The material flow of radioactive cesium-137 in the U.S. 2000

Takeshi Okumura

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List of acronym

AEC	U.S. Atomic Energy Commission (the precursor to the NRC)
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
GTCC	Greater than Class C
IAEA	International Atomic Energy Agency
INEEL	Idaho National Engineering and Environmental Laboratory
NPT	Nuclear Technology Products
NRC	U.S. Nuclear Regulatory Commission
NRDC	Natural Resource Defense Counsel
PSI	Product Stewardship Institute

1. Introduction

The purpose of this paper is to describe the life cycle of radioactive cesium-137 and to analyze its material flow in the U.S. It aims to show how much cesium-137 is produced, fabricated, used, and disposed of and how it is done.

Incidents involving commercial radioactive sources that have fallen out of control and entered into the public domain have been reported over the years. In some cases, sources entering into scrap processing facilities, have contaminated steel mills, resulting in millions of dollars in cleanup costs (Lubenau and Yusko, 1995). In other cases, sources have been breached, exposing the public to harmful radiation. In 1987, a sealed source containing cesium-137 was taken from abandoned medical equipment by scrap metal collectors. The sealed capsule was opened and people played with it, rubbing it on their bodies as "carnival glitter." This case resulted in four deaths, one arm amputation and 50 hospitalizations or placements in a temporary dispensary under medical care. (Petterson, 1988) In the wake of the terrorist attack on September 11th, 2001, there is a further security concern over radioactive materials. Traditionally, most commercial radioactive materials are managed less stringently than uranium or plutonium, since these commercial radioactive materials cannot be sources of nuclear weapons. However, the event raised the concern that such commercial radioactive materials could cause social disorder through their use in terrorist weapons, such as dirty bombs. The U.S. government and the International Atomic Energy Agency (IAEA) had shown their interest in more a stringent management system for commercial radioisotope materials and their plans were accelerated by the incident. Among these commercial radioactive materials, cesium-137 is one of those generating the most concern because of its beta and gamma emissions (gamma emission through its transitional daughter isotope barium-137m), large amount of radioactivity, and relatively long half-life (Ferguson, Kazi and Perera, 2003).

While these problems are more widely discussed than ever, only a little is known about the big picture. Pieces of information are owned by different parties concerned with different product life stages—such as governmental agencies, manufactures, waste management site operators—and these parties have different interests. Each has good knowledge of its own sector, but these pieces of information have not been integrated. This study aims to collect these pieces of information and to construct the big picture of cesium-137-related activity in the U.S. The year 2000 is taken as a sample year and information is gathered mainly by interviews with related parties. Where the actual figure is not available, an estimated figure from available information is used. Where possible, figures for a couple of years around 2000 are also shown to see temporal fluctuation. The main purpose of this study is an initial characterization of cesium-137 flow, for which ±50% for each flow is suggested as the margin of error. (Graedel et al 2002).

2. Cesium-137: Overview

2.1. Properties of cesium

Cesium is a soft, shiny, gold-colored metal. It reacts rapidly with oxygen or water. Its melting point is 301.55°K (28.4°C or 83.1°F) and boiling point is 951.6°K (678.5°C or 1253.2°F). Cesium-133 is the only naturally occurring isotope and is non-radioactive; all other isotopes, including cesium-137, are produced by human activity. (Emsley p.46-47). Among these other isotopes, cesium-137 is the most common and was discovered by Glenn T. Seaborg and Margaret Melhase in the 1930s. Cesium-137 has a half-life of 30.17 years. It emits beta particles and gamma rays when it decays to barium-137m, which then decays to non-radioactive barium. Exposure to cesium-137 will increase the risk of cancer. A very high exposure will bring serious burns and can be fatal. (EPA)

2.2. Regulatory scheme in the U.S.

Since uses of cesium-137 are governed by regulations and the life cycle of cesium-137 is heavily affected by the regulatory management system, the regulatory scheme in the U.S. needs to be discussed here, before moving to the discussion of cesium-137 flow cycle. Currently, radioactive materials are mainly regulated through the Nuclear Regulatory Commission (NRC).

2.2.1 Regulation for radiation protection

"Standards for protection against radiation" are established in the Code of Federal Regulation (CFR) 10 Part 20. Part 20.1201 sets the occupational dose limit for adults as 5rems, with some other specific amounts applicable to certain body parts such as individual organs or eyes. Assuming cesium-137 is the only radioactive material present at the site, the annual limits on intake for cesium-137 to comply with the 5rems limit are listed in Appendix B to Part 20. According to this document, the annual limit on intake by oral ingestion is 100μCi (0.0001Ci) and by inhalation is 200μCi (0.0002Ci). If cesium-137 is taken up through both pathways, total intake will be calculated by means of a weighted average. Each intake amount must be within the appropriate limit, and is then multiplied by its fraction relative to the total intake amount. The annual occupational dose limits for minors are stipulated in Part 20.1207 as 10 percent of that for adult workers.

2.2.2 Regulation for production and use

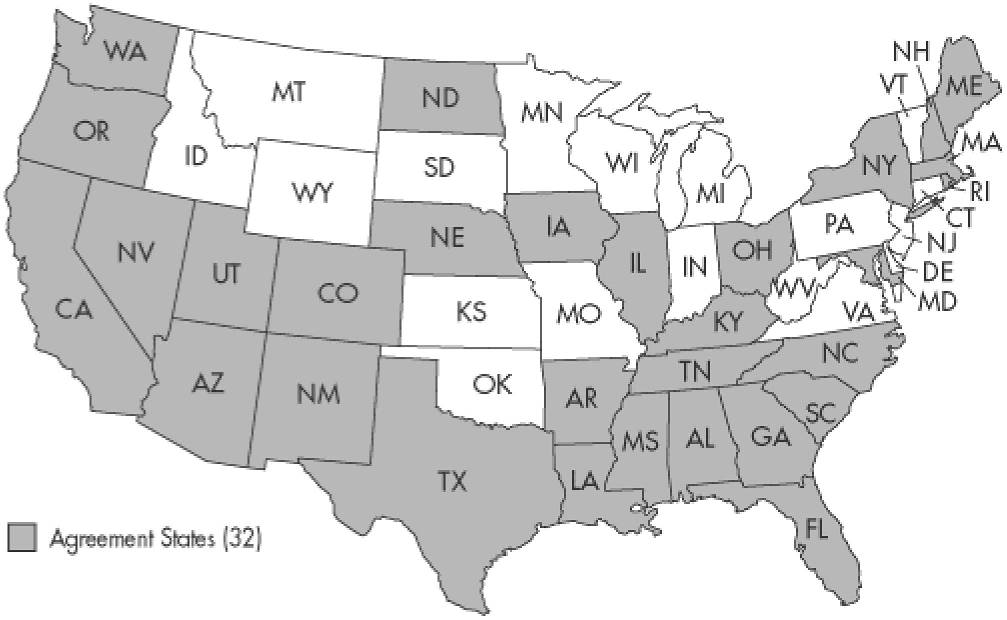
The Atomic Energy Act of 1954, as Amended (P.L. 83-703) says in Sec 2. d. that "[t]he processing and utilization of source, byproduct, and special nuclear material must be regulated in the national interest…" and establishes the Atomic Energy Commission (AEC), which was the precursor to the NRC, in later sections. The detailed definition of each type of material is given in Table 1 below.

Table 1. Definition of radioactive materials

	Definition	Source
Byproduct material	e. The term "byproduct material" means (1) any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material, and (2) the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content.	Atomic Energy Act of 1954, as Amended (P.L. 83-703) Sec. 11. Definitions.
Source material	z. The term "source material" means (1) uranium, thorium, or any other material which is determined by the Commission pursuant to the provisions of section 61 to be source material; or (2) ores containing one or more of the foregoing materials, in such concentration as the Commission may by regulation determine from time to time.	Atomic Energy Act of 1954, as Amended (P.L. 83-703) Sec. 11. Definitions.
Special nuclear material	aa. The term "special nuclear material" means (1) plutonium, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the Commission, pursuant to the provisions of section 51, determines to be special nuclear material, but does not include source material; or (2) any material artificially enriched by any of the foregoing, but does not include source material.	Atomic Energy Act of 1954, as Amended (P.L. 83-703) Sec. 11. Definitions.

The same act also grants regulatory autonomy to states that enter into an agreement with the AEC. States to which this authority is granted are known as "Agreement states" and others are designated "Non-agreement states". Sec. 274.d. of the act says that a state and the AEC can enter into an agreement if the governor of the state certifies that the state has a program for the control of radiation hazards that is adequate to protect the public health and safety and the AEC finds this program compatible with its own. As of 2001, 32 states were agreement states, and these states are listed in Figure 1 below (currently, the agreements are between the NRC and the states).

Figure 1. NRC Agreement State



Note: The State of Oklahoma became an Agreement State in September 2000.
Alaska and Hawaii are not Agreement States.

Source: U.S. Nuclear Regulatory Commission, 2001 *Information Digest 2001 Edition* NUREG 1350, Vol. 13

Since the AEC was abolished and "all the licensing and related regulatory functions" of the AEC were transferred to the NRC by Sec. 201 (f) of the Energy Reorganization Act of 1974 (P.L. 93-438), radioactive materials discussed earlier are currently either regulated by the NRC (non-agreement states) or by the state governments (agreement states).[1]

Assuming that agreement states have compatible programs, the regulation scheme of the NRC should be examined here. Details of the NRC's organization and its regulatory scheme are stipulated in Title 10 of the CFR. In the Atomic Energy Act of 1954, as Amended (P.L. 83-703), cesium-137 is categorized under "byproduct materials" and the licensing activity of such materials is regulated in Part 30 to 36, 39 of 10 CFR. As listed in Table 2 below, Part 30 provides basic information about licensing, Part 31 provides information about general licenses, while Parts 32 to 36 as well as Part 39 provide

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[1] The complete texts of those regulations are available on *Nuclear Regulatory Legislation: 107th Congress; 1st Session* (NUREG-0980, Vol. 1 & 2, Num. 6) at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0980/

information about a specific license for particular uses.

Table 2. Title of 10 CFR Part 30-39

Part No.	Title
Part 30	Rules of general applicability to domestic licensing of byproduct material
Part 31	General domestic licenses for byproduct material
Part 32	Specific domestic licenses to manufacture or transfer certain items containing byproduct material
Part 33	Specific domestic licenses of broad scope for byproduct material
Part 34	Licenses for radiography and radiation safety requirements for radiographic operations
Part 35	Medical use of byproduct material
Part 36	Licenses and radiation safety requirements for irradiators
Part 37,38	*DO NOT EXIST
Part 39	Licenses and radiation safety requirements for well logging

Part 30.3. reads "[e]xcept for persons exempt as provided in this part and part 150 [which is about Agreement States, etc] of this chapter no person shall manufacture, produce, transfer, receive, acquire, own, possess, or use byproduct material except as authorized in a specific or general license issued pursuant to the regulations in this chapter." There are three licensing categories: general, specific, and exempt. Every activity involving byproduct material is covered under one of these categories, based on the type of people involved, the type of material/device, and the type of application. Part 30.31 says "…a specific license [is issued] to a named person who has filed an application…", while "[a] general license…is effective without the filing of an application with the Commission or the issuance of a licensing document to a particular person..." Therefore, people who use generally licensed devices do not need to file an application with the NRC or a state government; they may simply buy and use the devices. With a specific license, people can use the devices for the uses and up to the maximum amount of sources stipulated in individual licenses.

The basic scheme of the regulation is that people have to apply for a specific license, unless conditions for a general license and/or exemption are met. The requirement becomes stricter with the potential hazard of the activity, in the following order: exemption, general license, specific license. Appendix D shows licensing regulations about byproduct materials, excerpted from 10CFR.[2] If the conditions in the list are met, the activity is eligible for exemption or a general license. The regulatory scheme for cesium-137 by

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[2] 10CFR is available at http://www.nrc.gov/reading-rm/doc-collections/cfr/

device type and activity is summarized in Table 3.

Table 3 Regulatory scheme for cesium-137

	Manufacture / initial transfer	Receive / possess / use / transfer / acquire	Own	Dispose	Import / Export	Note
Devices/sources less than 10µCi	Specific license	Exemption	Exemption	License under 10CFR Part 61	License under 10CFR Part 110	
Devices designed and manufactured for the purpose of detecting, measuring, gauging or controlling thickness, density, level, interface location, radiation, leakage, or qualitative or quantitative chemical composition	Specific license	General license	General license			Devices containing at least 10mCi of cesium-137 needs registration. (§ 31.5 (c) (13) (i))
Other devices	Specific license	Specific license	General license			

2.2.3 Regulation for import/export

The import and export of nuclear materials is regulated under 10CFR Part 110. Licenses for import and export are separated from those for production and use, but the licensing scheme is similar. There are specific and general licenses; specific licenses require the filing of an application with the NRC or state government, and general licenses do not. For exports, cesium-137 is under general licensing except for shipments to embargoed countries: Cuba, Iran, Iraq, Libya, North Korea and Sudan. For imports, if the importer has a proper license or an exemption from license to possess the material, a general license for import is issued.

2.2.4 Regulation for disposal

Radioactive wastes are divided into two groups, high-level waste and low-level waste. Detailed definitions according to regulatory documents are listed in Table 4. So far as cesium-137 is concerned, those in irradiated nuclear fuel (spent fuel) is categorized as high-level waste and others are categorized as low-level waste.

Table 4. Definition of High-level and Low level Waste

	Definitions in regulations	Source
High-level waste	(1) Irradiated reactor fuel, (2) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted.	10 CFR PART 60 -- Disposal of High - Level Radioactive Wastes in Geologic Respositories §60.2 Definitions
	(1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; (2) Irradiated reactor fuel; and (3) Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.	10 CFR PART 63 -- Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada § 63.2 Definitions
Low-level waste	[R]adioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or byproduct material as defined in section 11e.(2) of the Atomic Energy Act (uranium or thorium tailings and waste).	10 CFR PART 61 -- Licencing Requirements for Land Disposal of Radioactive Waste §61.2 Definitions

Disposal of high-level waste is regulated under 10 CFR, Parts 60 and 63, and it is to be disposed of in geologic repositories. Part 60 stipulates geologic repositories in general and Part 63 stipulates geologic repositories in Yukka Mountain, Nevada. However, these repositories are not in operation now and high-level wastes are stored and awaiting final disposal.

Low-level waste is further classified according to its activity in 10 CFR, Part 61.55. The classification is done by concentration and that of cesium-137 is given in Table 5. Class A is least radioactive and radioactivity increases as the classification increases from A to GTCC. Cesium-137 is usually classified in Classes A-C, but some sources used in irradiators fall in GTCC (Ferguson, Kazi and Perera, 2003; Kirk, 2001)

Table 5. Classification of cesium-137 low-level waste

Class	Concentration(Ci/m^3)
Class A	Less than 1
Class B	1 to 44
Class C	44 to 4,600
Greater than Class C	More than 4,600

Source: 10 CFR, PART 61 -- Licensing Requirements for Land Disposal of Radioactive Waste
§61.55 Waste classification

Disposal of low-level waste is regulated under 10 CFR, Part 61. Detailed definitions of these wastes by regulatory documents are listed in Table 6. Classes A-C can be disposed of at near-surface disposal sites, while GTCC wastes cannot be disposed of at near-surface disposal sites, unless approved by the NRC. Since the specific requirements pertaining to land disposal sites other than near-surface sites have not yet been developed in the regulations, such facilities do not yet exist. GTCC wastes are supposed to be disposed of in a geologic repository at this moment, once a geologic repository comes into operation.

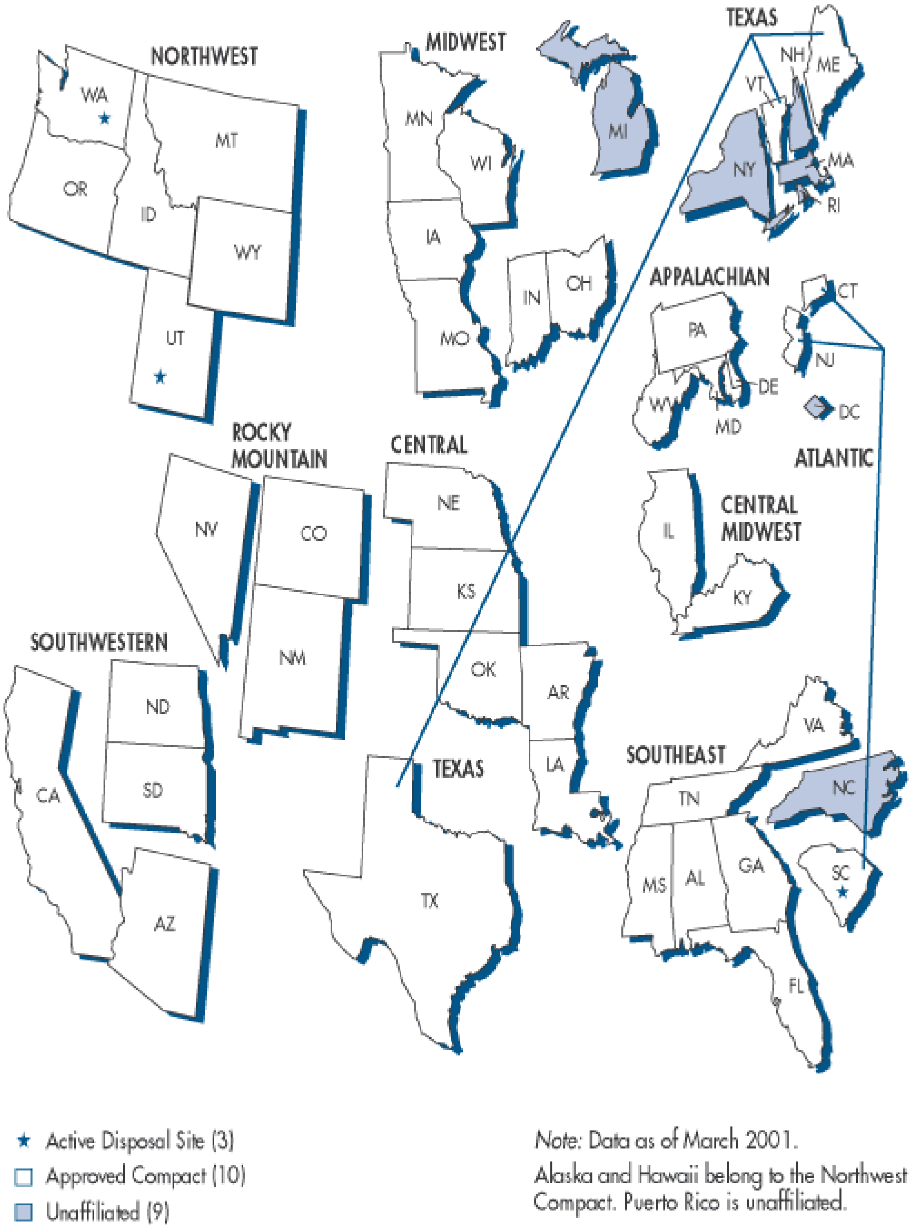
Table 6. Definition of land disposal and low-level waste classification

	Definitions in regulations	Source *
Land disposal	(a) The regulations in this part establish, for land disposal of radioactive waste, the procedures, criteria, and terms and conditions upon which the Commission issues licenses for the disposal of radioactive wastes containing byproduct, source and special nuclear material received from other persons… (b) …The regulations in this part do not apply to-- (1) Disposal of high-level waste as provided for in part 60 or 63 of this chapter; (2) Disposal of uranium or thorium tailings or wastes (byproduct material as defined in § 40.4 (a-1) as provided for in part 40 of this chapter in quantities greater than 10,000 kilograms and containing more than 5 millicuries of radium-226;…	§61.1 Purpose and scope
Near surface disposal	(1) Part 61 is intended to apply to land disposal of radioactive waste... It contains specific technical requirements for near-surface disposal of radioactive waste, a subset of land disposal, which involves disposal in the uppermost portion of the earth, approximately 30 meters. ... Technical requirements for alternative methods may be added in the future.	§61.7 Concepts
Land disposal other than near surface	(b) Disposal site suitability requirements for land disposal other than near-surface (reserved). *Requirements not established yet* (Italic words added by the author)	§61.50 Disposal site suitability requirements for land disposal
Disposal of Class A-C waste	(a) Classification of waste for near surface disposal. *Hereinafter classification of Class A-C follows, and Class A-C are to be disposed of in near surface disposal* (Italic words added by the author)	§ 61.55 Waste Classification
Disposal of GTCC waste	(iv) Waste that is not generally acceptable for near-surface disposal is waste for which form and disposal methods must be different, and in general more stringent, than those specified for Class C waste. In the absence of specific requirements in this part, such waste must be disposed of in a geologic repository as defined in part 60 or 63 of this chapter unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission.	§ 61.55 Waste Classification

* All parts are in 10 CFR PART 61 -- Licensing Requirements for Land Disposal of Radioactive Waste

In addition to those classification based on radioactivity, the Low-Level Radioactive Waste Policy Act of 1980, amended in 1985, stipulates that “Each State shall be responsible for providing, either by itself or in cooperation with other States, for the disposal of [Class A-C waste generated within the State] (Sec. 3 (a)(1))”, and that “the States may enter into such [interstate] compacts as may be necessary to provide for the establishment and operation of regional disposal facilities for low-level radioactive waste (Sec 4 (a)(2))” Therefore, the disposal of low-level waste is bound by class and region. The compacts and the proportion of waste generation by volume by compact in 2000 are shown below.

Figure 2 U.S. Low-Level Waste Compacts



Note: Data as of March 2001.
Alaska and Hawaii belong to the Northwest Compact. Puerto Rico is unaffiliated.

Source: U.S. Nuclear Regulatory Commission, 2001 *Information Digest 2001 Edition* NUREG 1350, Vol. 13

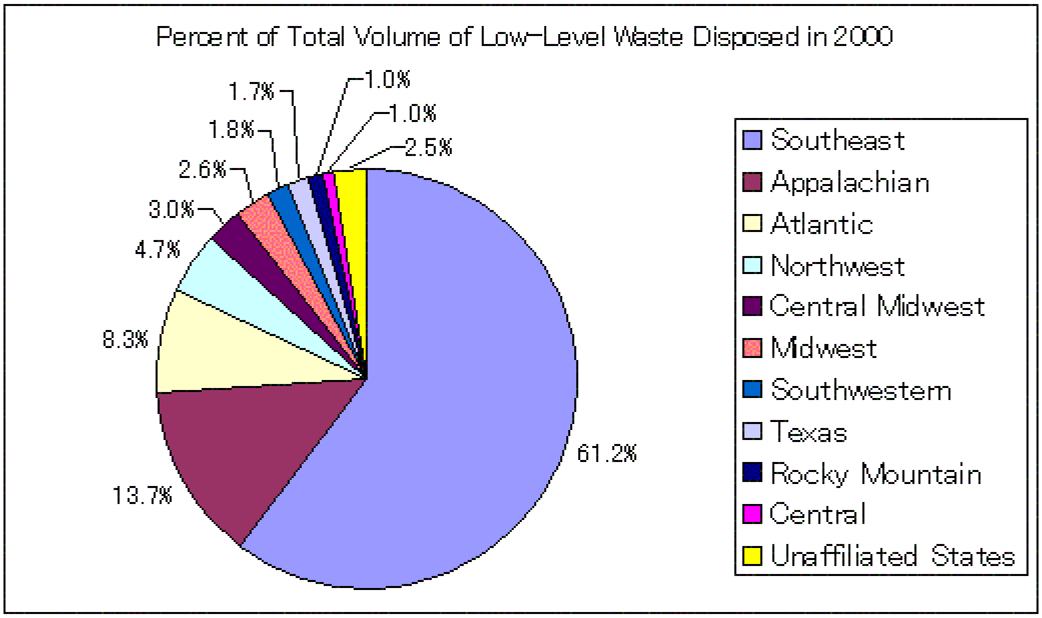
Table 7. Low-Level Waste Compacts

Compact	States in the compact *	Percent of Total Volume of Low-Level Waste Disposed in 2000
Southeast	AL, FL, GA, MS, TN, VA	61.2%
Appalachian	DE, MD, PA, WV	13.7%
Atlantic	CT, NJ, SC	8.3%
Northwest	AL, HI, ID, MT, OR, UT, WA, WY	4.7%
Central Midwest	IL, KY	3.0%
Midwest	IN, IA, MN, MO, OH, WI	2.6%
Southwestern	AZ, CA, ND, SD	1.8%
Texas	ME, TX, VT	1.7%
Rocky Mountain	CO, NV, NM	1.0%
Central	AR, KS, LA, NE, OK	1.0%
Unaffiliated States	DC, MA, MI, NH, NY, NC, PR, RI, ARMY	2.5%

* DC: District of Columbia, PR: Puerto Rico, ARMY: U.S. Army

Source: U.S. Nuclear Regulatory Commission, 2001 Information Digest 2001 Edition NUREG 1350, Vol. 13

Figure 3. Percent of Total Volume of Low-Level Waste Disposed in 2000



In the U.S, currently three low-level waste disposal sites are operating, as shown in Table 8. These sites are Barnwell, Hanford, and Clive. The Barnwell site is located in Barnwell, South Carolina, and run by a company called Duratech. The Barnwell site currently accepts waste of Classes A-C from all states except those in the Rocky Mountain and

Northwest compacts; however, beginning in 2008 the site plans to limit itself to waste from states in the Atlantic compact. The Hanford site is located in Hanford, Washington, and accepts waste of Classes A-C from the Rocky Mountain and Northwest compacts. The Clive site is located in Clive, Utah, and is run by a company called Envirocare. The Clive site accepts only Class A waste from all states. (Ferguson, Kazi, Perera 2003 p41-42, NRC 2001, Hamlin 2003 Feb 24) According to this schedule, most states including those in the Southeast compact - the largest, generating 61.2% of all waste - do not have a place to dispose of wastes other than Class A or sealed sources after the year 2008. This problem may affect the flow of cesium-137.

Table 8 Low-level waste management sites

Site name	State	Status	Operator	Accept waste from	Waste level
Barnwell	SC	In operation	Duratech	All compacts (-2007) Limited to Atlantic compact (2008-)	Class A to C
Richland	WA	In operation	US ecology	Limited to Northwest and Rocky Mountain compacts	Class A to C
Clive	UT	In operation	Envirocare	All compacts	Class A only
Beatty	NV	Closed in 1993			
Sheffield	IL	Closed in 1978			
Maxey Flats	KY	Closed in 1977			
West Valley	NY	Closed in 1975			

(Hamlin 2003 Feb 24)

Disposal options for radioactive materials are summarized in Table 9.

Table 9. Summary of disposal sites

Waste Property		Disposal site				
Level	Class	and disposal near-surface)	and disposa other than ear-surface)	eologic epositories	ucca nountain	esponsible arty
HLW				√	√	Federal Gov.
LLW	GTCC		√	√	√	Federal Gov.
	Class C	√	√	▲	▲	State/Compact
	Class B	√	√	▲	▲	State/Compact
	Class A	√	√	▲	▲	State/Compact

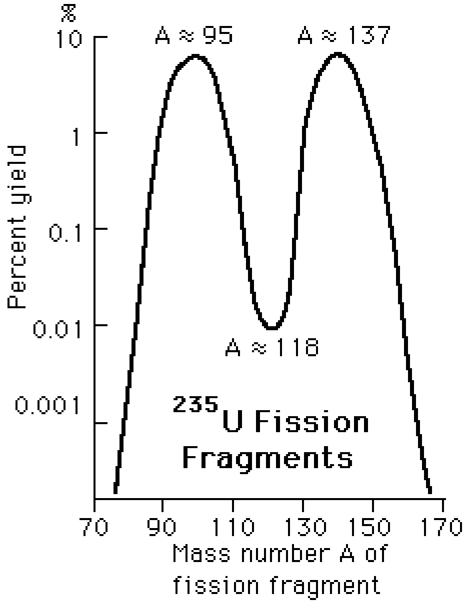
√: accepted ▲: accepted? (over qualified?)

* HLW: High-level Waste LLW: Low-level Waste

2.3. Cesium-137 cycle

Cesium-137 does not exist in the natural environment and is always produced by human activity. Cesium-137 is produced by reactors as a fission byproduct. As a result of fission, a uranium atom splits into two atoms. Figure 4 shows the yield of atoms resulting from the fission of uranium. There are many possible fission fragments produced corresponding to different mass numbers, but the largest yields occur at mass numbers 95 and 137. Therefore, cesium-137 is considered one of the major fission byproducts and remains in spent nuclear fuel. In some cases, cesium-137 is extracted from spent nuclear fuel and treated as a commercial product, while the rest is treated as waste.

Figure 4. ^{235}U Fission fragments



Source: Nave C. 2000 "Fission Fragments" *HyperPhysics*

For production of commercial sources, Russia has by far the largest capacity and almost dominates the current production. Germany, England, and South Africa also seem to have the capacity to produce commercial cesium-137; however, as far as the U.S. market is concerned, sources from these countries have not been reported in interviews with U.S. source fabricators. According to the interviews, in the past year or so the Russian raw material producer entered into the source fabrication business and has been trying to dominate the market. The Russian raw material producer drove the cost of raw material up for other source fabricators, including those in the U.S., and these fabricators are now facing some difficulty with procurement. (Hamlin, October 3, 2003) The produced raw material is then processed by the source fabricator as several types of radioactive sources which suits for its usages, and typically cesium-137 is sealed within a lead capsule there. Then device manufacturers incorporate these sources into their devices, such as irradiators or gauges. There are few reactors producing cesium-137 and only a handful of major source manufacturers in the world (Ferguson, Kazi, and Perera, 2003, p24-25). Cesium-137 is used mainly for industrial and hospital purposes, such as irradiator, several types of gauges, brachytherapy, or teletherapy. Because of relatively long half-life (30.17 years) of cesium-137, sources rarely need to be replaced, if it need at all, and the product life cycle of devices is long. Disused devices are supposed to be either taken back to the source/device manufacturer or disposed of in an appropriate radioactive material disposal site. Source/device manufacturers recycle used sources by reprocessing or disposing of them in appropriate manner. Abandoned devices may pose a potential risk of exposure, as occurred in Brazil in 1987.

Cesium-137 disappears naturally by radioactive decay, which should be counted to see cesium-137 cycle. The radioactive decay is expressed as the following equation (Chase and Rabinowitz, 1967, pp 162-164):

$$N = N_0 e^{-\lambda t}$$

where:

N_0 = original number of atoms present
N = number of atoms remaining at time t.
λ = decay constant
t = time

And the decay constant is

$$t_{1/2} = \frac{0.693}{\lambda}$$

$$\lambda = \frac{0.693}{t_{1/2}}$$

where:

$t_{1/2}$ = a half-life of the isotope

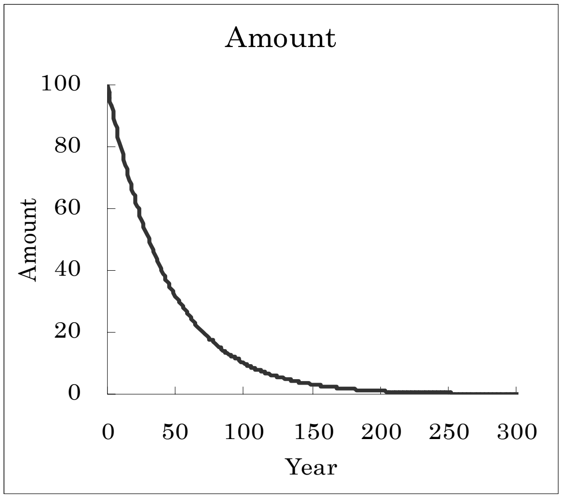
Since the half-life time for cesium-137 is 30.17 years, the decay constant and the amount of cesium-137 after 1 year are;

$$\lambda = \frac{0.693}{30.17} \approx 0.0230$$

$$N = N_0 e^{-0.0230 \times 1} \approx N_0 \times 0.977$$

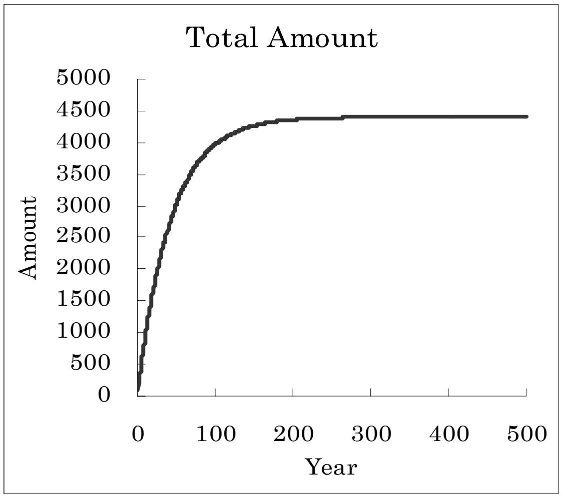
Therefore, the amount of cesium-137 is about 97.7% of the previous year and 2.3% is decayed annually. Figure 5 shows the natural decay of 100 units of cesium-137. It decays to half around Year 30, and by Year 201 only 1 unit remains radioactive.

Figure 5. Natural decay of cesium-137



In another scenario, Figure 6 shows the amount of cesium-137 if 100 units are added every year. The stock keeps growing and will reach equilibrium at about 4,400 units approximately 400 years later. At this point, annual amount of natural decay will be equal to 100 units, the annual input. In general, assuming a constant annual input of cesium-137, this material will accumulate up to a level 44 times the annual input.

Figure 6. The amount of cesium-137, if 100 units are added every year



In following sections, material flow of cesium-137 in each life stage will be examined. Material flow for entire life stages is presented in Figure 7 and the details in each stage are presented in Figure 8 - Figure 11. Flow numbers in following sections correspond to those in the Figure 7 - Figure 11.

Figure 7. Material flow of cesium-137 in th U.S. 2000 (Entire life stages)

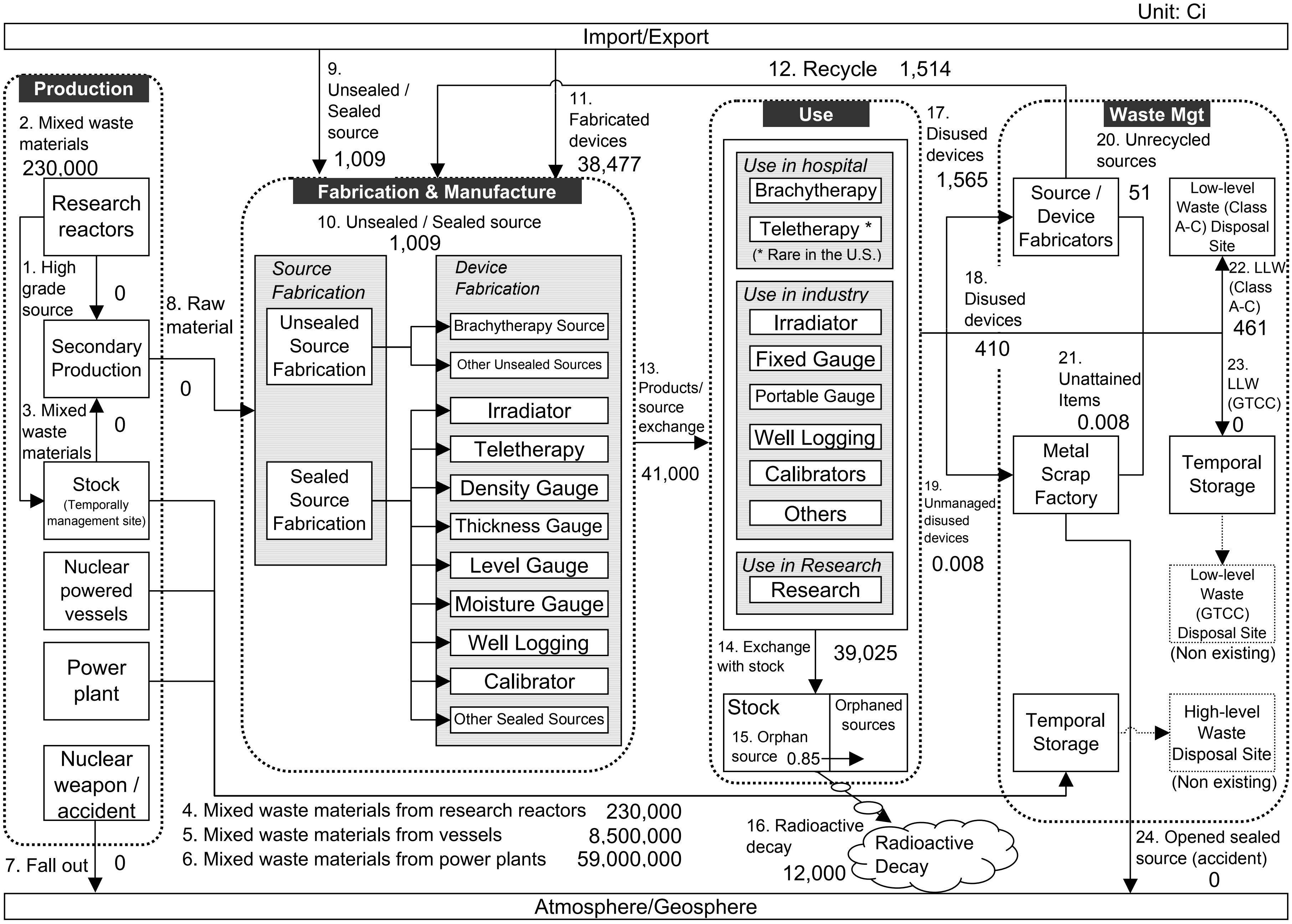


Figure 8. Material flow of cesium-137 in th U.S. 2000 (Production)

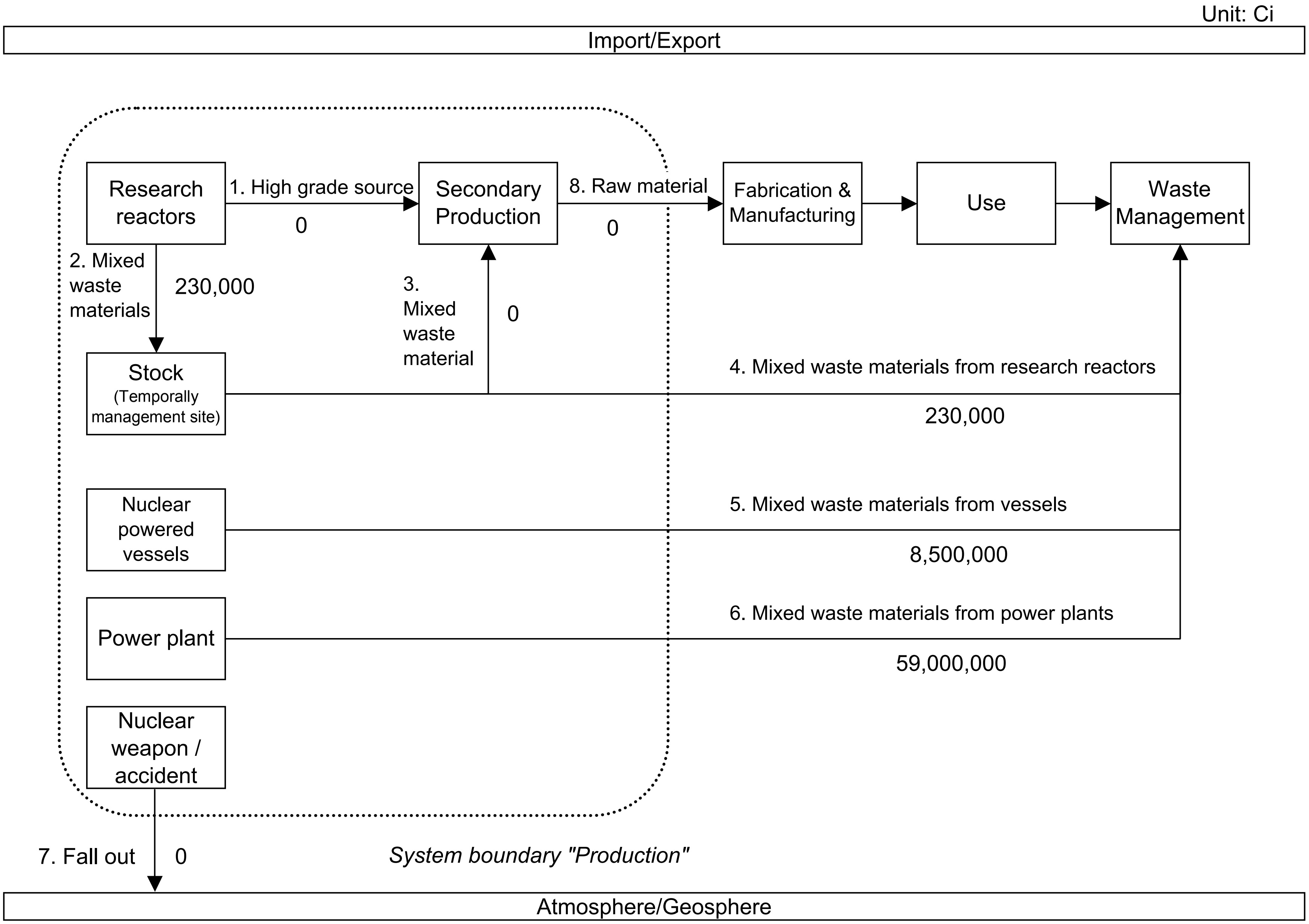


Figure 9. Material flow of cesium-137 in th U.S. 2000 (Fabrication and Manufacture)

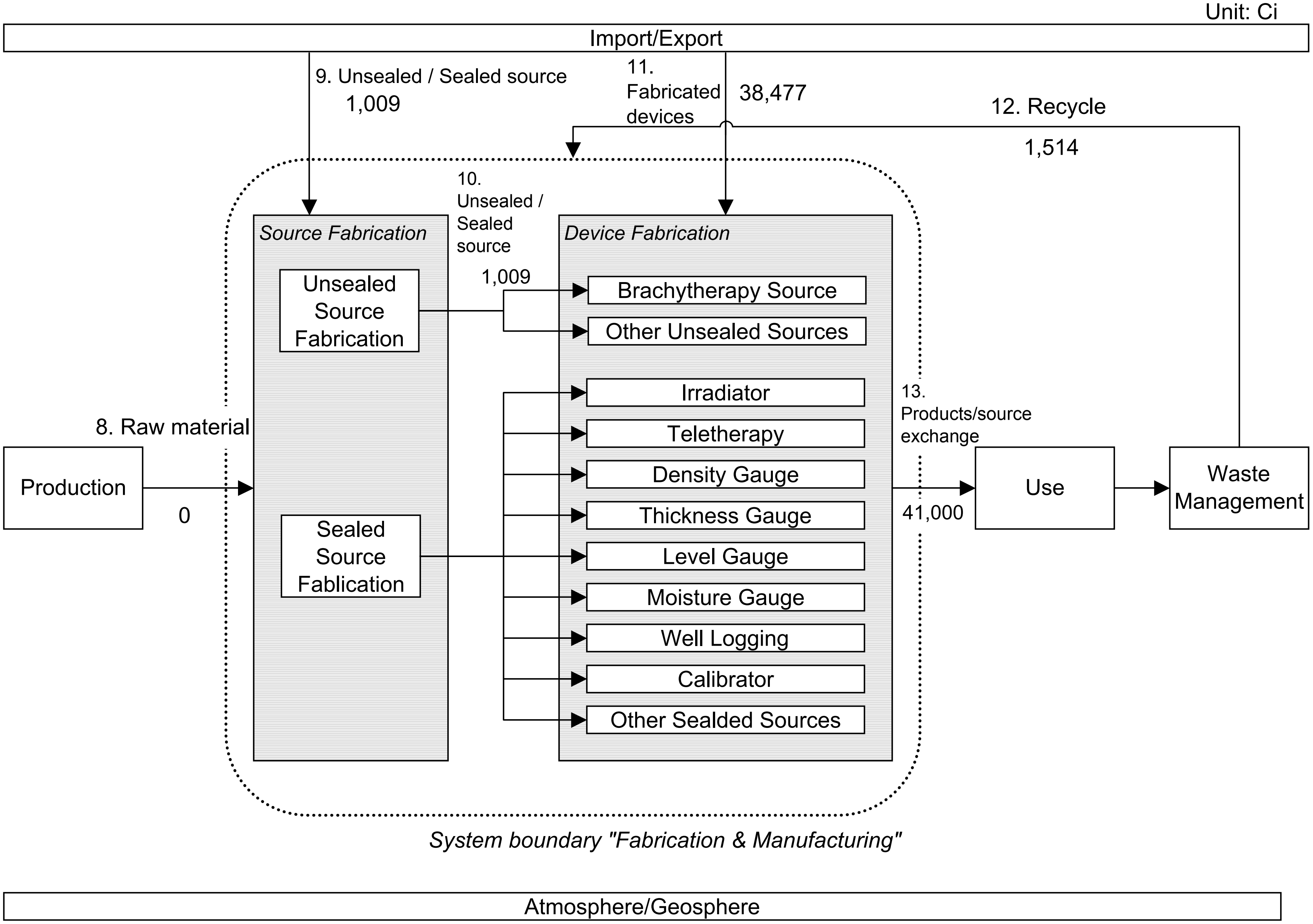


Figure 10. Material flow of cesium-137 in th U.S. 2000 (Use)

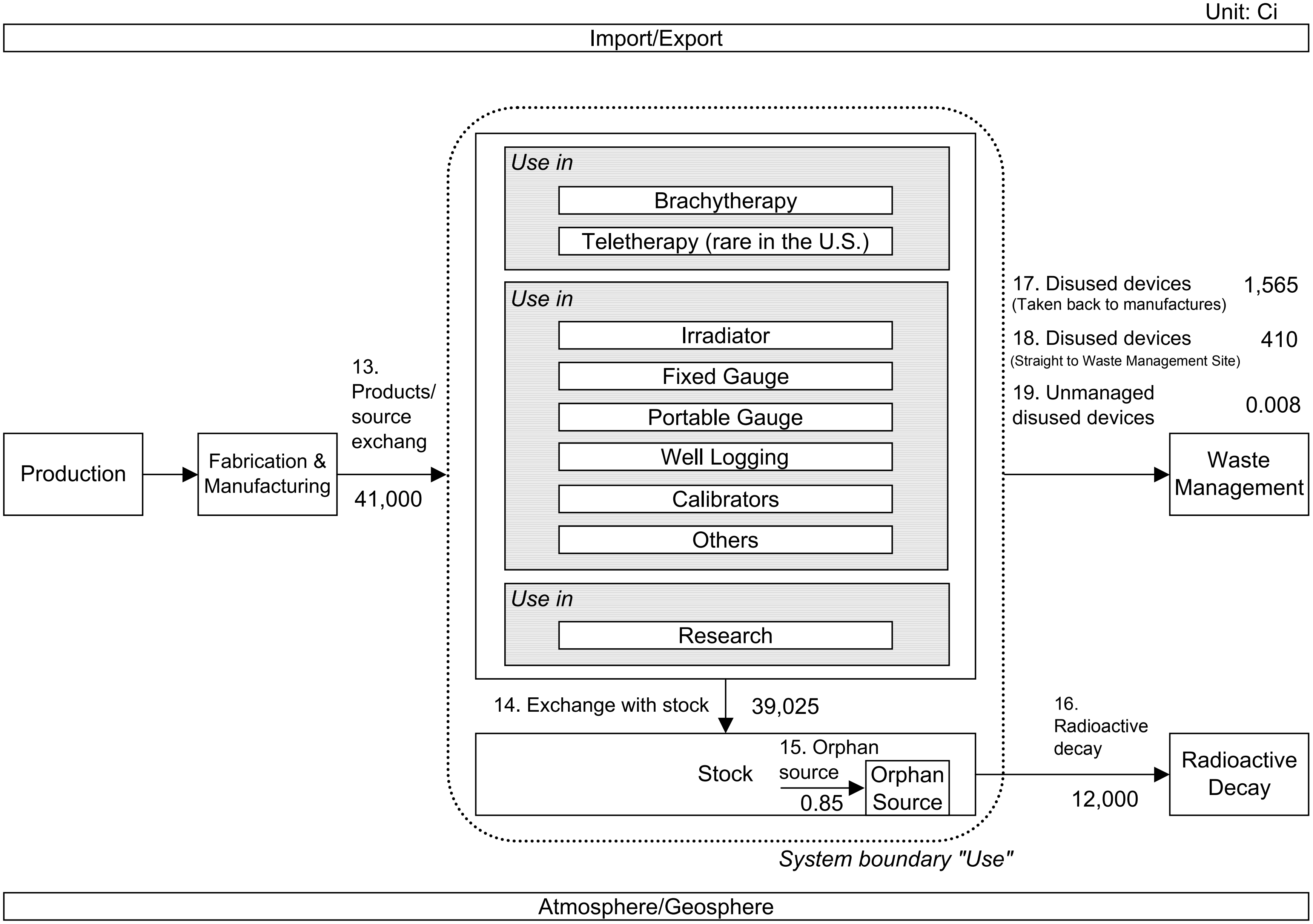
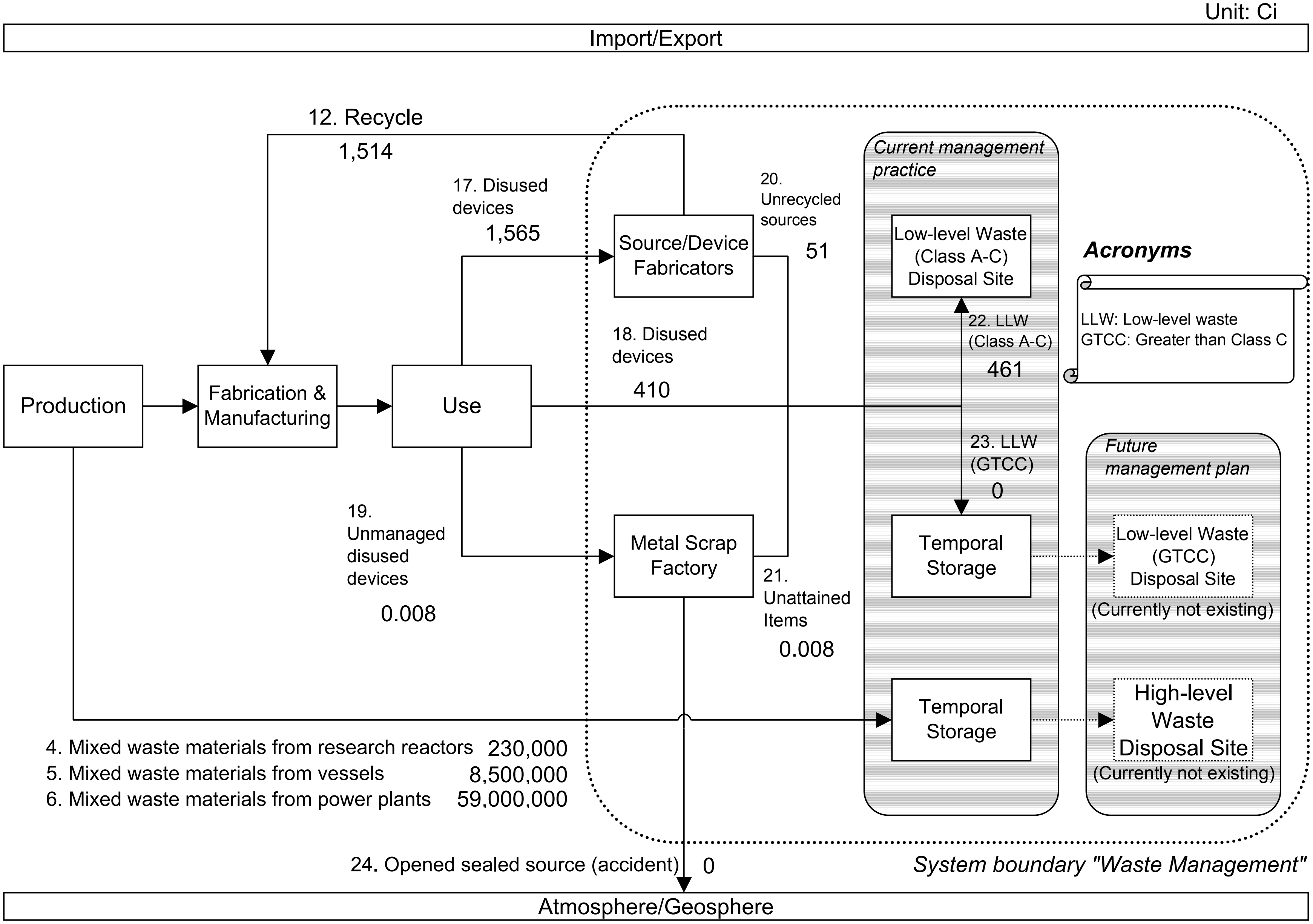


Figure 11. Material flow of cesium-137 in th U.S. 2000 (Waste Management)



3. Production

3.1. Commercial production

According to an interview with an official in the NRC, conducted by S. Hamlin, cesium-137 has not been commercially produced in the U.S. in recent years. Historically, during the 1950s and 60s, the facilities of Department of Energy (DOE), such as Hanford, Oakridge National Labs and Savannah River, produced cesium-137. Cesium-137 that has been produced in the past and not distributed is still stored and could still be distributed. The amount stored is very large compared to the amount that is actually used. (Hamlin, qtd. in Rejeski 2003 March 3). According to information from a officer in the DOE, 6,463 cesium-137 items with an activity of 49,079,440Ci were stored at DOE sites as of January 29, 1999. (Hamlin 2003 May 29) Since there was no commercial production of cesium-137 in the U.S. in 2000, the amount of Flow 1, 3 and 8 on the flow diagram are determined to be 0Ci.

3.2. Cesium-137 as waste production in commercial power plants

Cesium-137 is also produced by commercial power reactors as a residue of the nuclear fission of Uranium. Cesium-137 produced under these circumstances is part of the mixture of nuclear wastes in spent nuclear fuel and does not go into circulation. Appendix A shows the estimated amount of cesium-137 produced by commercial power reactors in the U.S. The reactor capacity data are taken from the NRC document, *Information Digest 2001 Edition* (Nuclear Regulatory Commission, 2001, Appendix A). According to this document, there are 104 reactors used in the nuclear power plants in the U.S. Net Maximum Dependable Capacity (MDC) is used as a basis for calculation rather than Licenced MWt. These two figures both show the size of a reactor but MDC gives the more conservative figure. MDC is multiplied by the capacity factor of each reactor to determine the actual production capacity in the year 2000. As a result, 86,080MWt is considered the total capacity of all the reactors in 2000. From that figure, the amount of cesium-137 is calculated, based on the assumption that reactors annually produce 9g of cesium-135 per 1MWt capacity (Garwin and Charpak 2001, 121), and that the yields of cesium-135 and cesium-137 are about 7% and 6% respectively in terms of number of atoms (INEEL 2001). 9g of cesium-135 equals 0.067mol (cesium-135: 135g/mol). 0.067mol is 7% of the yield; thus, the amount of cesium-137, which is 6% of the yield, is 0.057mol. 0.057mol of cesium-137 equals 7.8g (cesium-137: 137g/mol). Therefore, 7.8g of cesium-137 is produced per 1MWt of reactor capacity. As a result, 671,424g of cesium-137 is estimated to have been produced in commercial power plants in the U.S. in 2000. This amount equals approximately 59,000,000Ci, since the specific activity of cesium-137 is 88Ci/g. This amount is shown in the Flow 6 on the flow diagram. The estimate just described has been calculated using a very rough model. Still, it can be said that the contribution of commercial power plants to the production of cesium-137 is significant because of the size of the reactors.

3.3. Cesium-137 as waste production in research reactors

Cesium-137 is also produced in waste material as a result of nuclear fission conducted in research reactors. Research reactors in the U.S. are listed in the NRC document, *Information Digest 2001 Edition* (Nuclear Regulatory Commission, 2001, Appendix E). According to this document, there are 36 research reactors in the U.S. In addition, there are several research reactors owned either by the DOE or by the DOD. According to the IAEA's research reactor database, as of June 9, 2003, there are 16 reactors licensed by the DOE (of which 15 are owned by the DOE and one by the DOD), and one reactor licensed by the DOD (also owned by the DOD). Since all of these reactors began operating before the year 2000, we can assume that they were under operation in 2000 (IAEA). In total, 53 research reactors were in operation in the year 2000. Appendix B in this document shows the list of research reactors. Assuming operation in 2000 is same as the IAEA data retrieved on June 9, 2003, operation data on 52 out of 53 reactors are available from that database. From those data, "MW Days per Year" is used as the primary basis for estimation of cesium-137 production. Converting "MW Days per Year" into "MW year" by dividing by 365, the actual average capacity is calculated. Where "MW Days per Year" is not reported, "MW year" is calculated by multiplying reactor capacity by a utilization ratio, which is the percentage of time when a reactor is under operation. As a result, the total of 340MW is considered to be the capacity of research reactors in 2000. Finally, the same conversion rates as commercial reactors, which are 7.8g of cesium-137 per 1MW and 88Ci/g, are used to calculate the activity of cesium-137 produced in the research reactors. In 2000, about 2,700g or 230,000Ci of cesium-137 is estimated to have been produced by research reactors and this is represented in Flow 2 on the diagram. Since none of this cesium-137 is used commercially, it all goes to waste management as a Flow 4, and Flow 3 is consequently 0Ci.

3.4. Cesium-137 as waste production in nuclear powered ship/submarine

The U.S. navy owns nuclear-powered ships and submarines and the reactors in these vessels also produce cesium-137 as a fission waste product. A list of nuclear-powered vessels is shown in Appendix C. The data are taken from *Jane's fightingships 2000-2001* (Sharpe, Richard ed., 2001). According to this source, the U.S. Navy owned 84 nuclear-powered vessels as of June 1, 2000. Specifications of 83 vessels are given and expressed in horsepower and MW. Since the size of reactors is measured by thermal output rather than by power, these figures are converted to thermal output, using a thermal efficiency of 32.1%. In other words, 32.1% of the heat generated by a reactor is used as a power source and the rest is exhausted (DOE, 2002). The total size of reactors used in nuclear-powered vessels is estimated as 12,443Mw. The same conversion rates of 7.8g of cesium-137 per 1Mw and 88 Ci/g are used to calculate the activity of cesium-137 produced in reactors of nuclear-powered vessels. In 2000, about 97,000g or 8,500,000Ci of cesium-137 is estimated to have been produced by nuclear-powered vessels, which is represented by the Flow 5 on the flow diagram.

3.5. Other sources

Cesium-137 is also introduced into the environment by nuclear weapons. Actually, cesium-137 present in the soil is largely derived from atmospheric nuclear weapon tests in the past (INEEL). The last atmospheric test occurred in 1980 in China, and the last underground tests occurred in 1998 by India and Pakistan (NRDC 2002, 2002a). There were no nuclear weapons tested in 2000, either in the U.S. or elsewhere in the world. Therefore, no cesium-137 is produced by a nuclear weapon in 2000.

Cesium-137 can be released accidentally, such as the Chernobyl case in the Ukraine in 1986 (EPA). However, it is very rare and the accident is considered very serious if it happens. There was no accident involving a release of cesium-137 in 2000.

Since there was not an incident of release in 2000, the Flow 7 on the diagram will be 0Ci.

3.6. Summary of Production

The current production of cesium-137 in the U.S. is only in the form of mixed waste material. The production estimates for cesium-137 in the form of mixed waste material, such as production from commercial power plants, research reactors, and nuclear powered ships/submarines, are very crude. These estimates are based solely on reactor size, and there are no independent data available to verify them. However, the mixed waste materials go directly to waste management sites and do not affect other cesium-137 flows. It can be said, even from the crude estimate, that the potential amount of cesium-137 produced by these facilities is huge compared to other cesium-137 flows. 68,000,000Ci of cesium-137 is estimated to be produced in the form of mixed waste, while only 41,000Ci is estimated to be commercially distributed annually, as discussed in following sections.

4. Fabrication and manufacture

4.1. Source fabrication

The data about source fabrication are gathered through interviews with manufacturers. The source processors import the source from foreign countries or recycle sources in old devices, which are taken back to manufacturers after use. They process and/or distribute those sources in the U.S. market. There are few source processors and the major ones are AEA Technology (Massachusetts) and Isotope Products Laboratories (IPL) (California). (Hamlin, qtd. in Rejeski 2003 March 3). According to the data from AEA and IPL, the total amount of cesium sold by them was 1,009Ci in 2000, 1,177Ci in 2001, and 1,140Ci in 2002 (Mogan, qtd in Hamlin 2003, April 18, Martel, qtd in Hamlin 2003, August 29). The Flow 10 is determined to be 1,009Ci. Since all of these sources are made outside the U.S., the flow of import (Flow 9) is same as this amount.

4.2. Device fabrication

Since neither production nor sales data for cesium-137 devices are available, the number of devices and the amount of cesium-137 employed are estimated from the current use trend. First, the inventory – the amount of cesium-137 which has been distributed and is currently in use – is examined and then the annual input of devices is estimated from the inventory data and product life cycle.

The inventory data are taken from the NRC document, *Risk Analysis and Evaluation of Regulatory Options for Nuclear Byproduct Material Systems.* This document was published in 2000, and the trends are not likely to change much because of long half life of cesium-137. In the following sections, cesium-137 inventories are examined by use. Unless otherwise indicated, estimates about typical activity and number of devices are done by NRC and taken from the document, and inventories are calculated by multiplying the typical activity of cesium-137 in a device by the number of devices. The result is also shown in column "Total inventory" of Table 10 and Table 11

4.2.1. Irradiators

An irradiator using cesium-137 is of the self-shielded type, which is relatively small and used to irradiate blood, cosmetics, and other products, or to calibrate radiation measuring devices. Cesium-137 is not suitable as a source for large pool irradiators used for food irradiation or for the sterilization of medical products, because of its solubility in water. Typical source strength is 2,000Ci with a maximum of 2,500Ci, while the estimated number of devices is 300. (NRC 409-464) Total inventory is therefore calculated to be 600,000Ci.

4.2.2. Fixed gauge, small calibrators

Fixed gauges are mainly used for the purpose of quality control in manufacturing processes. They measure, for example, the thickness of paper, density of coal, level of materials in vessels and tanks, and volumetric flow rate. The source strength of cesium-137 for this application ranges from 10μCi to 110Ci. The NRC estimates the number of units using cesium-137 as 19,000 under general license and 9,500 under specific license. Unit activity is estimated as 170mCi (0.17Ci) under general license and 900mCi (0.9Ci) under specific license. (NRC 465-499) From that information, total inventories are calculated as 3,230Ci and 8,550Ci under general and specific license, respectively, and therefore as 11,780Ci in total.

4.2.3. Portable gauge

Portable gauges are mainly used to measure the density or other properties of soil, concrete, and other materials in a field setting. Some special types are also used for fluoroscopes, which are used for nondestructive inspection. The number of units using cesium-137 is estimated as 19,000 under general license and 9,500 under specific license. Unit activity is estimated as 170mCi (0.17Ci) for both licenses. Besides that, some neutron source units use both cesium-137 and americium-241/Be. The number of neutron source units is estimated to be 14,000. Unit activity of cesium-137 is estimated as 8mCi (0.008Ci). This unit activity is exclusive of americium-241/Be. (NRC 523-559) Total inventories of cesium-137 for these uses are calculated as 3,230Ci, 1,615Ci and 112Ci, for general license units, specific license units, and neutron source units respectively and as 4,957Ci in total.

4.2.4. Brachytherapy

Brachytherapy is a treatment of cancer, which places a radioactive source close to a tumor in the body of the patient. The source provides a lethal dose of radiation to the tumor. There are two types of brachytherapy. The first type places a source permanently in the body of the patient, while the second type removes the source from the body after the treatment period. The treatment using cesium-137 requires removal of the source after the treatment period, which usually lasts from 48 to 120 hours. Cesium-137 is typically a line source, which is a 2.5mm-wide stainless steel capsule containing glass beads of cesium-137. Each capsule contains 10-40mCi and up to 500mCi is used in one treatment. There are typically 48 treatments per license per year. Brachytherapy is done either manually or by automation. Manual brachytherapy (manual afterloading) typically uses 500mCi in one treatment and sources up to 4Ci may be stored at any one time. Automated brachytherapy (low dose rate remote afterloading) typically uses 100mCi in one treatment and a facility typically stores 7Ci. There are approximately 500 licensees of manual after loading and 130 licensees of low dose rate remote afterloading. (NRC 104-187). The total inventory is calculated using the amount in storage rather than the amount in one treatment. Assuming all licensees store the maximum amount of cesium-137, the inventory of cesium-137 in manual brachytherapy is calculated as 2,000Ci, and that in automated brachytherapy as 910Ci. The total inventory for brachytherapy use is 2,910Ci.

4.2.5. Well logging

Cesium 137 is used to collect geophysical information in well drilling operations. The information includes porosity, hydrogen content and bulk density, which are used to determine the potential availability of oil, natural gas, etc. Cesium-137 used in this application is doubly encapsulated. The typical source strength in use is 1.5Ci, while the maximum source strength is 10Ci. The estimated number of sources in use is 300. (NRC 360-383) Total inventory is calculated as 450Ci.

4.2.6. Other uses

There are other, minor uses of cesium-137, each of which accounts for less than 0.1 % of total cesium-137 usage; still other uses are so rare that the number of devices is not known, but usage is assumed to be very small.

Cesium-137 is used as a source for liquid scintillation counter calibration and other loose calibration sources. The typical source strength for liquid scintillation counter calibration is 40μCi (0.00004Ci) and the number of units is 12,000. The typical source strength for loose calibration sources is 100μCi (0.0001Ci) and the number of units is 6,000. (NRC 650-679) Total inventory is calculated as 0.48Ci and 0.6Ci for liquid scintillation counter calibration and loose calibration sources, respectively.

Bulk material elemental analyzers and depleted uranium collimators use cesium-137 as a source material. Bulk material analyzers use radioactive materials to analyze the composition of various materials. Most of them use californium-252, but some use cesium-137 with a typical activity of 300mCi (0.3Ci). The number of units using cesium-137 is not known but is probably significantly less than 100, which is the number of units using californium-252. The depleted uranium collimators use cesium-137. The typical activity of cesium-137 used is 300mCi (0.3Ci), but the number of units is not known. (NRC 680-702)

Teletherapy is a treatment of cancer using an external beam of ionizing radiation. This use could require a large source; for example, a cobalt-60 teletherapy unit uses 6,000Ci to 12,000Ci on average, depending on the type of unit. Cesium-137 is a possible source of teletherapy units; however, cobalt-60 is more commonly used for this purpose. In the U.S, cobalt-60 is the predominant source. (NRC 232-253)

4.2.7. Summary of device fabrication

According to Nuclear Technology Products (NPT), a source manufacturer in South Africa, the recommended lifetime of a typical cesium-137 sealed source for industrial use is up to 15 years. The activity of the source after 15 years is about 70% of the original (Nuclear Technology Products). Assuming users replace devices every 15 years, one fifteenth of the devices in inventory is replaced every year, by replacing either the devices themselves or the sealed sources in them. This leads to the estimation that new devices containing about 41,000Ci of cesium-137 are entering inventory annually, which is calculated on Table 10. This figure is expressed in Flow 13 on the diagram. The difference between the amount of source fabricated and the amount of source used is assumed to be accounted for by sources imported and exported. Since devices worth 41,000Ci are estimated to be consumed while only 2,523Ci of sources are estimated to be manufactured or recycled in the U.S., the flow is calculated to be 38,477Ci of net import, which is Flow 11. Among these, irradiators account for the most cesium-137 usage (95%), followed by fixed gauges and portable gauges. These three usages account for more than 99% of cesium-137 use in the U.S. An employee from a company manufacturing irradiators estimates that, on average six irradiators, each with 7,000Ci of cesium-137, are installed in the U.S. every year (Hamlin June 30, 2003). This means that 42,000Ci is entering the inventory annually, which is within 5% of the estimate of 40,000Ci calculated on Table 10. However, the size of the irradiator used in this estimate (7,000Ci) is more than three times bigger than that used in the NRC's estimate (2,000Ci). This difference should be further assessed if additional data become available.

Table 10. Inventory of Cs-137 by devices

Name	No. of devices	Total inventory (Ci)	Percentage	Estimated annual consumption (Ci) *
Irradiator	300	600,000	96.8%	40,000
Fixed Gauge, Small Calibrator	28,500	11,780	1.9%	785
Portable Gauge	42,500	4,957	0.8%	330
Brachytherapy	630	2,910	0.5%	194
Well Logging	300	450	0.1%	30
Electron Tube	200,000	0.6	< 0.1%	< 0.1
Loose Calibration Source	6,000	0.6	< 0.1%	< 0.1
Liquid Scintillation Counter Calibration	12,000	0.48	< 0.1%	< 0.1
Ionizing Radiation Measurement Instruments	10,000	0.006	< 0.1%	< 0.1
TOTAL	300,230	620,099	100.0%	41,340

* Based on 15 yrs life cycle, and depreciation caused by radioactive decay is not considered here

5. Use

The following table is a list of cesium-137 use tabulated from information in previous section.

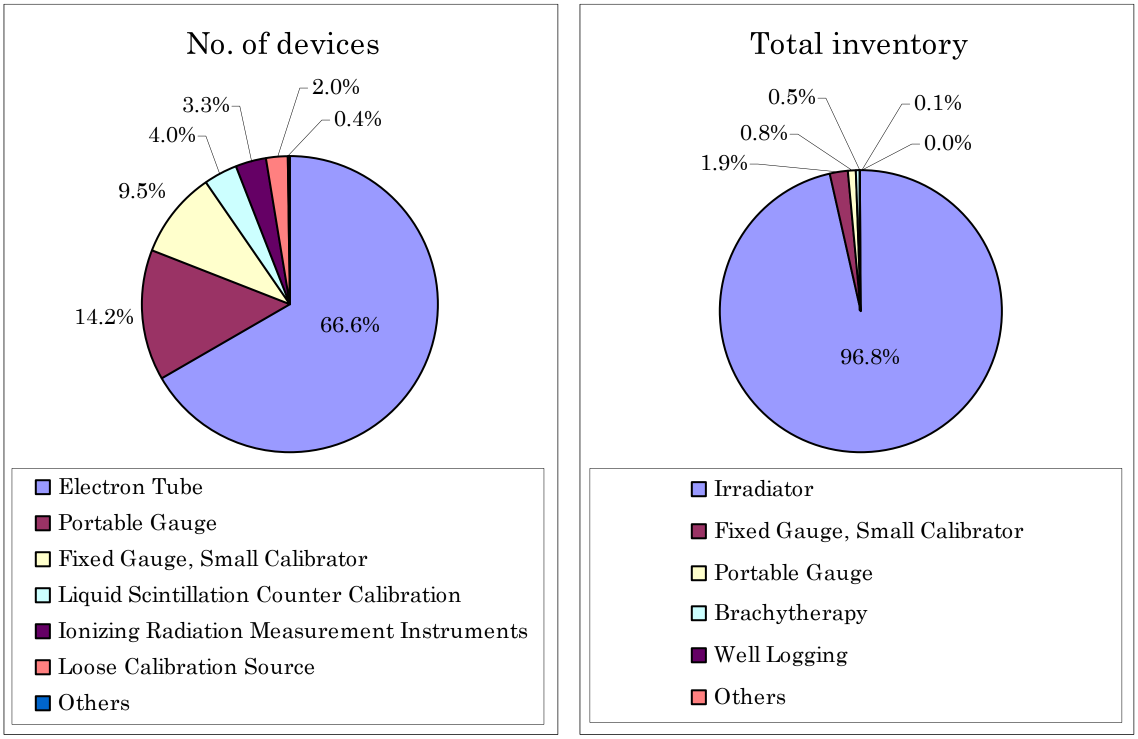
Table 11. Cesium-137 inventory

		By subcategory			By category			
Use Category	Use Sub category	Typical Strength (Ci)	No. of devices	Total inventory (Ci)	No. of device	Percent	Total inventory (Ci)	Percent
Brachytherapy	Manual Afterloading	4	500	2,000	630	0.2%	2,910	0.5%
	LDR Remote Afterloading	7	130	910				
Well Logging		1.5	300	450	300	0.1%	450	0.1%
Irradiator		2000	300	600,000	300	0.1%	600,000	96.8%
Fixed Gauge, Small Calibrator	General license	0.17	19,000	3,230	28,500	9.5%	11,780	1.9%
	Specific license	0.9	9,500	8,550				
Portable Gauge	General license	0.17	19,000	3,230	42,500	14.2%	4,957	0.8%
	Specific license	0.17	9,500	1,615				
	neutron source*	0.008	14,000	112				
Bulk Materials Elemental Analyzer		0.025	N/A	N/A	N/A	N/A	N/A	N/A
Depleted Uranium Collimator		0.3	N/A	N/A	N/A	N/A	N/A	N/A
Liquid Scintillation Counter Calibration		0.00004	12,000	0.48	12,000	4.0%	0.48	<0.1%
Loose Calibration Source		0.0001	6,000	0.6	6,000	2.0%	0.6	<0.1%
Electron Tube		0.000001	200,000	0.006	200,000	66.6%	0.006	<0.1%
Ionizing Radiation Measurement Instruments		0.000002	10,000	0.012	10,000	3.3%	0.012	<0.1%

Total	300,230	100%	620,098	100%

*Portable Gauge neutron source Cs-137 and Am-241/Be, the figure shows amount of Cs-137 only.

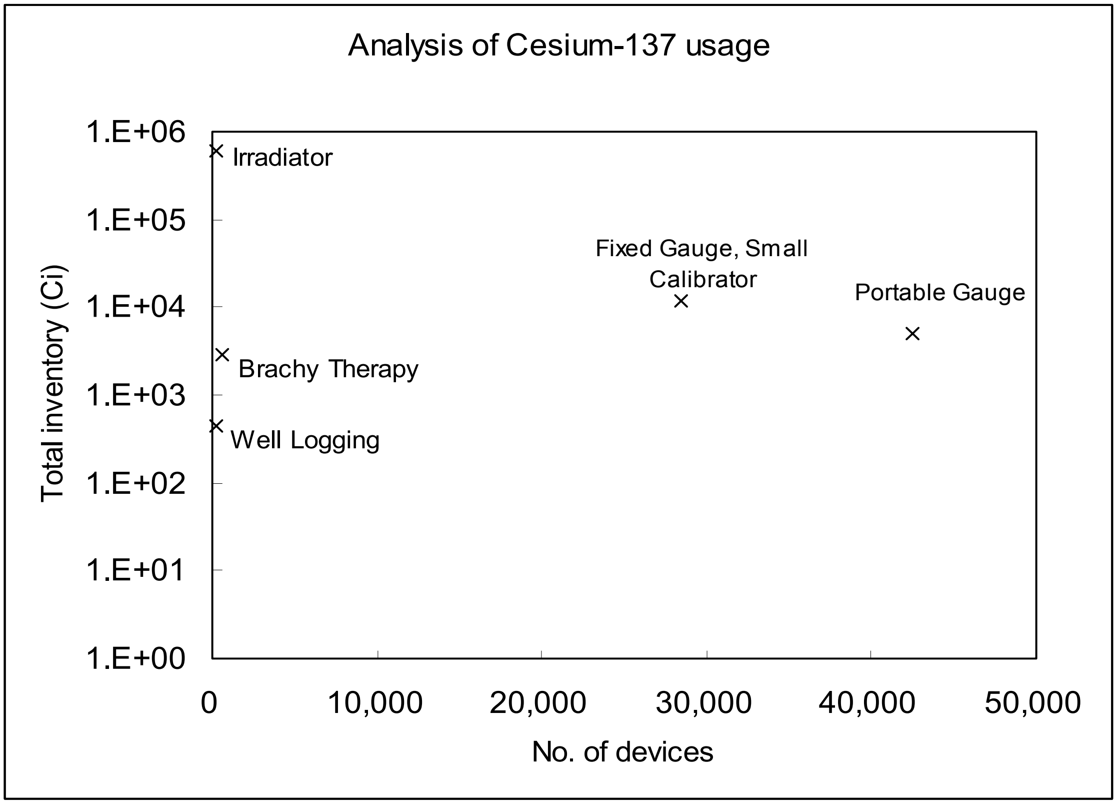
Figure 12. Cesium-137 inventory



Among these uses, the unit activity of each of the following four is less than the most stringent annual occupational intake limit of 0.001Ci (limit on oral ingestion), and devices employed in these uses therefore pose only minimal security risk associated with terrorism. The following for categories appear in Table 11: the use of cesium-137 in electron tubes and ionizing radiation measurement instruments, in liquid scintillation counter calibration, and as loose calibration sources.

In Figure 13, the total amounts of cesium-137 by major uses are plotted on the vertical axis in a log scale and the number of devices is plotted on the horizontal axis. Among them, the large total inventory of irradiators and large number of gauges are noticeable. The inventory of irradiators is about two orders of magnitude bigger than that of fixed gauges, which has the second biggest inventory. The inventory of irradiators consists of a small number of devices, each with a very large amount of cesium-137. On the other hand, the inventory of gauges consists of numerous devices, each with a small amount of cesium-137.

Figure 13. Analysis of cesium-137 use



In following sections, each flow in the product use stage is examined.

5.1. Exchange with stock

Exchange with stock is estimated as the difference between input to and output from product use stage. The input is 41,000Ci of Flow 13, and the output is 1,975Ci of Flow 17-19, of which details are discussed later. Therefore, the flow of exchange with stock (Flow 14) is 39,025Ci and the direction of flow is towards stock.

5.2. Orphaned sources

Some of the devices containing cesium-137 are improperly managed and have been lost or stolen. Most of them are found or recovered later, but some of them are not. Those materials not found or recovered become orphaned sources. The data for orphaned sources are gathered from the Nuclear Material Events Database (NMED), which is owned by NRC and maintained by INEEL. From the NMED database, the cesium-137 events under "Lost not found", "Stolen not found", "Material found" are examined. The first two categories represent materials lost or stolen that have become orphaned. The last category represents material found, which is supposedly lost or stolen from somewhere unidentifiable, and where those responsible are not aware of the loss or theft. The information from the NMED database as of June 23, 2003, is shown in Table 12. below. There is no event reported for these categories before 1998.

Table 12. NMED data base Amount (Ci)

Year	Lost not found		Stolen not recovered		Material found		Total	
	No. of event	Amount (Ci)	No. of event	Amount (Ci)	No. of event	Amount (Ci)	No. of event	Amount (Ci)
1999	2	0.028	4	0.036	0	0	6	0.064
2000	4	0.7954	6	0.05	1	0.008	11	0.8534
2001	11	0.619251	22	0.1877	7	0.2676	40	1.074551
2002	6	0.3131877	24	0.2182	3	0.0100013	33	0.541389
Total	23	1.7558387	56	0.4919	11	0.2856013	90	2.53334

Note: In some cases, the occurrence of the event is reported but not the amount.
Data source: INEEL, Nuclear Material Events Database

In 2000, about 0.85Ci of cesium-137 in total were reported under these categories and assumed to be orphaned sources, which is shown in Flow 15. It should be noted that this figure represents only reported events and there are possibly more orphaned sources that are not reported or even realized by the device licensees.

5.3. Radioactive decay

As is mentioned earlier, cesium-137 sources diminish by radioactive decay. Based on 2.3% annual decay, the estimated annual consumption of 41,340Ci and a lifetime of 15 years, actual inventory and the amount of radioactive decay will be the following:

Table 13. Amount of cesium-137 contained in existing devices in the year 2000 *1

Year of fabrication	Amount (Ci)	Year of fabrication	Amount (Ci)	Year of fabrication	Amount (Ci)
2000	41,340	1995	36,800	1990	32,758
1999	40,389	1994	35,953	1989	32,004
1998	39,460	1993	35,126	1988	31,268
1997	38,553	1992	34,318	1987	30,549
1996	37,666	1991	33,529	1986	29,847
				Total	529,561
				Decay *2	12,108

*1 Devices made before 1986 (more than 15 years old) are assumed to have been disposed of.
*2 Calculated as 2.3% of the total.

About 530,000Ci of cesium-137 are estimated to have been active in 2000, and approximately 12,000Ci are estimated to have been diminished by radioactive decay in the year 2000. This is shown in Flow 16.

6. Waste management

6.1. Recycling

Some source/device manufacturers reportedly recycle sources in the used devices. However, the possibility of recycling depends on the demand for source materials. For example, gauge manufactures were unable to recycle cesium-137 sources due to market condition in 2002. (Product Stewardship Institute 2003)

There are three major manufactures of cesium-137 irradiator: CIS, Inc, MDS Nordion, and J.L. Shepherd and Associates. As of 2001, MDS Nordion and J.L. Shephard would accept a spent irradiator for a fee. MDS Nordion only accepts irradiators of their own manufacture, however, J.L. Shephards even accepts competitors' units. The fee the manufacturers charge their customers for accepting used devices is considerably lower than that charged to the manufacturers for disposal of these devices at a waste disposal site (Kirk, 2001). Therefore, the manufacturers are obliged to recycle used devices in some way in order to avoid losing money in the transaction. In absence of the actual data for irradiator recycling, the amount is estimated assuming one irradiator of typical strength is recycled per year, since recycling of big sources, such as those found in irradiators happens occasionally, due to the market condition. After 15 years of use, typical irradiator source of 2,000Ci becomes approximately 1,420Ci by radioactive decay. Therefore, 1,420Ci of cesium-137 is assumed to be recycled from irradiators.

As for gauges, the Product Stewardship Institute (PSI) reports that two major manufactures of fixed gauge says that 200-350 gauges are returned to each of them annually, which means that they receive a total of about 550 gauges – of which those containing cesium-137 comprise a large share. One manufacturer says that 65% of returned items were recycled, and again, gauges containing cesium-137 are more likely to be recycled. However, recyclable material may go to waste management sites if the market situation is not good. (PSI 2003) Since detailed data about these returned gauges – such as the number of gauges with cesium-137 or the type of licenses – are lacking, the flow is estimated as follows. First, it is assumed that half of the 550 returned gauges contain cesium-137, and the activity of each gauge is a weighted average of typical strength under general and specific license. Then the typical strengths of gauges under general license and specific license are 0.17Ci and 0.9Ci, and the numbers of devices are 19,000 and 9,500 respectively. Therefore, the weighted average becomes 0.41Ci, which will decay to 0.29Ci after 15 years of use. Since 550 gauges are returned, 145Ci of cesium-137 is estimated to be contained in them. Within that, 65% (94Ci) is assumed to be recycled and the rest (51Ci) is assumed to go to waste management sites.

Although the recycling option may be available for other uses, other recycling practices are not assessed here because of limited data on them. Since irradiators and fixed gauges comprise more than 98% of total cesium-137 usage, recycling of these two uses reasonably represents the flow of recycling. Therefore, it is assumed that 1,565Ci of cesium-137 is returned to manufacturers (Flow 17), of which 1,514Ci is recycled (Flow 12) and 51Ci goes to waste management site (Flow 20).

6.2. Disposal

As mentioned previously, high-level wastes are temporarily stored at their production sites or designated storage sites. About 68,000,000Ci of cesium-137 produced by commercial power reactors, research reactors, and nuclear-powered vessels are high-level wastes and these are assumed to be in temporary storage for now. As for low-level wastes, according to information from site operators, the amount of cesium-137 received in the year 2000 at the Barnwell site was 446Ci, and that at the Hanford site, 15.4Ci. The year-to-year data from 1998 to 2002 are shown in Table 14. (Hamlin June 14, 2003; Ibid June 30, 2003). The amount of cesium-137 brought to the Clive site should be negligible. According to its license, the Clive site only accepts Class A waste and its average concentration must be as small as 60,000pCi/g (6×10^{-8}Ci/g). Its accepted materials are typically large-volume, bulky, or containerized soil or debris, such as radiologically contaminated paper, piping, rocks, slag or personal protective equipment (Envirocare of Utah, Inc., 2003). Spent radioactive sources in devices are not included among the items accepted at this site. Therefore, the flow to waste management sites (461Ci) in 2000 is estimated to be the total of wastes accepted by the Barnwell and Hanford sites, and is shown in the Flow 22.

Table 14. Cs-137 received at waste management sites (Ci)

Year	Hanford	Barnwell	Total
1998	13.57	89.44	103.02
1999	14.34	276.11	290.46
2000	15.35	445.87	461.22
2001	3.42	853.58	857.00
2002	5.77	44.11	49.88
Total	52.47	1,709.11	1,761.58

The amount of cesium-137 received at waste management sites is far less than that entering to the U.S. market. There are financial and logistical problems concerning the disposal of devices containing cesium-137 and the users may want to keep sources at their hands even after they become unwanted..

6.3. Cesium-137 at scrap metal facility

Some cesium-137 is found in scrap metal, when radioactive devices are improperly disposed of and brought to scrap metal facilities. In the worst case, at scrap metal facilities, metal capsules of sealed source may be opened and the leaking cesium-137 may cause severe contamination. In NMED database, there ware five cases with which cesium-137 sources were found in metal scrap factories and their total activity was 0.008Ci (INEEL), which is expressed in Flow 19. If cesium-137 is smelted with other scrap metals, it volatilizes and most of it ends up in the furnace dust (Lubenau and Yusko, 1995). According to the study by Lubenau and Yusko (1998), information from the scrap metal industry, and the NMED database, 17 melting accidents involving cesium-137 occurred between 1984 and 2001 in the U.S. In these accidents, where the activity is known, the average activity of cesium-137 per accident is 13GBq (0.35Ci), with a maximum amount of 56Gbq (1.5 Ci). The last accident happened in 1997 and no accident was reported for 2000 (Lubenau and Yusko 1998; Turner qtd in Hamlin March 27, 2003, INEEL). Therefore, all sources found in metal scrap factories in 2000 were assumed to go to proper waste management sites. Flow 21 is determined to be 0.008Ci and Flow 24 to be 0Ci.

7. Conclusion

7.1. Summary of cesium-137 material flow

Cesium-137 is unique in that it is totally anthropogenic. Unlike most other radioisotope, cesium-137 is not produced from its non-radioactive isotope, but from uranium. Its production results from any incidence of nuclear fission and its potential production is large compared to the amount which is commercially used – however, the cesium-137 that accounts for this difference in the U.S. goes directly to waste management sites. Almost all cesium-137 is imported, with the exception of recycled sources.

The vast majority of cesium-137 is used in irradiators. While the number of irradiators is rather small, each device contains a large amount of cesium-137. Since more than 96% of annual input consists of irradiators, only six of which are estimated to be sold annually, annual cesium input may fluctuate depending on annual irradiator sales.

The input and output of the product use stage do not quite balance. The output is very small compared to the input and a large amount of cesium-137 accumulates as stock, even taking radioactive decay into account.

This small output from the product use stage is largely because of a problem in waste management. There are not many options for disposing of devices containing cesium-137, and those that exist are expensive. The larger the source, the more problematic the disposal; no permanent disposal site for GTCC waste exists at this time. The greatest disposal problem is posed by irradiators, which use the most cesium-137.

Recycling is a good option but volumes of cesium-137 recycled are estimated to be small (1,514Ci), relative to the amounts used (41,000Ci). Only 3.7% of cesium-137 comes from recycled sources.

7.2. Conclusion

The following are local conclusions and possible further discussions from analysis on this paper.

- Cesium-137 is produced anyway as a fission byproduct. Quantity of reaction is not decided by the demand for cesium-137, but probably by the demand for electricity or research; therefore, reducing the demand for cesium-137 does not mean reducing the amount produced.
- In the U.S. all commercial cesium-137 is imported, so reducing the use of cesium-137 in the U.S. results in reducing cesium-137 coming to the U.S.
- In security point of view, the important thing is how to manage the safety of use and circulation. Non-commercial cesium-137 is classified as high-level waste, while commercial cesium-137 used at various places with various level of management.
- Recycling is a good option since it can reduce the amount of cesium-137 entering the U.S. At the same time, it diversifies disposal options and helps reduce unwanted stock, which can become orphaned sources.
- Most of the government owned data about radioisotope are ongoing base and not available in annual bases (people can get the status of today, but not status of, for example, year 2000). Data archive, at least once a year, will be helpful for future analysis.
- Since radioactive materials are national concern, complete national data including information about devices in agreement states would be helpful in creating appropriate policies. While keeping agreement-states autonomy system, the gathering of basic information from agreement states and construction of a database at the national level is encouraged. Information gathered should include at least data on number of devices, their use, and their radioactivity.
- Current licensing system does not track the actual amount, but only the maximum amount licensees can store or handle. Therefore, most of the figures in the product use stage in this report have to be estimated by an average activity of the devices, rather than using actual amounts. Some sort of amount tracking system would be helpful for more detailed material flow analysis.

Appendix A :

Cesium-137 Produced by U.S. Commercial Nuclear Power Reactors

Part A					Part B		
Unit	Operating Utility	Licensed MWt	Net MDC [*1]	Capacity Factor (%) Year 2000	Net MDC x Cap Factor [*2]	Cs-137 (g) [*3]	Cs-137 (Ci) [*4]
Arkansas Nuclear 1	Entergy Operations, Inc.	2,568	836	87.3	730	5,694	501,072
Arkansas Nuclear 2	Entergy Operations, Inc.	2,815	858	69.9	600	4,680	411,840
Beaver Valley 1	FirstEnergy Nuclear Operating Company	2,652	810	82.7	670	5,226	459,888
Beaver Valley 2	FirstEnergy Nuclear Operating Company	2,652	810	86.5	701	5,468	481,166
Braidwood 1	Exelon Generating Co., LLC	3,411	1,116	96.4	1,076	8,393	738,566
Braidwood 2	Exelon Generating Co., LLC	3,411	1,116	98.4	1,098	8,564	753,667
Browns Ferry 1	Tennessee Valley Authority	3,293	0	0	0	0	0
Browns Ferry 2	Tennessee Valley Authority	3,293	1,118	99.1	1,108	8,642	760,531
Browns Ferry 3	Tennessee Valley Authority	3,293	1,118	92.6	1,035	8,073	710,424
Brunswick 1	Progress Energy	2,558	820	93.7	768	5,990	527,155
Brunswick 2	Progress Energy	2,558	811	99	803	6,263	551,179
Byron 1	Excelon Generation Co., LLC	3,411	1,114	95.7	1,066	8,315	731,702
Byron 2	Excelon Generation Co., LLC	3,411	1,114	103.1	1,149	8,962	788,674
Callaway	AmerenUE	3,565	1,143	101.1	1,156	9,017	793,478
Calvert Cliffs 1	Calvert Cliffs Nuclear Power Plant Inc.	2,700	825	89	734	5,725	503,818
Calvert Cliffs 2	Calvert Cliffs Nuclear Power Plant Inc.	2,700	835	100.8	842	6,568	577,949
Catawba 1	Duke Power Co.	3,411	1,129	90	1,016	7,925	697,382
Catawba 2	Duke Power Co.	3,411	1,129	90.6	1,023	7,979	702,187
Clinton	AmerGen Energy Co.	2,894	930	84.3	784	6,115	538,138
Columbia Generating Station	Energy Northwest	3,486	1,107	88.5	980	7,644	672,672
Comanche Peak 1	TXU Electric & Gas	3,411	1,150	95.2	1,095	8,541	751,608
Comanche Peak 2	TXU Electric & Gas	3,445	1,150	87.8	1,010	7,878	693,264

Part A					Part B		
Unit	Operating Utility	Licensed MWt	Net MDC *1	Capacity Factor (%) Year 2000	Net MDC x Cap Factor *2	Cs-137 (g) *3	Cs-137 (Ci) *4
Cooper	Nebraska Public Power District	2,381	758	70.6	535	4,173	367,224
Crystal River 3	Progress Energy	2,544	843	97.2	819	6,388	562,162
Davis-Besse	FirstEnergy Nuclear Operating Co.	2,772	873	87.4	763	5,951	523,723
D.C. Cook 1	Indiana/Michigan Power Co.	3,250	1,020	1.5	15	117	10,296
D.C. Cook 2	Indiana/Michigan Power Co.	3,411	1,090	51.4	560	4,368	384,384
Diablo Canyon 1	Pacific Gas & Electric Co.	3,338	1,073	83.3	894	6,973	613,642
Diablo Canyon 2	Pacific Gas & Electric Co.	3,411	1,087	96.2	1,046	8,159	717,974
Dresden 2	Excelon Generation Co., LLC	2,527	784	101.3	794	6,193	545,002
Dresden 3	Excelon Generation Co., LLC	2,527	784	93.7	735	5,733	504,504
Duane Arnold	Nuclear Management Company	1,658	520	97.5	507	3,955	348,005
Edwin I. Hatch 1	Southern Nuclear Operating Co.	2,763	863	84.5	729	5,686	500,386
Edwin I. Hatch 2	Southern Nuclear Operating Co.	2,763	878	89.5	786	6,131	539,510
Fermi 2	Detroit Edison Co.	3,430	1,129	86.2	973	7,589	667,867
Fort Calhoun	Omaha Public Power District	1,500	476	92.8	442	3,448	303,389
Ginna	Rochester Gas & Electric Corp.	1,520	480	90.5	434	3,385	297,898
Grand Gulf 1	Entergy Operations, Inc.	3,833	1,204	100.6	1,211	9,446	831,230
H.B. Robinson 2	Progress Energy	2,300	683	104	710	5,538	487,344
Hope Creek 1	PSEG Nuclear, LLC & Gas Co.	3,293	1,031	80.3	828	6,458	568,339
Indian Point 2	Consolidated Edison Co.	3,071	951	12.1	115	897	78,936
Indian Point 3	New York Power Authority	3,025	965	99.5	960	7,488	658,944
James A. FitzPatrick	New York Power Authority	2,536	813	84.4	686	5,351	470,870
Joseph M. Farley 1	Southern Nuclear Operating Co.	2,775	847	71.5	606	4,727	415,958
Joseph M. Farley 2	Southern Nuclear Operating Co.	2,775	852	100	852	6,646	584,813
Kewaunee	Nuclear Management Co.	1,650	498	82.7	412	3,214	282,797

Part A					Part B		
Unit	Operating Utility	Licensed MWt	Net MDC *1	Capacity Factor (%) Year 2000	Net MDC x Cap Factor *2	Cs-137 (g) *3	Cs-137 (Ci) *4
La Salle County 1	Excelon Generation Co., LLC	3,323	1,077	99.6	1,073	8,369	736,507
La Salle County 2	Excelon Generation Co., LLC	3,323	1,087	92.4	1,004	7,831	689,146
Limerick 1	Excelon Generation Co., LLC	3,458	1,134	89.5	1,015	7,917	696,696
Limerick 2	Excelon Generation Co., LLC	3,458	1,115	99	1,104	8,611	757,786
McGuire 1	Duke Power Co.	3,411	1,129	103.4	1,167	9,103	801,029
McGuire 2	Duke Power Co.	3,411	1,129	87.5	988	7,706	678,163
Millstone 2	Dominion Nuclear Connecticut, Inc.	2,700	871	81.7	712	5,554	488,717
Millstone 3	Dominion Nuclear Connecticut, Inc.	3,411	1,137	99.9	1,136	8,861	779,750
Monticello	Nuclear Management Co.	1,775	615	83.6	514	4,009	352,810
Nine Mile Point 1	Niagara Mohawk Power Corp.	1,850	565	94.3	533	4,157	365,851
Nine Mile Point 2	Niagara Mohawk Power Corp.	3,467	1,142	81.1	926	7,223	635,606
North Anna 1	Virginia Electric & Power Co.	2,893	893	92	822	6,412	564,221
North Anna 2	Virginia Electric & Power Co.	2,893	897	101.8	913	7,121	626,683
Oconee 1	Duke Power Co.	2,568	846	84.9	718	5,600	492,835
Oconee 2	Duke Power Co.	2,568	846	100.9	854	6,661	586,186
Oconee 3	Duke Power Co.	2,568	846	88.5	749	5,842	514,114
Oyster Creek	AmerGen Energy Co.	1,930	619	71.9	445	3,471	305,448
Palisades	Consumers Energy Co.	2,530	760	89.6	681	5,312	467,438
Palo Verde 1	Arizona Nuclear Power Project	3,800	1,243	100.4	1,248	9,734	856,627
Palo Verde 2	Arizona Nuclear Power Project	3,876	1,243	87.2	1,084	8,455	744,058
Palo Verde 3	Arizona Nuclear Power Project	3,876	1,247	90.3	1,126	8,783	772,886
Peach Bottom 2	Exelon Generation Co., LLC	3,458	1,093	88.8	971	7,574	666,494
Peach Bottom 3	Exelon Generation Co., LLC	3,458	1,093	99.5	1,088	8,486	746,803
Perry 1	First Energy Nuclear Gen Co.	3,579	1,169	93.9	1,098	8,564	753,667

Part A					Part B		
Unit	Operating Utility	Licensed MWt	Net MDC [*1]	Capacity Factor (%) Year 2000	Net MDC x Cap Factor [*2]	Cs-137 (g) [*3]	Cs-137 (Ci) [*4]
Pilgrim 1	Entergy Nuclear Generation Co.	1,998	665	93.7	623	4,859	427,627
Point Beach 1	Nuclear Management Co.	1,519	515	92.3	475	3,705	326,040
Point Beach 2	Nuclear Management Co.	1,519	507	78.4	397	3,097	272,501
Prairie Island 1	Nuclear Management Co.	1,650	525	98.9	519	4,048	356,242
Prairie Island 2	Nuclear Management Co.	1,650	524	91.1	477	3,721	327,413
Quad Cities 1	Excelon Generating Co., LLC	2,511	762	91.3	696	5,429	477,734
Quad Cities 2	Excelon Generation Co., LLC	2,511	762	92.1	702	5,476	481,853
River Bend 1	Entergy Operations, Inc	2,894	936	89.4	837	6,529	574,517
Salem 1	PSEG Nuclear, LLC	3,411	1,106	92.2	1,020	7,956	700,128
Salem 2	PSEG Nuclear, LLC	3,411	1,106	86.3	954	7,441	654,826
San Onofre 2	Southern California Edison Co.	3,390	1,070	90.7	970	7,566	665,808
San Onofre 3	Southern California Edison Co.	3,390	1,080	101.6	1,097	8,557	752,981
Seabrook 1	North Atlantic Energy Service Corp.	3,411	1,161	78.1	907	7,075	622,565
Sequoyah 1	Tennessee Valley Authority	3,411	1,122	78.3	879	6,856	603,346
Sequoyah 2	Tennessee Valley Authority	3,411	1,117	92.3	1,031	8,042	707,678
Shearon Harris 1	Progress Energy	2,775	860	91	783	6,107	537,451
South Texas Project 1	STP Nuclear Operating Co.	3,800	1,250	78.2	978	7,628	671,299
South Texas Project 2	STP Nuclear Operating Co.	3,800	1,250	96.1	1,201	9,368	824,366
St. Lucie 1	Florida Power & Light Co.	2,700	839	102	856	6,677	587,558
St. Lucie 2	Florida Power & Light Co.	2,700	839	92.3	774	6,037	531,274
Summer	South Carolina Electric & Gas Co.	2,900	952	74.9	713	5,561	489,403
Surry 1	Virginia Electric & Power Co.	2,546	801	93.1	746	5,819	512,054
Surry 2	Virginia Electric & Power Co.	2,546	801	92.9	744	5,803	510,682
Susquehanna 1	PPL Susquehanna, LLC	3,441	1,090	85.4	931	7,262	639,038

Part A					Part B		
Unit	Operating Utility	Licensed MWt	Net MDC *1	Capacity Factor (%) Year 2000	Net MDC x Cap Factor *2	Cs-137 (g) *3	Cs-137 (Ci) *4
Susquehanna 2	PPL Susquehanna, LLC	3,441	1,094	97.3	1,064	8,299	730,330
Three Mile Island 1	AmerGen Energy Co.	2,568	786	103.5	814	6,349	558,730
Turkey Point 3	Florida Power & Light Co.	2,300	693	93.4	647	5,047	444,101
Turkey Point 4	Florida Power & Light Co.	2,300	693	91.9	637	4,969	437,237
Vermont Yankee	VT Yankee Nuclear Power Corp.	1,593	506	101.5	514	4,009	352,810
Vogtle 1	Southern Nuclear Operating Co.	3,565	1,149	91.2	1,048	8,174	719,347
Vogtle 2	Southern Nuclear Operating Co.	3,565	1,162	102.4	1,190	9,282	816,816
Waterford 3	Entergy Operations, Inc.	3,390	1,075	89.8	965	7,527	662,376
Watts Bar 1	Tennessee Valley Authority	3,411	1,118	92.4	1,033	8,057	709,051
Wolf Creek 1	Wolf Creek Nuclear Operating Corp.	3,565	1,170	88.3	1,033	8,057	709,051

TOTAL	86,080	671,424	59,085,312

Source

Part A: Appendix A, U.S. Commercial Nuclear Power Reactors, *Information Digest 2001 Edition (NUREG 1350, Vol. 13) http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v13/#_1_55*

Part B: Estimated figures from data in Part A

Note

*1 Net Maximum Dependable Capacity (MDC). Dependable main-unit net capacity, winter or summer, whichever is smaller. The normal station service loads are deducted from total capacity. The dependable capacity varies because the unit efficiency varies during the year because of temperature variations in cooling water. It is the gross electrical output as measured at the output terminals of the turbine generator during the most restrictive seasonal conditions (usually summer).

*2 Net MDC is used rather than Licensed MWt to get a conservative estimate.

*3 One-gigawatt reactor discharges 9kg of cesium-135 per year (R.Garwin and G. Charpak, 121). The yield of cesium-135 and cesium-137 are about 7% and 6% respectably in terms of number of atoms (INEEL, 2001). And the amount is considered roughly proportional to the capacity. Therefore, reactors produce 7.8g of cesium-137 per one mega-watt of capacity.

*4 Specific activity of cesium-137 is 88Ci/g (Ferguson, Kazi, and Perera, 16).

Appendix B : List of Research Reactors in the U.S.

Part A										Part B			
Facility Name	Owner	Operator	Licensing	Thermal Power (kW)	Type	Hours per Day	Days per Week	Weeks per Year	MW Days per Year	Utili -zation ratio *1	MW year *2	Cs-137 (g) *3	Cs-137 (Ci) *4
COMET	USDOE	COMET ASSEMBLY, LOS ALAMOS NATIONAL LAB	USDOE	0	CRIT ASSEMBLY	2	1	12	0	0.3%	0	0	0
PSBR PENN ST. UNIV.	THE PENNSYLVANIA STATE UNIVERSITY	THE PENNSYLVANIA STATE UNIVERSITY	USNRC	1,000	TRIGA MARK CONV	8	5	50	13	22.9%	0.036	0.28	24
HONEYCOMB	USDOE	HONEYCOMB ASSEMBLY, LOS ALAMOS NATIONAL LAB.	USDOE	0	CRIT ASSEMBLY	0	0	0	0	0.0%	0	0	0
AGN-201 TEXAS A&M UNIV.	TEXAS A & M UNIVERSITY	TEXAS A & M UNIVERSITY	USNRC	0.01	HOMOG (S)	0	0	0	0	0.0%	0	0	0
FLATTOP	USDOE	FLATTOP ASSEMBLY, LOS ALAMOS NATIONAL LAB	USDOE	0.1	CRIT ASSEMBLY	3	1	18	0	0.6%	> 0.001	> 0.01	> 1
FNR	UNIVERSITY OF MICHIGAN	UNIVERSITY OF MICHIGAN	USNRC	2,000	POOL	24	5	50	500	68.7%	1.370	10.68	940
NTR GENERAL ELECTRIC	GENERAL ELECTRIC COMPANY	VALLECITOS NUCLEAR CENTER	USNRC	100	GRAPHITE	3	5	50	3	8.6%	0.008	0.06	6
MITR-II MASS. INST. TECH.	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	USNRC	4,900	TANK	24	7	45	1,200	86.5%	3.288	25.64	2,257
UNIV. ARIZONA TRIGA	UNIVERSITY OF ARIZONA	UNIVERSITY OF ARIZONA	USNRC	100	TRIGA MARK I	3	2	42	0	2.9%	0.003	0.02	2
UFTR UNIV. FLORIDA	UNIVERSITY OF FLORIDA	UNIVERSITY OF FLORIDA	USNRC	100	ARGONAUT	8	5	50	1	22.9%	0.003	0.02	2
TRIGA, VET. ADMIN.	US DEPARTMENT OF VETERAN AFFAIRS	US DEPARTMENT OF VETERAN AFFAIRS MEDICAL CENTER	USNRC	20	TRIGA MARK I	?	?	?	?	?	?	?	?
WPI	WORCESTER POLYTECHNIC INSTITUTE	WORCESTER POLYTECHNIC INSTITUTE	USNRC	10	POOL	2	3	30	0	2.1%	> 0.001	> 0.01	> 1

Part A										Part B			
Facility Name	Owner	Operator	Licensing	Thermal Power (kW)	Type	Hours per Day	Days per Week	Weeks per Year	MW Days per Year	Utili-zation ratio *1	MW year *2	Cs-137 (g) *3	Cs-137 (Ci) *4
MUTR UNIV. MARYLAND	UNIVERSITY OF MARYLAND	UNIV. OF MARYLAND, DEPT. OF MATERIALS & NUC. ENG.	USNRC	250	TRIGA MODIFIED	4	5	48	0	11.0%	0.027	0.21	19
WSUR WASHINGTON ST. UNIV.	WASHINGTON STATE UNIVERSITY	WASHINGTON STATE UNIVERSITY	USNRC	1,000	TRIGA CONV	9	3	50	34	15.5%	0.093	0.73	64
OSURR OHIO ST. UNIV.	THE OHIO STATE UNIVERSITY	NUCLEAR REACTOR LABORATORY	USNRC	500	POOL	4	5	52	7	11.9%	0.019	0.15	13
UWNR UNIV. WISCONSIN	UNIVERSITY OF WISCONSIN	UNIVERSITY OF WISCONSIN, DEPT. OF ENG. PHYSICS	USNRC	1,000	TRIGA CONV	6	5	52	23	17.9%	0.063	0.49	43
UMRR	UNIVERSITY OF MISSOURI-ROLLA	UNIV. OF MISSOURI-ROLLA, NUC. REACTOR FACILITY	USNRC	200	POOL, MTR	5	4	48	10	11.0%	0.027	0.21	19
AFRRI TRIGA	UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES	ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE	USNRC	1,000	TRIGA MARK F	8	5	47	8	21.5%	0.022	0.17	15
NSCR TEXAS A&M UNIV.	Texas A&M University System	NUCLEAR SCIENCE CENTER, TEXAS A&M UNIVERSITY	USNRC	1,000	TRIGA CONV	11	5	50	90	31.5%	0.247	1.92	169
PUR-1 PURDUE UNIV.	PURDUE UNIVERSITY	PURDUE UNIVERSITY, SCHOOL OF NUC. ENGINEERING	USNRC	1	POOL	3	1	25	0	0.9%	> 0.001	> 0.01	> 1
TRIGA CORNELL	CORNELL UNIVERSITY	CORNELL UNIV., WARD CENTER FOR NUC. SCIENCES	USNRC	500	TRIGA MARK II	7	5	50	4	20.0%	0.011	0.09	8
KSU TRIGA MK II	KANSAS STATE UNIVERSITY	KANSAS STATE UNIVERSITY, MECH./NUCLEAR ENG.	USNRC	250	TRIGA MARK II	2	5	50	2	5.7%	0.005	0.04	4
FAST BURST (FBR)	US DEPARTMENT OF DEFENCE	US ARMY	USDOE	10,000	FAST BURST	0	0	0	0	0.0%	0	0	0
RPI RENSSELAER	RENSSELAER POLYTECHNIC INSTITUTE	RENSSELAER POLYTECHNIC INSTITUTE	USNRC	0.1	CRIT ASSEMBLY	0	0	0	0	0.0%	0	0	0

Part A										Part B			
Facility Name	Owner	Operator	Licensing	Thermal Power (kW)	Type	Hours per Day	Days per Week	Weeks per Year	MW Days per Year	Utili -zation ratio [*1]	MW year [*2]	Cs-137 (g) [*3]	Cs-137 (Ci) [*4]
ATRC	USDOE	BECHTEL BWXT Idaho, LLC, ATRC REACTOR	USDOE	5	POOL	0	2	24	0	0.0%	0	0	0
ARRR	OEA, INC.	AEROTEST OPERATIONS INC.	USNRC	250	TRIGA CONV	14	5	52	30	41.7%	0.082	0.64	56
RINSC RHODE ISLAND NSC	RHODE ISLAND ATOMIC ENERGY COMMISSION	RHODE ISLAND NUCLEAR SCIENCE CENTER	USNRC	2,000	POOL	4	2	52	35	4.8%	0.096	0.75	66
HFIR	USDOE	ORNL- RESEARCH REACTORS DIVISION	USDOE	85,000	TANK	24	7	35	21,000	67.3%	57.534	448.77	39,492
AGN-201 UNIV. NEW MEXICO	UNIVERSITY OF NEW MEXICO	UNIVERSITY OF NEW MEXICO, CHEMICAL & NUCLEAR ENG.	USNRC	0.01	HOMOG (S)	5	1	15	0	0.9%	> 0.001	> 0.01	> 1
MURR UNIV. OF MISSOURI	UNIVERSITY OF MISSOURI	RESEARCH REACTOR CENTER	USNRC	10,000	TANK IN POOL	24	6	52	3,285	85.7%	9.000	70.20	6,178
AGN-201 IDAHO ST. UNIV.	IDAHO STATE UNIVERSITY	IDAHO STATE UNIVERSITY, LILLIBRIDGE ENG. LAB	USNRC	0.01	HOMOG (S)	2	4	32	0	2.9%	> 0.001	> 0.01	> 1
GODIVA	USDOE	GODIVA ASSEMBLY, LOS ALAMOS NATIONAL LAB	USDOE	1	CRIT ASSEMBLY	4	1	14	0	0.6%	> 0.001	> 0.01	> 1
OSTR, OREGON STATE UNIV.	OREGON STATE UNIVERSITY	RADIATION CENTER, OREGON STATE UNIVERSITY	USNRC	1,100	TRIGA MARK II	7	5	52	40	20.8%	0.110	0.85	75
SPR II	USDOE	SANDIA NATIONAL LABORATORIES	USDOE	5	FAST BURST	0	0	0	0	0.0%	0	0	0
ANN. CORE RES. REACTOR (ACRR)	USDOE	SANDIA NATIONAL LABORATORIES	USDOE	4,000	TRIGA ACPR	8	5	50	4	22.9%	0.011	0.09	8
ATR	USDOE	Becht BWXT Idaho,LLC, ADVANCED TEST REACTOR	USDOE	250,000	TANK	24	7	52	0	100.0%	250.000	1,950.00	171,600
DOW TRIGA	DOW CHEMICAL COMPANY	DOW CHEMICAL COMPANY	USNRC	300	TRIGA MARK I	8	5	51	2	23.4%	0.005	0.04	4

Part A										Part B			
Facility Name	Owner	Operator	Licensing	Thermal Power (kW)	Type	Hours per Day	Days per Week	Weeks per Year	MW Days per Year	Utili -zation ratio *1	MW year *2	Cs-137 (g) *3	Cs-137 (Ci) *4
NBSR	NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY	NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY	USNRC	20,000	HEAVY WATER	24	7	35	5,000	67.3%	13.699	106.85	9,403
APRFR	DEPARTMENT OF DEFENSE	ARMY PULSED RADIATION FACILITY, U. S. ARMY	USDOD	10	FAST BURST		5	50		0.0%	0	0	0
RRF REED COLLEGE	REED COLLEGE	REED REACTOR FACILITY, REED COLLEGE	USNRC	250	TRIGA MARK I	1	3	50	40	1.7%	0.110	0.85	75
GSTR GEOLOGICAL SURVEY	U.S. DEPARTMENT OF INTERIOR	U.S. GEOLOGICAL SURVEY	USNRC	1,000	TRIGA MARK I	5	4	50	42	11.4%	0.115	0.90	79
UCI, IRVINE	UNIVERSITY OF CALIFORNIA, IRVINE	UNIVERSITY OF CALIFORNIA, DEP. OF CHEMISTRY	USNRC	250	TRIGA MARK I	1	6	50	2	3.4%	0.005	0.04	4
BIG TEN	USDOE	BIG TEN FACILITY, LOS ALAMOS NATIONAL LABORATORY	USDOE	5	CRIT ASSEMBLY	3	1	18	0	0.6%	> 0.001	> 0.01	> 1
PULSTAR N.C. STATE UNIV.	NORTH CAROLINA STATE UNIVERSITY	NORTH CAROLINA STATE UNIVERSITY	USNRC	1,000	POOL, PULSTAR	8	5	50	1,000	22.9%	2.740	21.37	1,881
MARS	USDOE	MARS FACILITY, LOS ALAMOS NATIONAL LAB	USDOE	0	CRIT ASSEMBLY	0	0	0	0	0.0%	0	0	0
UMLR UNIV. MASS. LOWELL	UNIVERSITY OF MASSACHUSETTS LOWELL	UNIVERSITY OF MASSACHUSETTS LOWELL	USNRC	1,000	POOL	6	3	45	40	9.3%	0.110	0.85	75
SPR III	USDOE	SANDIA NATIONAL LABORATORIES	USDOE	10	FAST BURST	8	5	20	0	9.2%	> 0.001	> 0.01	> 1
TRIGA UNIV. UTAH	UNIVERSITY OF UTAH	CENTER FOR EX. IN NUC. TECH., ENG., & RES. (CENTER)	USNRC	100	TRIGA MARK I	1	2	50	10	1.1%	0.027	0.21	19
NRAD	USDOE	ARGONNE NATIONAL LABORATORY	USDOE	250	TRIGA MARK II	8	5	20	6	9.2%	0.016	0.13	11
FAST BURST (SKUA)	USDOE	LOS ALAMOS NATIONAL LABORATORY	USDOE	1	FAST BURST	0	0	0	0	0.0%	0	0	0

Part A										Part B			
Facility Name	Owner	Operator	Licensing	Thermal Power (kW)	Type	Hours per Day	Days per Week	Weeks per Year	MW Days per Year	Utili-zation ratio [*1]	MW year [*2]	Cs-137 (g) [*3]	Cs-137 (Ci) [*4]
SHEBA	USDOE	LOS ALAMOS NATIONAL LABORATORY	USDOE	2	HOMOG (L)	4	1	52	0	2.4%	> 0.001	> 0.01	> 1
UC DAVIS / MCCLELLAN N. RAD. CENTER	UNIVERSITY OF CALIFORNIA	UNIVERSITY OF CALIFORNIA AT DAVIS	USNRC	2,000	TRIGA MARK II	15	5	48	300	41.2%	0.822	6.41	564
TRIGA II UNIV. TEXAS	UNIVERSITY OF TEXAS AT AUSTIN	NUCLEAR ENG. TEACHING LAB	USNRC	1,100	TRIGA MARK II	6	5	45	200	15.5%	0.548	4.27	376

TOTAL[*5]	340.252	2,653.97	233,549

Source:
Part A:
International Atomic Energy Agency Research Reactor Database
http://www.iaea.org/worldatom/rrdb/ retrieved on June 9, 2003
Nuclear Regulatory Commission, Appendix E U.S. Commercial Nuclear Power Reactors, Information Digest 2001 Edition (NUREG 1350, Vol. 13).
http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v13/#_1_55 retrieved on May 12, 2003.
Part B:
Estimated figures from data in Part A
Note:
*1 It shows the percentage of time when reactor is under operation in the year, calculated as "([Hours per Day] / 24) x ([Days per Week] / 7) x ([Weeks per Year] / 52)"
*2 Calculated as "[MW Days per Year] / 365", where available. If not, calculated as "([Thermal Power] / 1,000) x [Utilization ratio]"
*3 One-gigawatt reactor discharges 9kg of cesium-135 per year (R.Garwin and G. Charpak, 121). The yield of cesium-135 and cesium-137 are about 7% and 6% respectably in terms of number of atoms (INEEL, 2001). And the amount is considered roughly proportional to the capacity. Therefore, reactors produce 7.8g of cesium-137 per one mega-watt of capacity.
*4 Specific activity of cesium-137 is 88Ci/g (Ferguson, Kazi, and Perera, 16).

Appendix C : List of nuclear powered ships/submarines in the U.S. as of June 1st, 2000

Part A										Part B			
		Reactor(s) per ship			Propulsion per ship								
Class	Type[*1]	Manufacturer	Type	Q'ty	No. of Turbine	No. of Shaft	Size (hp)	Size (MW)	Q'ty of ships	Estimated Reactor Size (MWt) [*2]	Estimated Reactor Size Total (MWt)	Cs-137 (g) [*3]	Cs-137 (Ci) [*4]
Sturgeon	SSN	Westinghouse	S5W	1	2	1	15,000	11.2	2	34.89	69.78	544	47,872
Benjamin Franklin	SSN	Westinghouse	S5W	1	2	1	15,000	11.2	1	34.89	34.89	272	23,936
Seawolf	SSN	Westinghouse	S6W	1	2	1	45,000	33.57	2	104.58	209.16	1,631	143,528
Los Angeles	SSN	GE	S6G	1	2	1	35,000	26	51	81.00	4,131.00	32,222	2,835,536
Ohio	SSBN	GE	S8G	1	2	1	60,000	44.8	18	139.56	2,512.08	19,594	1,724,272
Nimitz	CVN	Westinghouse / GE	A4W / A1G	2	4	4	260,000	194	8	604.36	4,834.88	37,712	3,318,656
Enterprise	CVN	Westinghouse	A2W	8	4	4	280,000	209	1	651.09	651.09	5,079	446,952
NR1	RS	?	?	1	?	?	?	?	1	?	?	?	?

Total	84	Total[*5]	12,442.88	97,054	8,540,752

Source:
Part A: Sharpe, Richard ed., Jane's fightingships 2000-2001
Part B: Estimated figures from data in Part A
Note:
*1 SSN: Attack Submarine, SSBN: Strategic Missile Submarine, CVN: Multipurpose Aircraft Carriers, RS: Research Submarine
*2 Thermal efficiency of 32.1% is used (DOE, 2002).
*3 One-gigawatt reactor discharges 9kg of cesium per year (R.Garwin and G. Charpak, 121). The yield of cesium-135 and cesium-137 are about 7% and 6% respectably in terms of number of atoms (INEEL, 2001). And the amount is considered roughly proportional to the capacity. Therefore, reactors produce 7.8g of cesium-137 per one mega-watt of capacity.
*4 Specific activity of cesium-137 is 88Ci/g (Ferguson, Kazi, and Perera, 16).
*5 Excluding “NR1”, whose reactor data are not available.

Appendix D : List of regulations governing byproduct materials

1. Items exempted from regulation scheme

Part No. and title		Cs-137 applica-bility	Condition (person)	Condition (device)	Condition (activity)
30.11	Specific exemptions.	Y	The Commission may, upon application of any interested person or upon its own initiative, grant such exemptions		
30.11	Specific exemptions.	Y	Any	Any	Activities licensed under the requirements of part 72 (the independent storage of spent nuclear fuel and high-level radioactive waste)
30.11	Specific exemptions.	Y	DOE	Any	Activities subject to the requirements of part 60 (Disposal of high-level radioactive wastes in geologic repositories) or 63 (Ditto, at Yucca Mountain, Nevada)
30.11	Specific exemptions.	Y	Any	Any	Activities subject to the requirements of part 61 (land disposal of [low-level] radioactive waste)
30.12	Persons using byproduct material under certain Department of Energy and Nuclear Regulatory Commission contracts.	Y	Any prime contractor or subcontractor of the Department or the Commission	Any	Manufacturer, produce, transfer, receive, acquire, owns, possess, or use
30.13	Carriers.	Y	Common and contract carriers, freight forwarders, warehousemen, and the U.S. Postal Service	Any	Transport or store byproduct material in the regular course of carriage for another or storage incident thereto
30.14	Exempt concentrations.	N			

Part No. and title		Cs-137 applica-bility	Condition (person)	Condition (device)	Condition (activity)
30.15	Certain items containing byproduct material.	Y	Any	Electron tubes (< 5μCi), Ionizing radiation measuring instruments for purposes of internal calibration or standardization (< 10μCi)	Receive, possess, use, transfer, own, or acquire
30.16	Resins containing scandium-46 and designed for sand-consolidation in oil wells.	N			
30.18	Exempt quantities.	Y	Any	< 10μCi	Receive, possess, use, transfer, own, or acquire
30.19	Self-luminous products containing tritium, krypton-85, or promethium-147.	N			
30.20	Gas and aerosol detectors containing byproduct material.	N			
30.21	Radioactive drug: Capsules containing carbon-14 urea for “in vivo” diagnostic use for humans.	N			

2. Items governed by general license

Part No. and title		Cs-137 applica-bility	Condition (person)	Condition (device)	Condition (activity)
31.5	Certain detecting, measuring, gauging, or controlling devices and certain devices for producing light or an ionized atmosphere.	Y	Any	Devices designed and manufactured for the purpose of detecting, measuring, gauging or controlling thickness, density, level, interface location, radiation, leakage, or qualitative or quantitative chemical composition	Acquire, receive, possess, use or transfer
31.6	General license to install devices generally licensed in §31.5.	Y	Any person who holds a specific license issued by an Agreement State	Devices generally licensed in §31.5.	Install and service such device in any non-Agreement State
31.7	Luminous safety devices for use in aircraft.	N			
31.8	Americium - 241 in the form of calibration or reference sources.	N			
31.9	General license to own byproduct material.	Y	Any	Any	Own
31.10	General license for strontium 90 in ice detection devices.	N			
31.11	General license for use of byproduct material for certain in vitro clinical or laboratory testing.	N			

3. Items governed by specific license

Part No. and title		Cs-137 applica-bility	Condition (person)	Condition (device)	Condition (activity)
32.11	Introduction of byproduct material in exempt concentrations into products or materials, and transfer of ownership or possession: Requirements for license.	N			
32.14	Certain items containing byproduct material; requirements for license to apply or initially transfer.	Y	Any	The products specified in §30.15	Apply byproduct material to, or to incorporate byproduct material into, or to initially transfer for sale or distribution
32.17	Resins containing scandium - 46 and designed for sand-consolidation in oil wells: Requirements for license to manufacture, or initially transfer for sale or distribution.	N			
32.18	Manufacture, distribution and transfer of exempt quantities of byproduct material: Requirements for license.	Y	Any	[The products specified in] §30.18	Manufacture, process, produce, package, repackage, or transfer for commercial distribution
32.21	Radioactive drug: Manufacture, preparation, or transfer for commercial distribution of capsules containing carbon-14 urea each for "in vivo" diagnostic use for humans to persons exempt from licensing; Requirements for a license.	N			
32.22	Self-luminous products containing tritium, krypton-85 or promethium-147: Requirements for license to manufacture, process, produce, or initially transfer.	N			
32.26	Gas and aerosol detectors containing byproduct material: Requirements for license to manufacture, process, produce, or initially transfer.	N			
32.51	Byproduct material contained in devices for use under §31.5; requirements for license to manufacture or initially transfer.	Y	Any	31.5 Certain detecting, measuring, gauging, or controlling devices and certain devices for producing light or an ionized atmosphere.	Manufacture, or initially transfer

Part No. and title		Cs-137 applicability	Condition (person)	Condition (device)	Condition (activity)
32.53	Luminous safety devices for use in aircraft: Requirements for license to manufacture, assemble, repair or initially transfer.	N			
32.57	Calibration or reference sources containing americium - 241: Requirements for license to manufacture or initially transfer.	N			
32.61	Ice detection devices containing strontium-90; requirements for license to manufacture or initially transfer.	N			
32.71	Manufacture and distribution of byproduct material for certain in vitro clinical or laboratory testing under general license.	N			
32.72	Manufacture, preparation, or transfer for commercial distribution of radioactive drugs containing byproduct material for medical use under part 35.	Y?	Any	Radioactive drugs	Manufacture, prepare, or transfer for commercial distribution
32.74	Manufacture and distribution of sources or devices containing byproduct material for medical use.	Y	Any	A calibration or reference source or for the uses listed in §§35.400 [(brachytherapy)] and 35.500 [(diagnosis)], 35.600 [(a remote afterloader unit, teletherapy unit, or gamma stereotactic radiosurgery unit)]	Manufacture and distribute
33.11	Types of specific licenses of broad scope.	Y	Any	Type A: Any quantity Type B: < 0.1Ci Type C: < 0.001Ci	Receipt, acquisition, ownership, possession, use, and transfer
34.13	Specific license for industrial radiography.	Y	Any	Licensed material in industrial radiography	Use
35.11	License required.	Y	Any	Byproduct material for medical use	Manufacture, produce, acquire, receive, possess, prepare, use, or transfer
36.1	Specific licenses for irradiators.	Y	Any	Licensed material in an irradiator	Use
39.1	Specific licenses for well logging.	Y	Any	Licensed material in well logging	Use

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