical and biological processes (Nelson 1979).

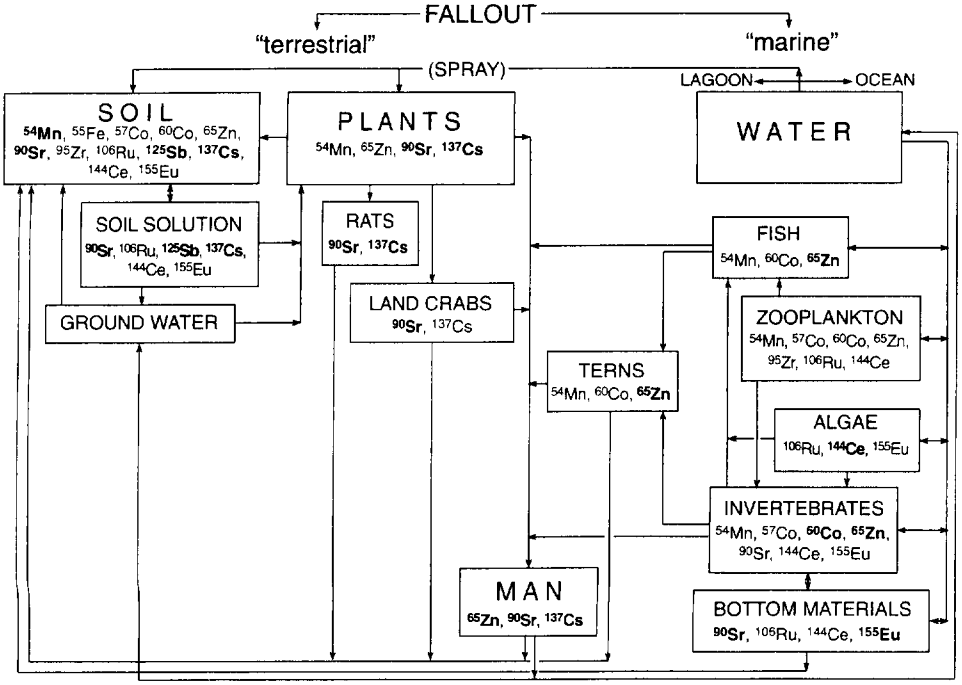

Fig. 1. Distribution of fallout radioisotopes at Rongelap Atoll, 1959, the dominant isotopes indicated in bold-faced type (Hines 1962).

The soils of the Marshall Islands consist of calcareous materials and a thin layer of organic matter that has produced a shallow, organic-rich horizon suitable for certain plant growth. Plutonium and americium measurements of surface soil samples collected on 6 of the 26 islands of Bikini Atoll in 1975 showed that ^{239,240}Pu values ranged from 0.02 to 13.3 Bq g^{-1} (0.5 to 360 pCi g^{-1}) and ^{241}Am values ranged from 0.04 to 1.7 Bq g^{-1} (1.2 to 45 pCi g^{-1}). The vertical distribution of plutonium in soil varied with soil types. Although about 98% of plutonium was retained in the top 25 cm in undisturbed soil, the remaining 2% was detectable as deep as 100 cm. The suspension and resuspension of plutonium and plutonium-bearing particles in the soil column by rain water (150–175 cm y^{-1}) seemed to be the principal mode of plutonium transport in the soil. Plutonium was found to be associated with the algal crust of the atoll soils. A comparison of ^{90}Sr and plutonium showed a similar pattern of vertical distribution in both disturbed and undisturbed areas, although the values for ^{90}Sr, 13.7 Bq g^{-1} (371 pCi g^{-1}), were much greater than for ^{239,240}Pu, 0.3 Bq g^{-1} (9.3 pCi g^{-1}) (Nevissi et al. 1976).

General findings from the terrestrial surveys are as follows:

1. Fission products are present in organisms of the terrestrial environment whereas activation products are prevalent in marine organisms.
2. The best biological indicators of fallout radionuclides are:
   a. terrestrial—coconuts, land crabs
   b. reef—algae, invertebrates
   c. marine—plankton, fish
3. The deficiency of potassium in Marshall Island soils enhances the uptake of ^{137}Cs by plants and animals.
4. Potassium fertilizers can diminish ^{137}Cs uptake.
5. In areas devastated by nuclear detonations signs of plant regrowth were seen within a week, and "greening" of the area within a month.
6. Rats living in underground tunnels and nests survived in areas close to large detonations.
7. The geographical, environmental, and biological distributions of fallout radionuclides were well established.

Lagoon

Generally, what happens to fallout after it arrives on the lagoon surface is similar to what occurs in the ocean, except that the basin is smaller and the circulation pattern is more restricted. The northeast trade winds move the surface waters from the east to the west side of the lagoon and in so doing there is upwelling on the east side of the lagoon to replace the westward flowing surface water. Hence, a circulation pattern is established in which surface water moves westward and sinks, and the bottom waters move eastward and upwell. The average depths of the lagoons are about 60 m (200 ft). The flushing time for Bikini lagoon, in term of half-time is about 1 mo (Van Arx 1954). Therefore, nearly complete flushing would occur in 7 mo—i.e., more than 99% of water present in the lagoon on day one would have been flushed into the ocean.

Plankton samples were collected in the lagoon as well as in the ocean. Following is an account of a representative lagoon plankton survey. In the 1949 surveys of Bikini, Eniwetok and Likiep, plankton collections were a part of each survey. (There were no nuclear detonations in 1949, but in 1946 there were two at Bikini and in 1948 three at Eniwetok). Likiep Atoll was a control area, i.e., outside of the fallout pattern but 280 miles SE of Bikini.

Forty-six samples were obtained by filtering water through nets of various mesh sizes. The nets were either towed or water was pumped from specific depths through them. The ratios of the radioactivity for test sites versus control were as follows: Bikini, (Island area)/Likiep, 1; Bikini, (target area)/Likiep, 3; and Eniwetok, (test site)/Likiep, 8.

The plankton samples from the fine-meshed nets were the most radioactive both in 1948 and 1949. For comparable samples at Bikini and Eniwetok the 1949 radioactivity values were about one-half the 1948 values.

The radioecology of plutonium and americium in Bikini Atoll lagoon was studied during 1971–1977. The largest source of radionuclides available for transport as indicated by ^{241}Am and ^{239,240}Pu in sediments and water samples resided in the deep water in the northwestern quadrant of Bikini Lagoon approximately 6 km south of the second thermonuclear detonation, Shot Bravo. The highest concentrations of ^{241}Am and ^{239,249}Pu were 2.9 Bq g^{-1} (77 pCi g^{-1}) and 4.4 Bq g^{-1} (120 pCi g^{-1}), respectively. The concentrations in the bomb craters were substantially lower than these values probably due to two processes: (1) dilution by eroding crater wall material and (2) loss of the fine particles containing the largest concentration of radionuclides by fluvial transport away from the crater (Nevissi and Schell 1975a).

Concentrations of soluble and particulate americium and plutonium in surface and deep water samples showed distributions similar to the sediment samples—that is, the highest concentration of these radionuclides in the water column were at locations with highest sediment concentration. Sixteen years after the last nuclear test on the atoll, the radionuclides were neither totally buried in the lagoon sediments, nor had they been completely transported to the ocean. Continuous circulation of water in the lagoon and the exchange of water with the open ocean resulted in removal rate of ^{241}Am, 111 GBq y^{-1} (3 Ci y^{-1}) and ^{239,240}Pu, 222 GBq y^{-1} (6 Ci y^{-1}) into the North Equatorial Current (Nevissi and Schell 1975a).

Measurements of radioactivity in water and biological samples from Bikini and Eniwetok lagoons in 1972 indicated that the values of naturally produced ^{210}Po were usually greater than the values of ^{239,240}Pu that were produced by nuclear detonations, by factors as great as 100 (Nevissi and Schell 1975b).

Ocean

What happens to fallout after it arrives at the ocean's surface? It will enter the surface water circulation systems, begin a downward descent and some will be absorbed or adsorbed by organisms in the water. Before the fallout radionuclides enter the deep waters of the ocean (average depth, 3,800 m), they move through a transitional zone where there are steep gradients for both temperature (thermocline) and salinity (pycnocline). This zone may temporarily delay the descent of the fallout radionuclides into the deep water, which is characterized by stratification and very slow movement.

In the Bikini-Eniwetok area, the surface waters are in the major gyre of the North Pacific Equatorial Circulation system, which rotates in a clockwise direction that moves westward to near the Philippine Islands. Here, the major portion of the stream turns northward in the direction of Japan and is known as the Kuroshio Current. The lesser portion flows southward and then eastward near the equator and is known as the North Equatorial Counter Current. In the surface current there is constant and vigorous mixing, which rapidly dilutes the concentration of the fallout radionuclides. Horizontal distribution of radionuclides is principally by surface water currents and to some degree by plankton and larger organisms. Plankton movement is passive except for some diurnal movement in surface waters; for larger organisms, their movement may be multidirectional.

There have been ocean surveys in search of radionuclides produced by the Bravo (Bikini Atoll) detonation of 1 March 1954, by both Japan and the United States. The general objectives have been to locate the fallout "foot print," determine its rate of advance, predict arrival time at specific locations and determine the kinds, amounts, and distribution of the radionuclides in the water and biota.

The Japanese oceanographers were the first to search for fallout radionuclides in the ocean from nuclear detonation at the Pacific Proving Grounds. There was great national concern in Japan about the consequences of Bravo fallout in the North Pacific Ocean. This concern was conditioned by the Hiroshima-Nagasaki experience, the illness that befell the fishermen who were aboard the Japanese fishing vessel near Bikini at the hour of the Bravo detonation, the contamination of the tuna caught by and sold to the Japanese, and the prediction that the Bravo "foot print" would reach Japan by early 1955, all of which contributed to the vast "unknown" about the hazards from ionizing radiation. As a consequence, the Japanese conducted a full-scale oceanographic survey from 15 May to 4 July 1954, with the research vessel "Shunkotsu Maru," in search of the Bravo "foot print." Also, between October 1954 and February 1955, two Japanese training ships made incidental collections of water and fish for radiological analyses while in transit through areas in the vicinity of the test site.

The first U.S. ocean survey to scope the Bravo fallout "foot print" was in March and April, 1955, in the area of the test site and westward, then northward, to Japan. One of the objectives was to answer the question, "Would it be safe to swim in Japanese coastal waters in 1955?" Otherwise, the objectives were similar to those for the "Shunkotsu Maru." The U.S. operation was known as "Troll" and the U.S. Coast Guard cutter "Roger B. Taney" was the platform for the survey (Harley 1956). The radioactivity in the surface water was constantly monitored by a specially built probe towed behind the ship; also, samples of deeper water, plankton and fish were obtained for radiological analyses. Direction of the Troll Operation was assigned to AEC's Health and Safety Laboratory, New York; the survey team members were from several laboratories, including one from the University of Washington.

After Troll, there were two ocean surveys in 1956, and three in 1958. Four of these surveys were Laboratory programs and the other (in 1958) was a joint effort of three teams, of which the Laboratory was one. All of these surveys were supported by ships from the U.S. Navy. The general objectives for study of the fallout "foot print" remained the same, and, in a sense, the later surveys were considered to be sequels to preceding surveys. Principal findings are as follows:

1. The Bravo (March 1954) radionuclide footprint was identified in water samples below the thermocline near the Philippine Islands in March 1955. The identification was by radioisotopes of nuclear detonation origin and the quantity was less than the abundance of naturally occurring radionuclides. (Significance—the coastal Japanese waters would be safe for swimming in 1955.)
2. The rate of advance of radioactivity in surface waters was estimated to be approximately 13–18 km (7–10 miles) per day and was reasonably close to previous predictions.
3. The U.S. surveys generally confirmed the results of the original survey by the Japanese.
4. After the underwater detonation in the ocean 3.7 km (2 miles) SW of Eniwetok Atoll, Test Wahoo on 16 May 1958, the distribution of the radioactivity in surface waters was as follows:
   - +6 h; major concentration, top 25 m; thermocline, little;
   - +28 h; major concentration, top 50 m; thermocline, little; and
   - +48 h; major concentration at thermocline (100 m); some to 300 m.
5. Immediately after detonation the short-lived fission products—^{99}Mo, ^{99}Tc; ^{132}Te, ^{132}I; ^{140}Ba—were dominant in plankton. The radioisotopes ^{90}Sr and ^{137}Cs accumulated slightly in marine organisms; in fish, radioisotopes of iron, zinc, and manganese prevailed. Some weeks after the detonation, the principal radionuclides in plankton were radioisotopes of zinc, cobalt and iron. Note: The principal factor in radionuclide accumulation by plankton could be adsorption (Lowman 1960).
6. To indirectly monitor the arrival of fallout radionuclides "downstream" from the test sites, collections of plankton, fish, invertebrates and algae were obtained from Guam, Palau and the Gulf of Siam from July 1958 to October 1959. Their distances from the test

sites were approximately 2,200, 3,600, and 7,900 km (1,200, 1,950, and 4,250 miles), respectively. Guam and Palau are in the North Pacific Equatorial Current System, the Gulf of Siam is not. In terms of gross beta activity of the plankton samples, the Guam samples were very much greater than the other two and Palau greater than the Gulf of Siam. Radioactivity of the Gulf of Siam samples was no greater than would be expected from naturally occurring radioisotopes. There was a major peak at Guam in January 1959 and a minor peak at Palau in August 1958. Conclusion: the feasibility of using biota for this indirect measure of identifying the presence of fallout radionuclides transported by water is demonstrated; however, a reliable prediction of the date of radionuclide origin (the date of nuclear detonation) cannot be made from the available data.

7. Plankton are the best indicators of radioactive contaminants in ocean waters. Collection and analyses are relatively simple. Concentration factors, plankton/water, are of the order of 104 shortly after the detonation but decrease rapidly with time, due to decay of short-lived radionuclides and dilution.
8. The probe used for constant monitoring of radioactivity in surface water provided data that compared favorably with data obtained by conventional water sample analyses.
9. Conclusion: In consideration of the hazards to man and biota from fallout radionuclides, the consequence would be less for fallout into the ocean than onto land for two principal reasons—the much greater dilution in the ocean and the very long residence time in the deep waters of the ocean.

Other observations in seawater and fish

^{55}Fe in seawater and fish. ^{55}Fe is a neutron-induced radionuclide produced in large quantities from ferrous materials in the immediate vicinity of a nuclear detonation. Usually this radioisotope was the most abundant fallout radionuclide in marine organisms at the time of, and a few months after, some of the detonations. In Bikini Atoll lagoon, concentrations of ^{55}Fe found in water were 4.4–25.2 Bq m^{-3} (120–680 pCi m^{-3}) in 1972 and were estimated to be partitioned into 45% particulate (>0.3 mm), 45% colloidal and 10% soluble (Schell 1976).

Samples of light and dark muscle from tuna obtained in 1968 and 1969 from the Japanese tuna fishery in the Pacific and at Bikini Atoll showed no significant trend in the data when ^{55}Fe-specific activities were compared by species, month of catch, location of catch, or size of fish (Held 1973). Tuna from the southern hemisphere tended to have lower concentrations and specific activities than tuna from the northern hemisphere. There was a close correlation of ^{55}Fe-specific activity in light muscle, dark muscle, and liver, and of ^{55}Fe concentration between dark muscle and liver. Yellowfin tuna caught near Bikini Atoll contained ^{60}Co believed to be derived from the atoll (Held 1973). ^{55}Fe in Rongelap people, fish, and soils were reported by Beasely et al. (1972). They reported that the ^{55}Fe body burdens for 60 residents of Rongelap Atoll were approximately three times higher than those of a similar number of residents from Tokai-mura, Japan, which in turn had substantial ^{55}Fe body burdens.

Biological accumulations of radionuclides from the ocean. Three factors appeared to control the selective uptake of radionuclides from sea water by the plankton, omnivorous fish, and carnivorous fish studied by Lowman (1963). These were isotope dilution (by the corresponding stable element or chemical analogue element) in the sea water, the tendency of divalent cations to complex strongly with biological substrates, and the biological requirements for specific elements in metabolic processes. The uptake patterns in the three trophic levels were as follows.

During the first 48 h after fallout, the plankton in the contaminated area accumulated radionuclides (the mechanism of this accumulation, whether by adsorption or by active metabolic uptake, was not known) in approximately the same ratio as they occurred in sea water. After 1 wk the radioisotopes of the three elements cobalt, iron, and zinc were actively taken up by the plankton. Omnivorous fish, which feed on plankton, almost completely excluded the fission products and concentrated ^{65}Zn and ^{55,59}Fe but discriminated against ^{57,58,60}Co. Carnivorous tunas, which feed primarily on omnivorous fishes, discriminated against zinc and manganese but concentrated iron and cobalt (Lowman 1963).

Aberrant growth forms. Instinctively, where radioactivity is present in an area that has been exposed to high levels of radiation some time in the past, one looks for aberrant growth forms and if these are seen, one is inclined to ascribe the abnormality to the radiation exposure; however, at a nuclear test site, establishment of a meaningful radiation exposure-effect relationship is nigh impossible. Biddulph and Biddulph (1950) observed ten or more plant species with morphological abnormalities, but some of the same abnormalities were found in non-fallout areas. Some were caused by insects, some by bird droppings, and some by chemicals. However, a rough estimate of the radiation-dose effect relationship can be obtained from the results of controlled field experiments by Gunckle and Sparrow (1954). They observed that chronic dose rates of gamma radiation of 0.13–0.37 Gy d^{-1} (13–37 R d^{-1}) for 2–4 mo [total dose, 7.8 to 55 Gy (780 to 5,500 R)] can cause plant abnormalities of various kinds similar to those found at Eniewetok Atoll (Palumbo 1962).

Certainly exposures equal to or greater than those of the Gunckel-Sparrow experiments were present at Bikini-Eniewetok. Apparently there is no aberrant growth form that is uniquely related to ionizing radiation exposure. The plant with the most obvious morphological abnormality was the morning glory. Instead of being a trailing vine, on occasion it grew upright as a foot-and-a-half-high stalk with regenerated, rudimentary leaves and many tumors (Hines 1962). Tumorous morning glories on Engebi Island (Eniewetok Atoll), first observed in 1949, were also present in 1957 (Palumbo 1962).

No morphologically changed fish or invertebrates were seen. However, there was one interesting nuclear-detonation fish-related observation. In 1954, in a shallow reef area near a detonation site, Eniewetok Atoll, a few mullet about 37 cm (15 inches) in length were caught that had a band of green algae growing on one side of their bodies near the top of the fish. One guess of what had occurred was that the fish had been near the surface in an area near ground zero and had received a thermal burn, and that omnipresent algae had successfully invaded the injured flesh. The collection was made only 1 wk after nuclear detonation at a nearby site. Since the injured flesh occurred on only one side of the fish, the injured side suggested the orientation of the fish to the heat source at the instant of the detonation.

In a non-Laboratory related program, a study of *Drosophila* (a fruit fly) mutation rates of natural colonies were made at Bikini and control atolls by W. E. Stone. Stone et al. (1957) have concluded from studies of the *Drosophila* populations at Bikini that, while there is evidence of genetic changes caused by radiation, other factors mask the radiation effects.

In regard to the number of aberrant growth forms in the near detonation site areas, perhaps the organisms with significant potential to produce morphological abnormalities did not survive the initial impact of the detonation, or if they did survive, they were lost by predation.

Survival of the Polynesian Rat at Engebi Island, Eniewetok Atoll

This 250 acre island has a population of rats that survived heavy bombardment by the U.S. Navy in 1944, and heavy construction and earth movement during the nuclear testing program, and was near ground zero for four nuclear detonations in 1952–1954, including a wash-over. The rats live underground in nests and pathways 15 to 60 cm (6 inches to 2 feet) below the surface but feed at the surface principally on seeds and vegetation. Apparently they survived because they were underground at the time of the detonations, but post-detonation survivors were exposed to significant external radiation plus some internal exposure from foodstuff. In 1955, both the number of rats and the size of their habitat were increasing. In 1964, populations appeared to be in equilibrium with the available food supply.

Resiliency

During the years of observations of the environmental damage in areas near ground zero for nuclear detonation, a subjective opinion developed that recovery by plants was more rapid than might be expected. To provide some objectivity to this opinion a program was planned to make both pre- and post-detonation observation of plants in an area near ground zero of a nuclear detonation.

The area selected was Belle Island, 5 km (2.7 miles) from ground zero for the Nectar detonation of 14 May 1954, at Eniewetok Atoll. Belle was far enough away that the plants were not expected to be uprooted, but heat, overpressure and ionizing radiation were expected to produce significant effects. Previously, Belle had been scathed by the November 1952 Mike detonation but the damage to plants and loss of topsoil was not documented.

Before the Nectar detonation, specific plants and shrubs were staked, labeled, measured and photographed (Palumbo 1962). After the detonation, observations were made for comparison with the pre-event plant conditions and gamma survey meter readings were obtained. The calculated dose rate at +1 min was ~0.01 Gy h^{-1} (1 R h^{-1}); the accumulated dose at 200 d was calculated to be ~4 Gy (400 R). The first post-event observation was +8 d, and from the air Belle looked scorched, i.e., brown and desolate with most of the surviving shrubs prostrate, but closer observation on ground showed signs of new growth. An abbreviated account of the observations follows:

+8 d	green buds were observed (there was a heavy rain 3 d post detonation)
+35 d	new shoots, leaves and flowers
+3 mo	some shrubs near pre-Nectar size
+6 mo	most shrubs near pre-Nectar size
+10 mo	generally, all vegetation back to pre-Nectar status

At Bikini Atoll in 1985, Fosberg observed the revegetation of the atoll and concluded, "The simple, quantitative effects of previous nuclear testing, construction and resettlement activities on vegetation have perhaps been minimal. The islands are all practically completely vegetated at present except at places where disturbance has been very recent . . . The total biomass may be as great or greater than at the time when the people were first removed" (Schultz and Schultz 1994).

The recovery of plants at Eniewetok in a general way is similar to plant recovery now seen following the 1980 Mt. St. Helens eruption and the 1988 Yellowstone Park Fire.

Archive samples

Over the years, personnel from the Laboratory have collected terrestrial and marine samples from various locations throughout the Central Pacific. In general, the collection trips and analytical programs were conducted to survey radiation at selected sites or to maintain a post-testing monitoring program. There have been few attempts to compare data from different sampling programs or to examine the results for long-term trends in radionuclide concentrations. Many of these samples have been analyzed for total radiation or for selected radionuclides, and the results have been forwarded to the granting agencies (AEC, ERDA, DOE). Many surplus samples have been stored for additional analyses at a later date.

Currently, there are several thousand samples stored at the School of Fisheries, and a few hundred have been transferred to the Nevada Test Site for storage. No similar collection of samples is known to exist elsewhere. Therefore, these samples represent a unique source of information for describing the initial uptake, accumulation, and subsequent loss of long-lived radionuclides by both terrestrial and aquatic biota. Furthermore, additional radiological analyses of some samples may be useful for calculating the dose that native populations were exposed to during the testing.

Availability of the laboratory reports

Some of the Laboratory reports of the early years of the Marshall Island studies bore military and/or AEC classification originally but later were declassified, and some were in the "gray literature" area and may remain difficult to find, but many were published in the open literature. After the Laboratory closed its doors in early 1980's, one set of the Laboratory's copies of their research reports was transferred to the Publications Office, School of Fisheries, University of Washington, and a duplicate set of early publications was retained at the University of Washington's Fisheries/Oceanography Library.

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THE ECOSYSTEM STUDY ON RONGELAP ATOLL

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Abstract—**During the 1950's and 1960's, the Laboratory of Radiation Biology at the University of Washington carried out an intensive study of this Atoll, which was contaminated with radioactive fallout from the "Bravo shot" in 1954. This study involved many aspects of the environment and the plant and animal life: soils, land plants, marine life, birds, geology and hydrology, and human diets as well. In much of the research, the fortuitiously present radioactive isotopes, especially ^{137}Cs and ^{90}Sr, were tracers. Although the term "ecosystem study" was not in vogue at that time, it is clear that this was an early use of the ecosystem approach. Soil types and their development, the distribution of mineral elements in plants and soils, including predominant radionuclides, distribution and growth of native terrestrial plants in relation to topography and salinity, some aspects of the human diets, micronutrient nutrition of the coconut palm, island and islet development and stability, were given attention in the studies. Some of the findings in the various areas of study will be presented and discussed.**

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Key words: ^{137}Cs; ^{90}Sr; Marshall Islands; food chain

INTRODUCTION

ALTHOUGH the first studies of the effects of atomic testing had concentrated on Eniwetok and Bikini atolls, the fallout from the "Bravo shot" in 1954 was substantial on Rongelap Atoll (this incident and the fallout distribution were described by Hines 1962). This led to intensive observational and research efforts on this atoll by the Laboratory of Radiation Biology (later Radiation Ecology) of the University of Washington, under the leadership of Lauren Donaldson, and other groups over the next twenty or more years (Hines 1962). In March 1958, the University of Washington group, upon request from the Division of Biology and Medicine, U. S. Atomic Energy Commission, and with special encouragement by John Wolfe, one of its program directors, started a comprehensive program of ecological studies including most aspects of the plant and animal life and their environment: soils, land plants, algae, fish, birds, invertebrate animals, geology and hydrology. The diet of the resident human population, which returned in 1957 three years after evacuation, was included as well. Such an inclusive approach would now be called an ecosystem study, although the term was not widely used at that time. The nature of the studies and some findings of investigations in a number of these areas will be covered below.

SOILS

Soil classification

Some background information was available on atoll soils (Stone 1951, 1953; Fosberg 1954), but little specific information on Rongelap soils. Over several years, Gessel and his associates made extensive field observations and collections on most of the islands of the atoll, followed by substantial laboratory studies of the samples.

They recognized five soil series (Kenady 1962), based primarily on the vegetation and on significant differences in the surface (A_1) horizon in the percentages of coarse material, organic matter, and total nitrogen, in phosphorus, and in cation exchange capacity (Table 1). Also there are sharp differences between the series deeper down in the profiles, as shown by the comparison between a Gogan soil from a *Pisonia* grove in the center of Kabelle Island and a Beach Ridge Sand developed under pioneer shrubs near the lagoon on Rongelap Island (Table 2). Organic matter, nitrogen, exchange capacity, and especially phosphorus are higher in the upper layers of the Gogan soil. These calcareous soils contain no clay, so exchange capacity is derived solely from organic matter. Our Gogan series may be a younger stage of the Jemo series described on Arno Atoll in the southern Marshall Islands (Stone 1951) and by Fosberg (1954) for the northern Marshall Islands. More complete discussions of atoll soils are given in Fosberg and Carroll (1965) and Morrison (1990), but were published after our studies.

Soil development

With age and stability, and the steady contribution of litter from the vegetation, soil organic matter and fertility increase. Both the amounts of litter and the nitrogen and phosphorus contents vary with the species growing on a site. *Pisonia* stands drop more litter than stands of pioneer species (*Scaevola* alone or *Scaevola* together with *Tournefortia* and *Guettarda*), and the *Pisonia* litter also has a much higher nitrogen content (Table 3), although in part this reflects the guano from

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Table 1. Properties of the A_1 horizons of the five principal soil series.[a]

Soil series→	Rongelap Gravelly Sand	Gogan Gravelly Sandy Loam	Lomuilal Sand	Beach Ridge Sand	Kabelle Sand
Soil property ↓					
% Material > 2 mm	46.	10.	0.0	8.0	8.0
% Nitrogen	0.57	1.71	0.26	0.09	0.14
% Organic matter	16.7	35.6	6.4	4.5	7.7
Exchange capacity[b]	22.2	37.7	12.6	3.7	5.7
Potassium[b]	1.95	1.80	0.79	0.37	0.46
Magnesium[b]	4.19	11.1	3.21	2.55	1.92
Sodium[b]	3.36	4.01	2.68	1.16	1.52
Phosphorus[c]	81.7	985	54.2	32.8	32.1
pH	8.1	7.8	8.4	8.6	8.6

[a] Data from Kenady (1962). The A_1 horizon is the top layer of mineral soil, dark in color because of its organic matter.

[b] Exchangeable cations in centiequivalents per kg of oven dry soil (2 mm fraction)

[c] Parts per million phosphorus extracted by bicarbonate (Olsen et al. 1954).

Table 2. Comparison of Gogan Gravelly Sandy Loam and Beach Ridge Sand.[a]

Sample depth (cm)	% > 2 mm	%N	%O.M.	Exchangeable cations (centieq kg^{-1})[b] Ca	Mg	K	Na	Capacity	P	pH
Beach Ridge sand										
0–5	8	0.08	3.8	2.63	2.07	0.39	1.29	2.8	18.1	8.4
5–12.5	16	0.13	3.9	3.48	2.61	0.50	1.06	4.6	14.1	8.4
12.5–22.5	10	0.07	3.2	2.26	2.49	0.23	0.85	2.1	10.0	8.6
22.5–30	12	0.15	5.3	3.50	1.51	0.38	1.96	7.0	10.1	8.3
30–45	32	0.09	3.7	3.13	1.21	0.26	1.31	2.4	8.0	8.5
45–92.5	7	0.03	1.9	2.76	1.67	0.23	1.09	0.8	9.0	—[c]
92.5–110	14	0.03	1.3	2.81	1.51	0.18	1.06	1.0	26.0	9.0
110+	21	0.01	1.1	2.63	1.51	0.21	1.28	0.1	10.0	8.5
Gogan Gravelly Sandy Loam										
—[d]	10	1.54	21.4	10.3	7.0	—[c]	2.0	20.5	1330	7.4
0–2.5	20	1.96	—[c]	—[c]	7.4	—[c]	3.0	43.6	893	7.1
2.5–12.5	20	0.42	5.9	14.1	4.0	—[c]	0.8	17.9	416	7.9
12.5–30	27	0.18	6.8	6.2	2.2	—[c]	0.4	7.2	216	8.2
30–50	39	0.07	2.6	7.7	1.2	—[c]	0.4	2.6	151	8.6
50–65	56	0.05	2.6	7.8	1.1	—[c]	0.4	1.7	25	8.8

[a] Data from Kenady (1962).

[b] Soil analyses performed on the 2 mm fraction; exchangeable cations determined by flame spectrophotometry after extraction with ammonium acetate; the adsorbed ammonium was displaced from the samples, then assayed to attain exchange capacity; phosphorus was determined in the sodium bicarbonate extract according to Olsen et al. (1954). *Note:* The total of exchangeable cations may exceed the capacity because of dissolving of carbonates in the extracting solution.

[c] Analysis not available.

[d] Organic layer above the mineral soil.

birds which favor *Pisonia* for roosting (Gessel and Walker 1992). *Pisonia* litter is also relatively high in phosphorus (Billings 1964). Litter decomposes rapidly in this warm environment, with half or more of its weight reported lost in 6 mo in a litter bag decomposition study (Gessel and Walker 1992).

Two features of the soils—organic matter contents, and the presence of buried horizons—are obvious in micromonoliths, prepared by impregnating samples, which were removed at increasing depths in soil pits, with plastic resins (Held et al. 1965a). Fig. 1 illustrates the differences between typical profiles of the different series as represented in micromonoliths. The buried horizons indicate that repeatedly in the past, especially at the unstable margins of islands, the growth of vegetation and the consequent development of soils occurred, only to be covered over by raw sand deposits in catastrophic storms, so that soil development had to start anew.

Retention and movement of ions

The differences described above between the soil series, reflecting primarily the ages of the soils and the amounts of organic matter accumulated, are also of importance in their retention of radioactivity and the movement of the elements and their isotopes. Since the exchange capacity is directly related to organic matter content, the adsorption of ions is on this organic matter and on the algal crust, which is common on the recently developed "young" sandy soils near the lagoon beaches. The distribution of the predominant radionuclides in the profiles of four soils is given in Table 4. The differences in the radionuclide levels can be understood in terms of

Table 3. Dry weight and nitrogen content of the vegetation litter above the mineral soil.[a]

			Litter weight[b]		Nitrogen[b]	
Location	Species	No. Samples	g m^{-2}	kg ha^{-1}	g m^{-2}	kg ha^{-1}
Various Islands	*Tournefortia* *Guettarda* *Scaevola*	11	1,074	10,740	6.7	67
Wash area Kabelle Is.	*Tournefortia*	19	1,340	13,400	7.3	73
Soil Pit 6 Kabelle Is.	*Pisonia*	20	1,610	16,100	20.7	207
Rongelap Is.	*Pisonia*	20	1,900	19,000	45.3	453

[a] Data from 1959–1963 collections (Gessel and Walker 1992).
[b] Mean values.

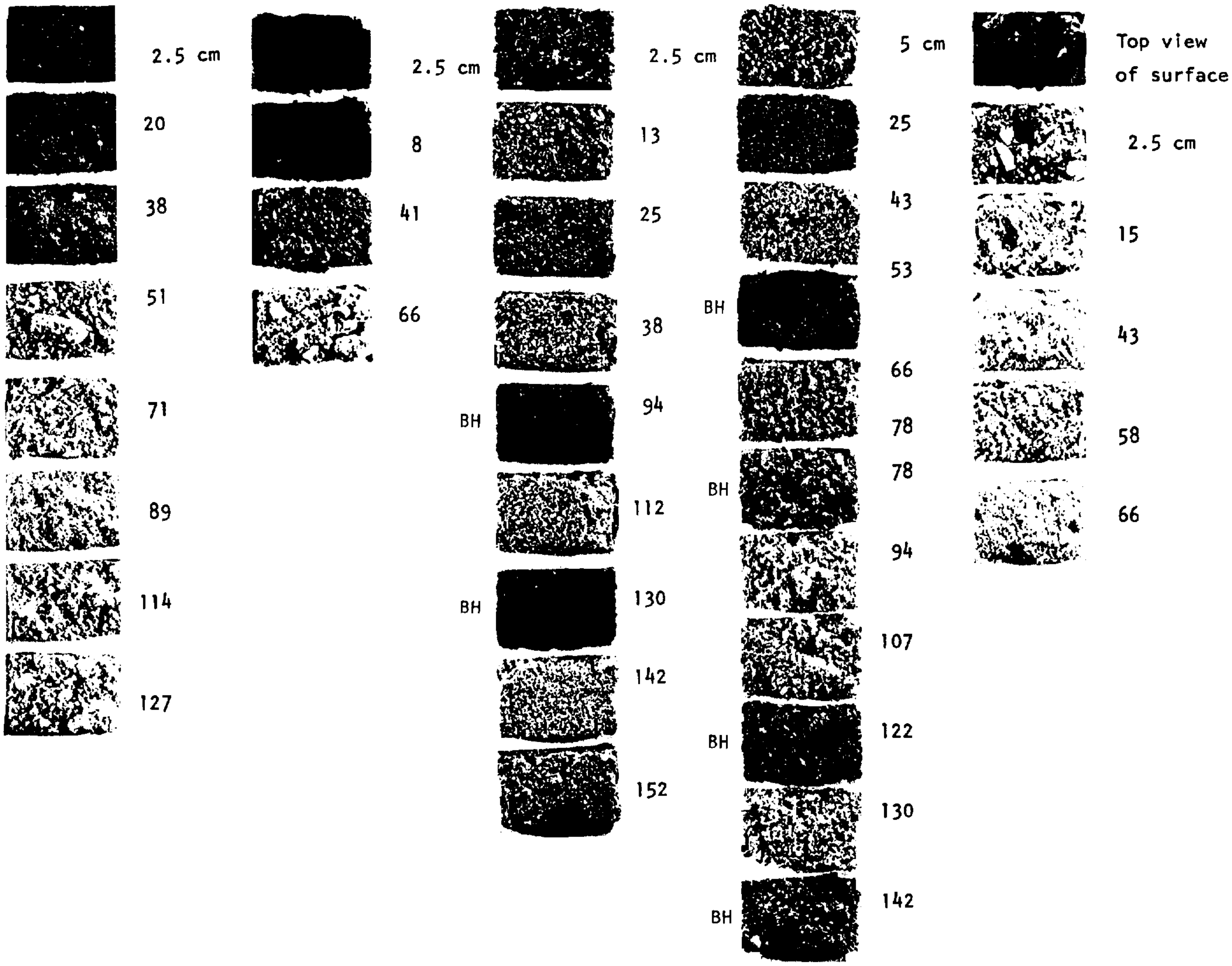

Fig. 1. Comparison of the micromonolith profiles of the principal soil series. Left to right: Rongelap gravelly sand; Gogan Gravelly Sandy Loam; Lomuilal Sand; Beach Ridge Sand; Kabelle Sand. BH means buried horizon.

the soil characteristics, and in relation to the at least fourfold greater fallout from the Bravo shot, which was received in the more northerly islands (Hines 1962). In general, the radionuclides decline with depth, reflecting the original deposition on the surface, the relatively high exchange capacities in the top layer of the soils, and the slowness of migration downward over time. An exception to this is seen with the Beach Ridge sand on

Table 4. Predominant radionuclides in several soil profiles (1974 collections[a]) (Bq g^{-1}, dry).

Sample depth (cm)	^{60}Co	^{125}Sb	^{137}Cs	^{155}Eu	^{241}Am	^{239,240}Pu	^{90}Sr
Rongelap Island (near lagoon beach, soil pit #3, Beach Ridge Sand soil series)							
0–2.5	0.013 ± .006	ns[b]	1.56 ± .033	0.018 ± .01	0.041 ± .011	0.012 ± .002	0.29 ± .026
2.5–5.0	0.044 ± .004	0.026 ± .012	1.22 ± .022	0.015 ± .013	0.20 ± .015	0.081 ± .026	0.59 ± .059
5.0–10	0.093 ± .006	0.081 ± .01	1.85 ± .026	0.14 ± .009	0.23 ± .01	0.23 ± .052	0.67 ± .009
10–15	0.03 ± .003	0.067 ± .007	0.70 ± .10	0.034 ± .006	0.059 ± .004	na[b]	na
15–25	0.01 ± .002	0.036 ± .006	0.23 ± .007	0.008 ± .004	0.020 ± .004	na	na
25–35	0.002 ± .001	0.0056 ± .004	0.024 ± .002	ns	0.0089 ± .004	na	na
35–50	0.004 ± .002	0.0070 ± .004	0.011 ± .002	ns	ns	na	na
Kabelle Island (Near cistern, pit #6, open and flat lagoon beach area, Kabelle Sand soil series)							
—[c]	0.33 ± .007	ns	18.1 ± .056	0.48 ± .019	0.67 ± .019	0.41 ± .056	11.1 ± 2.1
0–2.5	0.078 ± .004	0.030 ± .016	6.56 ± .026	0.34 ± .015	0.41 ± .019	0.19 ± .019	8.26 ± .74
2.5–5.0	0.013 ± .003	ns	0.17 ± .007	0.0077 ± .004	0.012 ± .004	0.0063 ± .0019	0.70 ± .067
5.0–10	0.0081 ± .002	0.0048 ± .004	0.067 ± .004	0.0063 ± .003	0.003 ± .003	na	na
10–15	0.0048 ± .001	0.0096 ± .003	0.30 ± .004	ns	ns	na	na
15–25	0.0026 ± .001	0.0014 ± .003	0.015 ± .004	ns	0.005 ± .004	na	na
25–50	0.0019 ± .0015	0.0093 ± .003	0.007 ± .004	ns	ns	na	na
Kabelle Island (Soil pit #7, toward center of island from cistern, Gogan Gravelly Sandy Loam)							
0–2.5	0.11 ± .007	0.070 ± .011	1.15 ± .019	0.56 ± .022	0.70 ± .022	0.19 ± .022	2.56 ± .24
2.5–5.0	0.024 ± .003	0.024 ± .008	1.07 ± .015	0.063 ± .007	0.085 ± .007	0.12 ± .007	1.15 ± .13
5.0–10	0.016 ± .002	0.021 ± .007	0.85 ± .011	0.029 ± .007	0.048 ± .007	na	na
10–15	0.006 ± .002	0.013 ± .008	0.56 ± .011	ns	0.011 ± .006	na	na
15–25	0.004 ± .001	0.006 ± .005	0.21 ± .007	0.014 ± .005	0.011 ± .005	na	na
25–35	ns	ns	0.019 ± .004	ns	ns	na	na
35–40	0.002 ± .0015	ns	0.011 ± .004	ns	ns	na	na
Lomuilal Island (Soil pit #5, Lomuilal Sand soil series)							
0–2.5	0.48 ± .01	0.25 ± .019	10.6 ± .052	1.41 ± .026	2.11 ± .033	2.48 ± .32	16.0 ± 1.41
2.5–5.0	0.17 ± .007	0.13 ± .018	11.0 ± .056	0.41 ± .015	0.67 ± .015	1.37 ± .17	10.6 ± .93
5.0–10	0.037 ± .003	0.036 ± .009	3.22 ± .026	0.056 ± .009	0.10 ± .011	0.078 ± .011	3.89 ± .37
10–15	0.015 ± .002	0.020 ± .007	1.19 ± .015	0.023 ± .007	0.041 ± .008	na	1.93 ± .16
15–25	0.0085 ± .002	0.013 ± .005	0.41 ± .007	0.009 ± .006	0.014 ± .006	na	0.74 ± .089
25–40	0.004 ± .001	ns	0.13 ± .005	0.004 ± .004	ns	na	0.33 ± .041
40–65	0.0015 ± .0007	ns	0.027 ± .002	0.0044 ± .002	0.007 ± .003	na	0.056 ± .011

[a] Data from Nelson (1977); error values for all radionuclides except ^{90}Sr and plutonium were two-sigma, propagated counting errors for a single sample; the error value for ^{90}Sr and plutonium were the two-sigma counting error for a single sample plus an analytical error. Counts adjusted for decay to 1975.

[b] na = not analyzed; ns = not significant, i.e., the net sample count was less than the two-sigma, propagated counting error.

[c] Algal crust on top of the soil.

Rongelap Island. In this soil, exchange capacity is low in the surface 5 cm, so there was apparently migration downward, especially to the 5–10 cm layer, which has somewhat higher exchange capacity. Both the Kabelle Island sand and the Lomuilal Island sand, from the northern part of the atoll, have expected higher radionuclide concentrations than those of the Rongelap Island Sand. In comparing the two soils from Kabelle Island, the sand from the lagoon beach area shows higher concentrations, especially of ^{137}Cs and ^{90}Sr, than the gravelly sandy loam from the interior of the island. This is particularly evident in the prominent algal crust at the beach location. However the gravelly sandy loam shows higher concentrations of ^{137}Cs in lower soil layers, presumably because of the greater exchange capacities at these depths.

Held et al. (1965b) compared the gamma-ray spectra of depth increments from "young" soils such as the Kabelle Sand with those from "older" soils such as the Gogan gravelly sandy loam. They found that ^{137}Cs and ^{125}Sb moved most readily in the older soils, while the principal gamma-emitting radionuclide moving in younger soils was ^{125}Sb. ^{90}Sr moved in both older and newer soils, and a vertical gradient was seen even in the surface 2 cm, but quantitative differences were obscured by the highly variable surface distribution of the radionuclides.

PLANTS

Mineral nutrition of plants

Soil pot experiments. Using atoll soils, plants were grown in pots both in a greenhouse in Seattle and under a wind/rain shelter on Enewetak Atoll, using several different soils, but in all cases ones which we would classify in the Gogan series. The principal objective of these trials was to test the effect of mineral fertilization on the uptake of ^{137}Cs into the plant shoots. For example, in an experiment using squash, fertilization with nitrogen and phosphorus increased yield and decreased the ^{137}Cs in the shoots, but application of potassium was more effective in the reduction of ^{137}Cs uptake (Table 5). The depression of ^{137}Cs uptake was great enough that dilution by increased yield could not be responsible. To test this effect in the field, in August 1958, two plots of 0.005

Table 5. Depression of ^{137}Cs uptake in squash by fertilization with potassium in a greenhouse test with Rongelap Gravelly Sand.[a]

Fertilization[b]	Ave. dry yield (g)	Ave. K in shoots (% dry weight)	Ave. ^{137}Cs in shoots[c] (Bq dry g^{-1})
No fertilizer	4.5	1.16	6.83 ± 0.57
$N_{3.36}P_{4.48}K_0$	8.0	0.69	2.83 ± 0.18
$N_{3.36}P_{4.48}K_{2.24}$	7.4	1.42	2.17 ± 0.23
$N_0P_{4.48}K_{2.24}$	5.5	1.86	2.50 ± 0.23
$N_{3.36}P_0K_{2.24}$	8.4	1.05	2.00 ± 0.27

[a] Data from Walker et al. (1961).

[b] Subscripts refer to equivalent rate of application in hundreds of kg per hectare.

[c] Error given is 95% counting error.

hectare were established in a stand of the grass *Lepturus repens* in a coconut grove on Rongelap Island, one as a control and one fertilized with KCl at the rate of 170 kg ha^{-1}. Grass collected on the plots in March 1959 gave the following analyses: Control = 0.395% K, 1.08 Bq g^{-1} dry ^{137}Cs; Fertilized = 0.645% K, 0.333 Bq g^{-1} dry ^{137}Cs, again showing markedly less uptake of ^{137}Cs with added potassium.

Mineral composition of foliage of woody plants. Many samples of foliage were collected on the different expeditions to Rongelap, especially of *Scaevola, Tournefortia, Guettarda,* and *coconut palm.* These samples were dried, carried to Seattle, then analyzed for the contents of various mineral elements. Table 6 gives representative data for mineral analyses of samples of leaves of these species. A general evaluation of these, with respect to the individual elements follows (see relations with radionuclide uptake in the next section:

- *Calcium:* The contents in the dicotyledenous species (as compared with coconut palm, a monocot) were high, as might be expected on the calcium carbonate substrate, and in most cases higher in lower than in upper leaves, characteristic of an element immobile in the phloem. In palm the contents were lower, to be expected in a monocotyledenous plant.
- *Magnesium:* The contents of this element are appreciable, and in most cases higher in lower than in upper foliage, indicating a more than adequate supply for the plants. Palm sometimes showed more magnesium than calcium in the leaves.
- *Potassium:* For all species the upper leaves showed fairly good levels of this element, but the lower leaves were almost always lower and sometimes very low, indicating a limiting supply.
- *Sodium:* The sodium contents of the dicotylenous species were high, as might be expected near the sea, but also because these species have a halophytic tendency (Walker and Gessel 1991). On the other hand, palm foliage was much lower in this element.
- *Nitrogen:*Contents of nitrogen were often low, especially in plants growing on the beaches, and often less in lower than in upper leaves, indicating a short supply of this mobile element.

Table 6. Analyses of the foliage of pioneer shrubs and coconut.[a]

		% of Dry weight						Parts per million		^{137}Cs
Island/location	Tissue	Ca	Mg	K	Na	N	P	Fe	Mn	(Bq g^{-1}, dry)
Tournefortia argentea										
Rongelap-Pit 25	UL[b]	2.14	0.62	1.30	2.74	1.84	0.23			2.77 ± .083
	LL[b]	3.48	0.86	0.26	4.73	0.88	0.21			1.73 ± .083
Kabelle-Pit 6	UL	3.96	0.52	2.13	1.99	2.50	0.23			4.96 ± .055
	LL	6.78	0.64	0.60	3.45	1.13	0.17			3.29 ± .152
Kabelle-cistern	UL	3.28	0.63	1.24	5.60	—	0.21	48	23	
	LL	5.25	0.77	0.35	4.30	—	0.16	43	16	
Scaevola sericea										
Rongelap-Pit 25	UL	1.41	0.64	1.33	1.34	—	0.20			1.27 ± .069
	LL	2.27	1.24	0.48	1.34	—	0.26			1.73 ± .083
Kabelle-cistern	UL	2.69	0.62	1.90	1.37	2.01	0.29	48	37	
	LL	2.99	0.75	1.25	1.89	1.45	0.32	33	28	
Guettarda speciosa										
Kabelle-cistern	UL	1.37	0.34	1.21	0.53	1.47	0.19	30	5.8	
	LL	2.21	0.43	1.04	0.72	0.59	0.18	21	33	
Cocos nucifera (coconut palm fronds)										
Kabelle-Tree #39[c]	UL	0.32	0.50	1.49	0.75	1.47	0.18	35	9.8	
(Lagoon beach)	LL	1.09	0.73	0.49	0.70	1.25	0.16	18	4.8	
Kabelle-Tree #21[d]	UL	0.20	0.28	1.69	0.57	0.85	0.11	11	19	
	LL	0.44	0.37	0.50	0.47	0.85	0.11	8.1	9.1	

[a] Data from Gessel and Walker (1992); ^{137}Cs activity adjusted for decay to 1975.

[b] UL = upper leaves; LL = lower leaves.

[c] Both upper and lower leaves green; had been sprayed with iron chelate solution.

[d] Both upper and lower leaves yellow; soil had been fertilized with Fe-Mn-Zn mixture.

- *Phosphorus:* These values vary widely, probably reflecting the amount of soil organic matter as well as the spotty nature of additions of bird droppings, which are high in this element, to the soils.
- *Iron and Manganese:* As might be expected on calcium carbonate dominated soils with pHs of 7 to 8, the uptake into plants was low to very low. This correlated with the widespread chlorosis in young coconut trees, although chlorosis was absent in older coconut trees and in the native shrubs and trees. Perhaps this can be attributed to more extensive rooting with age in coconut, and the very extensive fibrous root systems of the native woody species.

Radionuclides in the foliage of woody plants. Plants will absorb to some extent all mineral elements that are present in the soil solution, including of course the radionuclides found in the Rongelap soils. Indeed traces of all of those listed for the soils in Table 4 were detectable in many plant samples. However, among these only ^{137}Cs and ^{90}Sr were consistently present in appreciable concentrations, which is not surprising because these elements are absorbed by plant roots in a manner comparable to that for potassium and calcium, which are chemically similar elements required in plant metabolism. Also ^{40}K was a predominant isotope in plant samples collected on Rongelap, even though it is mostly a naturally occurring isotope and was not a predominant radionuclide in the soils. This can be explained by the ability of plants to absorb potassium from very low external levels and concentrate it in their tissues. Consequently, ^{40}K is included along with ^{137}Cs and ^{90}Sr in Table 7, which lists their concentrations in samples of foliage of several woody species collected from a number of islands in the atoll.

Although there are some exceptions, in general the radionuclide concentrations are higher in samples collected on the more northerly islands (Kabelle, Lukuen, Naen) than those collected on the more southerly islands (Rongelap, Eniaetok). This is consistent with the higher levels in the soils in the northerly islands as seen in Table 4. For the *Pandanus* samples from Rongelap Island, there seems to have been a greater decrease in ^{137}Cs activity in the leaves than can be attributed to isotopic decay (all values in the table are adjusted to 1975). This may indicate that the soils are declining in ^{137}Cs levels over time through leaching to the ground water.

Water relation of plants

General aspects. The annual precipitation at Rongelap Atoll is about 125 cm, with a pronounced dry

Table 7. Predominant radionuclides in leaves of plants collected on Rongelap Atoll.[a,b]

Island/Location	Year collected	No. of samples	Radionuclide concentration (Bq g $^{-1}$, dry)		
			^{40}K	^{137}Cs	^{90}Sr
Pandanus sp.					
Rongelap Is.	1958	9	na	2.93	0.63
Rongelap Is.	1959	19	na	2.26	na
Rongelap Is.	1961	16	na	2.74	na
Rongelap Is.	1963	13	na	1.96	0.44
Rongelap Is.	1971	3	na	0.52	na
Rongelap Is.	1974	1	na	0.48	0.41
Rongelap Is. #3	1976	1	0.27 ± .052	2.17 ± .022	0.54 ± .029
Kabelle Is.	1958	4	na	9.22	1.19
Kabelle Is.	1961	1	na	4.19	na
Kabelle Is.	1963	1	na	6.00	1.48
Lomuilal/Lukuen Is.	1974	2	na	1.59	1.46
Naen Is. #1	1976	1	0.81 ± .081	4.53 ± .033	na
Eniaetok Is. #2	1976	1	0.27 ± .059	1.27 ± .018	na
Scaevola sericea					
Rongelap Is. Pit #3	1974	1	0.23 ± .085	0.78 ± .026	na
Lukuen Is. Site 5	1974	1	0.56 ± .10	0.52 ± .011	0.96 ± .11
Artocarpus sp. (breadfruit leaves)					
Rongelap Is. Pit #3	1974	1	0.28 ± .070	1.00 ± .015	na
Eniaetok Is. village	1976	1	0.48 ± .067	0.51 ± .015	na
Cocos nucifera (coconut fronds-central leaflets)					
Rongelap Is. Pit #3	1974	1	ns	0.16 ± .007	0.078 ± .011
Rongelap Is. Site #5	1976	1	0.19 ± .044	2.21 ± .025	na
Eniaetok Is.	1976	1	0.09 ± .059	0.21 ± .014	na
Lukuen Is.	1974	1	ns	0.31 ± .015	0.36 ± .030
Lomuilal Is.	1974	1	0.059 ± .026	0.67 ± .004	0.37 ± .019
Naen Is. Site #1	1976	1	0.21 ± .044	1.52 ± .018	0.34 ± .029

[a] Data for 1958–1971 collections are from University of Washington, Laboratory of Radiation Ecology (unpublished). Data for 1974 and 1976 are from Nelson (1977, 1979). All counts adjusted for decay to 1975.

[b] na = not analyzed. ns = not significant, i.e., the net sample count was less than the two-sigma, propagated counting errors for a single sample. The error values for all radionuclides are two-sigma, propagated, counting errors for a single sample.

season from January to May. The mean annual temperature is 27°C, with afternoon highs reaching to over 30°C. This regime causes high evapotranspiration, especially during the dry season.

Thus with the very coarse coral sand as the rooting substrate, water stress is a major influence on the survival and growth of plants. This is attested to by the relatively sparse vegetation on this atoll in comparison with the lusher plant growth in the more southerly atolls such as Majuro. Salinity adds to this water stress through osmotic effects. Such effects are always present, but become extreme during storms, with the blowing of salty spray over the plants or even inundation of the root systems in lower lying areas. Thus all plants growing on the atoll have some tolerance of salinity, and those inhabiting the beach and sand spit areas must be very salt resistant.

From the above, it will not be surprising that plants such as the native *Scaevola* and *Pisonia* often show some temporary wilting in the afternoons during the dry season. Perhaps a rise in leaf temperature, which would increase transpiration as well as reduced water uptake, may explain this wilting, which commonly disappears overnight.

Ground water and the fresh water lens. An important feature of atoll islands, especially the larger ones, is the presence of a lens of fresh or brackish water in the coral sand matrix, beginning a meter or so below the surface and extending downward as much as several meters. We sampled these ground waters from several islands of the atoll, by driving galvanized steel pipes down into the lens of water, which was commonly reached at depths of 1.5 to 4 m, then drawing up samples with plastic tubing. Some samples were almost as saline as sea water [electrical conductivity (EC) = 50 mMhos cm^{-1}], but those from the interior of islands were typically brackish [such as EC = 28 at Pit #4 near the center of Kabelle Island), but just slightly salty (EC = 2.6) in the well in the interior of the larger Rongelap Island]. The ionic proportions were similar to those in sea water. Also, some data on soil solutions were gathered; they were not very saline, having electrical conductivities of about 1.5 to 2.0 mMhos cm^{-1} (Walker and Gessel 1991).

Osmotic relations of species growing along beaches. Walker and Gessel (1991) also reported on osmotic potentials (Ψ_π) and sodium contents of leaf samples collected on Rongelap, and grew several woody atoll species in the greenhouse using culture solutions with varying levels of added salt. The Ψ_π of the field-collected leaves ranged from -1.9 to -3.1 M Pascals, compared with that of sea water at -2.7 M Pa; sodium contents were high in the tissues, usually 1 to 3% of the dry weight. In culture solutions, seedlings of four shrubby species (*Cordia subcordata, Guettarda speciosa, Scaevola sericea,* and *Tournefortia argentea*) and an atoll variety of squash (*Cucurbita pepo*) all grew well at a salinity of about 1/10 that of sea water, but were depressed to about 50% yield at salinity of about 1/6 that of sea water. The woody species declined to about 10–20% yield at salinity of about 1/2 that of sea water, and survived but grew very little in solutions with salinity equal to sea water. We were unable to obtain viable seed of *Pemphis acidula*, a tree often observed to grow directly in sea water on Rongelap, for greenhouse trials. However one sample of field-collected foliage of that species had an osmotic potential of 3.1 M Pa, which would have permitted absorption from sea water.

The studies just described show that seedlings of the species which occur on or near the atoll beaches, can endure exposures of the roots to osmotic concentrations equal to that of sea water, but do not grow much at such high salinity. Nonetheless, these species often grow well in nature close to both the lagoon and seaward shores. Ground waters in such locations are usually considerably less saline than sea water, and the plants have root systems which penetrate to considerable depths. These species can tolerate the salinity of most of the ground waters and probably absorb much water from them, especially during the dry season.

GENERAL ATOLL ECOLOGY

Introduction

Some time ago Fosberg (1953) summarized the general nature of Pacific atoll vegetation, and more recently wrote a description of the vegetation of Bikini Atoll, which has relevance also to Rongelap Atoll (Fosberg 1988). The following sections are based on observations made on Rongelap Atoll, especially during the period 1958–1964, by Ralph Palumbo, Mark Behan, James Kimmel, and the authors. In 1986, we had the opportunity to visit Rongelap again for several days, and made comparisons with the notes from the earlier years (Gessel and Walker 1987, 1992). These and previous observations were generally in good agreement with those of Fosberg just cited.

Non-vascular plants

Reef building algae are important, along with corals, in the geo-biotic structure of the atoll. Nitrogen fixation by algae in the crusts on top of young soils are very beneficial in the establishment of pioneer plants (Léskó 1968). Phytoplankton are not very abundant in the lagoon, being about 0.00825 g dry m^{-3} (Mathisen 1964), but nonetheless support some fish.

Vascular plant communities

Kimmel (1960) described seven plant communities occurring on the northern half of Rongelap Island. These were also characteristic of all of the larger islands of the atoll in the 1950's. During the 1960's, coconut planting decreased the areas of these plant communities somewhat, but all could still be recognized in 1986. Since the atoll has been mainly uninhabited since that time, there has probably been substantial regrowth of native woody species. The seven plant communities are briefly described below.

***Scaevola-Guettarda* community.** This is the most prevalent community along the beaches, where typically it is wedge-shaped, with the shrubs taller with increasing distance from the shoreline. "Fingers" of sand may penetrate the shrubby vegetation, with the grass *Lepturus repens* frequently present there.

***Suriana* Society.** Pure stands of *Suriana maritima* form small communities along the seaward shores of some islets. *Suriana* also occurs occasionally in the interior of islands, in places where there is evidence of overwashing with sea water.

***Pisonia-Tournefortia* Community.** *Pisonia grandis* is a very large tree by atoll standards, rising to a height of as much as 20 m and forming a dense closed canopy in the wet season. During the dry season the canopy thins by shedding of many leaves. Although not as tall and often recumbent, scattered old specimens of *Tournefortia argentea* are usually present also. The trailing vine *Boerhaavia* is common as a ground cover.

Ochrosia (*Neiosperma oppositifolia*) Community. In 1959, there were several small but dense communities of this large leafed species on Rongelap Island, with the trees 6 to 9 m tall. By 1986, these had all succumbed to clearing for coconut planting.

***Cordia* Community.** *Cordia subcordata* communities occur in boulder areas and are best developed on Rongelap Atoll on the seaward sides of Mellu Island and Anielap Islet. Here the large-trunked trees form a tangled vegetation among boulders.

Coconut Plantation Community. The coconut trees are usually spaced 3 to 6 m apart, with a ground cover of the grass *Lepturus* and sometimes other herbaceous plants. In a well kept plantation there are no shrubs present.

Coconut Grove Community. This consists of three layers: first, a canopy of coconut fronds 10–13 m high; next, a layer .5 to 4 m high, consisting of coconut seedlings, a few *Pandanus* seedlings, *Tacca* (arrowroot), and occasional other shrubs; the third layer is a ground cover of grasses, the sedge *Fimbrystilis*, and scattered individuals of other small plants.

Mixed Forest Community. This is composed of a variety of trees, none of which is dominant. The 7 to 9 m tall canopy usually consists of *Pisonia*, coconut, and *Terminalia* or Cordia, with *Morinda*, *Guettarda*, *Tournefortia*, and *Scaevola* forming somewhat lower layers.

***Pemphis* Community.** Finally, there is a *Pemphis* community, which was not described by Kimmel (1960) because it does not occur on the northern part of Rongelap Island where he worked. This community is best developed on the leeward, lagoon shore of Mellu Island, where *Pemphis acidula* grows to a height of 4 to 6 m among the boulders and beach rock high in the intertidal zone. Both at Mellu and elsewhere, *Pemphis* trees can be seen standing in sea water at high tide.

Distribution of seeds

A conspicuous feature of the shores is the presence of seedlings of the pioneer species *Scaevola sericea* and *Tournefortia argentea*. The fleshy fruits of *Scaevola* are eaten by birds, especially curlews, and the hard seed-containing stones are deposited along the beaches after passing through the guts of the birds. *Tournefortia* seeds float in sea water and are not only unharmed by this soaking, but their germination is stimulated by the exposure to sea water (Léskó and Walker 1969). From the considerable amounts of seeds deposited on shores, an occasional seedling establishes (Léskó 1968).

Development of Vegetation on Islets and Islands

It is interesting to speculate on the development of plant life on islets newly formed from storm action, or on parts of larger islands which have been modified by typhoons. Evidence for the repeated development of vegetation and its obliteration is seen in the buried organic horizons depicted in Fig. 1.

A substantial part of our work on Rongelap Atoll was centered on Kabelle Island, which has an area of about 25 hectares, has been little disturbed by humans since it is remote in the atoll and is visited infrequently, and has only a few coconuts trees. We made a rough map of the vegetation on this island in 1958 (Fig. 2), and found that it had changed very little by 1986. From this distribution of plants and from observations of pioneer *Tournefortia* and other shrubs establishing along the beaches on various islands, we can propose a scenario for colonization of Kabelle Island. A feature of special interest is the presence of very large and obviously old *Tournefortia* trees in the center of this island. The hard solid trunks of these trees, which are often partially or completely recumbent, have diameters up to almost 1 m. Perhaps *Tournefortia* seedlings established on the island when it was small, newly formed after a major storm, and persisted as the island accreted and enlarged. Eventually birds carrying the sticky seeds of *Pisonia* could have led to the establishment and flourishing of this species in the central part of the enlarged island, but with the long-lived old *Tournefortia* still present. Such a scheme seems to fit with the presence of these old slow growing trees in the *Pisonia* groves of Kabelle Island, and perhaps such a development might have taken place on other islands as well.

The most fertile soils of the atoll (Gogan Series) are found in the *Pisonia* stands. Litter deposition is heavy, and a thick humus layer is often present. Fertility is enhanced by birds, since these stands are favorite nesting areas for both fairy and noddy terns. The late Frank Richardson estimated that some 1,400 terns, frequenting

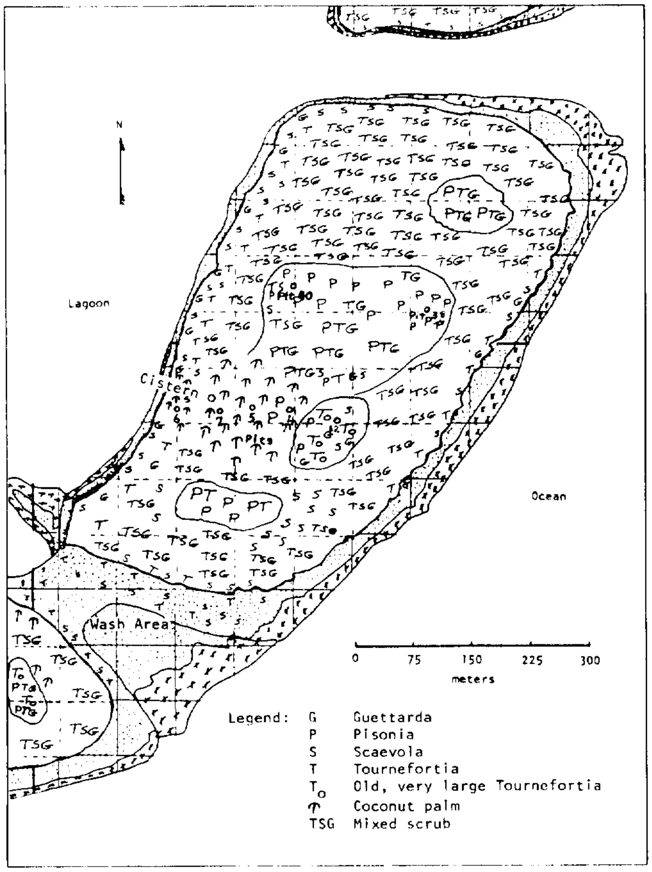

Fig. 2. Map of Kabelle Island, showing the distribution of vegetation (Charted in 1959, but little changed in 1986).

and nesting in a *Pisonia* community of about 0.25 hectare on Kabelle Island, consumed about 48 tons of fish per year, thus bringing large amounts of nitrogen, phosphorus, and other mineral nutrients from the sea to the island. On the larger islands the *Pisonia* areas with their relatively fertile Gogan Series soils have been largely converted to coconut plantations.

Rate of plant growth

In a tropical environment the diameter growth is difficult to follow because there are not well defined annual growth rings. We marked a large number of specimens and measured their diameters and heights each time we visited over a period of several years (Gessel and Walker 1992). In good situations, *Tournefortias* increased in diameter about 1 cm per year, and the medium sized shrubs grew about 17 cm in height per year. *Pisonias* averaged about 0.4 cm of diameter increase per year in general, but on a good site in the center of Kabelle Island they increased 1.3 cm per year. Medium-sized *Scaevolas* averaged about 21 cm of height growth per year. Although fragmentary, these data give some idea of the growth of these plants in an environment favorable in temperature but stressful with respect to mineral nutrient and water relationships.

Plants as food for humans

The principal plants eaten are coconut, breadfruit, pandanus, and arrow-root (*Tacca*), which are available in relative abundance. Together with fish and shellfish, these made up the bulk of the traditional diet. Coconut crab was considered a delicacy, although it is now rare on the inhabited islands. Also very limited amounts of squash, banana, and papaya were grown. Chakravarti and Held (1961) assessed the amount and composition of typical daily rations of Rongelapese individuals in 1959. Although there was a strong component of the native plant foods and fish, imported flour and rice as well as canned meat were also major components. As might be expected, they reported measurable amounts of radioactivity in the foods, with higher levels of ^{137}Cs and ^{90}Sr in diets which included coconut and local fruits. Table 8 gives the levels of the predominant radionuclides in samples of foodstuffs collected on Rongelap in 1974–1975 (Nelson 1977, 1979). The inclusion of ^{40}K reflects again the avid absorption of potassium by plants from low concentrations in the environment. A much more detailed study of the Rongelap Atoll foods and their radionuclide levels has been published recently by the Lawrence-Livermore Laboratory (Robison et al. 1994).

ANIMALS

Vertebrate animals

Sea birds are a very important component of the atoll ecosystem, and there are also some shore and land birds.[‡] Certainly the sea birds, present in large numbers, make a vital link in the movement of minerals from the sea to the land.

The small field rat (*Rattus exulans*) is the only endemic mammal on the atoll, although the Rongelapese kept some pigs for food. Reptiles are represented by skinks, geckos, and a blind snake, and occasionally the giant sea turtle (*Chelonia*) is encountered.

Fish are of course the most varied and numerous of the vertebrates associated with the atoll, there being over 700 species in the lagoon and nearby waters. Welander (1958) collected many of these species and determined their uptakes of radionuclides. Some data on the radionuclides in fish are included in Table 8.

Invertebrate animals

Insects are few, both in number of species and individuals, except for the numerous house flies. Land crabs are common, the most spectacular of these being the coconut or robber crab, *Birgus latro*, which grows to large size and was a favorite food of the Rongelap people (Chakravarti and Held 1960; Held 1960) (see Table 8 for radionuclide levels in the collections of this species from 1957–1976). In contrast with the low number of terrestrial forms, there is a rich variety of invertebrate species

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[‡] Richardson (1959, unpublished) surveyed the birds of Rongelap, identifying the species and estimating the sizes of the populations, especially of the most common ones: the fairy tern, *Gygis alba*, and the noddy terns, *Anous stolidus* and *A. tenuirostris*.

Table 8. Predominant radionuclides in some human foodstuffs collected at Rongelap Atoll.[a,b]

Island/location	Year collected	No. of samples	Mean radionuclide concentrations (Bq g $^{-1}$, dry)		
			^{40}K	^{137}Cs	^{90}Sr
Coconut meat (fresh:dry ratio = 1.6)					
Rongelap Is. Site #5	1976	1	0.13 ± .052	0.91 ± .014	<0.0043
Eniaetok Is. Site #1	1976	1	0.34 ± .059	0.47 ± .01	<0.007
Lukuen Is. Site #6	1974	1	0.14 ± .041	0.48 ± .011	<0.004
Lomuilal Is. Site #7	1974	1	0.144 ± .056	1.59 ± .019	0.007 ± .002
Naen Is. Site #1	1976	1	0.22 ± .052	1.27 ± .011	0.0065
Coconut milk (fresh:dry ratio = 37.5)					
Rongelap Is. Site #5	1976	1	ns	12.9 ± .51	<0.08
Eniaetok Is. Site #1	1976	1	2.00 ± 1.78	1.96 ± .22	na
Lukuen Is. Site #6	1974	1	0.122 ± .009	0.022 ± .001	0.152 ± .056
Lomuilal Is. Site #7	1974	1	ns	0.056 ± .002	0.133
Naen Is. Site #1	1976	1	na	12.6 ± .58	<1.16
Coconut crab muscle (fresh:dry ratio = 4.5)					
Rongelap Is.	1957–58	12			4.85
Kabelle Is.	1957–58	14			16.3
Arbar Is.	1974	2	0.32 ± .052	1.21 ± .017	0.045 ± .008
Tufa Is.	1976	2	0.30 ± .083	0.47 ± .016	0.047 ± .008
Busch Is.	1974	2	0.34 ± .076	1.29 ± .020	0.10 ± .012
Mellu Is.	1974	1	0.41 ± .059	1.96 ± .015	0.126 ± .011
Kabelle Is.	1974	3	0.318 ± .063	2.28 ± .031	0.179 ± .016
Kabelle Is.	1976	2	0.32 ± .071	1.67 ± .023	0.13 ± .010
Lomuilal Is.	1974	1	na	na	0.29 ± .048
Lukuen Is.	1974	1	0.34 ± .052	2.11 ± .022	0.10 ± .015
Naen Is.	1976	2	0.28 ± .062	5.63 ± .033	0.25 ± .035
Fishes (eviscerated whole)[c]					
Rongelap Is. (goatfish)	1974	1	0.44 ± .015	0.001 ± .0007	<0.003
Rongelap Is. (convict surgeon)	1974	1	0.32 ± .044	ns	<0.003
Kabelle Is. (mullet)	1974	2	0.26 ± .056	0.009 ± .002	0.0044 ± .007
Lukuen Is. (mullet)	1975	1	0.37 ± .037	0.003 ± .002	<.005

[a] Data from Nelson (1977, 1979).

[b] Counting procedures were the same as indicated for Table 7. All counts adjusted for decay to 1975.

[c] Fresh:dry ratios for fishes (eviscerated whole): goatfish, 3.64; convict surgeon, 3.89; mullet, 3.41.

in the lagoon and off shore waters, and in many cases very large numbers of individuals are present. Corals are dominant forms which played an essential role in the formation of the atoll and continue to be vital in the maintenance of reefs and shores. Among the invertebrates, some of the most numerous and often attractive in appearance are the Tridacnid clams, the wide variety of sea snails, and the sea cucumbers (*Holothuria, Stichopus*). Bonham and Held (1963) made a detailed population study of the very abundant *Holothurias*.

GEOLOGIC STUDIES

From the studies of soils and vegetation described above, some indications of the influences of the sea, especially during storms, could be envisaged. The presence of buried soil horizons high in organic matter and the size and age of pioneer plants on beaches, islets, and sand spits gave some indications of the unstable nature of the land areas.

Porter (1966) reported on geologic observations made on Rongelap in 1963. From these observations and from the literature, he drew a number of tentative conclusions:

a) Most islands along the windward side of the atoll show evidence of lagoonward migration within the recent past, with beachrock pavements extending outward from the modern beaches;
b) Erosion of windward coasts has been accompanied by sedimentation on leeward coasts;
c) From world-wide sea level changes, atoll islands may be no older than about 3,000 y;
d) Beachrock formation and history seem to be related to water tables rather than to sea water influences; and
e) The present rate of deposition of atoll sediments appears to be greater than the rise of sea level, which permits accretion of reef detritus on atoll margins to form emergent land.

A study of lagoon bottom sediments was made by Anikouchine (1961).

CONCLUSION

This study of the Rongelap Atoll ecosystem was incomplete, because the scientific expeditions were of necessity short and infrequent. Nonetheless, valuable data was accumulated on many aspects of the ecosystem: the physical environment, soils, plants, vertebrate and invertebrate animals, and human nutrition. The long lived isotopes ^{137}Cs and ^{90}Sr were useful as tracers in studying mineral uptake from the soils into plants and animals. An earlier evaluation of the distribution of isotopes in different components of the atoll was made by Held (1963), and a recent detailed assessment was made by the Lawrence-Livermore Laboratory (Robison et al. 1994).

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ASSESSMENT OF A RADIOACTIVE WASTE DISPOSAL SITE AT ENEWETAK ATOLL

Victor E. Noshkin and William L. Robison*

Abstract—The 43 nuclear tests conducted at Enewetak Atoll by the United States between 1948 and 1958 produced close-in fallout that contaminated the islands and lagoon of the atoll with radioactive fission and activation products, and unfissioned nuclear fuel. In 1972, the U.S. government announced that it would conduct a cleanup and restoration operation to return the atoll to the Enewetak people. The radiological cleanup began in 1977 and lasted to 1980 and focused on reducing the concentration of the transuranium elements (^{238,239,240}Pu and ^{241}Am = TRU) in soils on some of the islands that might eventually be used for residence or for subsistence agricultural. The cleanup plan called for relocating soil and some other contaminated debris to Runit Island on the eastern perimeter of the Atoll. Some of the contaminated soil was mixed with cement and the mixture placed below the water level in the Cactus Crater that was formed by a nuclear explosion in 1958. The remainder of the contaminated material was mixed with concrete and placed above ground over the crater in the shape of a dome. A concrete cap was constructed over the dome of soil. Concern has been expressed by the people of Enewetak and by others over the possible aquatic impacts from the radionuclides entombed in the crater. A National Academy of Sciences committee examined the dome and concluded that the containment structure and its contents present no credible health hazard to the people of Enewetak, either now or in the future. The committee suggested that "at least part of the radioactivity contained in the structure is available for transport to the groundwater and subsequently to the lagoon and it is important to determine whether this pathway may be a significant one." Therefore, a surveillance program was started in 1980, in conjunction with other research efforts, to study the radionuclides in samples of fish, groundwater, and lagoon seawater. Our data and conclusions support the findings suggested by the National Academy committee over a decade ago in that any assumption of rapid remobilization of all or any of the dome's transuranics or other radionuclides is an extreme one. Any fear that this structure contains amounts of activity whose release would cause damage to the environment that will result in greater effect on human health is unfounded.

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Key words: Marshall Islands; waste management; fallout; weapons

INTRODUCTION

THE 43 nuclear tests conducted at Enewetak Atoll by the United States between 1948 and 1958 produced close-in fallout that contaminated the islands and lagoon of the atoll with different amounts of radioactive fission products, activated products, and unfissioned nuclear fuel. Quantities of concrete, metal debris, cable, bunkers, buildings and other miscellaneous materials, some contaminated and some not, were also abandoned at the Atoll after the U.S. testing program finished. In addition there were U.S. non-nuclear programs between the years 1958 and 1972 that also modified the landscape on some islands of the Atoll.

Enewetak Atoll is located in the Equatorial Pacific Ocean at approximately 11°21′N and 162°21′E in the northwestern portion of the Republic of the Marshall Islands. The islands of the Atoll are shown in Fig. 1 along with the location of the major nuclear craters. The Marshallese name for each island and two large coral heads are also shown. U.S.-assigned names for the islands during the testing period are given in parenthesis.

In 1972, the U.S. government announced that it would conduct a cleanup and restoration operation to return the atoll to the Enewetak people. Planning for the cleanup extended from 1972 to 1977. The final project was conducted as a series of concurrent tasks between May 1977 and April 1979. It involved several departments of the federal government with the Defense Nuclear Agency (DNA) responsible for cleanup activities. The radiological cleanup concentrated on reducing the surface soil levels of the transuranium elements (^{238,239,240}Pu and ^{241}Am = TRU) on some of the islands that might eventually be used for residence or the growing of subsistence agricultural products. The justification for basing the cleanup on transuranic criteria can be found in the description of planning efforts, cleanup operations, and radiological guidelines in Defense Nuclear Agency and Department of Energy documents (U.S. DNA 1981; U.S. DOE 1982). Other miscellaneous debris and radioactive material from test-day burial sites were also identified for removal. Only the quantities of transuranics were measured during field operations, but soil relocation also involved moving undetermined amounts of long-lived fission and activation products associated with the carbonate soil.

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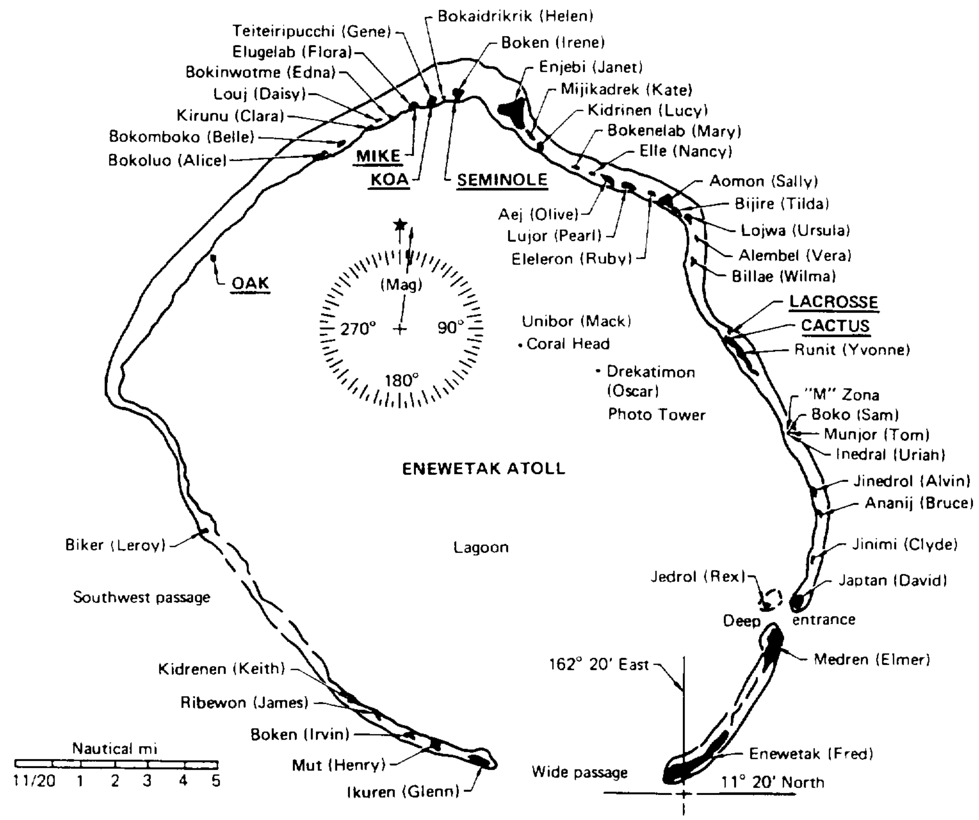

Fig. 1. Islands of Enewetak Atoll with Marshallese and English code names. Locations of major nuclear craters are indicated.

The cleanup plan called for collecting and transporting the soil and other contaminated debris to Runit Island on the eastern perimeter of the Atoll. The contaminated soil was mixed with cement and the mixture placed below the water level (tremie method) in the Cactus Crater that formed during a 1958 nuclear explosion on the northern tip of the Runit reef. The 10-m-deep crater was filled to the low-tide level by this method. Above the water level, the contaminated soil was blended with cement using a disc-harrow. Water was applied and the mixture was compacted. Some solid objects were added to the above ground slurry. A dome-shaped mound of contaminated material was thereby formed over the crater. A central "donut" hole was left in the center of the dome and eventually filled with soil and debris removed from other locations on Runit Island. The mound was finally covered with concrete panels to form a cap over the contents. The crater was surrounded by a concrete key wall to reduce scouring and undermining by wave action. A report on the radiological cleanup of Enewetak Atoll (U.S. DNA 1981) provides a detailed account on the construction and filling of the dome during cleanup.

The structure is referred to as a waste disposal site since it covers material contaminated with quantities of long-lived radionuclides. There have been many expressions of concern by the people of Enewetak and by others over the possible aquatic impacts from the radionuclides entombed in this disposal site. The people are convinced that it must be one of the most dangerous places at the Atoll since the United States spent millions of dollars to contain radioactive material under the domed structure. It is imagined that if leakage were to occur, many marine resources would be affected. News segments recorded on film and shown on television in the 1980's helped to establish a fear and concern about this disposal site.

In 1980, the Defense Nuclear Agency requested the National Research Council of the U.S. National Academy of Sciences to establish a committee of experts to evaluate the "effectiveness of the Cactus Crater structure in preventing harmful amounts of radioactivity from becoming available for internal or external human exposure." In a report published in 1982 (NAS 1982), the committee concluded that the Cactus Crater containment structure and its contents present no credible health hazard to the people of Enewetak, either now or in the future. However, there were issues related to the permeability of the tremie concrete. There were sections in the tremie that were in free communication with the ocean. This led the committee to suggest that "at least part of the radioactivity contained in the structure is available for transport to the groundwater and subsequently to the lagoon and it is important to determine whether this pathway may be a significant one." Therefore we initiated an environmental surveillance program in 1980 to study the radionuclides in samples from the vicinity of the dome. This included the collection, processing and analysis of samples of fish, groundwater, and lagoon seawater. Samples were taken until 1984 when the program was terminated.

Subsequent to the cleanup there were data from comparable samples collected from Runit and other islands of the Atoll in support of other research activities. Comparison of the pre- and post-cleanup data indicated that there was no adverse radiological impact on the environment from the radionuclides contained in the Cactus crater structure. All aquatic data generated during the period appeared in U.S. Department of Energy progress reports and has not been previously published outside this report. During the 1990's, we again collected samples to assess what, if any, changes in radionuclide concentrations occurred during the intervening years. This document examines the present and past concentrations of plutonium and other radionuclides at the Atoll and in the immediate environment of the disposal site. Published and unpublished concentrations measured in aquatic environmental samples (seawater, sediment, species of fish, groundwater) collected before filling the crater are compared with levels in corresponding samples collected after the crater was filled. The concentration of plutonium and other radionuclides measured in the material filling the crater and found above ground level under the dome is summarized. Implications of all results that relate to the disposal site on Runit Island are discussed.

METHODS

The majority of results from samples discussed in this report were generated over the last three decades. Field and laboratory personnel changed during this period, but collection methods, sample processing, and radiochemical procedures did not significantly change. Therefore, previously published documents adequately describe field collections in the Marshall Islands and the analytical techniques used at Lawrence Livermore National Laboratory for analysis and data reduction. Collection and processing sea and ground-water may be found in Marsh et al. (1975); Noshkin et al. (1976); Marsh et al. (1978); Noshkin et al. (1981b); Noshkin et al. (1974); and Noshkin et al. (1987). Collection, description, and analysis of parts of different species of fish are found in Noshkin et al. (1981a) and Noshkin et al. (1988). Sediment collection, processing, and analysis are given in Nelson and Noshkin (1973) and Noshkin (1980). It will not be possible to list the many results discussed in this report. Only summaries of available data will be shown in the Tables and Figures appearing in this document.

RESULTS AND DISCUSSION

Radiological conditions Runit Island prior to cleanup

Runit (Yvonne) Island, identified in Fig. 1, is located on the eastern perimeter of the Atoll. The island and the adjoining reef were used for several nuclear tests (4-surface; 5-tower; 1-atmospheric), and 8 more devices were detonated on barges located off-shore of the island in the lagoon. It was the most severely radiologically contaminated island at the atoll. Barges for seven of the tests were anchored in the lagoon from 170 to 1,200 m offshore the island. During the 1958 Quince test on Runit, only the high explosive component of the device was detonated. This resulted in scattering the plutonium nuclear fuel over a large area of the island. To prepare for the Fig event, scheduled 12 d later in the same location, 3 to 5 inches of the plutonium contaminated soil was bulldozed from the site and disposed of in the lagoon immediately offshore the center of the island (U.S. DNA 1981; U.S. DOE 1982). The transuranics resulting from the barge events and the bulldozing operations were identified in the near shore sediments and quantified during a 1972 radiological survey (Nelson and Noshkin 1973). These results show that the mean quantity of TRU's distributed over the surface sediments (to a depth only of 2.5 cm) in a 0.7 km^2 region extending 0.8 km lagoonward of the island is about 64 GBq. The mean concentration and inventory of the transuranics in the surface sediment offshore Runit and in the entire lagoon (Nelson and Noshkin 1973; Noshkin 1980) is summarized in Table 1. The lagoon sediment contains the largest reservoir of plutonium at the Atoll. These sediments are exposed to the bottom waters of the lagoon and the radionuclides are remobilized continuously to the hydrosphere from the sedimentary source term. Mean water concentrations of plutonium measured in the lagoon over time are shown in Table 1. These data demonstrate that remobilization is occurring from the sediments to maintain an inventory of plutonium in the lagoon water mass decades after testing. At Runit, the plutonium in the near shore sediments is also mobilized and measured in seawater and has been available for uptake by near shore organisms for many years (Nelson and Noshkin 1973; Noshkin et al. 1974; Noshkin et al. 1976; Noshkin 1980; Noshkin et al. 1981a).

Radiological conditions at Cactus Crater subsequent to cleanup

Cactus Crater was formed in May 1958 by the 18-Kt Cactus event detonated on a manmade extension of Runit island on the lagoon side of the reef. Cactus Crater in the foreground and LaCrosse Crater with the ocean in the background are shown in Fig. 2a at a time before cleanup. The test produced a crater roughly 112 m in diameter and 10 m deep. When the device exploded, some of the pulverized material fell back into the crater so that the original hole was deeper than 10 m. Quantities of different radionuclides are distributed non-uniformly throughout the sediment sampled in the 10–15-m-thick

Table 1. Transuranic radionuclide lagoon sediment and plutonium water column inventories. Sediment and water data from Noshkin (1980); Noshkin et al. (1987).

	Sediment concentrations			
Enewetak Atoll (area, 933 km^2)	$^{239+240}$Pu	^{238}Pu	^{241}Am	Total TRU[b]
Areal activity to 2.5 cm depth (GBq km^{-2})	9.9	1.4	3.0	14.3
Total to 2.5 cm depth (GBq)	9,200	1,300	2,800	3,300
Total to 16 cm depth (GBq)[a]	44,000	6,200	17,600	67,800
Region to 0.7 km offshore Runit (0.86 km^2)				
A real activity to 2.5 cm depth (GBq km^{-2})	56.5	14.1	5.7	76.3
Total to 2.5 cm depth (GBq)	47.5	11.9	4.8	64.2
Total to 16 cm depth (GBq)[a]	225	57	30	312

Average $^{239+240}$Pu lagoon water concentration (Bq m^{-3})/inventory (GBq)
(Enewetak Lagoon area 933 km^2; mean depth 0.049 km)

Date of collection	Number of samples	Soluble	Concentration particulate	Total	Total inventory
October–December 1972	35	0.81	0.3	1.18	53.9
July 1974	71	0.93	0.70	1.63	74.5
May 1976	29	0.59	0.48	1.07	48.9
May 1982	23	0.63	—[c]	—[c]	—[c]

[a] Core samples collected over the lagoon in 1972 and 1977 showed only 21 ± 11% of the plutonium and 16 ± 6% of ^{241}Am in the sediment column are associated with the surface 2.5 cm surface layer. These values are assumed representative for sediment anywhere in the lagoon to estimate inventories to 16 cm from measured surface concentrations (Noshkin 1980).

[b] Total transuranics (^{238}Pu + $^{239+240}$Pu + ^{241}Am)

[c] Particulate phase not measured.

Fig. 2a. Cactus crater in foreground with LaCrosse crater and the ocean reef in the background at a time before cleanup activities.

fallback zone of altered carbonate material (Ristvet et al. 1978). The crater resembled a spherical segment with a flat base and had an average volume at mean sea level of 3.3 × 104 m^3 but could hold up to 4.4 × 104 m^3 of water during periods of highest tide. The total surface area is approximately 6,900 m^2, of which only an estimated

2,060 m^2 were covered with sedimentary deposits. The remaining upper slopes were littered with rock rubble although some areas of the wall did have thin veneers of coarse sand. Much of the surrounding rock is heavily fissured from events detonated nearby. The majority of the crater rim is on land, but about a quarter of the eastern circumference was open to permit exchange of water between the crater and ocean during periods of high tide. Circulation of seawater in the region is directly affected by the windward cross-reef currents.

The groundwater in the area immediately southeast of the crater flows generally southwest into the lagoon (Noshkin et al. 1976). Dye tracer studies (Marsh et al. 1978) showed that most of the water lost from the crater is by overflow during periods of high tide. The water eventually flows into the lagoon through a break in the land extension some 400 m northwest of the crater (Noshkin 1980; Marsh et al. 1978). The dye studies also showed that only small amounts of crater water enter the island's groundwater or flow subterraneanly into the lagoon. The residence time of the water in the crater was a function of the tidal range and could be predicted for any period with available tide data. The mean residence time of the water, averaged over a month, was about 2.6 d (Marsh et al. 1978).

Plutonium and other radionuclides were supplied to the crater water by three processes: transportation of some quantities were associated with surface ocean water advecting over the reef; release to the bottom interstitial water occurred from the contaminated bottom sediments of the fallback zone; and by interactions involving resuspended bottom sediments with the crater water.

The latter two mechanisms contributed most of the plutonium radionuclides to the crater water column. Between January 1975 and May 1977, 27 seawater samples from different depths in the crater were obtained for radionuclide analysis. Table 2 summarizes the mean concentrations for $^{239+240}$Pu, ^{137}Cs, ^{90}Sr and S values [amount of ^{238}Pu to total plutonium ($^{238+239+240}$Pu) alpha activity] in filtered water and particulates from depths in the crater. Filtered interstitial water and short sediment cores were sampled between 1974 and 1977. Concentrations in these samples are also shown in Table 2. With the estimated exchange rate and size of the plutonium sediment reservoir it is estimated that 11.5 MBq of $^{239+240}$Pu and approximately half this amount of ^{238}Pu is annually released from the crater bottom sediments. This plutonium mixes with the seawater along the reef and subsequently merges with the inventory contained in the lagoon water mass. The crater source contributed about 0.03% to the annual average lagoon water (soluble) inventory of $^{239+240}$Pu (see Table 1). Filling the crater with solid debris and closing the access of ocean water on the eastern perimeter during cleanup was an effective means of eliminating this small contri-

Table 2. Concentrations of radionuclides in cactus crater water, sediment, and interstitial water samples collected between February 1974 and May 1977 prior to cleanup activities.

Mean concentration of some radionuclides in filtered water and particulate samples (Bq m^{-3}).

	Solution		Particulate		Solution	Particulate	Solution
	$^{239+240}$Pu	S Value[a]	$^{239+240}$Pu	S Value[a]	^{137}Cs	^{241}Am	^{90}Sr
Mean surface water	2.6 ± 0.7	0.32	4.0 ± 2.1	0.33	8.9 ± 2.6	<1.5	
Mean mid-depth (4.5m)	3.2 ± 1.1	0.33	4.2 ± 1.3	0.33	8.1 ± 1.8		
Mean bottom (9 m) water	3.6 ± 1.7	0.33	16.1 ± 8.6	0.33	8.9 ± 2.5		
Mean crater water (27 samples for plutonium)	3.2 ± 0.9	0.33	8.3 ± 5.1	0.33	8.6 ± 0.6	<1	17.0 ± 3.0

Concentration of $^{239+240}$Pu and ^{137}Cs in interstitial sediment pore water (Bq m^{-3}).

	$^{239+240}$Pu	SValue	^{137}Cs
29 May 1977 Outgoing tide	8.8 ± 0.4	0.35	10.1 ± 1.3
Outgoing tide	8.5 ± 0.5	0.34	8.3 ± 1.1
30 May 1977 Low tide	12.3 ± 0.6	0.34	7.7 ± 0.4
Average	9.9 ± 2.1	0.34	8.7 ± 1.2

Concentration of some radionuclides in crater bottom sediment (Bq g^{-1} dry wt.)

	$^{239+240}$Pu	SValue	^{137}Cs	^{241}Am
Collected 2/2/74				
0–5.7 cm surface section	3.04 ± 0.07	0.35	0.46 ± 0.04	0.34 ± 0.07
5.7–11.4 cm section	2.93 ± 0.19	0.35	0.52 ± 0.04	0.39 ± 0.07
11.4–17.2 cm section	3.74 ± 0.26	0.35	0.56 ± 0.04	0.39 ± 0.07
Collected 4/26/76				
0–2 cm surface fine fraction	3.85 ± 0.15	0.34		
0–2 cm surface coarse fraction	1.38 ± 0.12	0.33		
4–6 cm fine fraction section	3.26 ± 0.32	0.32		
4–6 cm coarse fraction section	2.46 ± 0.25	0.36		
10–14 cm fine fraction	4.06 ± 0.32	0.35		
10–14 cm coarse fraction section	2.82 ± 0.28	0.39		

[a] S Value, ^{238}Pu to total plutonium alpha activity ratio.

bution of plutonium and other radionuclides to the lagoon water.

The cleanup

The cleanup of Enewetak extended from May 1977 to April 1980. Island surveys were made with *in-situ* monitoring equipment to measure surface levels (to a depth of 3–5 cm) of ^{241}Am over an established grid on each island. Soil samples were obtained for laboratory analysis of plutonium radionuclides and americium to develop ratios between the TRU's and ^{241}Am. These analyses provided the data to develop radiological contour maps that were used by crews during cleanup activities. After sections of islands were identified for cleanup, solid rubbish was removed followed by the removal of several centimeters of topsoil. The soil was loaded onto barges and transported to Runit where it was off-loaded in a stockpile near the crater. The soil was filtered through a 3.8-cm screen to remove oversized particles, mixed with cement and attapulgite to form a mixture designed for use in the "tremie" method of placing a concrete mixture under water. A concrete pump transferred the slurry through a pipe to the bottom of the crater, displacing the overlying water. A number of problems were encountered during the tremie operation, but in the end some 41,600 m^3 of soil filled the crater to the low-tide water level using this method. Above the water level the soil was blended with cement using a disc-harrow, and each layer was compacted. Following this procedure a dome-shaped mound of soil was formed over the crater. This material is not in communication with the subterranean groundwater. A central "donut" hole was left in the soil dome. This space was reserved primarily for debris translocated from other parts of Runit Island. After the hole was filled with soil and other debris, the 46-cm-thick concrete cap or dome was completed. A view taken over the lagoon of the dome in the final stages of the cleanup operation is shown in Fig. 2b with LaCrosse Crater and the ocean reef in the background.

The amount of soil and TRU's transferred both to the crater and placed above ground under the dome are abstracted from clean up records (U.S. DNA 1981) and shown in Table 3. Table 3 also provides the quantity of soil and TRU's removed from the different islands. Only 24% of the total TRU was buried below ground level in the crater while the remaining activity is associated with material placed above the water level under the dome. Using a dry weight soil density of 1.29 g cm^{-3} (U.S. DOE 1982), the average soil TRU concentration in the undiluted crater fill is computed from the data in Table 3 to be 2.4 Bq g^{-1}. Table 2 shows that the total TRU in the surface 17 cm of bottom sediment from the crater sampled in 1974 was about 4.7 Bq g^{-1}. This is nearly twice the concentration in the material used to fill the crater. Therefore, if leakage were to occur into the groundwater from the fill, it would be difficult to detect. There should be less TRU mobilized to solution from the fill than was previously mobilized from the crater bottom sediments and found in the crater water (shown in Table 2) before 1977.

Fig. 2b. View from over the lagoon of the Cactus dome in the final stages of completion. LaCrosse crater and ocean reef in the background.

Table 3. TRU activity and volume of soil excised and placed in Cactus Crater and under the dome on Runit Island.[a]

Island	TRU Activity GBq	Soil removed (m^3) to Crater	Dome
Aomon (Sally)	48.1	8,100	0
Aomon Crypt (Sally)	33.3	342	7,130
Boken (Irene)	37.0	322	3,450
Enjebi (Janet)	96.2	32,890	7,633
Lujor (Pearl)	63.0	0	11,415
Runit (Yvonne)	267.4	0	8,210[b]
Total	545[c]	41,654	37,838

[a] Data from DNA 1981.

[b] Most activity and soil in central donut hole under dome.

[c] TRU estimated in Crater 131 GBq.

[c] TRU estimated in Dome 147 GBq without amount in Donut hole and 414 GBq including amount in Donut Hole.

Approximately one-half of the total inventory of TRU now under the concrete dome originated from only 5 northern islands. The remaining material was surface material translocated from one or more areas on Runit and dumped above ground in the crater donut hole. The amount of activity moved to Runit from the 5 northern islands is comparable to the inventory of TRU already in the lagoon sediments to a depth of 16 cm in the 0.86 km^2 area off-shore the island (see Table 1). Comparison of values in Tables 1 and 3 also shows that the inventory of the TRU's in this waste disposal site is equivalent to only 0.8% of the total TRU inventory in the lagoon sediment to a depth of 16 cm. Therefore, if the contents were to find its way into the lagoon, the inventory of the TRU's in the local area, and especially in the entire lagoon, would not change by any significant amount and no unacceptable hazard would result (NAS 1982) if such a catastrophic event was ever to occur.

Results from the 1980 National Academy study

In March 1980, members of the National Academy of Sciences committee visited the Atoll to conduct a series of sampling and observations at the dome. Tests included taking solid core samples from holes drilled through the soil-cement and tremie fill. Three holes were drilled through the third concrete ring from the top. Material from the center "donut" hole was not sampled during these tests. Water samples were also taken from two different levels in one drill hole from below ground level in the zone of incompletely cemented tremie concrete. In the tremie zone there was relatively free communication with the groundwater (NAS 1982). The soil-cement above the water level also did not achieve the concrete-like character that was anticipated. The cores from the bore holes were sectioned and the material from different depth intervals was described. Sections were then analyzed by gamma spectrometry, and the transuranics and ^{90}Sr were determined following radiochemical separation (Robison and Noshkin 1981). Table 4 shows a description of the material encountered at depths in the different zones of the structure along with the concentration of $^{239+240}$Pu measured in sections of the 3 cores. Concentrations of the radionuclides measured in the filtered water samples and the particulates are shown in Table 5. The description in Table 4 shows there is poorly cemented soil in both regions under the dome, and there also appears to be considerable amounts of debris in the fill, other than soil. Table 6 lists the mean concentrations for the principle radionuclides measured in the samples from the tremie section below ground and from the soil-cement region above ground under the dome. These mean values are developed from the core data in Robison and Noshkin (1981). The mean concentration of the TRU shown in Table 6 is approximately 3–4 times less than the soil concentration expected from the results shown in Table 3. However, this difference should not be considered unreasonable since the estimates of radionuclide concentrations made during the cleanup are not likely to be very accurate (NAS 1982), and the dilution of the soil concentrations with the uncontaminated cement (estimated to be about 30% of the measured value) was not considered.

It is probable that the measured concentrations from the Academy samples more accurately represent the TRU's in the material below ground in the crater and above ground, exclusive of the contents in the center hole, than the estimates made from the field measurements (U.S. DNA 1981) during the cleanup. Based on these measured values, the mean TRU inventory below ground would be 34 GBq and above ground the inventory would be 50 GBq, exclusive of the amount associated with the fill of the center hole. Interestingly, the mean concentrations of 0.62 Bq g^{-1} and 1.3 Bq g^{-1}, respectively, in the crater and dome soil, shown in Table 3, are less than the post cleanup average TRU levels (U.S. DOE 1982) measured in surface soils (1–3 Bq g^{-1}) on many of the northern islands such as Alice, Belle, Clara, or Daisy (see Fig. 1). These islands satisfy cleanup criteria where the Enewetak people can visit and gather food.

The average concentration of $^{239+240}$Pu found in solution within the containment structure is approximately one-half the value found in the crater seawater before the crater was filled with debris. Comparing the soluble water concentrations in Table 5 with the levels in water from Table 2 shows that the fill lowered the concentration of plutonium (and TRU) but also caused a significant increase in the dissolved concentrations of ^{137}Cs and ^{90}Sr. Therefore, if leakage of crater material were to occur through the groundwater aquifer, ^{137}Cs would be a better tracer for this source of water since it is released to and moves in solution more readily than the TRU's.

Concentration of radionuclides in samples from the surrounding environment of North Runit

Groundwater and off-shore seawater. A groundwater program was initiated at Enewetak Atoll in 1974 to study the hydrology and groundwater geochemistry on selected islands of the Atoll including Runit. Groundwater from 2 well sites (XRU 5 and XRU 6) between the

Table 4. Description of material and plutonium in samples from interior sections of the dome.

Depth (m)		Description of sample material[a]	Mean $^{239+240}$Pu (Bq g^{-1}) in extracted soil sample[b] drill hole		
Under	Dome		CD-1	CD-12	CD-17
0	0				
	0.43	Dome cap	—		
1					
			1.41		
2		Uncemented medium-fine soil-cement	—	1.22	1.70
3			0.37		
4	3.8			1.37	0.74
		Oversize material cobble, limbs, wire, rebar			
5					
	5.2		dome fill above this depth and crater fill below		
6		0.15-m layers of poorly cemented tremie	0.06		
7	6.7	with uncemented soil	—	0.19	
	7.3	Oversize debris and cobble			
8			0.44	0.23	0.55
9		Layers of poor to moderate cemented tremie and soil, cobble, rebar, wood	0.78		
10	9.8		—	0.28	0.41
11		Soil, wood, minor gravel-size tremie	—		
	11.3			0.005	0.59
12		Fallback material below this depth. Original crater sediment			
13				0.056	
			0.41		
14					
				0.008	
15					
16	15.8			0.008	
		Bottom original crater			

[a] Description of material in core hole CD-1 as provided in NAS (1982). Radiological data from Robison and Noshkin (1981).
[b] Measured concentration is indicated within depth interval sampled.

crater and the lagoon were regularly sampled between 1974 and 1979. Some of our early results on radionuclide concentrations in Runit groundwater have been discussed previously (Noshkin et al. 1976). The well sites were destroyed during cleanup operations sometime between April and October 1979, but they were replaced by DNA in March 1980. The two new wells were identified as CW1 and CW2. CW1 is approximately 5 m from the base of the dome near where XRU 5 was located, and CW2 is 15 m lagoonward of the base near the site of XRU 6. Since there was a small but perceptible groundwater flow in the region towards the lagoon, it was felt important to monitor the surface water for any changes in radionuclide concentration. Water was sampled during trips to the Atoll from 1980 to 1984 and again during the 1990's. Average concentrations of $^{239+240}$Pu and ^{137}Cs in groundwater during periods of pre- and post-cleanup are shown in Table 7. ^{137}Cs measurements are included because it is more mobile than plutonium and is therefore a better indicator of any leakage from the crater site.

Seawater was sampled from the lagoon 50–100 m opposite well CW2 in approximately 8 m of water. We designate this location as station CL-1. Station Cl-1 was the location where the research vessel usually anchored in the lagoon near Runit, approximately 400 m from the shore directly west of the crater. Water samples were routinely obtained from this location before and after the cleanup. On several occasions seawater was sampled in

Table 5. Concentration of radionuclides measured in water from 2 levels in drill hole CD-1; 3/28/80 (Bq m^{-3}).

CD-1 depths sampled (m)	$^{239+240}$Pu	*S* Value	^{241}Am	^{137}Cs	^{90}Sr
7.6–8.2					
Solution (<0.45 micron)	2.1	0.097	0.26	10.0×10^3	1.1×10^4
Particulate (>0.45 micron)	1.6×10^3	0.090	1.6×10^3	2.9×10^3	3.0×10^3
8.2–9.7					
Solution (<0.45 micron)	1.5	0.068	<0.1	8.4×10^3	1.3×10^4
Particulate (>0.45 micron)	4.2×10^3	0.046	3.3×10^3	8.0×10^3	8.5×10^3

Table 6. Mean activity of radionuclides measured in soil core samples extracted from the dome and crater by the NAS in 1980.[a]

	Bq g^{-1} dry wt	
Radionuclide	Dome[b]	Crater[b]
$^{239+240}$Pu	1.13 ± 0.49	0.35 ± 0.25
^{241}Am	0.15 ± 0.06	0.23 ± 0.48
Total TRU (estimate from *S* value in water)	1.30	0.62
^{137}Cs	0.34 ± 0.23	0.34 ± 0.34
^{90}Sr	0.71 ± 0.45	0.81 ± 0.60

[a] Material encased in the donut hole in the center of the dome was not sampled.

[b] Mean value is from 5 samples of soil under the dome and 9 samples below ground level in tremie region.

the lagoon in the area of the break in the reef north of the crater. A summary of the concentrations of $^{239+240}$Pu and ^{137}Cs measured during different periods in the filtered seawater samples from these three locations is shown in the lower section of Table 7.

Results in Table 7 show there has been essentially no change in the concentration of $^{239+240}$Pu or ^{137}Cs in the surface groundwater from the two well sites. Of significance are the results in Fig. 3 showing changes in surface groundwater salinity. Prior to capping the crater, the groundwater (XRU-5 and 6) at these sites was always brackish and had essentially the salinity of seawater. Rainfall impacting on the cement dome results in quantities of freshwater runoff that alters the groundwater quality as is evident from the change in water salinity at CW-1 and 2. Before cleanup, the beach area lagoonward of the crater was barren of vegetation (see Fig. 2a). Now the well sites are overgrown with scrub vegetation and ground cover because of the added fresh water supplied by runoff to the area.

The results shown in the lower section of Table 7 indicate a reduction over time in the amount of dissolved $^{239+240}$Pu in the offshore surface seawater. The reduction was most notable in the water immediately offshore the crater (CL-1). The $^{239+240}$Pu concentration in seawater at the station most distant from land was similar to measurements in previous years (CI-1). All concentrations are lower than the levels in the groundwater from the lagoon well sites near the crater that were sampled during comparable times. The water data suggest that the presence of the dome structure has apparently acted to restrict rather than increase transuranic movement from the crater to the lagoon.

The present mean concentration of ^{137}Cs in the lagoon surface water off the crater is many times lower than the groundwater levels in CW-1 and 2 and is now only twice the value of "global fallout" levels found in California Pacific coastal surface waters (Wong et al. 1992) in the late 1980's. It is now comparable to the surface concentrations found in California surface waters during the late 1970's (Noshkin et al. 1978). There has been no evidence of change in the nearshore lagoon seawater concentration of ^{137}Cs during the last 16–18 y that could be attributed to any major leakage of from material contained under the dome.

Concentrations in edible flesh of reef fish. The purpose for collections and analysis of specific radionuclides in fish, and in particular plutonium, changed over the years. In the 1970's we were tasked with comparing the levels of radionuclides in tissues of different species of fish from different locations. As the program progressed, dose assessment became the more important issue. This focused our attention on the analysis of the edible flesh from the different species. More than 2,000 fish have been collected from Enewetak Atoll for radionuclide analysis since 1972. Each fish was dissected and the tissue and organs of the species from the same catch were pooled for analysis. It was necessary to pool tissues from a particular catch for analysis because of the low concentrations of transuranic radionuclides encountered in edible muscle tissue and some other parts of the fish.

Differences encountered in the concentration of any radionuclide in the flesh are found to relate to fish species and size; the location where the fish are caught; feeding habits; concentrations in the material ingested; and trophic level. Some of these relationships are demonstrated with the ^{137}Cs data in different reef fish from Runit Island shown in Table 8 (Noshkin et al. 1997). The fish described in Table 8 were all caught using throw nets on the lagoon reef near or north of the crater. Data for 2 species of mullet are given along with concentrations in flesh of surgeonfish and goatfish, all used in the local marine diet by Marshallese people. Mullet are herbivorous and detritus feeders. Considerable quantities of bottom sediment are ingested along with food. Adult mullet belong to the 2nd trophic level. Surgeonfish are herbivorous browsers, feeding on algae fronds and fila-

Table 7. Concentration of radionuclides in filtered surface groundwater from 2 wells lagoonward of the crater and in lagoon surface seawater off-shore North Runit Island. ^{137}Cs (d) mean concentration decay corrected to 1/1996. Values in parenthesis are number of samples averaged. Concentrations only in filtered (0.45 micron) surface groundwater or lagoon water.

		Bq m^{-3}		
Years sampled	Groundwater wells	$^{239+240}$Pu	^{137}Cs	^{137}Cs(d)
1975–1979	XRU 5 & 6 mean	3.3 (8)	667 (8)	430
(pre disposal)	range	0.4–8.9	74–3,000	
1980–1984	CW 1 & 2 mean	3.2 (16)	890 (10)	640
(post disposal)	range	0.9–9.6	40–2,260	
1994	CW 1 & 2 mean	3.3 (2)	555 (2)	560
(post disposal)	range	2.6–4.1	370–740	
		Lagoon seawater (3 stations 70–400 m off shore N. Runit)		
1975–1979	mean	2.5 (14)	16 (9)	10
(pre disposal)	range	0.9–4.4	8–22	
1980–1984	mean	1.8 (9)	19 (4)	14
(post disposal)	range	0.6–2.6	10–26	
1994	mean	0.7 (3)	10 (3)	10
(post disposal)	range	0.7–0.8	6–14	

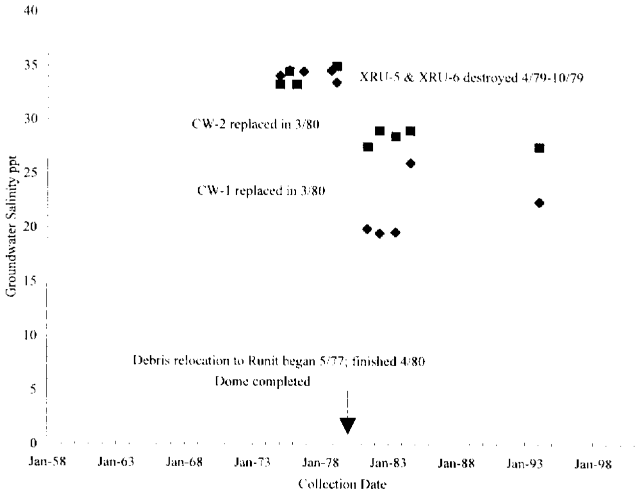

Fig. 3. Salinity in the surface groundwater from 2 wells located lagoonward of the crater.

mentous algae. This species is in the 2nd trophic level. The goatfish consume fossorial as well as surface benthic fauna including small clams, crustaceans, and small benthonic fish and belong to the 3rd trophic level (Noshkin et al. 1981a). The surgeonfish contain higher levels of ^{137}Cs in the flesh than either species of mullet or the goatfish. Surgeonfish are more territorial where the mullet and goatfish move in schools to different locations. The concentration in surgeonfish decreases with time, but no such trend is evident in the data for mullet or goatfish. The concentration of ^{137}Cs is similar for mullet and goatfish and is essentially below the detection limit in flesh from the fish caught in the 1990's from this region. These differences in muscle concentration relate to the feeding habits of the fish.

Fig. 4 is from Noshkin et al. 1997 and shows a semi-log plot of the data in Table 8 for surgeonfish from North Runit and two additional data points for these fish caught from different locations of the island. One sample was from the ocean reef approximately at mid-island and the other group of surgeonfish was caught in the lagoon from the southern tip of the island. These results demonstrate there are differences related to location sampled even on the same island. The reef fish are territorial and reflect the concentrations in the local environment from which they are caught. The results of repeated sampling of surgeonfish from N. Runit lagoon show a steady rate of decline in concentration with time. This suggests that the data can be used to estimate the change in availability of ^{137}Cs to this species from the local environment. The best fit to these data yields a slope related to an effective decay constant of $0.104 \pm .012$ y^{-1} with a correlation coefficient of 0.88. The physical half life of ^{137}Cs is 30 y. The computed environmental half-life for ^{137}Cs in the lagoon near N. Runit is therefore 8.6 ± 1.0 y. More on the environmental half-life in fish will be discussed in another paper in this volume (Noshkin et al. 1997). The important feature to note is that in recent years the levels in fish indicate no increase that could relate to leakage of ^{137}Cs from the material under the dome.

The rate of $^{239+240}$Pu disappearance from the environment does not follow that of ^{137}Cs because the geochemical behavior of the two radionuclides is significantly different. Between 1972 and 1978, the concentration of global fallout $^{239+240}$Pu in surface water of the north equatorial Pacific ocean was equivalent to or less than 0.014 Bq m^{-3} (Noshkin et al. 1987). Table 1 shows that the mean lagoon concentration of $^{239+240}$Pu during any year is much greater than fallout background in the Pacific ocean. The difference between the average soluble concentration measured during the different periods indicated is not considered significant, and the assump-

Table 8. Concentration of ^{137}Cs in the flesh of four species of reef fish caught in the lagoon off North Runit Island.

Month/Year collected	^{137}Cs (Bq kg^{-1} wet wt)[a] Mullet (*Neomyxus chaptalii*)	Mullet (*Crenimugil crenilabis*)	Surgeonfish (*Acanthurus triostegus*)	Goatfish (*Mulloidichthys samoensis*)
8/64[b]			52.0	
11/78		1.0 (2)	14.4 (2)	
9/80	0.58 (4)	0.35 (5)		0.64 (4)
9/80	0.26 (8)	1.0 (3)	7.94 (2)	1.41 (2)
7/81	0.52 (12)		9.67 (2)	1.9 (7)
6/82	0.66 (20)		9.11 (2)	
8/83	0.67 (18)	1.1 (5)	5.42 (3)	
11/93			8.07 (14)	0.54 (60)
2/94	1.6 (50)		4.73 (11)	
2/94	1.4 (60)		4.52 (6)	
11/94			1.70 (30)	<1
5/95	<1		1.83 (35)	<0.4
5/95			1.93 (11)	<1
4/76 Ocean reef-mid island			1.6 (5)	
9/80 Lagoon south tip of island			1.7 (3)	

[a] Numbers in parenthesis are the 1-sigma counting error expressed as percent of the listed value.

[b] Result from Welander et al. (1967).

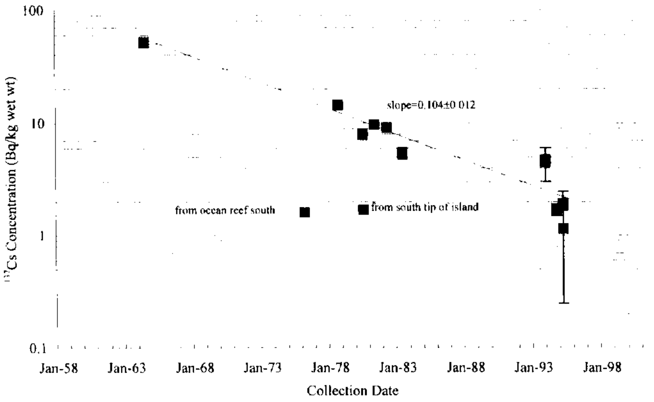

Fig. 4. ^{137}Cs concentrations in the flesh of Surgeonfish collected over time from Runit Island.

tion is made that the standing average amount of plutonium mobilized to the lagoon water mass from the Atoll sediments, at any time, is constant. Highest concentrations are generally found in the NE and NW quadrants of the lagoon and lowest levels are generally found in seawater from the SE quadrant. Steady state conditions have been established for $^{239+240}$Pu partitioning from the sedimentary reservoir to solution. Between 1972 and 1982, the average "soluble" $^{239+240}$Pu was 0.74 Bq m^{-3}. The quantity in solution represents only a small fraction of the inventory associated with the sediment. Unlike ^{137}Cs, the mobilization of $^{239+240}$Pu is a slower process. A similar mean concentration is expected to persist in the lagoon through the remainder of the 1980's and 1990's. Because the physical half-life of $^{239+240}$Pu is very long, it is therefore anticipated that the mean concentration of the radionuclide in the flesh of fish from different locations will relate to water levels and will also be relatively constant over time.

Table 9 shows the islands and other locations in the lagoon where reef and pelagic fish were caught since 1972 for plutonium analysis. The islands can be located by referring to Fig. 1. Table 10 shows the ln normal and geometric (median) mean levels of $^{239+240}$Pu in flesh of all reef and pelagic fish species collected during different intervals from regions of the lagoon. As with ^{137}Cs, there are differences encountered among species with different and similar feeding habits and locations sampled. In general, the level of $^{239+240}$Pu found is higher in reef species and lower in pelagic fish. Among the reef fish caught at the same location, the flesh of mullet generally has higher concentrations of plutonium than surgeonfish or goatfish. Fewer samples have been processed for ^{241}Am, but the median concentration in samples of flesh from fish from different locations sampled between 1976 and 1982 was 0.0024 Bq kg^{-1} wet wt. The median concentration best reflects the "average" value in fish but

Table 9. Fish collection locations at Enewetak Atoll.

Island or location ID	Name	US Designator
E-2	Bokombako	Belle
E-9	Boken	Irene
E-10	Enjebi	Janet
E-19	Aomon	Sally
E-20	Bijile	Tilda
E-24	Runit	Yvonne
E-33	Japtan	David
E-35	Medren	Elmer
E-36		Walt
E-37	Enewetak	Fred
E-38	Ikuren	Glenn
E-39	Mut	Henry
E-43	Biken	Leroy
E-45	Drekatimon	Remains-Oscar Tower
E-53		Wide Pass
E-54		Deep Pass

Table 10. Summary of $^{239+240}$Pu concentrations (Bq kg^{-1} wet wt) in the flesh of reef and pelagic fish collected from islands and other locations in Enewetak Atoll.

Period	Samples	Number of fish	ln n mean	Geometric mean
Before cleanup completed				
Fish from 5 islands (E-2, E-9, E-10, E-19, E-20)[a] North and West of Runit (E-24)				
1972–1978[b]	21	483	0.22 ± 1.22	0.039
1976–1978	10	464	0.019 ± 0.030	0.010
Fish from Runit (E-24) Period				
1972–1978[a]	9	129	0.089 ± 0.28	0.027
1976–1978	6	123	0.009 ± 0.006	0.007
Fish from 6 islands (E-33, E-35, E-36, E-37, E-39, E-43 and passes)[a] South and West of Runit (E-24)[c] Period				
1972–1978[a]	26	179	0.074 ± 0.28	0.019
1976–1978	6	156	0.003 ± 0.004	0.002
After Cleanup Completed				
Fish from 4 islands (E-2, E-9, E-10, E-19)[a] and tower remains (E-45) North and West of Runit (E-24) Period				
1980–1995	27	341	0.007 ± 0.016	0.003
Fish from Runit (E-24) Period				
1980–1995	32	819	0.009 ± 0.014	0.005

[a] Island names are identified in Table 8 and locations are shown in Fig. 1.

[b] Data for flesh in 1972 survey considered suspect and are supplied in this summary for completeness and information only.

[c] No fish were collected from the southern islands after the cleanup because of resettlement.

the ln normal mean is shown for information. We tend not to accept some of the data for plutonium generated during the 1972 survey (Nelson and Noshkin 1973) because contamination of the samples is suspected. However, mean values are also included in Table 10 using these data. This is for completeness and comparison if there is disagreement with our assessment on contamination.

Before the cleanup, the median level of $^{239+240}$Pu in the flesh of the fish was very low (everywhere only a few mBq kg^{-1} wet wt). Highest levels were encountered in species from the north islands. The mean concentration was comparable to the average found in all fish from Runit. Lowest levels were measured in fish from the southern part of the Atoll. These observations are supported by the lagoon water concentration data. After the radiological cleanup, no fishing was attempted from the southern part of the Atoll because the Enewetak people were in the process of resettling islands in this region. Fish were collected from Runit and from islands to the north during the early 1980's and 1990's. Again the median concentration of $^{239+240}$Pu in the flesh of all fish from both regions during the periods was comparable. The mean in the early 1980's was somewhat lower than the mean computed from the 1993–1995 collections. The 93–95 mean value is comparable to the value in fish from the pre-cleanup years of 1976–1978. There are many explanations for finding a lower mean level in fish during the early 1980's. In the context of this report it is only important to note that there has been no significant change in the mean concentration of plutonium in the flesh of fish caught in the lagoon near the crater over time. Concentrations are comparable to levels in fish collected from islands on the northern reef of the Atoll during periods before and after the Atoll cleanup exercise. Any TRU's from material at the disposal site have not impacted the marine resources in this region.

SUMMARY

Based on $^{239+240}$Pu concentrations measured in soils from regions within the dome after it was filled, the original estimates of the TRU's buried under the dome are questionable. The mean concentrations of the TRU, computed from the core soil sections, are equivalent to or greater than present mean surface soil levels on several northern islands (U.S. DOE 1982). These islands are unrestricted for food gathering. Only 24% of the of transuranics contained under the dome is in communications with the groundwater and available for remobilization. The TRU in the crater is no more than the quantity that has been exposed to seawater for years in the nearshore lagoon sediments off Runit Island. The TRU's in the lagoon are in continuous contact with seawater and are available for uptake by marine fish and other organisms. Levels of ^{137}Cs in the flesh of some reef fish from North Runit island are decreasing at a rate faster than radioactive decay alone. No impact is evident from ^{137}Cs associated with the debris under the dome. There has been essentially no change in the mean concentration of $^{239+240}$Pu in the flesh of reef or pelagic fish over time. The concentrations are comparable to levels measured in the flesh of fish from other regions of the Atoll that are caught and used as part of the marine diet by the Marshallese people. This near constant level in fish is regulated by the slow release and loss of the plutonium from the Atoll sediment reservoir.

Our recent data and conclusions support the findings suggested by the National Academy committee over a decade ago in that any assumption of rapid remobilization of all or any of the dome's transuranics is an extreme one. There is still a presence of TRU's in exposed soils of Runit Island, and for this reason the island has been made off limits. This recommendation should continue to be respected. Quantities of radioactive material in the crater, below ground level, are in communications with seawater and may be mobilized to solution and transported elsewhere. However, levels already present in the sediments and seawater of the lagoon overshadow by orders of magnitude the amounts found under the dome. Concentrations of transuranics in fish are no different now than pre-cleanup levels found in fish from the local environment. Therefore, the present and projected low dose estimates from the marine food chain are little different from those determined in previous years for residents of the Atoll (Robison 1973; Robison et al. 1970; Robison et al. 1987). Any fear that this structure contains amounts of activity whose release would cause damage to the environment that would result in a greater effect on human health is unfounded.

Acknowledgments—The collection and publication of the data in this report was made possible through the efforts of a group of people too numerous to list. They include the crews on several Marshall Islands research vessels and a number of individuals associated with Lawrence Livermore National Laboratory who assisted in the field collections and sample processing over three decades. The work was performed under the auspices of the U.S. Department of Energy under contract number W-7405-Eng-48.

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Paper

RESUSPENSION STUDIES IN THE MARSHALL ISLANDS

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Abstract—**The contribution of inhalation exposure to the total dose for residents of the Marshall Islands was monitored at occasions of opportunity on several islands in the Bikini and Enewetak Atolls. To determine the long-term potential for inhalation exposure, and to understand the mechanisms of redistribution and personal exposure, additional investigations were undertaken on Bikini Island under modified and controlled conditions. Experiments were conducted to provide key parameters for the assessment of inhalation exposure from plutonium-contaminated dust aerosols: characterization of the contribution of plutonium in soil-borne aerosols as compared to sea spray and organic aerosols, determination of plutonium resuspension rates as measured by the meteorological flux-gradient method during extreme conditions of a bare-soil vs. a stabilized surface, determination of the approximate individual exposures to resuspended plutonium by traffic, and studies of exposures to individuals in different occupational environments simulated by personal air sampling of workers assigned to a variety of tasks. Enhancement factors (defined as ratios of the plutonium-activity of suspended aerosols relative to the plutonium-activity of the soil) were determined to be less than 1 (typically 0.4 to 0.7) in the undisturbed, vegetated areas, but greater than 1 (as high as 3) for the case studies of disturbed bare soil, roadside travel, and for occupational duties in fields and in and around houses.**

Health Phys. 73:248–257; 1997

Key words: Marshall Islands; plutonium; soil; inhalation

INTRODUCTION

A STUDY of inhalation exposure from plutonium-contaminated soil was conducted on Bikini Atoll to provide the parameters for a rigorous assessment of the inhalation dose to humans. The study was needed for improved dose assessments through field observations of total suspended particulates ("mass-loading," $\mu g\ m^{-3}$), aerosol size, and radioactivity per unit mass. In addition, this study undertook to describe the distribution of suspended radioactivity within the respirable size range and how either the concentrations of radioactivity or the particle size distributions vary with surface conditions and local resuspending (dust-lifting) mechanisms.

Our investigations conducted on Bikini and Enewetak Atolls in the Marshall Islands provided data that have implications not only for the local dose assessment concerning rehabitation of those sites, but that confirm observations elsewhere regarding inhalation exposure due to plutonium resuspension. This research was supported by U.S. Department of Energy, Office of Health and Environmental Research, and is compiled here from a series of older internal reports.

BACKGROUND

A study conducted on Bikini Island in May 1978, provided a more complete set of data following earlier studies on Enjebi Island of Enewetak Atoll in February 1977 (Homan et al. 1978). The Bikini Island study utilized extensive soil sampling and *in situ* gamma spectroscopy to determine isotope concentrations in soil. Also various air sampling devices were used to determine particle size distribution and mass loading, and micrometeorological techniques were used to determine aerosol fluxes. Subsequent wet chemistry analysis provided radionuclide and elemental concentrations in collected aerosols. Four simultaneous experiments were conducted: (1) a characterization of the normal (background) suspended aerosols and the contributions from sea spray off the windward beach leeward across the island using Na and Mg as tracers for sea spray and an array of air samplers; (2) a study of resuspension of radionuclides from a field purposely laid bare by bulldozers as a worst-case condition followed by detailed air sampling; (3) a study of resuspension of radioactive particles by vehicular and foot traffic using an integrating nephelometer and air sampling along a road; and (4) a study of personal inhalation exposure using small air samplers carried by volunteers during their daily routines. Less complete, unreported studies similar to (1) and (2) had been performed previously on Enjebi Island at Enewetak Atoll and background studies similar to (1) were performed later on Eneu Island at Bikini Atoll.

METHODS

Soil samples were collected for analysis of radionuclide concentrations. ^{238}Pu, $^{239+240}$Pu and ^{241}Am concentrations were determined by isotope dilution and alpha spectrometry. These analyses were performed by LFE Corporation. Also, because the ratios ^{241}Am:$^{239+240}$Pu and ^{238}Pu:$^{239+240}$Pu are constant on Bikini, it was possible to estimate plutonium soil con-

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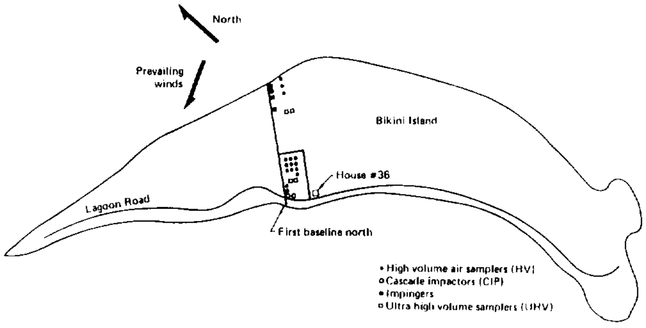

Fig. 1. Plan view of instrument locations on Bikini Island.

centrations by measuring ^{241}Am soil concentrations using a gamma spectroscopy system consisting of a planar, high-purity germanium diode which attained a minimum detectability for ^{241}Am less than 0.037 Bq g^{-1} (Kirby et al. 1977). The detector was mounted facing downward on a tripod so that the volume of soil integrated was contained in a circle of 3 m radius and 5 cm depth. Because the nuclear events causing the original contamination of Bikini Island were far removed, the fallout was relatively evenly dispersed across the Island.

Impingers were used to collect soluble sea spray aerosols in a 250-mL distilled water trap similar to the method of Hsu and Whelan (1976). Air flow rates were 0.36 m^3 h^{-1} (6 L min^{-1}) through the water trap and measured amounts of water were added each day to replace evaporated water (nominally 40 mL d^{-1}). Impingers were set at four tower locations along a 60 m wide clearing from the windward beach inland, spaced at 3, 26, 52, and 102 m from the high-tide waterline and at 1 m and 4 m above the ground. Elemental analysis on the remaining water was obtained by inductively-coupled plasma-optical emission spectroscopy for Na, K, Mg, Ca, and Zn and by a standard autoanalyzer (Technicon) for Cl.

The major particle collection system was an array of 14 standard, high-volume (HV) air samplers, with 8 × 10-inch filters, and two cascade impactors, all using Gelman type AE glass fiber filters. Flow rates for HV (General Metal Works) were monitored at a pressure tap on the fan; discharge was kept at 100 m^3 h^{-1} (60 cfm). The lapsed time of filter operation was recorded for each HV and cascade impactor by counting pulses from a crystal-controlled clock activated by a pressure-sensitive switch. Cascade impactors (CIP) were the 5-stage, jet-plate type.[†] Three HV with the air inlets at 1.1 m above ground were located on a line from the windward beach inland at 5, 70, and 158 m from the high-tide waterline; the latter two were beneath a coconut grove canopy. The tree canopy was expected to shelter the soil surface from wind and to provide a stabilized soil surface. One HV was located downwind of a road at the traffic study site, and ten HV and two cascade impactors were placed in a square array nominally 10-m apart in the middle of a field (1 hectare area) cleared by bulldozing. Special chemistry methods[‡] were employed on the filters to determine the concentration of the stable elements Na, K, Ca, Mg, S, and Cl, and the radioactive isotopes ^{238}Pu, $^{239+240}$Pu, ^{90}Sr, ^{137}Cs and ^{241}Am. Filter blanks were used to correct the stable elements. See map, Fig. 1, for locations of instruments.

In addition to the HV, three non-standard ultra-high volume air samplers (UHV) were used having air inlets at 1.5 m height. Flow-rates, nominally 2,550 m^3 h^{-1} (1,500 cfm), were monitored both by a pitot tube pressure tap on the fan discharge and by a modified anemometer-transducer measuring total discharge in the fan outlet, which was ducted 4 m downwind before discharge. Filters were 1 m^2 area of special fiber-type.[§] One UHV was placed in the coconut grove 370 m from the windward high-tide waterline, and two UHV were operated in the cleared field at the downwind edge of the HV array. The UHV provided the advantage of detection of suspended radioactive aerosols at extremely low levels (e.g., worldwide background) in a matter of a few hours run time. (Locations of UHV are shown on Fig. 1.)

Personal air samplers[||] were used to determine inhalation exposure rates of individual persons. These personal air samplers (PAs) are small, belt-mounted pumps with a hose connection to a cyclone particle discriminator and filter holder suspended by a chain worn around the neck. Flow rates were 0.11 m^3 h^{-1} (0.064 cfm) and filters were porous-type membrane filters (37 mm diameter, 1 μm pore diameter[¶]). It was found that blank membrane filters inexplicably gained weight with time but that standard deviations within 10% of mass could be achieved where filter blanks from the same lot were monitored for weight gains over the time period of the experiment. The membrane filters were used as a substrate for a scanning electron microscope (SEM) study of particle characteristics. The SEM operated by the LLNL Particle Characterization Facility has a large chamber for specimens (90 mm) and has a resolution of 0.015 μm. In the SEM mount, microprobe chemistry of individual aerosol particles on the membrane filters was accomplished by x-ray fluorescence with a resolution of 160 eV, which provided quantitation of particles containing elements with atomic numbers equal or greater than sodium.

Light-scattering instruments capable of sizing and counting particles within the diameter range 0.3 μm to 10 μm were used in two modes. In the first mode, a particle analyzer[#] was operated so that *in situ* particle-size number-densities could be determined. Particles in air entering the view volume at a rate of 0.43 m^3 h^{-1} (0.25 cfm) are counted individually by the resulting pulses that have a height linear with particle diameter, and classified

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[†] Model 65-000, Graseby-Anderson, Atlanta, GA.

[‡] LFE Corporation, Richmond CA.

[§] Microsorban N-98, Aerosol Filter Grade S, Delbag Luftfilter, Holzhauser Strasse 159, 13509 Berlin, Germany.

[||] Model S, Monitor, Mine Safety Appliances Co., P.O. Box 426, Pittsburgh, PA 15230.

[¶] Corning Costar Corp., 45 Wagag Park, Action, MA 01720.

by means of a conventional 200-channel pulse-height analyzer at a resolution of about 20 channels μm^{-1} (latex sphere calibration). Particle sizes were measured in this mode at the 1.0-m height in the cleared field with the aid of a vane-mounted isokinetic inlet. Particle counts were integrated over 120-s periods at frequent intervals during the experiment. In the second mode, light-scattering instruments were used as continuous monitors of total particle concentration. Two instruments were used in this mode: one, similar to the above but without size discrimination,[**] was also placed at the 1.0 m height in the cleared field. The second instrument used as a mass concentration monitor was an integrating nephelometer which measures the bulk scattering coefficient. In the 1–10 μm size range, the nephelometer samples ambient air at a flow rate of 17 m^3 h^{-1} (10 cfm) and has a fast response (about 1 s) with a continuous DC analog output that is linearly related to mass concentration using the manufacturer's calibration.[††] On Bikini, the nephelometer was used as a dust monitor for foot and vehicular traffic.

Two portable wind systems were utilized. For monitoring wind speed and direction in the open field at the 4.5-m height, a wind speed transmitter with reed switch contact closure each revolution and a wind direction transmitter with 540° dual potentiometer were operated through a battery-powered translator with 30-s filter, and recorded on a dual channel, strip chart recorder with an 8-d spring-driven chart. Wind-speed vertical profiles for aerosol flux estimates were determined using a portable, sensitive, cup-anemometer system[‡‡] operated at five height levels up to 4 m for selected 15-min periods (stall speed 0.20 m s^{-1}, distance constant 1.1 m).

RESULTS AND DISCUSSION

Characterization of background aerosols

The contribution of sea spray to aerosol mass loading was investigated thoroughly because it is a diluent of the resuspended mass fraction from the soil, which is the host to plutonium in the atmosphere. The stable element analyses showed that the ratios Cl:Na and Na:Mg were conservative and had values predicted by the composition of seawater (1.8 and 8.3, respectively) (Horne 1969). Other elements, in particular, calcium, were expected to be a tracer for calcareous soil from the parent coral material. The ratio Na:K was somewhat more variable and had a mean value of 11 which is intermediate between those values predicted for sea spray (5.7) and for seawater (27) (Horne 1969; Goldberg et al. 1971). Hence, the concentration of sea spray in the air was calculated by 3.25 × Na concentration and 27 × Mg concentration, based on the ionic composition of seawater (Goldberg et al. 1971). These two values were averaged to minimize random error of determination. The impingers were determined to be 77% efficient for collection of the sea spray by comparison with HV; after this correction and averaging the samples from 1-m and 4-m heights, it was found that the concentration of sea spray was constant over the island to within 52 m from the windward, high-tide waterline (Table 1). The leeward decrease was verified by HV measurements as well, but it occurred in a surprisingly short range compared to sea spray aerosols measured by other investigators (Hsu and Whelan 1976; Yaalon and Lomas 1970; Rossknecht et al. 1973). The rapid drop-off of sea spray from the shoreline was thought to be due to the presence of a massive vegetative barrier along the shore, and we expect that the horizontal flux was already reduced at the shore because the sea spray is mostly generated at the surf line on the coral reef nearly a kilometer upwind from the beach. The HV measurements show that the background sea spray aerosol calculated from Na and Mg concentrations was remarkably uniform throughout the remainder of the island ($\bar{x}$ = 34 μg m^{-3} S = 8.7, n = 27). The HV results are summarized in Table 2.

Background is here defined as the aerosol concentrations at the 1.1 m height over surfaces that are relatively stabilized and under normal wind conditions. After a week, even the bare soil tended to reach the same average level of dust aerosol concentrations (21 μg m^{-3}) as the coconut grove (Table 2). The background concentration of plutonium in air from resuspension of surface soil was measured in 1972 at Bikini and Eneu Islands (Smith and Moore 1972; Lynch et al. 1972). At that time Bikini and Eneu Islands had been cleared, houses built, and a coconut grove planted on both islands. The vegetation height was very low and the islands were partially barren so that conditions were optimal for maximum resuspension. Smith and Moore reported a plutonium concentration in air at Bikini Island of 3.6 μBq m^{-3} (mean of 4 stations) and 1.5 μBq m^{-3} (mean of 4 stations). Lynch et al. reported a mean plutonium concentration in air at Bikini of about 1.3 μBq m^{-3}. All of these results are consistent with our observations listed in Table 2.

An analysis of the personal dosimeter data (discussed later) showed that about 10% of the background dust aerosol was organic. $^{239+240}$Pu concentration (μBq

Table 1. Variation of Na and Mg aerosols and sea spray with distance from the waterline (impingers, effectively at a 2-m height).

Distance (m)	Na (μg m^{-3})	Mg (μg m^{-3})	Calculated sea spray (μg m^{-3})
3	56.2	6.17	175
26	13.3	1.45	41
52	10.5	1.21	35
102	10.4	1.30	34
Background (HV)	10.5	1.26	34

[#] Model CI-201, Climet Instruments Co. 1320 W. Coulton, Ave., Redlands, CA 92374.

[**] Model CI-208A, Climet Instruments Co. 1320 W. Coulton, Ave., Redlands, CA 92374.

[††] Model 1560, Meteorology Research Inc. Balforte Instrument Co., Wolfe St, Baltimore, MD 21231-3513.

[‡‡] Modified, from C.W. Thornthwaite Associates; 1725 Parvin Mill Road, Pittsgrove, NJ 08318.

Table 2. Summary of mass and plutonium aerosol concentrations on Bikini Island.

Date 1978	Distance to windward shore (m)	Ground cover	Sea spray (μg m^{-3})	Dust aerosol (μg m^{-3})	Plutonium concentration (μBq m^{-3})[a]	Type (number) of instruments	Wind speed direction[b] (m s^{-1})	(deg)
5/6–8	780	Bare soil	—	167	270	CIP (2)	4.7	53
5/9–16	780	Bare soil	—	9	9.1	CIP (2)	4.6	43
5/6–8	600–700	Bare soil	34	136	240	HV (3)	4.7	53
5/10–11	600–700	Bare soil	34	23	13	HV (10)	4.1	52
5/12–16	600–700	Bare soil	35	18	7.0	HV (10)	4.6	33
5/8–16	70–160	Coconut trees	34	21	2.4	HV (2)	4.6	45
5/8–16	820	Road	33	41	16	HV (1)	4.6	45
5/8–16	5	Shrubs	40	8	1.1	HV (1)	4.6	45
5/10–11	370	Coconut trees	—	—	1.9	UHV (1)	4.1	52
5/12–16	760	Bare soil	—	—	7.8	UHV (2)	4.6	33
Background[c]	>50	Bare soil	34	21	9.5	CIP (2), HV (20), UHV (2)	4.6	33
Background[c]	>50	Coconut trees	34	21	2.2	HV (2), UHV (1)		

[a] One μBq = 27.027 aCi, and one aCi (attocurie) = 10^{-18} Curie.

[b] Wind measurements recorded for the 4.5 m height at a station in the open field.

[c] Averaged over the surfaces that are stabilized.

m^{-3}) was a factor of 4.3 greater over bare soil than in the coconut grove. (Soil activity was 0.57 and 0.30 Bq g^{-1}, respectively, which is not significantly different within the normal variation encountered.)

The net vertical flux of plutonium is used in risk assessments to estimate the residual remaining on the surface after many years of erosion, especially where downward migration appears to be negligible. If we examine the vertical fluxes of plutonium (μBq m^{-2} s^{-1}) the ratio of fluxes from the two sites will be proportional to the ratio of their wind friction velocities, u', where

$$u' = C_D U_1, \tag{1}$$

and C_D is a drag coefficient equal to 0.106 in the coconut grove and 0.077 in the bare field as determined by our wind profile measurements and U_1 is the wind speed at the 1 m height, which was 4.1 times greater for the bare field than the coconut grove. By eqn (1), the ratio of friction velocities is 3 times greater in the bare field than in the coconut grove. The ratio of their plutonium fluxes is also proportional to the ratio of their concentrations; hence, the plutonium flux is a factor of 4.3 × 3 = 12.9 greater in the stabilized bare field than in the coconut grove. In our previous work, we calculated plutonium aerosol flux with the equation,

$$F = K\,(d_\chi/dz) = -pku'\chi, \tag{2}$$

where p is the exponent of a presumed power-law distribution of plutonium with height z (negative sign indicating decreasing concentration with height), k is Karman's constant equal to 0.4, and χ is the mean plutonium concentration in the height range from 0.5 to 2.0 m (Anspaugh et al. 1975). The exponent p is the slope of the plutonium concentration vs. height on a log-log scale. The impinger measurements at the 1-m and 4-m heights along the 60-m wide clearing parallel to the mean wind direction showed a p-value of 0.55 for calcium on Bikini Island, which we presume is the major host of terrestrial plutonium contamination. Previous work indicates p-values between 0.25 and 0.35 for dust aerosols in Western U.S. (Anspaugh et al. 1975).

Using the local p-value of 0.55 and measured values of u' and the background plutonium concentration, χ (2.2 μBq m^{-3}), as typical for the coconut grove, we obtain a plutonium resuspension flux of 0.057 μBq m^{-2} s^{-1} (1.8 Bq m^{-2} y^{-1}) which compares to 0.74 μBq m^{-2} s^{-1} (23 Bq m^{-2} y^{-1}) from the stabilized bare field. Dividing the resuspension flux values by the deposition (Bq m^{-2}, converting Bq g^{-1} using soil density 1500 kg m^{-3} and depth 0.05 m) we obtain a fractional rate of resuspension of 2.5×10^{-12} s^{-1} for the coconut grove and 1.7×10^{-11} s^{-1} for the stabilized bare field. These resuspension rates correspond to resuspension half-times of 8,800 y and 1,300 y, respectively, and are much shorter than the decay half times for plutonium (24,100 y). By comparison, plutonium resuspension rates from a bare field at H-Area, Savannah River Site, South Carolina, was 4.4×10^{-11} s^{-1} (halftime 5,000 y), and resuspension rates at Nevada Test Site ranged from 3.9×10^{-11} s^{-1} (halftime 560 y) for a sandy soil site in Plutonium Valley to 6.0×10^{-13} s^{-1} (halftime 37,000 y) for Little Feller II nuclear detonation site (Shinn et al. 1989).

Resuspension of radioactive particles from a bare field on Bikini Island

On 6 May 1978, a field was chosen for convenience (adjacent to House No. 36) and bulldozed bare of vegetation without stripping the soil. At the middle of the 100-m × 200-m field, the array of instruments (10 HV, 2 CIP, and 2 UHV) were set up in a regular grid covering about one hectare. The upwind fetch to the nearest instrument was 60 m and lateral borders were 30 m wide. During 6–8 May, three HV and two cascade impactors (CIP) were run during the highest resuspension (disturbed) phase immediately after bulldozing, followed by extensive runs with all instruments during the stable phase, 9–16 May. Wind speeds and direction remained relatively constant (Table 2). Plutonium aerosol concentration (μBq m^{-3}) was greater in the period 6–8 May over the period 9–16 May, by a factor of 25 to 30 as shown by the HV and CIP data of Table 2. Because the disturbed surface was stabilized by light rain at the end of the run on 8 May, the cascade impactor data showed significant differences in the plutonium-activity size distribution as shown on Fig. 2 (ordinate $d\chi/d(\ln D)$ in units Bq g^{-1} of dust aerosol, where D is particle diameter). The plutonium activity curves of Fig. 2 are calculated using a log-normal distribution with the median aerodynamic diameters (MAD) and geometric standard deviations (GSD) obtained by fitting cascade impactor data (Table 3). The aerosol size distributions for plutonium activity determined by CIP and the total mass loading (sea spray plus dust) determined by optical particle analyzer were satisfactorily approximated by a log normal distribution with the given GSD values in Table 3. All other MAD values of Table 3 were determined by cascade impactor.

Two typical cases of number density, $dN/d(\ln D)$, and volume density distributions, $dV/d(\ln D)$, determined by the optical particle analyzer over the stabilized bare soil surface on 9 May and 11 May are shown in Fig. 3. (The data points represent averages across size bins.) It should be noted that the optical particle analyzer sees all liquid and solid aerosols, including both dust and sea spray, so that the total mass obtained by integrating the volume distribution and multiplying by a density factor would not be expected to agree with the dry, residual mass loading measured by HV and CIP.

The relatively good agreement obtained between the different measurement systems indicated in Tables 1, 2, and 3 gives us the confidence to draw conclusions about the significance of resuspension for enhanced inhalation exposure in this worst case example. The MAD decreased from about 2.5 μm to 2 μm and the GSD increased from 2.2 to about 2.9. These changes, if the measurements are significant, would amount to a relatively small change in the lung deposition of the particles.

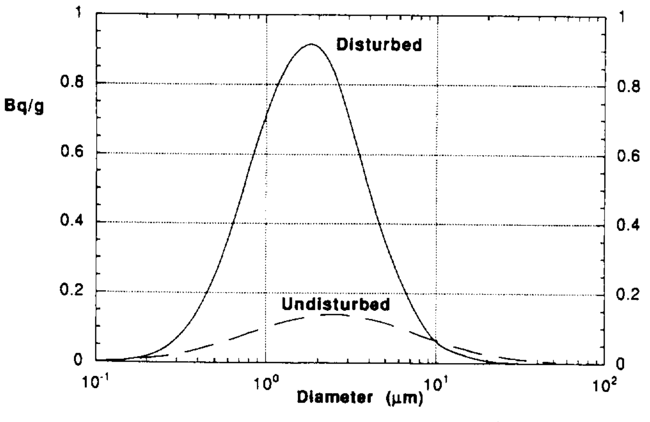

Fig. 2. Plutonium activity size distributions (Bq g^{-1} per $\Delta\ln$ D) for disturbed soil (6–8 May) vs. undisturbed soil (stabilized soil 12–16 May).

Table 3. Aerosol size characteristics on Bikini Island determined by cascade impactors and the optical particle analyzer at a height of 1.1 m.

	Disturbed bare soil	Stabilized bare soil
Median aerodynamic diameters (μm)		
Pu activity	1.73	2.46
Pu concentration	2.05	2.43
Mass loading	2.03	2.46
Mass loading—optical	—	2.40 (.11)[a]
Sea spray—Mg	—	2.59
Geometric standard deviation (dimensionless)		
Pu activity	2.16	3.09
Mass loading—optical	—	2.82 (.25)[a]

[a] Optical particle analyzer data with standard deviations in parentheses.

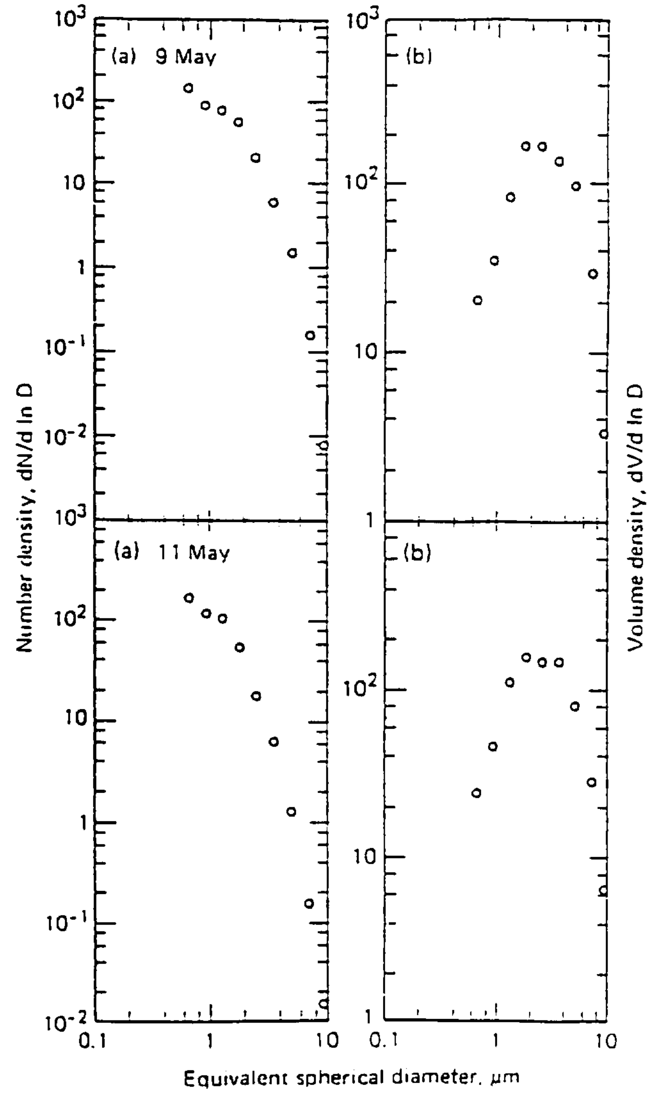

Fig. 3. Typical aerosol size distributions measured by the optical particle counter over the stabilized bare soil surface. Curves (a) are number density (ΔN/ΔlnD; particles cm^{-3}) and curves (b) are volume density (ΔV/ΔlnD; μm cm^{-3}) shown for two different days.

Table 4. Enhancement factors for plutonium activity of aerosols on Bikini Island (HV data).

Site	Date	Soil activity (Bq g^{-1})	Aerosol activity (Bq g^{-1})	Enhancement factor
Disturbed bare soil	5/6–8	0.57	1.8	3.10
Stabilized bare soil	5/10–11	0.57	0.54	0.96
Stabilized bare soil	5/12–16	0.57	0.39	0.69
Coconut grove	5/8–16	0.30	0.12	0.41
Road with traffic	5/8–16	0.15	0.38	2.5

If the total plutonium activity (Bq g^{-1}) is obtained by integration of the curves of Fig. 2, we find that there is, however, a significant change in the aerosol plutonium activity relative to the plutonium activity of the surface soil. Let us define an enhancement factor (EF) as follows:

$$EF = \frac{\text{total aerosol activity (Bq g}^{-1}\text{)}}{\text{soil activity (Bq g}^{-1}\text{)}} \quad . \qquad (3)$$

Upon investigation of the enhancement factors, we find that the values apparently were less than one under normal conditions (Table 4), probably because of selective resuspension of particles by size. We have found EF values in the range of 0.2 to 1.0 with a median of 0.6 at undisturbed continental sites as well (Shinn 1992). The EF values are expected to be a measure of both the distribution of plutonium with soil particle size and the manner that these particles are aggregated, since EF changes with the degree of disturbance to the soil (Shinn 1992). Organic debris could also dilute the aerosol. The ratio of organic particles to calcareous soil particles remained about constant (10%) as determined by x-ray fluorescence on the PAs filters exposed at this site during the same period. We know from previous studies that one component of organic matter, plant leaves, had a ratio of 10^{-5} plutonium concentration relative to soil and could serve to dilute the inorganic aerosol.

Under dusty conditions, EF values exceed unity, such as in the cases of the disturbed bare soil (3.1) and the road with traffic (2.5). So there are two different factors producing increased plutonium aerosol concentrations (μBq m^{-3}) during unusual resuspension. The aerosol dust concentration increases, but also the plutonium activity increases. For example, averaged over 10 HV instruments, the ratio of plutonium concentration over bare soil on 6–8 May compared to 10–11 May is caused by a 5.91 times increase in dust aerosol concentrations (Table 2) and 3.23 times increase in enhancement factor (Table 4) for a combined effect on aerosol plutonium concentration (239 μBq m^{-3}/12.5 μBq m^{-3}) of 19.1.

Resuspension of radioactive particles by vehicular and foot traffic

The integrating nephelometer was installed with intake at 1.2 m height and 2 m leeward from the position of average tire tracks on a frequently-traveled, one-lane dirt road on Bikini Island. Even though the traditional vehicular traffic of light trucks at low speeds was increased in frequency by our experimental activity, we were interested in characterizing the resuspension of plutonium and inhalation exposure per vehicle pass. The nephelometer provided details on magnitude, duration, and frequency of dust concentrations, while plutonium and dust aerosol concentrations (Table 2), and plutonium activity and enhancement factors (Table 4) were obtained by a co-located HV.

Dust concentrations above background rose in a pulse exceeding 10 s duration where the peak was obtained in a period about 4.5 s after the passage of the vehicle (Fig. 4). This characteristic time to arrival of the peak, regardless of concentration, was determined by X/σ_u where the travel distance X is 2 m and the RMS turbulent velocity σ_u is about one-tenth the local wind speed of 4.5 m s^{-1}. Hence, the dust pulse was traveling by diffusion and not characterized by translation in the wake of the passing vehicle. The dust pulse example of Fig. 4 represents an extreme case (more than 90% of occurrences had lower concentrations) but demonstrates the characteristic peak to mean ratio of 3. 6 and the slow return to background on the trail of the pulse. The amplitude and frequency of dust pulses due to motor vehicle, bicycle, and foot traffic were recorded during 11–15 May. The 68 cases of motor vehicle passes observed showed an approximate log-normal frequency distribution with median peak concentration (above background) of 100 μg m^{-3} and geometric standard deviation of 3.4 (Fig. 5). Bicycle traffic could not be distinguished from foot traffic. In the seven observed cases of foot traffic, we found an approximate median peak concentration above background of 26 μg m^{-3}.

It should be emphasized that the log-normal concentration implies a 5% chance of an exposure to a vehicular-induced peak concentration of 760 μg m^{-3} having a mean concentration 760/3.6 = 211 μg m^{-3} for about 10 s. The plutonium enhancement factor was estimated at 2.5 in this study (Table 4).

Personal inhalation exposure and dosimetry

Until now, the discussion has centered on the (combined) isotope $^{239+240}$Pu, since in fact this is the most important component of inhalation exposure. Extensive soil sampling on Bikini Island has established that a relatively homogeneous mixture of isotopes exists in the soil (Table 5). In the aerosols, some of the isotopes become significantly enhanced (^{137}Cs), but they remain of lesser inhalation-hazard.

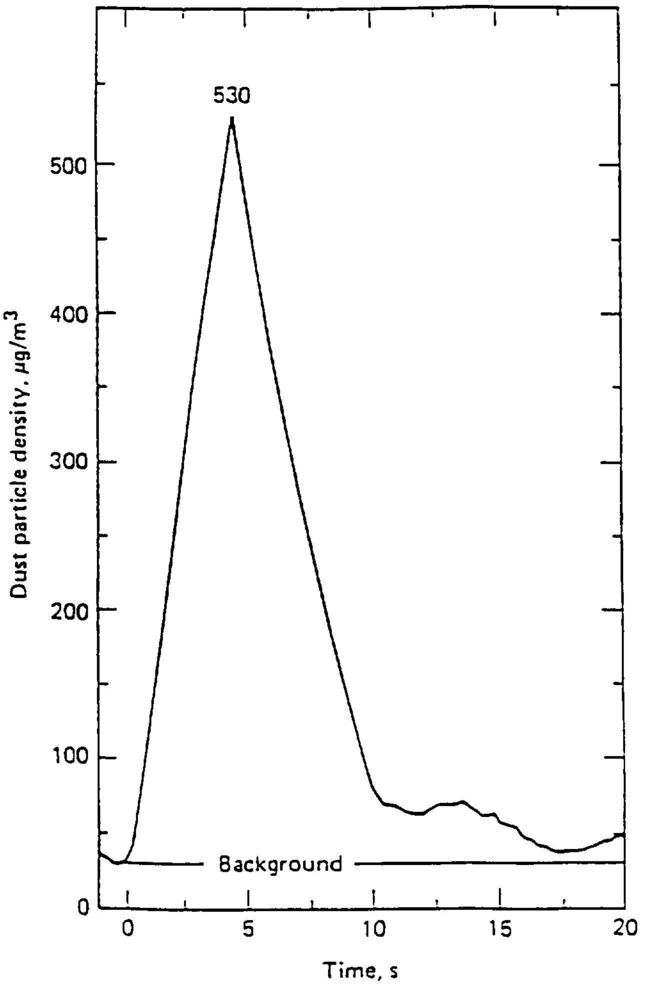

Fig. 4. An example of a dust concentration pulse on the downwind side, 2 m from the edge of a dirt road, showing a peak mass loading of 530 μg m^{-3} following the passage of a light motor vehicle.

In the case of ^{238}Pu, the concentrations in air were so low that they were probably greatly influenced by the contribution from sea spray.

The *in situ* gamma (ISG) spectroscopy system that measured ^{241}Am in the soil at Bikini was highly correlated to that measured in surface soil samples by special chemistry methods (R^2 = 0.910), which gives confidence in both methods. However, data from the ISG system was consistently lower than the soil sampling method by a factor of 0.7 because it integrated a view volume about 5 cm depth and the exponential decrease of isotope concentration with depth gives lower mean values. After correction by a factor 1.44, the ISG method was the primary method for mapping ^{241}Am as a tracer for the source of suspended plutonium isotopes. The horizontal variations in soil isotope concentrations (ISG data) were small enough so that one could justify mean values as local regional values for soil. For example, on the 2-hectare bare field, it was determined that plutonium in surface soil had the mean value 0.57 Bq g^{-1} with an observed range of 0.085 to 1.0, and a fractional standard deviation of 0.57. There was no apparent pattern to the soil concentrations and they exhibit approximately normal, random variation perhaps due to previous tilling and blading locally. (The data did not fit a log-normal distribution any better.)

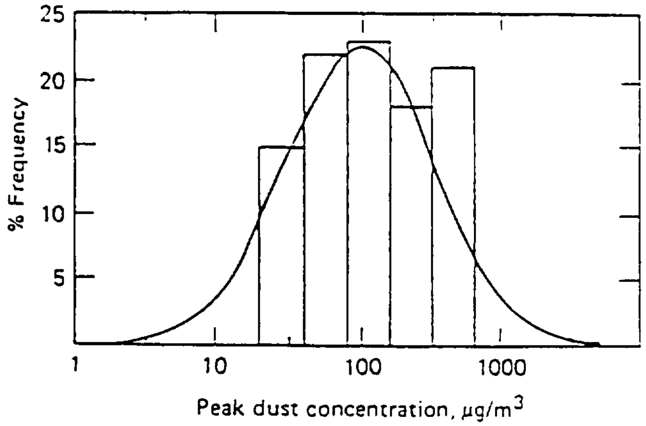

Fig. 5. Frequency of peak dust concentrations on the downwind side of a one-lane dirt road following passages of a light motor vehicle.

In the context of living condition effects on exposure, personal air samplers dosimeters (PAs) provided information about inhalation exposure of individuals relative to the reference HV monitors after a necessary adjustment. It was found that the fraction of dust in the total aerosol collected by the PAs was greatest for workers exposed during heavy tilling but was also high for workers exposed in and around houses (Table 6). In this and prior studies, we found that the ratio of PAs Dust:HV Dust has a value of approximately 0.5 where both PAs and HV are sampling the same aerosol cloud of this size particles (2.5 μm MAD) because of the cyclone particle-discriminator on the PAs. Therefore, the enhancement of inhalation exposure by a worker's own actions where the PAs and HV are not sampling the same cloud can be estimated by a personal dosimeter enhancement (PAE):

$$PAE \cong 2 \times (\text{PAs Dust/HV Dust}). \quad (4)$$

Values so computed show significant enhancement (PAE) of inhalation exposure (2.64) during heavy work outdoors by persons sitting or kneeling while digging or using tools on the ground (Table 6). The second highest enhancement (1.86) came from persons with duties in and around the houses. Other work, including heavy tilling, produced inhalation exposures satisfactorily monitored by HV and, thus, their PAE values were close to unity. The main limitation of the PAs data and the derived enhancement values (PAE) is that no information is obtained about the plutonium enhancement factors expressed by eqn (3). It should be recalled that plutonium enhancement factors (EF) of the same magnitude as these PAE were detected by HV (Table 4).

Table 5. Radioactive isotope ratios in soil and aerosols at a stabilized bare field on Bikini Island.

	$^{238}Pu^{b}$ / $^{239+240}Pu$	^{241}Am / $^{239+240}Pu$	^{137}Cs / $^{239+240}Pu$	^{90}Sr / $^{239+240}Pu$	$^{239+240}Pu$ (Bq g^{-1})
Soil	0.0013	0.556	9.80	9.15	0.57
FSD[a]	0.56	0.55	0.48	0.52	0.57
Aerosols (HV)	0.050	0.439	61.4	12.8	0.47
FSD[a]	0.64	0.34	0.32	0.51	0.35

[a] Fractional standard deviations ($s/\bar{x}$).
[b] A significant fraction of ^{238}Pu in air was due to sea spray.

Table 6. Comparative effects of living conditions from personal air samplers (PAs) worn by volunteers in various work assignments.

Activity	Outdoors over disturbed bare field	Outdoors over stabilized and vegetated surfaces		Inside and outside around houses
	During tilling	Light work	Heavy work	Light work
Number of volunteers	2	4	3	3
PAs dust fraction[a]	94%	56%	56%	89%
PAs dust ($\mu g\ m^{-3}$)	62	12	28	20
PAs dust/HV dust	.46	.55	1.32	.93
PAs enhancement[b]	.92	1.10	2.64	1.86

[a] Personal dosimeter dust is corrected for sea spray but contains about 10% organic matter, both estimated by x-ray fluorescence.
[b] PD enhancement = 2 × (PD dust/HV dust).

Table 7. Inhalation exposure to plutonium ($^{239+240}Pu$) for worst case and best case conditions on Bikini.

Condition	Inhalation rate (m^{3} h^{-1})	Dust aerosol ($\mu g\ m^{-3}$)	Soil Pu activity ($\mu Bq\ \mu g^{-1}$)	Enhancement factor (EF)	Personal enhancement (PAE)	$\mu Bq\ h^{-1}$ Exposure
Bare field during tilling	1.04	136	0.57	3.10	0.92	230
Stabilized field, heavy work	1.04	21	0.57	0.83	2.64	27
In and around houses, light work	0.83	21	0.57	0.83	1.86	15
Coconut grove, light work	0.83	21	0.30	0.41	1.10	2.4
At roadside, one vehicle/h[a]	0.0023	28	0.15	2.50	(1.0)	0.024

[a] Based on the exposure to one, 10-s, median, vehicular dust-pulse per hour, *not* including background (BG).

Inhalation exposure ($\mu Bq\ h^{-1}$) using an inhalation rate (IN-RATE) and previously defined terms may be estimated as follows:

$$\text{INHAL. EXPOSURE} = \text{IN-RATE} \times \text{HV DUST} \times \text{SOIL ACTIVITY} \times \text{EF} \times \text{PAE} \quad (5)$$

$$(\mu Bq\ h^{-1}) = (m^{3}\ h^{-1})\ (\mu g\ m^{-3})\ (Bq\ g^{-1})\ (10^{-6}\ g\ \mu g^{-1})\ (10^{6}\ \mu Bq\ Bq^{-1}).$$

Using eqn (5), data from Tables 2, 4, and 6, the subtraction of mass loading of sea spray, and the best estimates for the enhancement factors and inhalation rate, we calculated inhalation exposure of $^{239+240}Pu$ for four cases on Bikini (Table 7). Under the worst case condition (during tilling in a disturbed bare field), the inhalation exposure was 230 $\mu Bq\ h^{-1}$, and in the best case (light work in a coconut grove), the inhalation exposure was 2.4 $\mu Bq\ h^{-1}$. Intermediate values were 27 $\mu Bq\ h^{-1}$ for heavy work in a bare field, and 15 $\mu Bq\ h^{-1}$ for light work in and around houses. (In the latter case, we had to use an enhancement factor measured in the nearby field rather than in and around the houses.)

Walking along the road with one vehicular passage per hour produced an estimated 50% chance of additional inhalation exposure of 0.024 $\mu Bq\ h^{-1}$ (above background) and the soil plutonium activity on the road was notably lower (0.15 Bq g^{-1}) compared to the field (0.57 Bq g^{-1}) (Table 7).

SUMMARY AND CONCLUSIONS

Mass loading (all aerosols) on a HV filter was 55 $\mu g\ m^{-3}$ on Bikini Island over stabilized and vegetated surfaces (e.g., in a bare field following rain and in a coconut grove). This compares to 56 $\mu g\ m^{-3}$ measured at a vegetated site on Enjebi Island of Enewetak Atoll in February 1977, and a 42 $\mu g\ m^{-3}$ weekly average for 10 wk in a coconut grove on Eneu Island of Bikini Atoll May–August 1978. (Wind speeds were comparable, 4–5 m s^{-1}, in all cases.) The more detailed studies at Bikini revealed that 34 $\mu g\ m^{-3}$ of the mass loading was salt

Table 8. Plutonium aerosol concentrations on Bikini and Enewetak Atolls compared (winds 4–5 m s^{-1}).

Location	Surface description	Plutonium aerosol concentration (μBq m^{-3})	Suspended soil activity (Bq g^{-1})	Surface soil plutonium activity (Bq g^{-1})	Estimated enhancement factor
Normal "Background"					
Bikini	Coconut grove	2.2	0.12	0.30	0.41
Bikini	Stabilized bare soil	9.8	0.47	0.57	0.82
Enjebi	Vegetated field	8.9	0.40[a]	0.90	0.45[a]
Enjebi	Downwind of road	4.0	0.73[a]	1.30	0.56[a]
Unusual Conditions					
Bikini	Field, freshly tilled	2.4	1.8	0.57	3.10
Enjebi	Garden, freshly tilled	2.8	4.0[a]	0.90	4.41[a]
Enjebi	Garden, 1 wk after tilled	1.1	2.3[a]	0.90	2.55[a]
Bikini	Road with traffic	1.6	0.38	0.15	2.50

[a] Calculated by assuming 34 μg m^{-3} sea spray which has been verified by measurement on Bikini.

from sea spray, and that this sea spray contribution remained constant across Bikini Island beyond 20–50 m from the windward beach.

The "background" concentrations of aerosol plutonium on Bikini are comparable to those on Enjebi Island, Enewetak, when one considers the surface soil plutonium activity (Table 8). And, by assuming that Enjebi Island had the same aerosol sea spray background (34 μg^{-3}) as Bikini (which has not been verified by actual measurement) we found that the enhancement factors agree reasonably well. The normal enhancement factor is 0.56, if one assumes that values less than 1 (Table 8) represent normal variations about the mean of 0.56. Apparently, the process of resuspension is preferentially selective by particle size on these atolls to the extent that an aerosol plutonium dilution of 1.8:1 normally occurs.

During unusual surface conditions, such as immediately after tilling, plutonium aerosol activity (normalized by means of the enhancement factor) also agree well. The corresponding enhancement factors were 4.41 on Enjebi Island and 3.10 on Bikini Island.

Plutonium resuspension fluxes due to continuous wind erosion and resuspension were estimated for Bikini by a meteorological flux-gradient equation to be a minimum of 1.8 Bq m^{-2} y^{-1} in the coconut grove and 23 Bq m^{-2} y^{-1} over a bare field stabilized by light rain. Since fields do not remain unvegetated for more than a few months, the coconut grove resuspension flux is probably representative of the island as a whole, even though the wind speeds are one-fourth as high in the coconut grove canopy as in the open.

Particle size distributions measured by both optical and cascade impactor methods show that over the rain-stabilized bare field, the total aerosol size distribution is log-normal with median aerodynamic diameter of 2.4 μm and geometric standard deviation of 3.0, but there is no significant size difference between aerosol plutonium activity and aerosol mass concentration. During the unusual condition of tilling, the size distribution shifts from a median aerodynamic diameter of 2.5 μm to about 2.0 μm with a concurrent increase in plutonium enhancement factor from less than one to 3.1 on Bikini (4.4 on Enjebi). The change in particle size distribution would not contribute to large changes in lung deposition, while the change in plutonium activity would. In the case of a soil disturbed by tilling on Bikini, the plutonium concentration increased by a factor of 19.1 due to a 3.23 × increase in enhancement factor and a 5.91 × increase in dust aerosol concentrations.

Vehicular traffic produced dust pulses of nominal 10 s duration in a 4.5 m s^{-1} wind, which were log-normally distributed having time-averaged concentrations above background of 28 μg m^{-3} less than 50% of the time and 211 μg m^{-3} less than 5% of the time. (Peak concentrations were a factor of 3.6 higher.) The plutonium enhancement factor for vehicular traffic was 2.5. Foot and bicycle traffic produced dust pulses about one-fourth as large as vehicular traffic.

Personal air sampling showed that under various exposure conditions, workers inhaled different fractions of inorganic dust and salt, while the organic fraction remained constant at about 10%. Consequently, a personal air enhancement factor was defined to express the effect a worker has by stirring up dust in his own immediate environment.

In conclusion, this study has been as comprehensive as necessary to provide the key parameters for inhalation dose assessment of exposure to plutonium contaminated aerosols. Preliminary dose assessments have been verified now by aerosol measurement methods and at different locations. There remain several unexplained and untested results. It is not yet clear why the aerosol dust concentration is apparently uniform for different surface cover and wind conditions (e.g., coconut grove vs. bare field). It is also not known why the plutonium enhancement factor is less than unity in the normal case, while at the same time, the aerosol plutonium activity and the aerosol mass size distributions are not significantly different. Long-term monitoring on these remote atolls is not yet very practical.

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A COMPILATION OF NUCLEAR WEAPONS TEST DETONATION DATA FOR U.S. PACIFIC OCEAN TESTS

S. L. Simon* and W. L. Robison[†]

Abstract—**Prior to December 1993, the explosive yields of 44 of 66 nuclear tests conducted by the United States in the Marshall Islands were still classified. Following a request from the Government of the Republic of the Marshall Islands to the U.S. Department of Energy to release this information, the Secretary of Energy declassified and released to the public the explosive yields of the Pacific nuclear tests. This paper presents a synopsis of information on nuclear test detonations in the Marshall Islands and other locations in the mid-Pacific including dates, explosive yields, locations, weapon placement, and summary statistics.**

Health Phys. 73(1):258–264; 1997

Key words: weapons; fallout; Marshall Islands; atomic bomb

INTRODUCTION

DURING THE years 1946 through 1962, nuclear weapons testing was conducted by the U.S. over the mid-Pacific ocean and on several islands and atolls in the region. In particular, Bikini and Enewetak, two neighboring coral atolls in the Marshall Islands, were used as sites for nuclear weapons testing during the years 1946 through 1958. In 1962, the U.S. continued atmospheric testing at Christmas Island, Johnston Atoll and several other mid-Pacific locations outside of the Marshall Islands.

During the years of nuclear testing, the Marshall Islands was part of the U.N. constructed Trust Territory of the Pacific (TTP), a group of small island countries entrusted to the U.S. following the end of WWII. The TTP remained in effect until the mid-1980's when the Marshall Islands chose to became an independent republic.

Testing began in the Marshall Islands with shot ABLE (Operations Crossroads) on 30 June (GCT) 1946 and ended with FIG (Operation Hardtack I) on 18 August (GCT) 1958. On 31 October 1958, the U.S. began a unilateral testing moratorium based on the assumption that the Soviet Union would also cease atmospheric weapons testing. When the Soviet Union resumed testing in September 1961, the U.S. resumed testing in Nevada and in the Pacific; the first of the Pacific series was in April 1962 in the area by Christmas Island. Thirty-nine nuclear weapon tests were conducted outside of the Marshall Islands by the U.S. near Johnston Atoll and Christmas Island.

This report presents (1) summary statistics of the explosive yields at each of the four mid-Pacific test site locations; (2) a detailed list of the date, explosive yield, location and weapon placement for each test; and (3) a brief examination of the temporal and yield distributions for each of the four main Pacific test sites. Some of this information has been obtainable over the years in various documents, reports and conference proceedings (see for example, U.S. Congress 1959; Carter and Moghissi 1977; U.S. DOE 1977; DNA 1979; Schell et al. 1980; BARC 1984; Norris et al. 1989; BAS 1992), although the yields for 45 of the 66 tests in the Marshall Islands were not available to the public at the time of those publications.[‡] The availability of data on yields of the tests followed a 1992 request by one author (SLS) through the Ministry of Foreign Affairs of the Republic of the Marshall Islands. Late in 1993, the U.S. Secretary of Energy released the yields of the tests to the Marshall Islands Government and the U.S. public (U.S. DOE 1993). The most recent comprehensive report to date is U.S. DOE (1994).

DATA SUMMARY

Marshall Islands tests

Bikini Atoll, located in the northwest sector of the Republic of the Marshall Islands, was the site of 23 of 66 underwater, ground level and above ground nuclear tests; one additional test was conducted 100 km W of Bikini. Enewetak Atoll, located 350 km west of Bikini, was the site of 42 nuclear tests including two with zero yield. The combined explosive yield (kt TNT equivalent) for both test sites was 1.08×10^5 kt TNT (U.S. DOE 1993). The proportions of the total explosive yield at Bikini and

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0017-9078/97/$3.00/0

[‡] BAS (1992) gave explosive yields for the test data unreleased at that time though the values were slightly different than the data subsequently declassified and released by the Department of Energy in 1993.

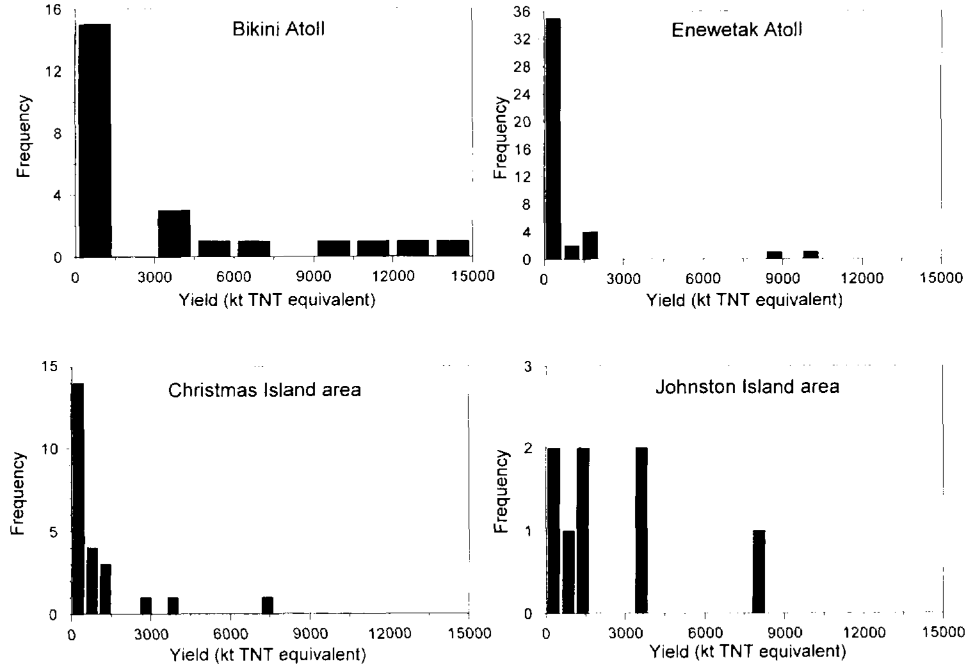

Fig. 1. Frequency distributions for explosive yield (kt TNT equivalent) of nuclear tests at Bikini Atoll (Marshall Islands), Enewetak Atoll (Marshall Islands), Christmas Island area (Kiribati), and Johnston Atoll area.

Table 1. Summary statistics of numbers of U.S. tests and explosive yields at mid-Pacific locations.

	Bikini Atoll	Christmas Island area	Enewetak Atoll	Johnston Atoll area	Other Pacific locations
Number of tests	24[a]	24	42	12	3
Missing yield values[b]	0	0	0	4	2
YIELD (kt TNT equivalent)					
Minimum[c]	1.7	2.2	0.0	11.3	30.0
Maximum[c]	15000.0	7650.0	10400.0	8300.0	30.0
Mean[c]	3201.6	968.9	736.1	2472.0	30.0
Median[c]	388.5	310.0	45.5	1495.0	30.0
Total[c]	76838.8	23253.3	31653.4	19776.3+	30+

[a] Includes shot YUCCA, 100 km W of Bikini.

[b] Data not released.

[c] Based on available data only; not strictly correct for Johnston Atoll and Other Pacific locations because of missing values.

Enewetak were 70.8% (76.8 Mt) and 29.2% (31.6 Mt), respectively.

The testing program in the Marshall Islands during the first 6 y of the 12-y program was relatively sparse. The first two nuclear explosions (21 kt each) were at Bikini Atoll in 1946 as part of Operations Crossroads. The next six tests were conducted at Enewetak Atoll, three in 1948 and three in 1951. Less than 1% of the total explosive yield of the Marshall Islands series was released in the tests prior to 1952. Beginning in 1952 with the Ivy series and continuing in 1954 with the Castle series, the testing program escalated in frequency and size of tests. The percentages of the total explosive yield of Marshall Islands tests during 1952, 1954, 1956 and 1958 were 10.2%, 45%, 19.4% and 24.9%, respectively.

On seven different occasions, two nuclear tests were conducted on a single day: once in 1956, five times in 1958, and once in 1962. On five of those occasions, both Enewetak and Bikini Atolls were used as test sites within the same day.

The United States' first experimental thermonuclear test explosion, GEORGE (Operation Greenhouse), was detonated at Enewetak on 8 May (GCT) 1951 and yielded 225 kt (U.S. DOE 1994). The first thermonuclear (hydrogen) bomb tested by the U.S. was MIKE (Operation Ivy), detonated at Enewetak on 31 October (GCT) 1952, yielding 10.4 Mt. On 28 February (GCT) 1954, the U.S. exploded its largest thermonuclear device ever, Castle BRAVO.[§] BRAVO was detonated at Bikini Atoll and yielded approximately 15 Mt equivalent TNT. The

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[§] Castle BRAVO is often cited as having been detonated on 1 March 1954. The local time of the detonation was 6:45 a.m., 1 March 1954.

Table 2. Summary data listing of U.S. nuclear tests in the Marshall Islands and at other mid-Pacific Ocean locations. Data taken from DNA (1979) and USDOE (1994). Time of test is listed as Greenwich Civil Time (GCT); local time of detonation at Pacific Proving Ground would be 12 h later (dates would also be 1 d later). (Abbreviations: n/a = not available; DOD = Department of Defense; LASL = Los Alamos National Laboratory; LRL = Lawrence Radiation Laboratory; UCRL = University of California Radiation Laboratory; low yield means <20 kt, submegaton means >200 kt but <1 Mt).

Shot name	Operation	Date (GCT)	Time (GCT)	Yield (kt TNT equivalent)	Sponsor	General location	Latitude °N	Longitude°	Height of burst (m)	Weapon placement
ABLE	Crossroads	6/30/46	22:00	21	LASL/DOD	Bikini Atoll	11.62	165.48 E	158.5	airdrop
BAKER	Crossroads	7/24/46	21:35	21	LASL/DOD	Bikini Atoll	11.62	165.48 E	−27.4	underwater, cable supported
X-RAY	Sandstone	4/14/48	18:17	37	LASL	Enewetak Atoll	11.67	162.23 E	61.0	tower over coral
YOKE	Sandstone	4/30/48	18:09	49	LASL	Enewetak Atoll	11.62	162.32 E	61.0	tower over coral
ZEBRA	Sandstone	5/14/48	18:04	18	LASL	Enewetak Atoll	11.55	162.35 E	61.0	tower over coral
DOG	Greenhouse	4/7/51	18:34	81	LASL	Enewetak Atoll	11.55	162.35 E	91.4	tower over coral
EASY	Greenhouse	4/20/51	18:27	47	LASL	Enewetak Atoll	11.67	162.23 E	91.4	tower over coral
GEORGE	Greenhouse	5/8/51	21:30	225	LASL	Enewetak Atoll	11.62	162.30 E	61.0	tower over coral
ITEM	Greenhouse	5/24/51	18:17	45.5	LASL	Enewetak Atoll	11.67	162.23 E	61.0	tower over coral
MIKE	Ivy	10/31/52	19:15	10400	LASL	Enewetak Atoll	11.23	162.18 E	0.0	surface burst over coral and water
KING	Ivy	11/15/52	23:30	500	LASL	Enewetak Atoll	11.55	162.35 E	451.1	airdrop
BRAVO	Castle	2/28/54	18:45	15000	LASL	Bikini Atoll	11.68	165.27 E	2.1	surface burst from platform over coral
ROMEO	Castle	3/26/54	18:30	11000	LASL	Bikini Atoll	11.68	165.27 E	2.1	barge
KOON	Castle	4/6/54	18:20	110	UCRL	Bikini Atoll	11.48	165.37 E	4.1	surface burst from platform over coral
UNION	Castle	4/25/54	18:05	6900	LASL	Bikini Atoll	11.65	165.38 E	2.1	barge
YANKEE	Castle	5/4/54	18:10	13500	LASL	Bikini Atoll	11.65	165.38 E	2.1	barge
NECTAR	Castle	5/13/54	18:20	1690	LASL	Enewetak Atoll	11.67	162.78 E	2.1	barge
WIGWAM	Wigwam	5/14/55	20:00	30	DOD	Pacific Ocean (250 km SW of San Diego)	28.73	126.27 W	−600.00	subsurface (underwater) burst suspended by cable from barge
LACROSSE	Redwing	5/4/56	18:25	40	LASL	Enewetak Atoll	11.55	162.35 E	5.2	surface burst from platform on coral
CHEROKEE	Redwing	5/20/56	17:51	3800	LASL	Bikini Atoll	11.67	165.38 E	1325.9	airdrop
ZUNI	Redwing	5/27/56	17:56	3500	UCRL	Bikini Atoll	11.48	165.37 E	2.7	surface burst from platform over coral and water
YUMA	Redwing	5/27/56	19:56	0.19	UCRL	Enewetak Atoll	11.50	162.30 E	62.5	tower over coral
ERIE	Redwing	5/30/56	18:15	14.9	LASL	Enewetak Atoll	11.53	162.35 E	91.4	tower over coral
SEMINOLE	Redwing	6/6/56	00:55	13.7	LASL	Enewetak Atoll	11.67	162.22 E	1.4	surface burst in water tank over coral soil
FLATHEAD	Redwing	6/11/56	18:26	365	LASL	Bikini Atoll	11.60	165.45 E	4.6	barge
BLACKFOOT	Redwing	6/11/56	18:26	8	LASL	Enewetak Atoll	11.55	162.35 E	61.0	tower over coral
KICKAPOO	Redwing	6/13/56	23:26	1.49	UCRL	Enewetak Atoll	11.50	162.32 E	91.4	tower over coral
OSAGE	Redwing	6/16/56	01:14	1.7	LASL	Enewetak Atoll	11.53	162.35 E	204.2	airdrop
INCA	Redwing	6/21/56	21:56	15.2	UCRL	Enewetak Atoll	11.62	162.28 E	61.0	tower over coral
DAKOTA	Redwing	6/25/56	18:06	1100	LASL	Bikini Atoll	11.60	165.45 E	0.0	barge
MOHAWK	Redwing	7/2/56	18:06	360	UCRL	Enewetak Atoll	11.50	162.30 E	91.4	tower over coral
APACHE	Redwing	7/8/56	18:06	1850	UCRL	Enewetak Atoll	11.67	162.20 E	0.0	barge over MIKE crater
NAVAJO	Redwing	7/10/56	17:56	4500	LASL	Bikini Atoll	11.65	165.38 E	4.6	barge
TEWA	Redwing	7/20/56	17:46	5000	UCRL	Bikini Atoll	11.67	165.33 E	4.6	barge
HURON	Redwing	7/21/56	18:16	250	LASL	Enewetak Atoll	11.67	162.37 E	0.0	barge
YUCCA	Hardtack I (Operation Newsreel)	4/28/58	02:40	1.7	DOD	97 km W Bikini	12.62	163.02 E	26200.0	air burst from free balloon over water

Table 2. (Continued)

Shot name	Operation	Date (GCT)	Time (GCT)	Yield (kt TNT equivalent)	Sponsor	General location	Latitude °N	Longitude°	Height of burst (m)	Weapon placement
CACTUS	Hardtack I	5/5/58	18:15	18	LASL	Enewetak Atoll	11.55	162.35 E	0.9	surface burst from platform on coral
FIR	Hardtack I	5/11/58	17:50	1360	UCRL	Bikini Atoll	11.68	165.27 E	3.0	barge
BUTTERNUT	Hardtack I	5/11/58	18:15	81	LASL	Enewetak Atoll	11.33	162.35 E	3.1	barge
KOA	Hardtack I	5/12/58	18:30	1370	LASL	Enewetak Atoll	11.67	162.20 E	0.9	surface burst from 3 m deep tank of water on coral
WAHOO	Hardtack I	5/16/58	01:30	9	LASL/DOD	Enewetak Atoll	11.33	162.17 E	−152.4	underwater, suspended by cable
HOLLY	Hardtack I	5/20/58	18:30	5.9	LASL	Enewetak Atoll	11.53	162.35 E	4.0	barge
NUTMEG	Hardtack I	5/21/58	21:20	25.1	UCRL	Bikini Atoll	11.48	165.37 E	3.7	barge
YELLOWWOOD	Hardtack I	5/26/58	02:00	330	LASL	Enewetak Atoll	11.65	162.22 E	3.2	barge
MAGNOLIA	Hardtack I	5/26/58	18:00	57	LASL	Enewetak Atoll	11.53	162.35 E	4.2	barge
TOBACCO	Hardtack I	5/30/58	02:15	11.6	LASL	Enewetak Atoll	11.65	162.22 E	0.0	barge
SYCAMORE	Hardtack I	5/31/58	03:00	92	UCRL	Bikini Atoll	11.68	165.27 E	3.5	barge
ROSE	Hardtack I	6/2/58	18:45	15	LASL	Enewetak Atoll	n/a	n/a	4.7	barge
UMBRELLA	Hardtack I	6/8/58	23:15	8	DOD	Enewetak Atoll	11.37	162.22 E	−45.7	underwater, lagoon bottom
MAPLE	Hardtack I	6/10/58	17:30	213	UCRL	Bikini Atoll	11.68	165.40 E	3.5	barge
ASPEN	Hardtack I	6/14/58	17:30	319	UCRL	Bikini Atoll	11.68	165.27 E	3.3	barge
WALNUT	Hardtack I	6/14/58	18:30	1450	LASL	Enewetak Atoll	11.65	162.22 E	2.2	barge
LINDEN	Hardtack I	6/18/58	03:00	11	LASL	Enewetak Atoll	11.53	162.35 E	2.5	barge
REDWOOD	Hardtack I	6/27/58	17:30	412	UCRL	Bikini Atoll	11.68	165.40 E	3.3	barge
ELDER	Hardtack I	6/27/58	18:30	880	LASL	Enewetak Atoll	11.65	162.22 E	2.8	barge
OAK	Hardtack I	6/28/58	19:30	8900	LASL	Enewetak Atoll	11.60	162.10 E	2.0	barge
HICKORY	Hardtack I	6/29/58	00:00	14	UCRL	Bikini Atoll	11.48	165.37 E	3.7	barge
SEQUOIA	Hardtack I	7/1/58	18:30	5.2	LASL	Enewetak Atoll	11.53	162.35 E	2.0	barge
CEDAR	Hardtack I	7/2/58	17:30	220	UCRL	Bikini Atoll	11.68	165.27 E	3.3	barge
DOGWOOD	Hardtack I	7/5/58	18:30	397	UCRL	Enewetak Atoll	11.65	162.22 E	3.7	barge
POPLAR	Hardtack I	7/12/58	03:30	9300	UCRL	Bikini Atoll	11.68	165.25 E	3.6	barge on water over reef
SCAEVOLA	Hardtack I	7/14/58	04:00	0 (safety experiment)	LASL	Enewetak Atoll	11.55	162.35 E	6.1	barge
PISONIA	Hardtack I	7/17/58	23:00	255	LASL	Enewetak Atoll	11.55	162.32 E	2.0	barge
JUNIPER	Hardtack I	7/22/58	04:20	65	UCRL	Bikini Atoll	11.48	165.37 E	3.7	barge
OLIVE	Hardtack I	7/22/58	20:30	202	UCRL	Enewetak Atoll	11.65	162.22 E	2.4	barge
PINE	Hardtack I	7/26/58	20:30	2000	UCRL	Enewetak Atoll	11.65	162.22 E	2.4	barge
TEAK	Hardtack I (Operation Newsreel)	8/1/58	10:50	3800	DOD	Johnston Island area	16.73	169.53 W	77000	high altitude burst from Redstone missle
QUINCE	Hardtack I	8/6/58	02:15	0	UCRL/DOD	Enewetak Atoll	11.55	162.35 E	0.9	surface burst from platform on coral
ORANGE	Hardtack I (Operation Newsreel)	8/12/58	10:30	3800	DOD	Johnston Island area	16.35	169.53 E	43000	high altitude burst from Redstone missle
FIG	Hardtack I	8/18/58	04:00	0.02	UCRL/DOD	Enewetak Atoll	11.55	162.35 E	0.5	surface burst from platform on coral
ADOBE	Dominic	4/25/62	15:45	190	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
AZTEC	Dominic	4/27/62	16:01	410	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean

Table 2. (Continued)

Shot name	Operation	Date (GCT)	Time (GCT)	Yield (kt TNT equivalent)	Sponsor	General location	Latitude °N	Longitude°	Height of burst (m)	Weapon placement
ARKANSAS	Dominic	5/2/62	18:01	1090	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
QUESTA	Dominic	5/4/62	19:04	670	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
FRIGATE BIRD	Dominic	5/6/62	23:30	n/a	LRL	Pacific Ocean	4.83	149.82 W	n/a	missle launched from Polaris submarine
YUKON	Dominic	5/8/62	18:01	100	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
MESILLA	Dominic	5/9/62	17:01	100	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
MUSKEGON	Dominic	5/11/62	15:37	50	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
SWORDFISH	Dominic	5/11/62	20:02	low	DOD	Pacific Ocean (250 km W of San Diego)	31.24	124.22 W	n/a	underwater burst from antisubmarine rocket
ENCINO	Dominic	5/12/62	17:02	500	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
SWANEE	Dominic	5/14/62	15:21	97	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
CHETCO	Dominic	5/19/62	15:36	73	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
TANANA	Dominic	5/25/62	16:08	2.6	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
NAMBE	Dominic	5/27/62	17:02	43	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
ALMA	Dominic	6/8/62	17:02	782	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
TRUCKEE	Dominic	6/9/62	15:37	210	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
YESO	Dominic	6/10/62	16:01	3000	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
HARLEM	Dominic	6/12/62	15:37	1200	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
RINCONADA	Dominic	6/15/62	16:00	800	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
DULCE	Dominic	6/17/62	16:00	52	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
PETIT	Dominic	6/19/62	15:01	2.2	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
OTOWI	Dominic	6/22/62	16:00	81.5	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
BIGHORN	Dominic	6/27/62	15:19	7650	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
BLUESTONE	Dominic	6/30/62	15:21	1270	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean
STARFISH PRIME	Dominic (Operation Fishbowl)	7/9/62	09:00	1400	DOD	Johnston Island area	16.47	169.62 W	400,000	high altitude from Thor missile
SUNSET	Dominic	7/10/62	16:33	1000	LASL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	airdrop (freefall) over Pacific Ocean
PAMLICO	Dominic	7/11/62	15:37	3880	LRL	Christmas Island area	n/a (~2.0)	n/a (~157 W)	n/a	air (parachute drop) over Pacific Ocean

Table 2. (Continued)

Shot name	Operation	Date (GCT)	Time (GCT)	Yield (kt TNT equivalent)	Sponsor	General location	Latitude °N	Longitude°	Height of burst (m)	Weapon placement
ANDROSCOGGIN	Dominic	10/2/62	16:17	75	LRL	Johnston Island area	13.64	172.19 W	n/a	air (parachute drop) over Pacific Ocean
BUMPING	Dominic	10/6/62	16:02	11.3	LRL	Johnston Island area	14.50	168.25 W	n/a	air (parachute drop) over Pacific Ocean
CHAMA	Dominic	10/18/62	16:01	1590	LASL	Johnston Island area	14.53	108.75 W	n/a	airdrop (freefall) over Pacific Ocean
CHECKMATE	Dominic (Operation Fishbowl)	10/20/62	08:30	low	DOD	Johnston Island area	16.06	169.60 W	10s of kms	high altitude from XM-23 Strypi (Sergeant) missile
BLUEGILL 3 PRIME	Dominic (Operation Fishbowl)	10/26/62	09:59	submegaton	DOD	Johnston Island area	16.40	169.60 W	10s of kms	high altitude from Thor missile
CALAMITY	Dominic	10/27/62	15:46	800	LRL	Johnston Island area	14.52	168.26 W	n/a	air (parachute drop) over Pacific Ocean
HOUSATONIC	Dominic	10/30/62	16:01	8300	LRL	Johnston Island area	13.61	172.22 W	n/a	air (parachute drop) over Pacific Ocean
KINGFISH	Dominic (Operation Fishbowl)	11/1/62	12:10	submegaton	DOD	Johnston Island area	16.10	169.67 W	10s of kms	high altitude from Thor missile
TIGHTROPE	Dominic (Operation Fishbowl)	11/4/62	07:30	low	DOD	Johnston Island area	16.10	169.67 W	10s of kms	high altitude from Nike-Hercules missile

first airdrop of a U.S. thermonuclear weapon was CHEROKEE (Operation Redwing, 20 May 1956), also at Bikini Atoll; it yielded 3.8 Mt. For comparison, the largest above-ground test at the Nevada Test Site was 74 kt (Plumbbob HOOD, 5 July 1957). Fifty percent of the tests in the Marshall Islands were larger than any of the tests at Nevada.

Christmas Island, Johnston Atoll, and other Pacific locations

Thirty-nine nucleai tests were conduced by the U.S. at locations in the mid-Pacific outside of the Marshall Islands. The total explosive yield of those tests equaled 43 Mt. All of the tests at these locations were conducted in 1962 as part of Operation Dominic except for 3 tests in 1958 as part of Operation Hardtack I (Operation Newsreel).

Twelve tests were conducted in the area near Johnston Atoll, an atoll which today remains as a U.S. military installation. The tests near Johnson Atoll were of large yields (see Fig. 1) though all were airbursts. Many of the tests near Johnston were high altitude explosions (greater than 10^4 m); the weapon exploded at the highest altitude (4×10^5 m) was STARFISH PRIME (Operation Dominic, 9 July 1962).

Twenty-four tests were conducted in the area near Christmas Island. Christmas Island, a small atoll in the Line Islands of Kiribati (also known as the Gilbert Islands), is about 3,700 km E of Bikini Atoll and 2,500 km S of Hawaii. All of the Christmas Island tests and all but two of the Johnston Island tests were conducted in 1962 as part of Operation Dominic. All the U.S. tests at Christmas Island were air bursts.

Two of the other three tests conducted in the Pacific Ocean were underwater detonations (WIGWAM and SWORDFISH). The third of that group (FRIGATE BIRD) was launched from a Polaris submarine (depth of firing and altitude of detonation unknown).

Summary statistics of the nuclear tests conducted by the U.S. at its four mid-Pacific test sites are presented in Table 1. A complete listing of the date, time, explosive yield, location and weapon placement for these tests is given in Table 2. Fig. 1 provides frequency distributions of the explosive yields at each of the four mid-Pacific test sites.

CONCLUDING REMARKS

Of the four mid-Pacific test sites, Bikini Atoll had the largest total explosive yield, although the distribution of yields at Bikini was the widest (see Fig. 1). The number of tests that exceeded 1 Mt in yield was 11 at Bikini (45.8%), 7 at Christmas Island (29.2%), 7 at Enewetak Atoll (20.3%) and 5 at Johnston Atoll (41.7%). The 18 tests in the Marshall Islands that were greater than 1 Mt contributed about 95% of the total explosive yield of the Marshall Islands series.

Of interest to physicists and historians is the fission yield of the thermonuclear tests. Those data have not been made available; however, estimates of 50% fission yield for those tests is an assumption which is often used.

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SOME REFLECTIONS ON THE ROLE OF THE SCIENTIFIC ADVISORY PANEL TO THE MARSHALL ISLANDS NATIONWIDE RADIOLOGICAL STUDY

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Abstract—**As a consequence of the U.S. Atomic Weapons Testing Program in the Trust Territory of the Pacific, now the Republic of the Marshall Islands, numerous scientists have advised the Marshallese on matters of radiation and radioactive contamination. Some of the previous advice has appeared to vary or conflict resulting in consequent uncertainty for the people. In a new initiative in 1989, the RMI Government engaged a five member multi-disciplinary Scientific Advisory Panel to oversee the assessment of, and to advise on, the radiological status of the entire nation. The formation of the Panel was accompanied by the establishment of a Resident Scientist position, and ultimately a small scientific team and laboratory on Majuro. The nationwide radiological study was conducted using ground survey methods over the period 1990–1994. Tasks undertaken by the Panel included formulating reasonable objectives for the study and attempting to establish effective communication and understanding of issues with political leaders and RMI Government agencies and people, as well as advising on and monitoring the scientific integrity of the study itself. The attempt was also made to initiate investigations to address matters of concern that emerged. The problem was faced of providing not only technical guidance on radioactivity and radiation measurements, but also explaining the significance of measured values and concepts, such as risk and probability of health effects to a diverse but nontechnical audience, generally across cultural and language barriers. The experience of the Panel in providing advice and guidance to the Republic of the Marshall Islands, while unique in many ways, parallels the difficulties experienced elsewhere in communicating information about risks from radiation exposure.**

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Key words: Marshall Islands; thyroid; health effects; radiation risk

HISTORICAL CONTEXT AND BACKGROUND

Enewetak and Bikini atolls in the northern Marshall Islands were used as bases for a series of nuclear weapons tests conducted by the U.S. over the period 1946–1958. One of these tests, designated Castle BRAVO, which took place on 1 March 1954, deposited heavy radioactive fallout on the islands of Rongelap atoll about 160 km to the east of Bikini, and, at a lower level, on the islands of Utirik further to the east.

About 50 h after the BRAVO detonation, the U.S. Navy removed the 64 Rongelap residents from Rongelap Island and another 18 residents who were visiting Sifo Island, Alinginae Atoll. A further 157 residents were later removed from Utirik Atoll. The Rongelap Island exposed group received external radiation doses estimated to have been about 1.9 Sv and thyroid doses from ingestion of iodines estimated at between about 50 Sv for a 1-y-old child to about 12 Sv for an adult.

Doses to Utirik residents were only of the order of one tenth of those to residents on Rongelap Island, and these residents were returned to Utirik a few months later. Rongelap Islanders did not return to Rongelap until 1957. In March 1958, there were 81 persons there who had been exposed in 1954 on Rongelap or Alinginae, and about another 100 who were not.

The USAEC commissioned Brookhaven National Laboratory's Medical Division to establish a medical follow-up program for the exposed group. Visits continue to be made, with the primary finding being damage to the thyroid gland with, in particular, increased incidence of thyroid nodules. The late appearance of thyroid effects and one case of acute leukemia worried the Rongelap people, as did measurements made on Bikinians who had returned to their atoll after the nuclear tests. These measurements showed somewhat higher than expected body burdens of ^{137}Cs. The Rongelap people therefore abandoned Rongelap again in 1985, and a community has been resident on Majetto Island on Kwajalein Atoll. Resettled Bikinians had been removed to Kili Island in 1978.

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A detailed assessment of the radiological status of the Northern Marshall atolls was made by the U.S. Department of Energy (DOE) in 1977–1978. External radiation levels were measured using airborne (helicopter) instruments (EG&G 1981), and soil and other samples were taken for radioactivity analyses (Robison et al. 1981a). From these measurements, which were reported to the Marshallese people (DOE 1982), dose estimates were made for resident populations (Robison et al. 1981b; Noshkin et al. 1981; Robison et al. 1982).

A study of the incidence of thyroid nodules in Marshallese by place of residence in 1954, published in 1987 (Hamilton et al. 1987), appeared to show an elevated incidence of thyroid nodules outside the region that had been surveyed by the U.S. DOE in 1977–1978. This increased distrust of the DOE, and DOE survey work, led to calls for further monitoring.

NATIONWIDE RADIOLOGICAL STUDY

Under Section 177 of the Compact of Free Association (U.S. Public Law 99-239) between the Republic of the Marshall Islands and the United States, funding was established to compensate displaced atoll communities and, through a Nuclear Claims Tribunal, to provide for compensation of any individuals who had suffered personal injury or loss of or damage to property as a result of the testing program. Some limited funding was also provided under the Compact for further radiological studies. In 1989 the Marshall Islands Government resolved to undertake further investigations into the extent of residual fallout and the effects on the Marshallese population. These new radiological studies were at least partly motivated by the wish to have evidence that could support or refute claims for compensation made to the Nuclear Claims Tribunal.

A five member Scientific Advisory Panel comprising two health physicists, two radiation biologists and a radiation geneticist, together with a Resident Scientist, were selected by the Office of the Chief Secretary and the Nuclear Claims Tribunal. Of those selected only the Resident Scientist (SLS) was a U.S. citizen, to avoid any association with previous advice from U.S. agencies. Subsequently the Panel recommended that an environmental radioactivity laboratory be constructed in Majuro to serve as a base for the resident scientific survey team. The laboratory, which began operation in 1991, had radiochemical facilities and gamma and alpha counting equipment.

At the first meeting of the Advisory Panel in November 1989, a set of objectives for the study was defined that changed only slightly subsequently. Briefly, these were as follows:

1. To establish the extent of fallout radioactivity throughout the nation and determine the past and present levels;
2. To reassess the radiological conditions of Rongelap and Utirik Atolls;
3. To advise on effects associated with the derived radiation exposure levels;
4. To advise and assist the Nuclear Claims Tribunal in the determination of whether an individual's particular disease, illness or property damage was caused by the US Nuclear Testing Program or provide other information and/or advice which may be defined at a later date; and
5. To provide information to the public of the Marshall Islands which explains and clarifies the findings of this study and to participate in educational activities concerning radiation and radioactivity, and its potential health and environmental effects.

The Scientific Advisory Panel to the Nationwide Radiological Study followed a succession of largely atoll-specific advisory committees, and indeed operated contemporaneously with some individual advisers and a Rongelap advisory committee. It did, however, for the first time have oversight of a major radiological study involving the whole of the Marshall Islands. The study therefore necessarily overlapped in scope with prior studies. The findings were reported in brief to the RMI Government (Simon and Graham 1994) and are presented in detail in this issue (Simon and Graham 1997). This paper reflects on the role of the multi-disciplinary Advisory Panel and, in particular, experiences of the Panel in attempting to establish effective communication and understanding of issues with the RMI Government, government agencies and Marshallese people.

Given the budgetary constraints, planning proceeded with a ground-based radiological survey in mind, using *in-situ* gamma-spectrometry to determine the concentrations of gamma emitting radionuclides (principally ^{137}Cs) in the soil. The logistical problems associated with surveying all significant islands of all atolls by small survey parties resulted in the study extending over several years. As much as was possible, Marshallese were employed as staff to support survey work and to provide support laboratory services in an endeavor both to broaden local involvement in the study and assist in providing local employment and training opportunities. The sample analysis and counting was all undertaken at the RMI laboratory in Majuro. It was hoped that this involvement, and the fact of the study base being within the Marshall Islands, would aid ownership both of the study and its results by the Marshallese people.

THE PANEL'S WIDER ROLE

Apart from its major role in advising on the objectives of the nationwide study, the scope and methodology of measurements, and monitoring the study's scientific integrity and progress, attempts were made at an early stage to meet and explain the objectives of the study to the public and government officials. Meetings were held with the RMI Nuclear Claims Tribunal, the Cabinet, Nitijela (parliament), and local press, and public meetings were convened at Majuro, Ebeye and Mejatto. (Majuro, and Ebeye island on Kwajalein Atoll are the largest centers of population, and part of the Rongelap community is resident on Mejatto island, also in Kwajalein Atoll.) These meetings had a common purpose of introducing the Panel and Resident Scientist to the different groups and outlining the study objectives and types of information that would be obtained. The public meeting in Majuro, in particular, was poorly attended, although the session was videotaped and aired at least twice on local television. Meetings of this type did not appear to be particularly effective for communicating an understanding of radiation issues, such as the significance of radioactivity or exposure levels. The Marshallese people are aware of many scientists having come and gone in the past, and it appeared essential for effective communication that a base of adequate time, repeated visits and a degree of familiarity was established for there to be trust and acceptance. For people with very limited understanding of radioactivity and radiation physics, and no words to express such concepts in their language, trust in the messenger may be more important than the message for its acceptance. In the outer atolls in particular, social interaction with visitors is of importance, as is respect shown to residents as owners of the atoll. Individual panel members accompanied ground survey parties on visits to five of the outer atolls.

Recurring questions that arose at these meetings were the background and expertise of the panel members, the time scale of the study (particularly having in view its perceived link to the Nuclear Claims Tribunal compensation strategy and payments), and whether the money available was adequate for the purpose of a comprehensive study. The latter question arose against the background of the 1977–1978 DOE study of the northern Marshalls for which the costs were very much greater. A more specific concern raised at Mejatto was that the continuing late presentation of thyroid nodules was related to current levels of contamination rather than exposure in 1954. The development of late effects clearly engendered anxiety about present contamination.

A continuing dialogue with the Nuclear Claims Tribunal was held throughout the course of the study. Two significant areas of concern on which the Tribunal requested advice were conditions which could be presumed to be caused by radiation exposure and a mechanism by which compensation could be awarded for claims on land contamination. Though the Nuclear Claims Tribunal requested detailed advice and guidance, in the end few if any of the recommendations of the Panel were implemented. In particular, the list of compensable medical conditions decided upon by the Claims Tribunal was more expansive than was suggested by the Panel as having firm evidence as likely radiogenic conditions. Other suggestions by the Panel to use probability of causation methods to determine financial awards and a plan to develop equitable compensation for "land damage" (principally contamination) were also not adopted.

One of the reasons underlying the establishment of the Nationwide Radiological Study was the report by Hamilton et al. (1987) that there is pronounced heterogeneity of the prevalence of thyroid nodules in the Marshall Islands among those living during the nuclear test period, with prevalence varying with distance from Bikini. As an extension of the radiological monitoring of all atolls and islands, the Panel proposed a further study to test Hamilton's hypothesis and seek to establish whether causes other than radiation might be contributing to an apparently high incidence of thyroid nodules and cancers in the Marshallese population. The study proposed was an investigation of the prevalence of benign thyroid nodules, thyroid cancer and hypothyroidism with atoll of residence during the weapons test program, and comparison with prevalences of these conditions with atoll of residence in a control population born after radioiodine from the tests had decayed. Establishing this study met with considerable difficulties in acceptance, as well as logistics, with health officials originally perceiving it as an unnecessary expenditure of funds, which, in their view, could have been expended more usefully in providing other health services, and some resistance from others based on a perception of the Marshallese people being further treated as guinea pigs for scientific studies. Even more remarkable was that some health officials viewed a comprehensive thyroid study as potentially disproving any association between thyroid disease and radiation exposure, thus eliminating hopes for additional compensation. In spite of these difficulties, during 1993–1994, over 6,500 Marshallese were examined for evidence of thyroid abnormalities. Though data analysis is not yet complete enough to allow conclusions to be drawn, the medical findings have been described (Takahashi et al. 1997) and appear to indicate disease rates that may be unusually high and warrant further examination.

Another area proposed for investigation arose from a concern of the Rongelap community that children resident on Rongelap on their return to the island might ingest sufficient plutonium in soils to receive appreciable doses from this route. On the face of it, taking account of measured soil concentrations and likely intakes, it appeared unlikely to be a major contributor to exposure. However, consideration was given to carrying out measurements of infant soil ingestion rates for coralline soils and the general living conditions of the outer atolls (Simon et al. 1994). Some investigations carried out in conjunction with the Rongelap Resettlement Project had included exhuming, with the agreement and cooperation of community members, the bones of some former residents of Rongelap, and assessing the plutonium content of bone samples. The extremely low measured concentrations gave additional confidence that ingestion of plutonium was not a significant source of exposure (Franke et al. 1995). Ultimately, for logistical reasons the infant soil ingestion study was not able to be performed, but it was concluded that the intake of actinides by soil ingestion was not likely to be more than a minor contributor to infant doses.

PRESENTING THE STUDY FINDINGS

A presentation of the findings of the study was made to the President and Cabinet by the Panel and Resident Scientist in December 1994. A presentation was also made to the Nuclear Claims Tribunal, and copies of the Summary Report (Simon and Graham 1994) were made widely available. The local press gave extensive coverage to the results and conclusions. Distribution of the Summary Report was followed by individual atoll community reports in both English and Marshallese. In a foreword to the Summary Report the Panel wrote: "We believe that the current levels of radioactive contamination of the territory of the Marshall Islands pose no risk of adverse health effects to the present generation. Similarly, on the basis of current genetic knowledge, we judge the risk of hereditary diseases to future generations of Marshallese to be no greater than the background risk of such diseases characteristic of any human population.

Four atolls have been identified where exposure rates are elevated to the extent that remedial actions are indicated for some islands.

There are indications that the prevalence of thyroid disease in the Marshall Islands may be higher than in some other countries. While there is a well recognized association with exposure to fallout radio-iodines, which has given rise to elevated rates in the 1954 Rongelap and Utirik populations, the amount of variation in prevalence throughout the Marshalls, and the overall level, remains to be determined. The conduct of the thyroid study therefore has the potential to give important new information on the rate of thyroid disease in the Marshall Islands, as well as allowing inferences to be drawn on the extent to which fallout radio-iodines may have contributed."

In the Summary Report attempts were made to respond with simple explanations to questions commonly asked and to set the exposure levels reported in an understandable context. Some Marshallese do not accept comparisons made between derived exposure levels and background radiation rates, which are commonly used as a basis of comparisons in other contexts. This is because they adopt the view that exposure from radioactive fallout is all additional to the assumed low natural levels that they and their ancestors have experienced. The comparison between radiation exposure levels and risks incurred with smoking and the risks this habit carries, was therefore emphasized. Smoking one pack of cigarettes a day carries a risk more than 100 times greater than an exposure level of 1 mSv y^{-1} (100 mrem y^{-1}). The impact of this comparison, however, may have been only poorly appreciated as many Marshallese may not be well informed on the causative association between smoking and adverse health outcomes. The level of natural background radiation in the Marshall Islands, however, was also referred to. For atolls it has commonly been assumed in the past that natural radiation exposure arises almost entirely from cosmic rays, because of the absence of significant terrestrial radioactivity and radon. The study by Noshkin et al. (1994), however, on dietary intake of ^{210}Po and ^{210}Pb from sea foods, indicates annual doses from this source of about 2 mSv in the Marshalls. Annual doses from natural sources in the Marshalls may therefore be little different from many continental areas. The amount of seafood in diet could give rise to greater variation in annual doses than the 1 mSv y^{-1} accepted as a basis for Rongelap resettlement. This comparison caused problems of acceptance by the Marshallese community because the background exposure rates cited were significantly different from what had been previously understood.

As in other communities there was again the perceptual difficulty of interpreting any limit proposed or set as anything other than a boundary between "safe" and "unsafe," rather than as a point on a scale of risk. Attempts were therefore made in discussion to indicate that the benefits of resettlement of a community expected to incur dose rates of a few mSv y^{-1} would far outweigh the risk, if there was a genuine desire to return. Reluctance or tardiness in taking steps towards resettlement may, however, be related not only to anxieties about risk but also to compensation eligibility and magnitude.

The findings of the Nationwide Radiological Study (Simon and Graham 1994) summarized in the Panel comments above, and given in more detail elsewhere in this issue (Simon and Graham 1997), were not universally accepted. Indeed, a Nitijela resolution (Nitijela 1995), to which the Panel responded (McEwan 1995), was both formulated and passed, rejecting the findings. This resolution, in its reasons for rejection and explanations, showed obvious misunderstanding of the methods and results of the study and reflected a lack of effort and perhaps willingness on the part of the proposers in attempting to study and understand the results. This negativity may have arisen from a sense of hurt, or wish for compensation, from the nuclear tests and fallout, which in the perception of the resolution proposers did not appear to be sufficiently supported or corroborated by the study findings, or from a feeling of deep and long standing distrust of any scientific evaluation of the situation in the Marshall Islands. As with the Chernobyl affected population in the former USSR, there is a widespread belief that most illness is traceable to radiation effects, which may make any discussion on scientific facts difficult, if not impossible.

Two persistent rumors in the Marshalls are the attribution of poor arrowroot crops and the delivery of "jelly babies" to radiation effects. The apparent poor productivity of arrowroot after returns to formerly evacuated areas has been traced to the lack of cultivation of the soil over the intervening years, and perhaps also to loss of knowledge of cultivation requirements (Spennemann 1992). "Jelly babies" are grossly deformed, sometimes limbless fetuses which have been born not only in the Marshalls but also in French Polynesia (Sunday Times Star 1995) and have been considered to be the result of exposure to radiation. Possible causes are viral or other infections, toxic fish or other poisoning, or genetic causes.

CONCLUSIONS

It is the Panel's view that the Nationwide Radiological Study has provided a comprehensive and soundly based survey of the radiological status of the Marshall Islands. However, a less successful aspect of the study has been the ability to convey an understanding and perspective of the findings to the RMI government and people. It would be most regrettable if, after concluding this major study, the results were not incorporated in constructive future planning, or worse, set aside on the flimsy grounds of not satisfying preconceptions or falling in line with political agendas.

The findings of the study are consistent with recent reports from Lawrence Livermore National Laboratory (LLNL) for Bikini Atoll (Robison et al. 1995), not only in measured soil and plant concentrations but also in the assessment of doses to resident populations, although the dietary models used were developed quite independently. The findings of both the Nationwide Radiological Study and the LLNL reports were endorsed by an IAEA international Advisory Group which met in December 1995 and reassessed options for intervention measures on Bikini Island (IAEA 1996).

It is perhaps not an uncommon experience of advisory groups that political constraints, lack of cooperation and support, and lack of acceptance of the findings can lead to a certain disillusionment with participation in such groups. While the experience of the RMI's Scientific Advisory Panel was unique in many respects, the difficulties in communicating information about risks from radiation exposure, and the conflict with political strategies, are common to experience elsewhere.

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BEYOND LINEARITY

Dear Editors:

In a recent Forum article, Patterson provides convincing scientific evidence for a re-examination of the linear no-threshold (LNT) model in setting standards for radiation protection (Patterson 1997). However, the LNT debate goes beyond science.

Economic considerations also provide a forceful argument. Regulatory compliance costs too much. The LNT model is used widely to predict the reduction in risk for a given reduction in dose. However, there is little epidemiological evidence to show that reducing exposure to ionizing radiation leads to a reduction in health risk. Regulations aimed at reducing occupational safety and health risks have imposed compliance costs of over $9 billion annually for negligible risk-reduction benefits (Hahn and Hird 1991).

Perhaps public relations fallout is the most compelling reason to re-examine LNT. Support of the LNT theory and the idea that any radiation dose is potentially harmful has resulted in a public relations nightmare for the nuclear industries (including medical applications of radiation). Unwavering support of the LNT theory has made it almost impossible to respond effectively to alarmists' claims that any dose of radiation is dangerous. Public "outrage" from dangerous radiation has led to over-regulation of nuclear industries resulting in billions of dollars in compliance costs.

Opponents of the LNT model need to move the debate beyond scientific arguments. If the LNT model is unacceptable, what should be the basis for standards setting? Alternative models (e.g., quadratic, linear-quadratic and threshold models) to predict risk at low dose may prove to be equally unacceptable. All biologically plausible predictive models have significant uncertainties and cannot be readily distinguished from one another in the low dose range. Perhaps consideration should be given to model-independent strategies to set standards. One possible strategy involves a dosimetric approach. Exposure limits might be based on the average natural background level to the U.S. population (~3 mSv y^{-1}). Epidemiological studies of populations around the world exposed to background levels several times the U.S. average have not detected an increase in health effects due to natural background radiation (NAS 1990). Another strategy is based on an epidemiological approach. After more than 50 years of epidemiological observations, 100 mSv is the lowest dose which has been consistently associated with a statistically significant radiogenic risk. Using 100 mSv as a lifetime (70 y) dose limit and correcting for the lower dose rate associated with environmental exposures (DREF = 2), a public exposure limit of 2–3 mSv y^{-1} is calculated. These are simple, straightforward methods to establish public exposure limits. Such methods are rational and may be readily explained to the public.

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RESPONSE TO MOSSMAN

Dear Editors:

Mossman correctly points out that the process for setting standards for radiation protection goes beyond science. He mentions economics and public perception as other ingredients; and we all know this to be true.

However, in my view, the standard setting process must first be scientifically based on a consideration of all pertinent data on human exposure to radiation. Unfortunately, as my Forum article shows, this is not now the case.

Standard setting groups have selected, manipulated and even overlooked human data, simply to conform to an assumptionfor which scientific evidence is scanty at best. This practice is common, and in my Forum article I was able to give only a few of many examples.

Nowhere, to my knowledge, have standards been set using a "best fit" to the data. Instead they are based on a scientifically unjustified downward extrapolation using a risk-response curve whose origin is either at 0.0 (absolute risk model) or at 1.0 (relative risk model), and whose slope is everywhere positive. This procedure guarantees that all derived risks will be positive.

First, give proper scientific scrutiny to all the data; second, come to scientific consensus on what the data have to say about human response to radiation exposure; only then consider other factors which bear on the standards themselves.

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