Neptunium 237 and Americium: World Inventories and Proliferation Concerns

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Although no nation is known to have used either neptunium 237 or americium in nuclear explosives, the nuclear community has long known that explosives could be made from these materials. In November 1998, the U.S. Department of Energy (DOE) declassified the information that neptunium 237 and americium can be used for a nuclear explosive device. France, and perhaps other nuclear weapon states, may have tested a nuclear explosive using neptunium 237 or conducted experiments involving neptunium 237 during nuclear explosive tests.

As of the end of 2003, the world inventory of neptunium 237 and americium was estimated to exceed 140 tonnes (metric tons), enough for more than 5,000 nuclear weapons, and the amount is growing at a rate of about 7 tonnes per year. Almost all neptunium and americium is in irradiated fuel or mixed with high level nuclear waste. Only relatively small quantities of these materials have been separated into forms usable in nuclear weapons.

But concerns that this situation could be changing first emerged internationally in the late 1990s. By then, several key countries, including several non-nuclear weapon states, had stepped up research into the removal of these and other actinides from radioactive nuclear waste. Their goal has been to learn to separate these radioactive materials from fission products in order to ease nuclear waste disposal and to use these materials later as fuel in fast reactors. Besides giving non-nuclear weapon states a potentially unsafeguarded stock of nuclear explosive material, the separation of neptunium and americium could encourage their commercial use, and thus also increase international commerce in these materials, raising concerns about terrorism.

In response, the International Atomic Energy Agency (IAEA) has instituted a monitoring program in non-nuclear weapon states to track the currently small stocks of separated neptunium and americium. If the stocks become significant, the monitoring system is designed to provide early warning, allowing the IAEA to increase the level of monitoring as necessary.

Properties of Neptunium and Americium

Nuclear weapon states and other states, such as Australia, have long agreed that neptunium 237 can be used in a nuclear explosive. However, states have differed over the usefulness of americium in nuclear explosives. Russia and France have challenged its

usefulness in a nuclear explosive, while the United States has stated that americium can in fact be used in nuclear explosives.

Neptunium 237 can be separated from irradiated reactor fuel as a single isotope. Americium separated from reactor fuel would be composed of americium 241, americium 242m, and americium 243, although older spent power reactor spent fuel contains mostly americium 241. Pure americium 241 can also be extracted from aged separated plutonium.

Table 1 summarizes several physical properties of neptunium 237 and the key isotopes of americium, as well as the corresponding properties of the relevant isotopes of plutonium and uranium. This information is from documents prepared by the IAEA in the late 1990s that are derived from open sources. According to IAEA documents, this information is consistent with that provided to the IAEA by experts from two nuclear weapon states.

A comparison of the physical properties of neptunium and americium with those of plutonium 239 and uranium 235, the principal isotopes in nuclear explosives, supports the view that they can be used in nuclear explosives. The critical masses of neptunium 237 and americium 241 are similar to that of uranium 235. According to the IAEA, their significant quantities would also be similar to the significant quantity for uranium 235 in highly enriched uranium (HEU), namely 25 kilograms.[1]

Neptunium in metal form is easier to compress than HEU. With a half-life of more than two million years, neptunium 237 has no heat properties that would complicate its use in a nuclear explosive. Because it has a low neutron background, it could also be used in a gun-type device, although a larger quantity would be required.

The debate over the usefulness of americium in a nuclear explosive centers on its heat production and radiation emission values. Critics compare it to plutonium 238, which is viewed as unsuitable for use in nuclear explosives because of its high heat rate. However, advocates state that the heat rate of americium 241 is one-fifth of that of plutonium 238, making the former more usable in nuclear weapons.

The United States has released the most definitive information about the use of americium in nuclear explosives. In 1998, the United States stated that it has "considered the problems posed by the heat and radiation properties of americium and believes that they could be overcome with a relatively low level of sophistication."[2] In 1999, the Department of Energy released more details about its research into this issue:

[1] "Significant quantity" is defined as the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded.

[2] Letter to Mike Pankratz, Classification Group, LANL, from W. Gerald Gibson, Office of Declassification, DOE, Germantown, MD, January 29, 1999.

> In 1994, four independent design teams from Livermore and Los Alamos [National Laboratories], involving about 16 nuclear weapon specialists, evaluated several different calculational designs that used americium as a nuclear weapon fuel. All four teams concluded that, in spite of the heat problems posed by americium, designs using americium as a nuclear weapon fuel could be made to work.[3]

Neptunium Production and Separation

Neptunium 237 is routinely produced in nuclear reactors as a result of the neutron irradiation of uranium 235 and uranium 238, the two most common constituents of nuclear fuel. It is also a decay product of americium 241.

Neptunium from Civil Reactors

Large quantities of neptunium 237 are found in spent nuclear fuel. Each year, a 1,000-megawatt-electric pressurized-water reactor (PWR) may produce about 25 tonnes of spent fuel containing about 10-12 kilograms of neptunium 237. The same spent fuel contains about 250 kilograms of plutonium. By weight, typical neptunium 237 discharges from a pressurized water reactor (PWR) are roughly four to five percent of plutonium discharges, depending on the irradiation level, or burnup, of the fuel. Magnox and Candu reactors produce significantly less neptunium, typically about 0.5 percent of plutonium discharges from these reactors.

At the end of 2003, the world's nuclear power reactors had produced almost 55 tonnes of neptunium 237. Current annual production is estimated at about three tonnes. Table 2 provides a listing by country of the estimated amount of neptunium discharged from power reactors.

Commercial reprocessing programs aimed at plutonium and uranium recovery have not separated significant amounts of neptunium, although the chemical steps to separate the neptunium are straightforward. These programs use the plutonium/uranium extraction (PUREX) process. Depending on how the PUREX process is operated, neptunium can appear in various reprocessing wastes or in the uranium or plutonium product. In current plutonium separation programs, the vast bulk of neptunium 237 enters various waste streams, principally high level waste. An exception is Japan's Tokai reprocessing plant where almost half of the neptunium ends up in the plutonium product. However, in a recent interview, Japanese officials stated that the neptunium at the nearly operational commercial-scale Rokkasho reprocessing plant will go into the high level waste and not into the plutonium product.

Through 2003, an estimated 10 tonnes of neptunium 237 have been contained in civil spent fuel that has been reprocessed. This neptunium is primarily contained in high level

[3] Letter to Mike Pandratz, op. cit.

waste. Over 60 percent of this neptunium has been processed at the La Hague reprocessing plant. Much of this neptunium came from spent fuel owned by other countries and has been or will be returned to the country of origin in the form of vitrified waste.

As table 3 shows, a large reprocessing plant, modeled on the Rokkasho reprocessing plant, would have an annual throughput of about 250 kilograms of neptunium. Almost all of the neptunium would end up in the high level waste, with a small fraction in the recovered uranium and plutonium.

Neptunium from Military Reactors

The nuclear weapon states produced neptunium 237 in their military reactors. Little, however, is known about neptunium production and separation in these programs.

The United States is estimated to have produced more neptunium in its military production reactors than the other nuclear weapon states. Because many U.S. production reactors used recycled HEU fuel instead of natural or low-enriched uranium fuel (LEU), the discharged fuel contained a higher proportion of neptunium 237 than irradiated fuel from graphite-moderated reactors, the most common type of reactor used in other nuclear weapon states.

The bulk of the US military neptunium was produced in the plutonium and tritium production reactors at the Savannah River site in South Carolina. A lesser amount was produced in the reactors at the Hanford reservation in Washington. All of these reactors are now closed. Some neptunium has also been produced in naval reactor fuel, but it is a relatively small amount. A crude estimate of total neptunium production in US military reactors is about 1-2 tonnes.[4]

[4] Based on IAEA publications, quoting declassified Hanford documents, irradiated fuel from the Hanford reactors had a neptunium content of about 1.9 grams per tonne of uranium, or about 3.8 grams of neptunium per kilogram of weapon-grade plutonium. Total weapon-grade plutonium production at the Hanford site was 54.5 tonnes, implying a total production of about 210 kilograms of neptunium. The N reactor at Hanford also produced about 13 tonnes of fuel-grade plutonium. It is crudely estimated that the neptunium concentration was roughly 0.5 percent of the plutonium, or about 65 kilograms of neptunium 237. Prior to 1968, plutonium was produced in the Savannah River reactors by using natural uranium fuel, while tritium was produced with HEU fuel. After 1968, both plutonium and tritium were produced by using HEU fuel. The Savannah River reactors, which produced both plutonium and tritium, had a much higher yield of neptunium than the Hanford reactors, because for most of their operational history they used HEU "driver" fuel that was recycled multiple times, leading to a sizeable fraction of uranium 236 in the fuel, which becomes neptunium 237 through neutron capture. A crude estimate of total neptunium production in the HEU fuel is 700 to 1,650 kilograms of neptunium. This estimate is derived by determining the energy output from the total consumption of about 50 tonnes of uranium 235 in the Savannah River reactors, or about 41 terrawatts, and applying a conversion factor of 0.17 to 0.04 grams of neptunium 237 per megawatt-thermal-day. The conversion factors are derived from W. E. Bickford, *Large-Scale Production of Pu-238 to 'Denature' Weapons-Grade Plutonium*, WSRC-TR-96-0382, Westinghouse Savannah River Company, December 2, 1996. Prior to 1968, the neptunium produced in the natural uranium fuel is estimated in a manner similar to the case of the Hanford reactors. Up to 1968, the Savannah River reactors produced about 18 tonnes of weapon-grade plutonium and about 70 kilograms of neptunium 237. The naval reactors, which use HEU fuel, also produced neptunium 237. These reactors

Neptunium was regularly recovered at the Savannah River site and periodically at the Hanford site until all US production reactors closed in the late 1980s. The primary reason for separating neptunium 237 was to obtain material that can be irradiated in a reactor to make plutonium 238, which is used in long-life thermoelectric electricity generators and heat sources in civil and military programs. After irradiation in special targets for plutonium 238 production, the remaining neptunium was also recovered and reused.

As of March 31, 1998, the Department of Energy (DOE) owned an inventory of 466 kilograms of neptunium 237, of which 351 kilograms were in separated form and 115 kilograms were in unseparated form.[5] The DOE also has an inventory of neptunium in a wide variety of nuclear waste forms at many sites. As of 2001, about 300 kilograms of neptunium were in high level nuclear waste at Hanford and the Savannah River site. Several hundred kilograms of neptunium had also been converted into plutonium 238.

The United States is planning to use its supply of separated neptunium 237 to once again make plutonium 238. The DOE has announced its intention to restart plutonium 238 production early next decade at Idaho National Laboratory.

The draft Environmental Impact Statement for the proposed action lists the available and usable amount of neptunium 237 in the DOE inventory as 300 kilograms.[6] The Idaho National Laboratory had 6 kilograms of neptunium 237. The Savannah River Site held 294 kilograms of neptunium of this material, which is being moved to the Idaho National Laboratory. The reason has not been determined for the difference of 51 kilograms between the 1998 DOE inventory of 351 kilograms of separated neptunium 237 and the amount of available and usable separated neptunium 237.

Table 4 lists the estimated amount of neptunium produced in military reactors in all nuclear weapon states. In total, these reactors have produced about 1.7 to 3 tonnes of neptunium. The estimates for the other nuclear weapon states are derived from their total weapon-grade plutonium production and information about US military production reactors. The upper bounds in the case of France and Russia assume additional production of neptunium in non-graphite-moderated military reactors. Most of the neptunium is assumed to have been separated. Russia is believed to still have an inventory of several hundred kilograms of separated neptunium remaining from its original inventory.

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used fresh HEU fuel, and the amount of neptunium production was significantly less than in the Savannah River reactors. Total production in naval reactors is estimated at less than a few hundred kilograms of neptunium 237. Adding outputs from each of these sources, the military reactors produced in total about 1 to 2 tonnes of neptunium 237 through 2003.

[5] Facsimile to David Albright from the Office of Declassification Security Affairs, DOE, April 14, 1998, listing declassified inventories of DOE-owned americium and neptunium. These inventories excluded neptunium 237 and americium in nuclear waste but included neptunium 237 in certain, recoverable spent fuel.

[6] The draft Environmental Impact Statement is available at www.consolidationeis.doe.gov. The neptunium values are from Chapter 2, "Project Description and Alternatives," Table 2-1, p. 2-6.

Russia, the United States, and other nuclear weapon states have also exported neptunium 237, although the quantities are small. From 1950 to April 1998, the United States exported only about a kilogram of separated neptunium 237 to 12 countries (see table 5). In order of amounts, the recipients of more than 98 percent of the material were Germany, Belgium, Britain, Israel, Japan, and India. Russian exports are less known; it has not provided the IAEA with an accounting of its neptunium exports before 1994.

Britain sold Iraq 200 milligrams of neptunium oxide in the 1980s. Iraq irradiated about a quarter of this material to produce plutonium 238, which it evaluated as a material for a neutron initiator for nuclear weapons. The rest of the plutonium 238 was used in reprocessing research and development activities at the Tuwaitha Nuclear Research Center south of Baghdad.

Americium Production and Separation

Americium is routinely produced in nuclear reactors. The three most important americium isotopes are americium 241, americium 242m, and americium 243. At discharge, spent fuel contains a mixture of these three isotopes. Americium 241 is also a decay product of plutonium 241, which has a relatively short half-life of 14.4 years, and constitutes up to about 15 percent of the plutonium discharged from power reactors.

Americium from Civil Reactors

Large amounts of americium are found in irradiated power reactor fuel. The total americium content of spent power reactor fuel at discharge is modest, but over time considerable amounts of americium 241 accumulate as a result of the decay of plutonium 241.

At the end of 2003, the amount of americium produced as a result of civil nuclear power reactor operation was 87 tonnes. About 68 tonnes of this americium resulted from the decay of plutonium 241 subsequent to its discharge from the reactors. Currently, the americium inventory increases by about 4 tonnes per year. Table 2 lists the amount of americium produced as a result of civil power reactor operation by country as of the end of 2003.

Americium has not been separated in civil reprocessing programs. During reprocessing, americium normally goes into the high level waste with the fission products. Americium is relatively difficult to separate from the waste using traditional chemical separation methods, although several countries are developing methods to separate americium from nuclear waste (see next section).

Americium has been separated from aged plutonium in MOX fuel fabrication plants, although the quantities are believed to be relatively small. The purpose of this separation is to reduce the radiation doses to workers during fuel fabrication. If americium

separation were performed regularly at MOX fabrication plants, a significant amount of americium could be separated. A plant with a capacity to make 40 tonnes per year of MOX fuel could separate about 90 kilograms of americium 241 each year (see table 3).

Americium from Military Programs

The nuclear weapon states have produced limited quantities of americium in their military programs. In total, such stocks are crudely estimated to contain over a tonne of americium, almost all which of is americium 241 produced from the decay of plutonium 241.[7]

Only a small fraction of americium from military programs exists in separated forms. The total worldwide inventory of separated americium is very roughly estimated to be less than a hundred kilograms.

Americium isotopes have been used as target material to make high-purity plutonium 238 and curium. Americium is also used in smoke detectors, as medical diagnostic tracers, and in neutron sources. However, all of these uses require gram quantities at most.

A major source of separated americium 241 was nuclear weapons programs that removed this isotope from aged plutonium at warhead recycling facilities, such as the Rocky Flats plant near Denver.

As of March 1998, the DOE owned an inventory of about 16 kilograms of americium 241, excluding americium 241 in nuclear waste forms at DOE sites.[8] In addition, the DOE owned about 11 kilograms of americium 243. About 10 kilograms of the americium 243 were in 4,000 gallons of americium-curium solutions at the time.

In 1998, the Rocky Flats Plant near Denver had an inventory of about 12 kilograms of separated americium 241.[9] Before operations stopped in 1989, Rocky Flats could separate and purify about one kilogram per year of americium 241.

The United States and other nuclear weapon states have also exported small amounts of americium 241. For information on past US exports of separated americium 241, see table 5.

Greater Separation of Neptunium or Americium?

Compared to the quantities of plutonium separated, neptunium 237 and americium have been separated in relatively small quantities, and then only in significant quantities in the

[7] Out of a total of about 260 tonnes of military plutonium, almost 1.5 tonnes were originally plutonium 241, most of which had decayed into americium 241 by the end of 2003.
[8] Facsimile to David Albright from the Office of Declassification Security Affairs, op. cit.
[9] Telephone interview with Laura Ramsey, Office of Public Affairs, Rocky Flats Environmental Technology Site, Golden Colorado, October 16, 1998.

nuclear weapon states. In addition, international commerce in neptunium and americium has been small.

Non-nuclear weapon states do not appear to have accumulated significant inventories of separated neptunium 237 or americium. Since the late 1990s, the IAEA has tracked the amount of separated neptunium and americium in the non-nuclear weapon states (see next section). In 1999, the IAEA reported that it had found no evidence that any state with a comprehensive safeguards agreement possessed inventories of separated neptunium or americium in quantities greater than one kilogram, although its information at that time was incomplete.[10] Based on available information, inventories in non-nuclear weapon states appear to remain small. According to the IAEA, as of spring 2005, there has been no change in the IAEA's assessment of the proliferation risk posed by neptunium and americium.

However, the amounts of neptunium and americium being separated are increasing as a result of concerns about the long periods necessary to isolate high level nuclear waste. Several countries, particularly those where civil plutonium is being separated, are studying the separation and use of minor actinides such as americium and neptunium as part of a comprehensive method to drastically reduce the necessary storage period for nuclear waste.

The aim of these studies is to develop ways to reduce the radiotoxicity of nuclear waste by separating or partitioning certain, long-lived radioactive isotopes from spent fuel or high level waste. For example, because of neptunium's long half-life and the radiotoxicity of its decay products, it could eventually leak from a geological repository and become dissolved in groundwater. Its long half-life means that neptunium decay products will remain a hazard long after plutonium, americium, and curium have essentially disappeared.

After partitioning long lived actinides and fission products, the half-lives of these radioisotopes would be transformed through transmutation into shorter half-lived or stable elements by fission or neutron capture. A reactor or accelerator would produce the neutrons.

Fast reactors or accelerator systems are significantly more efficient than thermal reactors, such as LWRs, in accomplishing transmutation. However, few fast reactors, such as breeder reactors, have been built because of economic and technical difficulties. As a result, the separation of americium and neptunium as part of partitioning and transmutation (P&T) programs has been limited. Nonetheless, P&T programs continue to make progress in a number of countries, including non-nuclear weapon states, and these programs include considerable research into the separation of minor actinides, particularly neptunium and americium.

[10] In this evaluation, any neptunium mixed with separated plutonium was not considered separated neptunium.

France, Japan, Russia, and the United States have the largest P&T programs. However, many other countries are participating in P&T research.

Based on a search of publications in the International Nuclear Information System (INIS), a number of countries are researching the separation of neptunium 237 or americium. Table 6 shows the results of a survey of INIS publications that can be indicative of a state's interest in neptunium or americium separation. Based on this list, the most active countries currently appear to be China, France, Germany, India, Japan, Russia, and the United States. In general, states that have had reprocessing programs are more interested in neptunium and americium separation. Of the non-nuclear weapon states, Germany and Japan have published the most on the separation of neptunium or americium.

The French P&T program appears to be the most advanced. It operates under a legislative mandate to develop sufficient information about partitioning and transmutation by 2006 in order to permit the French government and parliament to implement a national strategy for the management of long-lived radioactive waste, in particular whether the creation of a repository for high level, long-lived nuclear waste is appropriate. The 1991 legislation initially fostered a competition among the three main strategies: P&T, deep geological disposal, and waste conditioning and long-term interim storage. However, the current situation does not clearly favor any option.[11] Instead, France may choose to pursue all three strategies. By 2006, the French plan to have finished demonstrating the technical feasibility of partitioning and to have conducted an assessment of the industrial feasibility of partitioning.

Of the non-nuclear weapon states, Japan appears to have the largest program investigating the separation and use of neptunium and americium. For over 15 years, it has been carrying out P&T research.

The separation of neptunium has been the easiest to demonstrate, in particular its separation from LWR spent fuel and reprocessing waste. The most straightforward method to separate neptunium 237 from irradiated uranium fuel is the PUREX process. The French in particular are focusing on this method as part of their P&T research. To reduce the proliferation problems associated with the PUREX process, the United States has focused on processing methods that tend to separate the transuranics together, or at least pyroprocessing methods without initial separation of plutonium. The Japanese are researching a variety of approaches, although these programs tend to focus on separating neptunium and plutonium together.

Americium separation is more complicated. Progress in americium separation, however, has occurred in the last decade. The French are focusing on separating americium downstream of the PUREX process in a complementary extraction process.

[11] See for example the discussion in "French Hail Strides in P&T but Question Strategy, Cost," by Ann MacLachlan, *Nuclear Fuel*, February 28, 2005.

A review of the literature supports the view that the amounts of neptunium and americium separated in existing P&T programs have been relatively small, particularly in non-nuclear weapon states. French officials have stated that in 2005 the CEA's Atalante center plans to conduct separation experiments for the minor actinides using about 15 kilograms of spent fuel, with technologies close to industrial ones. This amount of spent fuel would contain only gram quantities of americium and neptunium. Japanese separation experiments in 1999 and 2000 involved processing 2.5 kilograms of irradiated fuel, a level one thousand times less than would be expected to be processed in a commercial-scale plant. In this experiment, neptunium was extracted with plutonium, and americium was extracted with other elements. Japan has also separated americium 241 from aged separated plutonium in MOX fuel scrap, obtaining gram quantities of americium 241 in this manner. The United States has demonstrated high purity separation of laboratory quantities of a plutonium and neptunium mixture and of an americium and curium mixture.

Several countries are irradiating gram quantities of minor actinides in fast and thermal reactors. France is conducting irradiation experiments in the Phenix fast reactor and has irradiated small quantities of neptunium and americium mixed with plutonium at this reactor. In addition, americium fuel pellets have been irradiated in the HFR in the Netherlands. The United States has irradiated laboratory-scale quantities of neptunium and americium.

Japan has irradiated gram quantities of americium mixed with plutonium in the Joyo experimental fast reactor. Future experiments are expected to involve the irradiation of fuel pellets in the Joyo reactor that contain gram quantities of americium and neptunium mixed with plutonium. When the Monju reactor starts its expected operation in a few years, it is expected to irradiate fuel pins containing americium and neptunium.

Russia is using its BOR-60 fast reactor for fuel pin experiments. It has irradiated at least two pins, each containing about 5 grams of neptunium in a neptunium-uranium oxide. Russia is also investigating the irradiation of gram quantities of americium mixed with plutonium in the BOR-60 reactor.

No country appears to be separating or using kilogram quantities of neptunium or americium in its P&T programs. However, the major programs envision doing so, if their research is successful and their governments approve larger scale efforts. Given the uncertainties facing nuclear energy and advanced reactor systems, predicting when larger amounts of minor actinides could be separated remains highly uncertain.

IAEA Response

In response to growing interest in separating and using neptunium and americium among non-nuclear weapon states, the IAEA took steps in the late 1990s to reduce the risk of proliferation posed by potential inventories of these nuclear explosive materials, short of applying safeguards to them. The principal proliferation concern was that a non-nuclear

weapon state, in full compliance with its safeguards obligations, could extract neptunium or americium at a civilian reprocessing facility, a waste treatment facility, or a laboratory investigating the separation of actinides that would not be under any IAEA inspections or monitoring regime. In essence, a non-weapon state could accumulate significant quantities of separated nuclear explosive materials outside of IAEA verification.

Neptunium or americium mixed with separated plutonium is indirectly safeguarded. In addition, the Model Additional Protocol provides the IAEA with additional information and access to monitor neptunium and americium in non-nuclear weapon states. However, the IAEA decided that these measures would not be sufficient.

In 1999, the IAEA Board of Governors agreed that the IAEA would, under voluntary arrangements, monitor international transfers of separated neptunium to non-nuclear weapon states and any activity to produce separated neptunium in non-nuclear weapon states with a comprehensive safeguards agreement. The board was divided on the proliferation risk posed by americium and opted in 1999 to have the IAEA continue its activities to determine the availability of separated americium and to track emerging programs to separate americium.

The board rejected treating neptunium or americium as a special fissionable material, such as plutonium or enriched uranium, a step which would have required placing these materials under safeguards. However, this decision was based on the IAEA's determination that non-nuclear weapon states had only small quantities of separated neptunium and americium, few exports of these materials were occurring, and IAEA monitoring could ensure that inventories in non-nuclear weapon states remained insufficient to pose a proliferation risk.

A goal of the IAEA in the 1990s was to establish a cost-effective monitoring system so that it could determine if and when accumulations of separated neptunium or americium in a non-nuclear weapon state were about to become substantial and to inform the board of such an eventuality in a timely manner. The IAEA initially believed that a reasonable threshold value for triggering notification to the board was five kilograms of separated neptunium or americium in any non-nuclear weapon state. Reflecting differences among Member States regarding the perceived proliferation threat of americium, the IAEA agreed to increase the threshold value for americium to 10 kilograms. The rationale was that these thresholds would be large enough to indicate that separation activities were approaching industrial scale, but small enough to allow time to modify current monitoring arrangements.

The IAEA has requested that non-nuclear weapon states provide, on a voluntary basis, information on neptunium and americium exports and imports and inventory declarations from those non-weapon states with past or current reprocessing or plutonium clean-up operations.[12] The IAEA has also instituted monitoring, called flow sheet verification (FSV), of neptunium 237.

[12] Reporting would occur for annual cumulative exports of 50 grams of neptunium 237 or 100 grams of americium to any one recipient state.

FSV is to be implemented at large actinide partitioning research and development facilities and at facilities that have neptunium 237 in spent fuel, high level waste, or separated plutonium and have the capability to separate 100 grams per year of neptunium 237.[13] The IAEA's actions aim to provide assurance that the quantities of separated neptunium and americium in the non-nuclear weapon states remain insufficient to pose a proliferation risk. FSV is not designed to provide assurances about the absence of undeclared activities involving neptunium separation.

FSV would be applied at facilities with the actual or potential capability for separating neptunium. Because neptunium can be separated only when in a solution form, FSV is designed to be applied only at facilities that process, store, or use neptunium in solutions.

At the time of the board's 1999 decision, the IAEA identified nine facilities that would be subject to verification for neptunium and americium.[14] Two other facilities, which were under construction at the time, would be eligible for verification and monitoring when finished. One of the operational facilities has now closed and one of the facilities under construction is now in operation. No new facilities have been added to the original list, according to a recent IAEA statement to the authors of this report. The IAEA has declined to provide a list of all of the facilities subject to FSV.

Four facilities that had neptunium and americium solutions were identified as having separation equipment. The Tokai reprocessing plant is an example of such a facility. It was projected to have an annual neptunium feed of about 50 kilograms and an annual americium feed of about 50 kilograms. Two others were MOX fuel fabrication plants, and the fourth was a research and development facility involved in criticality experiments.

Two facilities that had neptunium and americium in solution had no separation equipment. One was a waste vitrification facility associated with a reprocessing plant, and the other was a plutonium conversion facility that produced MOX powder for fuel manufacturing. These two facilities are likely associated with the Tokai reprocessing plant.

The IAEA also identified three actinide partitioning and transmutation laboratories. The amounts of neptunium and americium at these facilities were expected to be small. One or two of these facilities is in Japan, and another is likely in Germany.

Two sites were identified as under construction, the Rokkasho reprocessing plant and a reprocessing facility for fast reactor fuel. The former facility is nearing commercial

[13] Under the IAEA's old plan for FSV that included americium, the threshold value would have been 500 grams per year of americium.

[14] One facility, a plutonium conversion facility, was identified as having essentially no neptunium but enough americium potentially in solution to qualify for inclusion in flow sheet verification under the original IAEA proposal.

operation, and will process hundreds of kilograms of neptunium and americium, almost all of which is expected to end up in the high level waste.

Since the 1999 decision, implementation has apparently progressed slowly. The IAEA safeguards reports for 2003 and 2004 stated that the IAEA continued to experience difficulties in getting responses from member states with regards to neptunium and americium. Nonetheless, FSV has been implemented at a European Commission laboratory, and the Rokkasho reprocessing plant has built-in measures for monitoring neptunium and perhaps americium

Conclusion

The proliferation risk currently posed by neptunium and americium remains relatively small. However, the situation could change over the next decade.

IAEA monitoring of neptunium and americium in non-nuclear weapon states has progressed more slowly than expected. States have not cooperated adequately with the IAEA on this issue.

Partitioning and transmutation strategies should have nonproliferation as their top priority. The programs should concentrate on alternatives that create proliferation-resistant processes and facilities.

To better institutionalize controls and broaden transparency measures to all states, the IAEA needs to encourage all nations separating—or considering separating—neptunium or americium to create a management arrangement similar to that created for civil plutonium. In addition to requiring declarations of inventories of neptunium and americium, a management arrangement could also include commitments concerning adequate physical protection and monitoring of these materials. Such an arrangement could help reduce the risk posed by these materials and provide a clearer, non-discriminatory warning when these materials would need to be fully safeguarded.

Table 1 Nuclear Explosive-Related Properties of Actinides

Nuclide	Half-Life (years)	Critical Mass (kg)	Heat Emission Rate (Watts/kg)	Spontaneous Fission Neutron Emission Rate (n/kg/sec)	Gamma Ray Dose Rate (mSv/hr/kg at 1 cm)
U-235	7.038×10^8	53	negligible	negligible	negligible
Np-237	2.14×10^6	56	negligible	negligible	1.04
Pu-238	87.74	10	567	2.59×10^6	0.19
Pu-239	24,119	13	1.9	16	0.05
Am-241	433.6	60	114	1 375	50
$Am\text{-}242_m$	141	9(a)	1.5 – 380(b)	$4.6 \times 10^4 – 6.5 \times 10^7$(b)	6,500(c)
Am-243	7,370	150(a)	6.4	714	38

a) Calculated
b) The lower values of heat and neutron emissions correspond to freshly separated $Am\text{-}242_m$. These values increase sharply as the curium radioactive daughter product accumulates and decays.
c) The gamma ray dose rate includes the contribution from the curium daughter.

Source: IAEA

Table 2 Neptunium 237 and Americium Production in Civil Power Reactors (as of end 2003, in kilograms)(a,b)

Country	Neptunium 237	Americium			Total
		At discharge	Am-241 from decay of Pu-241	Total	(rounded)
Argentina	**66**	17	181	**198**	**264**
Armenia	**97**	17	192	**209**	**306**
Belgium	**1280**	452	1290	**1742**	**3020**
Brazil	**60**	9	49	**58**	**118**
Bulgaria	**595**	207	645	**852**	**1450**
Canada	**807**	210	2120	**2330**	**3140**
China	**156**	28	91	**119**	**275**
Czech Republic	**291**	101	261	**362**	**653**
Finland	**517**	194	645	**839**	**1360**
France	**9800**	3180	9720	**12900**	**22700**
Germany	**4870**	1640	6030	**7670**	**12500**
Hungary	**289**	108	321	**429**	**718**
India	**142**	37	253	**290**	**432**
Italy	**96**	16	339	**355**	**451**
Japan	**5120**	1880	6990	**8870**	**14000**
Kazakhstan	**0**	0	0	**0**	**0**
Lithuania	**220**	39	303	**342**	**562**
Mexico	**76**	26	69	**95**	**171**
Netherlands	**147**	51	198	**249**	**396**
Pakistan	**8**	1	18	**19**	**27**
Romania	**12**	2	17	**19**	**31**
Russia	**3470**	953	4360	**5313**	**8780**
Slovakia	**390**	162	399	**561**	**951**
Slovenia	**132**	47	110	**157**	**289**
South Africa	**274**	92	216	**308**	**582**
South Korea	**1540**	511	1340	**1851**	**3390**
Spain	**1130**	393	1450	**1843**	**2970**
Sweden	**1170**	796	2290	**3086**	**4260**
Switzerland	**859**	304	952	**1256**	**2120**
Taiwan	**648**	441	1070	**1511**	**2160**
Ukraine	**2340**	788	1820	**2608**	**4950**
United Kingdom	**1010**	530	3280	**3810**	**4820**
United States	**16300**	5850	21000	**26850**	**43200**
Total (rounded)	**54,000**	**19,100**	**68,000**	**87,100**	**141,000**

a) An uncertainty in these values has not been determined, but these values are not as certain as the number of significant digits imply.

b) These values do not account for the transfer of ownership of spent fuel, nuclear waste, or unirradiated plutonium to other countries. For a discussion of such transfers, see *Civil Plutonium Produced in Power Reactors*, June 10, 2005

Table 3 Neptunium and Americium Throughputs in Major Nuclear Fuel Cycle Facilities

Facility	Typical Amounts		Separation Capability	
	Neptunium (kg)	Americium (kg)	Neptunium (kg)	Americium (kg)
Reprocessing Plant(a) 800 tonnes LWR fuel per year	250	420	none	none
MOX Fuel Fabrication Plant(b) 40 tonnes per year with americium removal	0	90	0	90

a) The model for this example is the Rokkasho reprocessing plant in Japan. Half of the fuel is assumed to be BWR fuel and the other half PWR fuel. In this case, the plant will separate about 7.2 tonnes of plutonium per year and the neptunium will comprise about 3.5 percent of the plutonium. The spent fuel is estimated to have contained about 90 kilograms of americium at discharge and is assumed to have been discharged ten years prior to reprocessing, resulting in an additional 330 kilograms of americium from radioactive decay of plutonium 241. In total, the 800 tonnes of fuel contains about 420 kilograms of americium.

b) The fuel is assumed to be for PWRs and the plutonium is assumed to have been separated ten years prior to fabrication into fuel. The throughput of plutonium in the plant is taken as 2 tonnes per year.

Table 4 Estimated Neptunium Production in Military Production Reactors

Country	Weapon-Grade Plutonium Production(a)	Neptunium Production
Britain	4 tonnes	15 kilograms
China	4 tonnes(b)	20 kilograms
France	6 tonnes	20-50 kilograms
Russia	160 tonnes	600-1000 kilograms
United States	103(c)	1,000-2,000 kilograms
Total	**278 tonnes**	**1655-3085 kilograms**

a) Except in the case of the United States, these values represent best estimates of total production of weapon-grade plutonium. They are not current inventories, because they do not include draw downs from nuclear testing, sales to other countries, or processing losses. The US value is from its official declaration of total plutonium production at the Hanford and Savannah River sites and includes about 13 tonnes of fuel-grade plutonium. The British military reactors also produced a large quantity of non-weapon-grade plutonium that was ultimately assigned to its own or another country's civil stock. The neptunium produced with this plutonium is included in the estimate of civil neptunium produced in Britain in table 2.
b) The Chinese value includes about 1.4 tonnes of fuel-grade plutonium.
c) The US value includes about 13 tonnes of fuel-grade plutonium.

Table 5 US Exports of Neptunium 237 and Americium 241
(From January 1, 1950 through March 31, 1998)

Country	Quantity (gr)	
	Np-237	Am-241
Australia	2	--
Austria	--	10
Belgium	96	5
Canada	4	--
Czech	--	28
France	3	136
Germany	742	40
India	18	1
Israel	31	1
Japan	24	39
Netherlands	1	--
Poland	--	10
Switzerland	1	--
Taiwan	--	4
UK	82	474
Venezuela	1	--
Total	**1005**	**748**

Source: Facsimile to David Albright from the Office of Declassification Security Affairs, DOE, November 10, 1998. The numbers were taken directly from DOE's Nuclear Materials Management Safeguards System.

Table 6 Indication of Neptunium and Americium Separation by Country*

Country of Input	1997	1998	1999	2000	2001	2002	2003	2004	Total
Australia	11	5	1	1	7	13	0	0	**38**
Belgium	0	0	0	0	0	0	0	0	**0**
Brazil	4	2	4	1	7	13	0	0	**31**
Bulgaria	0	0	0	0	1	0	0	2	**3**
China	48	40	25	2	50	25	0	7	**197**
Czech Republic**	0	34	64	0	0	43	15	1	**157**
France	37	20	30	3	44	14	5	105	**258**
Germany	28	48	40	29	46	51	26	59	**327**
Hungary**	45	56	64	28	43	37	30	24	**327**
IAEA	16	15	14	16	37	40	23	74	**235**
India	111	15	95	38	85	19	68	59	**490**
Israel	0	0	0	0	0	3	0	1	**4**
Japan	148	88	77	24	64	188	20	33	**642**
Kazakhstan	0	1	2	0	1	3	0	0	**7**
NEA	1	16	38	0	59	10	47	0	**171**
Netherlands	42	21	14	0	30	21	15	27	**170**
Pakistan	0	2	0	0	0	1	0	0	**3**
Romania	4	1	6	1	6	9	9	0	**36**
Russia	84	71	41	8	101	32	0	9	**346**
Slovakia**	40	12	32	3	25	2	0	0	**114**
South Korea	6	2	10	10	16	11	0	2	**57**
Spain	0	1	0	1	2	0	3	2	**9**
Sweden	5	4	8	1	1	1	3	1	**24**
Switzerland	20	47	2	3	2	0	0	1	**75**
Ukraine	2	0	1	0	1	2	4	0	**10**
United Kingdom	25	10	8	3	20	11	6	27	**110**
United States	168	91	79	33	47	23	16	42	**499**

Search of the INIS database: “separat” and either Neptunium or Americium or Actinide. “Country of Input” refers to the country in which each study was published, rather than the country of authorship.

**These countries had relatively high numbers, but these numbers do not appear to indicate a significant domestic program involved in separating minor actinides. The INIS search for studies in the Czech Republic and Slovakia led to high numbers because of international conferences held in these countries that attracted many foreign participants whose countries were involved in separation activities. Hungary has a high number because this country has an international journal, the *Journal of Radioanalytical and Nuclear Chemistry*, that publishes a number of internationally authored articles.