Separated Civil Plutonium Inventories: Current Status and Future Directions

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The amount of separated (unirradiated) civil plutonium in the world continues to increase. Many national programs to use separated plutonium in mixed-oxide (MOX) fuel for light-water reactors (LWRs) have progressed slower than expected. The few "breeder" or fast reactors have played only a small role in absorbing these stocks of separated plutonium.

This upward trend in stocks of unirradiated plutonium is expected to continue, at least for several more years. There is consensus in the international community that stockpiles of separated plutonium should be minimized because they are a proliferation hazard. Achieving this goal, however, remains difficult.

A newer category of civil plutonium is plutonium declared excess to defense requirements. Britain, Russia, and the United States have each declared a portion of their military stock of plutonium excess to military requirements. Russia and the United States have each agreed to convert 34 tonnes of weapon-grade plutonium into MOX fuel and to irradiate the resulting MOX fuel in civil power reactors.

This report first estimates and discusses plutonium separated and used in civil nuclear power programs. Subsequently, it addresses excess US and Russian military plutonium that has been dedicated to civil uses. Britain has also declared several tonnes of excess unirradiated military plutonium, but this plutonium is a small fraction of Britain's total stock of unirradiated civil plutonium and is not distinguished from the civil stock in subsequent tabulations and discussions.

Unirradiated Civil Power Reactor Plutonium, end 2003

From the end of 1997 to the end of 2003, the world's stock of civil unirradiated plutonium in civil programs grew at an average rate of about 10 tonnes per year. During this period, about 20 tonnes of plutonium per year were separated worldwide from commercial spent fuel, and roughly 10 tonnes of plutonium per year were fabricated into MOX fuel for use almost exclusively in LWRs. During the next five years, the net amount of unirradiated plutonium is projected to grow at about half the earlier rate. This slowdown in the growth of the global stock reflects a decrease in the amount of plutonium being separated and an increase in the amount of plutonium fuel being fabricated and irradiated.

Table 1 shows that about 238 tonnes of civil separated plutonium were held and owned by 12 countries at the end of 2003, the last year for which detailed country-specific information is available. Most of the figures have come from official public declarations that nine countries make annually to the International Atomic Energy Agency (IAEA) through INFCIRC/549 declarations.[1] Several of the entries in table 1, however, are estimates, because some official declarations are incomplete or ambiguous. In addition, India, Italy, Netherlands, and Spain have not made declarations of their separated plutonium inventories to the IAEA or the public.

Table 1 shows that the largest inventories are in the nuclear weapon states. However, Germany and Japan also possess large stocks.

Most INFCIRC/549 declarations for stocks at the end of 2004 were not available from the IAEA at publication time. Nonetheless, based on an assessment of the amount of spent fuel reprocessed and the amount of plutonium used in MOX fuel, about 242 tonnes of plutonium are estimated to have been in unirradiated forms at the end of 2004.

Future Stocks of Civil Separated Plutonium

The size of the unirradiated plutonium inventory depends on the amount of plutonium separated each year and the quantity of plutonium inserted into reactors in that year. Although plutonium separation continues, often with little justification other than inertia, the main reason for such a large and growing stock of unirradiated plutonium is that too little plutonium is being irradiated or otherwise disposed of.

Over the next several years, the total amount of unirradiated plutonium is expected to continue growing. In about seven years, however, the total amount may start to decrease as separation slows and MOX use picks up. This assessment is based on industry and government plans for plutonium separation and recycling.

Figure 1 is a projection of the inventory of unirradiated plutonium through 2020 based on these plans. As can be seen in the figure, the peak of about 260 tonnes of unirradiated plutonium is projected to be reached around 2012. The inventory is then projected to decrease to about 240 in 2015, and then to about 195 tonnes in 2020.

The major assumptions involved in making this projection are:

- France reprocesses its own spent fuel at a rate of 825-900 tonnes per year and recycles the resulting plutonium into its LWRs. Recycling at this rate will require France to produce about 100 tonnes of MOX fuel per year at its MELOX plant.

[1] Nine countries annually submit communications to the IAEA concerning their policies regarding the management of plutonium that contain their quantitative annual holdings of civil unirradiated plutonium. The annual communications are listed as addendums or additions to the original 1998 INFCIRC/549 document, *Guidelines for the Management of Plutonium*. These declarations are available at www.IAEA.org. For a summary of annual holdings, see ISIS report, *Guidelines for the Management of Plutonium (INFCIRC/549): Background and Declarations*, April 1, 2004, Revised March 3, 2005.

- France's foreign reprocessing contracts are largely finished by 2010.
- Britain ends reprocessing around 2012 and starts commercial operation of its Sellafield MOX plant (SMP) in 2005. SMP reaches about 60 percent of full capacity by 2008 and continues to operate at that level to make MOX fuel for its foreign reprocessing clients, particularly Germany, Japan, Sweden, and Switzerland.
- Japan starts commercial operations at its Rokkasho reprocessing plant in 2007. Its large-scale MOX plant starts in 2012 and reaches commercial operation in 2014.
- France's MELOX MOX fabrication plant and Belgium's Dessel MOX fabrication plant make MOX fuel for Belgium, Germany, Japan, and Switzerland, and the MOX fuel is inserted into reactors without significant delays.
- MOX fuel burnups increase, resulting in the need for greater plutonium concentrations in fresh MOX fuel.

During the next fifteen years, the amount of plutonium separated annually is expected to remain at about 15-20 tonnes. Decreases in plutonium separation in Europe are expected to be off-set by increases in Japan. The amount of plutonium fabricated into MOX fuel in this estimate is projected to rise from current levels of roughly 10 tonnes per year to almost 25 tonnes per year during this period. This increase in the amount of plutonium being made into MOX fuel explains why, in this estimate, the amount of unirradiated plutonium is expected to peak and then decrease.

This projection has uncertainties. To understand the nature of the uncertainties, a comparison can be made to a similar projection done by ISIS in 2000 (see *Separated Civil Plutonium Inventories, Current and Future Directions*, June 2000, on ISIS web site). That projection, based on industry and government plans from the late 1990s, estimated that the amount of separated plutonium would increase to about 190 tonnes by 2010 and then decrease to about 150 tonnes by 2015. These estimates are roughly 70-90 tonnes less than the current projections.

There are several reasons that the current estimate projects higher global plutonium inventories during the next decade. The British MOX fabrication plant, or Sellafield MOX plant (SMP), was unable to commence commercial operation as originally scheduled around 2000, and many now doubt that it will ever reach its full capacity of 120 tonnes of MOX fuel per year. In addition, the lack of Japanese orders to make MOX fuel in Europe led to the unexpected growth of Japanese separated plutonium stocks. Japanese utilities have been unable so far to start loading MOX fuel into their light water reactors due to intense local opposition to their plans, causing the utilities to delay their European MOX contracts. Continuing controversies in Britain and Japan could cause further delays in MOX fabrication and use during the next decade.

This projection nonetheless demonstrates that the peak in the civil unirradiated plutonium inventory may occur by 2012, and then the inventory is expected to slowly decrease. If history is a guide, however, these benchmarks may be further delayed. In almost any conceivable case, the international community must expect to face a large stock of civil separated plutonium for years.

This estimate also highlights the large amount of unirradiated plutonium that will be transported among reprocessing plants, MOX fuel fabrication plants, and power reactors. In France, for example, roughly 10 tonnes of separated plutonium are currently transported to the MELOX and Dessel plants each year, which then send a similar amount of unirradiated plutonium in the form of MOX fuel to about 30 power reactors in several countries. Adequate physical protection of this plutonium remains critical.

Future Civil Separated Plutonium Stocks in Key Countries

An analysis of plutonium use must inevitably focus on individual countries and utilities that are loading or trying to load MOX fuel. This section evaluates future directions in 12 countries that have significant stocks of civil unirradiated plutonium. The US civil stock is not considered here, but instead in the next section on the disposition of excess military plutonium. China is also included in table 2, because it may have significant stocks of civil unirradiated plutonium after 2010.

Table 2 contains estimates of the size of plutonium inventories in key countries involved in commercial reprocessing and MOX use for the years 2010, 2015, and 2020. These estimates are based on current plans for reprocessing, MOX fabrication, and MOX fuel irradiation. Unlike the projection in figure 1, these estimates include information on specific reactors scheduled to use MOX.

Many of the estimates are ranges, reflecting uncertainties about MOX fabrication capacity and subsequent MOX use in a reactor. These considerations are discussed below or summarized in the footnotes to the table. In some cases, the projections are rather broad ranges that attempt to capture most of the possible futures for plutonium separation and use during the next 15 years.

The lower bounds in table 2 correspond roughly to the values presented in figure 1. The upper bounds in table 2 reflect the types of problems that have traditionally led the unirradiated plutonium stocks to increase. These include the separation of more plutonium than can be used, delays in gaining approvals in loading MOX fuel, and the impact of unexpected events such as nuclear accidents or incidents that further delay MOX programs.

A striking conclusion is that under a wide variety of reasonable assumptions, total civil separated plutonium stocks are not expected to decrease significantly in this period. Most countries listed in the table will have to store unirradiated plutonium either domestically or overseas for the foreseeable future.

Table 2 also shows that Belgium, Sweden, Switzerland, and likely Germany are embarked on a strategy of MOX use in LWRs that is expected to reduce their stocks of unirradiated plutonium to as close to zero as feasible. These countries have all decided against further commercial reprocessing but have stocks of separated plutonium from earlier or pre-existing foreign reprocessing contracts.

Once they have finished using MOX fuel in their reactors, these countries will likely have some residual unirradiated plutonium stocks, but these stocks should in most cases be relatively small and can be expected to be disposed as waste or perhaps sold to other countries that have on-going plutonium recycle programs. The one exception could be Germany which may end up with several tonnes of separated plutonium. One German utility may be unable to recycle about five tonnes of separated plutonium into its reactors because of local government opposition to MOX use in its reactors, and other utilities may not be willing to recycle this plutonium. In addition, Germany has plutonium in various forms left from closed domestic plutonium reprocessing and MOX fabrication activities. Although Germany has decided to phase out its nuclear reactors, it is doing so on a schedule sufficient to permit recycling of its plutonium. However, if it experiences significant delays in being able to obtain or use MOX fuel, or is unable to obtain sufficient MOX fuel, it could end up with a stock of separated plutonium that exceeds ten tonnes.

On the other hand, Britain, Italy, Netherlands, Russia, and perhaps Spain will soon possess about 150 tonnes of civil unirradiated plutonium. These countries have no firm plans to use MOX fuel or otherwise dispose of their civil plutonium stocks through 2020. Britain faces a daunting choice about its large stock, and it may need to dispose of most of its separated plutonium as waste, if it cannot organize the recycling of this plutonium in power reactors.

Italy, Netherlands, and Spain also need to find a way to dispose of their stocks. Neither Italy nor the Netherlands has any plans to dispose of their plutonium. Italy does not have any nuclear reactors operating anymore, and the Netherlands has decided not to recycle its recovered plutonium in its remaining power reactor. Spain has sold about half of its plutonium recovered or scheduled for recovery after reprocessing in Britain, and it is seeking buyers for the remainder, although few buyers exist. If it does not find a buyer for the rest of this plutonium by 2008, it must take the plutonium back to Spain, although it has no plans to recycle this plutonium in its power reactors. Netherlands is trying to sell its separated plutonium, and Italy may also follow this course.

Because of intense opposition to storing spent fuel domestically, Italy may contract Britain or France to reprocess its residual stock of 235 tonnes of spent LWR fuel. If this spent fuel is reprocessed, Italy would add roughly 1.5 to 2 tonnes of plutonium to its projected stock of 3 tonnes of unirradiated plutonium.

Russia has no immediate plans to recycle its civil separated plutonium inventory, although it is committed to a long-term plan to use MOX in both LWRs and fast reactors. Russian government officials have announced plans to convert this separated plutonium into MOX fuel after Russia finishes converting 34 tonnes of excess military plutonium to MOX, which is not expected to occur before 2020 (see next section).

In the meantime, Russia plans to blend a small amount (3-4 tonnes) of this civil plutonium with the 34 tonnes of excess weapon-grade plutonium to disguise the isotopic composition of the military plutonium, which is classified. As a result, during at least the next 15 years, Russia does not plan to significantly reduce its stock of plutonium produced in civil reactors, which will grow to about 65 tonnes by 2020.

France, Japan, and India are all embarked on programs to both separate more plutonium and use MOX fuel in their reactors. China has announced plans to implement a similar program, although its program has been slowed.

France could face a large separated plutonium stock well into the future. It is bringing its current annual separation of plutonium into balance with its use in MOX by significantly increasing the fraction of fresh plutonium put into MOX fuel, in essence increasing the "burn-up" of the spent fuel. However, France does not appear to be taking aggressive steps to reduce its existing inventory of unirradiated plutonium. It could do so by expanding the output of the MELOX plant and increasing the number of reactors using MOX, or reducing the amount of plutonium it separates for several years as it reduces its existing inventory.

India is separating plutonium and plans to use MOX fuel in breeder reactors. The first prototype breeder is slated for operation in 2010, with larger breeders to follow. Whether India can meet this schedule remains unclear. In addition, its civil reprocessing plants have not worked as planned, raising questions as to whether India can produce enough separated plutonium for a breeder reactor program.

China plans to reprocess a limited amount of LWR spent fuel and recycle separated plutonium into its civil reactors. Its efforts to establish a 100 tonne per year reprocessing plant and associated MOX fuel fabrication plant have gone considerably slower than expected. In addition, its pilot breeder reactor, which is under construction, is slated, at least initially, to use HEU fuel imported from Russia.

Japan has experienced significant delays in starting to load MOX fuel in its LWRs. In addition, its fast breeder program has suffered several delays, and its prototype Monju fast reactor may not operate for at least two more years. As a result, projections of future MOX use remain highly uncertain, and models to generate such projections can vary significantly depending on the decisions made by Japanese utilities and the government over the next few years.

The ranges in table 2 for Japan reflect the results of an assessment of several specific scenarios, based mainly on varying expected dates for MOX loading in individual Japanese LWRs and the amount of plutonium separated at the Rokkasho reprocessing plant. The ranges are wide, reflecting the rather large uncertainties in the start dates for MOX loadings and difficult choices facing Japanese utilities and government about the output of the Rokkasho reprocessing plant.

This assessment considered five scenarios, or cases, that bound projected inventories or possible futures.

1) Case 1 is an optimistic scenario based on a schedule for loading reactors with MOX fuel and full operation of the Rokkasho reprocessing plant. The first two reactors are loaded with MOX fuel in 2008 and two more in 2009. The number of reactors loaded with MOX gradually increases over the next several years, reaching 8 reactors in 2010 and 18 reactors in 2012 including the all plutonium-core Ohma reactor. In addition, the Monju breeder reactor is estimated to start operation in 2008. The maximum amount of plutonium loaded each year is about 9 tonnes of plutonium.
2) Case 2 involves a two-year delay in the Case 1 MOX loading schedule, where everything else is held constant.
3) Case 3 involves a four-year delay in the Case 1 MOX loading schedule, where everything else is held constant.
4) Case 4 uses the case 1 MOX loading schedule supplemented by a policy to first use the separated plutonium stored in Europe. MOX fuel would be made in Europe and shipped back for use before any domestically separated plutonium was used. After all the overseas reprocessing contracts are completed, the quantity of overseas plutonium is expected to reach almost 50 tonnes in total. Because the licensing limit on the amount of unirradiated plutonium that can be stored at Rokkasho is 30 tonnes, this option is modeled by limiting reprocessing at Rokkasho to about 2 tonnes of plutonium per year for about seven years. For this case to be realized, Japan would need to have about 60-100 tonnes of MOX fuel fabricated per year from the plutonium stored in Europe. This capacity should be available in Europe if the SMP operates, as expected. If not enough capacity can be found in Europe, Japan could repatriate some of its separated plutonium from Europe and fabricate it into MOX fuel at the Rokkasho MOX fabrication plant.
5) Case 5 assumes that no MOX is used, but the Rokkasho facility separates plutonium until it reaches its storage limit of 30 tonnes.

Table 3 summarizes the results of this assessment. The ranges in table 2 are drawn from the maximum and minimum values for a specific year.

The reason the plutonium estimates in cases 1, 2, and 3 remain relatively high is that the Rokkasho reprocessing plant is scheduled to produce separated plutonium at a rate of over seven tonnes a year by about 2010. Because only about 7-9 tonnes a year of plutonium are being loaded into reactors, the total inventory of plutonium changes little through 2020, even when the MOX loading schedules are delayed by several years. Interestingly, if no MOX is used in Japanese reactors, the total inventory through 2020 will be comparable to case 3, which has a four-year delay in MOX loading from the schedule established in case 1. The lower bound is defined by case 4, where the output of the Rokkasho reprocessing plant is limited for many years while Japan's inventory of separated plutonium in Europe is preferentially loaded into power reactors.

As case 4 demonstrates, if Japan decides to limit operations at the Rokkasho reprocessing plant, it can systematically reduce its inventory of separated plutonium. Senior Japanese utility officials have stated informally in interviews that such a practice may be Japanese utility practice. If implemented, this strategy could allow the Rokkasho reprocessing plant to operate albeit at a reduced throughput, permit extra time to build the Rokkasho MOX fabrication plant, and reduce Japan's separated plutonium inventory dramatically.

Japan could also reduce its plutonium stock by loading more reactors with MOX fuel and increasing the plutonium concentration in the MOX fuel.

Excess Military Plutonium

Britain, Russia, and the United States have each declared a portion of their military plutonium stocks excess to military requirements. Russia and the United States have each declared about 50 tonnes of plutonium excess, and Britain has declared 4.4 tonnes. In the future, Russia and the United States are expected to declare more excess plutonium.

In 2000, the United States and Russia each agreed to dispose of 34 tonnes of weapon-grade plutonium declared excess to defense requirements. Because Russia views the isotopic composition of its weapons-grade plutonium as classified, it plans to blend the weapon-grade plutonium with about 3-4 tonnes of civil, reactor-grade plutonium.

More recently, each country has focused on building a MOX fabrication plant and selecting specific reactors to use the surplus plutonium. The United States announced that it intended to start its MOX plant in 2009 and to use the resulting MOX fuel in about six LWRs. However, the anticipated start-up date has been delayed, although the extent of the delay is not known publicly. In any case, Russia is expected to follow a schedule similar to the United States and use the MOX in both LWRs and fast reactors. Because the programs are currently expected to proceed in "rough parallel," a delay in one country can delay the other's program.

United States. The United States has declared a total of 52.5 metric tons of plutonium as excess to its military requirements. The majority of this plutonium was formerly part of its nuclear weapons programs. About 7 tonnes of this plutonium is in spent fuel. Subtracting the plutonium in the spent fuel leaves an unirradiated inventory of about 45 tonnes, which is the amount declared by the United States in its INFCIRC/549 declarations to the IAEA. About 4-5 tonnes of this material is estimated to have originated in civil reactors, particularly British civil power reactors, and to have been transferred to the United States under a barter arrangement several decades ago. The rest of this plutonium originated in US plutonium production reactors operated by the Department of Energy and its predecessors.

In addition to the 34 tonnes scheduled for MOX fuel, another three tonnes are scheduled for dilution and disposal in a geological repository in New Mexico. Undecided is the fate of the other 7-8 tonnes of unirradiated plutonium which is non-weapon grade material. Original plans to immobilize up to 17 tonnes of the excess plutonium, including the non-weapon grade plutonium and about nine tonnes of weapon-grade plutonium, were suspended in early 2002. In addition, two tonnes of the original 34 tonnes that is impure and hard to process into plutonium oxide may be disposed as waste and substituted with weapon-grade plutonium that would be declared excess to defense requirements later.

The plutonium disposition program is focused on starting construction of the MOX fuel fabrication facility at the Department of Energy's Savannah River Site in South Carolina. The start of construction has been delayed because of disputes between the US and Russian governments over liability protection for US government employees and contractors working in Russia. As a result, the plant is not expected to start MOX production in 2009, which already represented a two-year delay in the schedule established in early 2002.

According to DOE’s early 2002 plans, disposition would occur over a roughly 10-12 year period, with the goal of turning almost 3.5 tonnes of plutonium each year into MOX and using it in six LWRs. Such an ambitious schedule may be impossible to meet. For example, only four LWRs have agreed to use MOX fuel. In addition, the maximum throughput of the MOX plant may not be achieved quickly after initial operation commences or sustained over the expected lifetime of the plant.

Unknown is the fate of the MOX plant after it processes the 34 tonnes of plutonium. Under current plans, the MOX plant will not conduct any mission other than recycling excess military plutonium. However, questions remain as to whether the facility will process newly declared excess plutonium.

Russia. Less is known about Russia’s excess plutonium. Russia has declared 50 tonnes of plutonium excess to its defense requirements. The 34 tonnes of weapon-grade plutonium it has committed to use in MOX fuel are part of this 50 tonnes. Unlike the United States, none of Russia’s 50 tonnes of excess plutonium is included in its INFCIRC/549 declaration of unirradiated civil plutonium.

With Western financing, Russia plans to build a MOX fabrication plant at Seversk (Tomsk-7), Siberia that will make MOX fuel for LWRs and perhaps fast reactors. Unlike the United States, Russia wants to recycle its excess plutonium into VVER-1000s and the fast reactors, BN-600 and the pilot BOR-60.

Britain. Britain has not stated what it intends to do with its excess plutonium, declared as 4.4 tonnes. This plutonium is included in the civil unirradiated plutonium Britain declares in its INFCIRC/549 and is included with Britain’s civil unirradiated plutonium in table 1. Excess military plutonium is expected to be disposed in a similar manner to the rest of Britain’s unirradiated plutonium.

Plutonium Disposition Rate. Table 4 summarizes estimates of the amount and rate of MOX irradiation of the 68 tonnes of US and Russian weapon-grade plutonium covered by the 2000 agreement. The MOX plants are estimated to produce their first significant amounts of MOX between 2010 and 2012. The US program is estimated to be able to irradiate about 1-3.5 tonnes of plutonium per year, with two to three tonnes per year as the most likely value. The Russian program is estimated to irradiate about 1.5-2.5

tonnes per year. These estimates of the production and use of MOX fuel remain highly uncertain, but they show that disposition of this plutonium will likely take over 15 years.

Table 5 combines the information about the MOX disposition of the excess plutonium with the remainder of the excess plutonium. These projections could be affected by decisions to declare more plutonium excess or to dispose of more of the plutonium as waste.

Summary of Projected Civil Separated Plutonium Stocks

Table 6 projects civil separated plutonium inventories, including excess military plutonium, through 2020. As can be seen, the inventories remain large during this period.

Table 1 Unirradiated Civil Plutonium, end 2003 (in tonnes) (a)

	A: Holdings in-country	B: Holdings in other countries	C: Tonnes of A that are foreign-owned	D: Plutonium owned by a country (A+B-C)
Britain	96.2	0.9	22.5	74.6
France	78.6	less than 0.05	30.5	48.1
Belgium	3.5	0.4	2.5-3.5(b)	0.4-1.4(b)
Germany	12.5	~13.5(c)	0	26(c)
Japan	5.4	35.2	0	40.6
Switzerland(d)	0.5-1.0	1–2	0	1.5-3.0
Russia	38.2	0.0006	0	38.2
China	0	0	0	0
United States	(e)	0	0	(e)
India (f)	~1-1.5	0	0	1-1.5
Netherlands (g)	0	2-2.5	0	2-2.5
Italy (h)	0?	2.5	0	2.5
Sweden (i)	0	0.83	0	0.83
Spain(j)	0	0.3	0	0.3
TOTAL(k)	**236-237**			**236-240**

a) For the first eight countries in the table, the main sources of information are the IAEA's INFCIRC/549 declarations. The last five countries depend on a variety of sources of information. The totals of Columns A and D do not match exactly because the declarations are incomplete and several estimates are required to complete the table. For the United States, see footnote (e).

b) Belgium did not declare the value in column C, which is the amount of foreign-owned plutonium, in its INFCIRC/549 because of commercial proprietary concerns. The estimate of 2.5-3.5 in column C is based on discussions with Belgian nuclear officials, partial information in Belgian INFCIRC/549 declarations, and official statements about Belgium's use of its own plutonium that had been separated at the LaHague reprocessing plant in France. Almost all of the unirradiated plutonium in Belgium is foreign-owned and is held at the Dessel plutonium fuel fabrication plant. As of the end of 2003, Belgium had finished fabricating all its plutonium recovered at La Hague into MOX fuel, according to the European Supply Agency's Annual Report for 2003. However, it is unknown if all this MOX had been inserted into Belgian reactors by the end of 2003; thus, up to one tonne of Belgian-owned plutonium could be stored domestically. This amount could include a few hundred kilograms of plutonium in unirradiated MOX fuel that was made for the cancelled Kalkar breeder reactor and is now believed to be stored at the Dessel MOX fabrication plant.

c) The estimate of 26 tonnes in column D is the sum of the declared value in column A and an estimate of the undeclared value in column B, or German separated plutonium holdings in other countries. This estimated value assumes that this plutonium is held in Britain, France or Belgium and that the vast bulk of Belgian, German, Japanese, Swiss, Dutch, Italian, Spanish, and Swedish holdings outside of their countries (Column B) is equal to the amount of plutonium in Britain, France and Belgium that is foreign-owned (column C). As a result, the value in column B is estimated at 13-14 tonnes, with a central estimate of 13.5 tonnes.

d) Three tonnes of plutonium in spent fuel or in separated form are located at foreign reprocessing plants, according to Switzerland's declaration to the IAEA. At least one tonne of this plutonium is estimated to remain in spent fuel, based on information about Swiss spent fuel remaining unreprocessed at the La Hague and Thorp reprocessing plants at the end of 2003. In addition, one tonne is believed to be in separated form at Thorp or La Hague.

e) US declared values in INFCIRC/549 are the amounts of unirradiated military plutonium that the United States has declared excess to military requirements and is included in tabulations of such excess plutonium. In total, the United States has declared 52.5 tonnes of plutonium excess. Of this 52.5

tonnes, the United States has declared in its INFCIRC/549 that 45 tonnes are in unirradiated or separated forms. Earlier versions of this report included a fraction of this declared amount, namely an estimate of the amount of unirradiated plutonium originally produced in civil reactors. This estimate was 4 to 5 tonnes, the bulk of which was produced in British civil reactors and exported to the United States several decades ago.

f) India does not declare its civil plutonium stock to the IAEA or the public. Estimates of the amount of plutonium India has separated from civil reactors are complicated because of Indian government secrecy about many of its nuclear activities related to reprocessing. The estimate in this table draws on available information, particularly the difficulty India has had getting its two main civil reprocessing plants, “Prefre” and “Kalpakkam,” to operate at anywhere near their nominal outputs. Because of the shortage of information, the estimate in this table remains highly uncertain.

g) As of the end of 1997, the Netherlands had about 3.6 tonnes of plutonium separated or scheduled for separation from power reactor fuel, from Dutch Ministry of Economic Affairs, Tweede kamer, vergaderjaar 1996-1997, 25422, nr 1. As of the end of 2003, about 0.8-1.2 tonnes of plutonium in spent fuel remained to be separated. In addition, the Netherlands earlier sold about 200 kg of separated plutonium to Italy and other countries, and it assigned 140 kg of separated plutonium to the Superphenix reactor, where the plutonium was irradiated.

h) Italy may have a small in-country stock on the order of a hundred kilograms of unirradiated plutonium that was leftover from its domestic breeder reactor and MOX programs. Italy has unirradiated plutonium stored in Britain and France. The plutonium in Britain resulted from reprocessing contracts at the Thorp plant. The plutonium in France is in the form of unirradiated Superphenix fuel.

i) Sweden publicly declares its separated plutonium stocks; see, for example, Swedish Nuclear Power Inspectorate (SKI), Granskningspromemoria 99:30, 199-07-01. Dnr 8.26-981480.

j) Spain contracted to have 154 tonnes of spent fuel reprocessed at the Thorp reprocessing plant (57 tonnes from the Zorita reactor and 97 tonnes from the Garona reactor). As of the end of 2003, 106 tonnes of this spent fuel had been reprocessed, including all 57 tonnes of spent fuel from the Zorita reactor and 49 tonnes from the Garona reactor. The remaining 48 tonnes of spent fuel from the Garona reactor are expected to be reprocessed by the end of 2005. The owners of the Zorita reactor sold their recovered plutonium to BNFL, and this plutonium should be included in Britain’s INFCIRC/549 declaration at the end of 2003. No one has yet bought the plutonium in the Garona spent fuel. The amount of plutonium separated from the Zorita spent fuel is estimated at about 500 kilograms, and the amount of plutonium separated from the Garona spent fuel by the end of 2003 is estimated at about 300 kilograms.

k) Totals rounded.

TABLE 2 Separated Civil Plutonium Inventories and Projected Inventories (in tonnes)

	Separated Civil Plutonium Owned by a Country, end of 2003[a]	**Separated Civil Plutonium Owned by a Country, 2010 Central estimate or median, (uncertainty range)**	**Separated Civil Plutonium Owned by a Country, 2015 Central estimate or median, (uncertainty range)**	**Separated Civil Plutonium Owned by a Country, 2020 Central estimate or median, (uncertainty range)**
Countries with firm plans to use civil MOX				
Belgium[b]	0.4-1.4	0	0	0
France	48.1	48 (44-53)[c]	46 (38-54)[c]	43 (32-55)[c]
Germany	26	27 (22-31)[d]	15 (7-22)[d]	3 (0-13)[d]
India[e]	~1-1.5	~2	~1	~1
Japan	40.6	62 (51-64)[f]	58 (24-91)[f]	50 (15-86)[f]
Sweden[g]	0.83	0?	0	0
Switzerland[h]	1.5-3.0	0?	0	0
China	0	0?	?	?
Countries without firm plans to use civil MOX through 2020[i]				
Britain[j]	74.6	90	92	92
Italy [k]	2.5	3	3?	3?
Netherlands [l]	2-2.5	3	3.5	4
Spain	0.3	0.6?[m]	0.6?[m]	0.6?[m]
Russia	38.2	50[n]	58[n]	66[n]
Countries with plans to dispose of excess military plutonium which includes some civil plutonium, see table 4 and text				
Total (rounded)	**238 (236-240)**	**286 (266-297)**	**277 (227-325)**	**263 (214-321)**

Comments and Notes for Table 2

a) Source of this column is table 1. The United States is not included, but see table 4.

b) Belgium has stopped reprocessing its spent fuel but has maintained the ability to recycle plutonium in MOX fuel. Thus, it is expected to recycle its separated plutonium stocks into its reactors by the end of 2010. Despite the zero in the columns, Belgium may retain small stocks of separated plutonium, which are viewed here as less than a few hundred kilograms of unirradiated plutonium. This plutonium could be at research facilities, in unused Kalkar breeder reactor fuel, or old fuel cycle facilities. Much of this plutonium could be disposed as waste.

c) The ranges for France are derived from public statements by Cogema and French government officials. France's separation and recycle policies are relatively well-defined and credible indicators of future performance. The projection summarized in this table assumes that France will continue to reprocess about 825-900 tonnes of spent fuel per year and load about 90-110 tonnes of MOX fuel per year into its reactors. Starting after 2005, the MOX fuel is expected to contain 8.65 percent plutonium. The values in the table are the median and the 5^{th} and 95^{th} percentiles which are calculated using the forecasting software Crystal Ball®. This software allows a more systematic uncertainty analysis. If France loads more of its reactors with MOX fuel, it will reduce its separated plutonium inventory more than projected above.

d) The estimates for Germany reflect uncertainties in amounts of plutonium separated and the rate of MOX use. About 16-18 tonnes of separated plutonium are expected to be separated at Thorp and La Hague from the end of 2003 through 2010, by which time reprocessing of German spent fuel is scheduled to end. Thus, including Germany's end of 2003 inventory, it needs to dispose of a total of about 42-44 tonnes of separated plutonium. Germany has up to 12 reactors that can be loaded with MOX fuel, giving it sufficient capacity to reduce its separated plutonium to zero by 2020. In the estimate, Germany is assumed to obtain between 35 and 60 tonnes of MOX fuel each year through 2020. This rate requires Germany to obtain MOX fuel from Belgium, France, and Britain. A potential constraint is that Germany and Japan will compete for the same MOX capacity in Europe. If SMP does not operate, and Japan is also seeking MOX fuel in Europe as expected, Germany may have difficulty obtaining over 40 tonnes of MOX fuel per year. The values in the table are the median and the 5^{th} and 95^{th} percentiles which are calculated using the Crystal Ball® program.

e) India has ambitious plans to separate plutonium and use the plutonium in breeder reactors, the first of which is scheduled for operation in 2010. This first breeder would need about 2 tonnes of plutonium for its initial core and have a refueling requirement of several hundred kilograms of plutonium each year. Whether India can build the breeder on schedule and separate enough plutonium is doubtful based on the past performance of its reprocessing plants and breeder research program. The estimates in this table are crude and essentially extrapolations from a limited set of data.

f) These central estimates and ranges reflect the uncertain timing of Japan's use of MOX in reactors and the amount of plutonium it plans to separate in the Rokkasho reprocessing plant. If Japan implements its MOX use plan on its current schedule, it will load 16-18 reactors with MOX fuel by about 2012. The range in the estimates in the table reflects five scenarios that are detailed in the text. The lower bound reflects a decision to reduce output from the Rokkasho reprocessing plant to about 2 tonnes of plutonium per year until almost all the Japanese plutonium stored in Europe is put into reactors, about 7 years in the scenario considered here. The maximum value corresponds to a delay in the start of MOX loading until 2012 and then a gradual buildup of MOX use in 18 reactors and full-scale operation of Rokkasho reprocessing plant.

g) The Swedish utility that owns the plutonium has contracted with SMP to make MOX fuel from its plutonium stock by 2005. A final approval to use the MOX in its reactor has not been given.

h) Switzerland has been separating and recycling plutonium for many years. It has a decreasing supply of separated plutonium and has sufficient reactors to use MOX fuel that it has contracted to be fabricated elsewhere in Europe. If SMP does not operate, Switzerland may have difficulty recycling all its plutonium slated for separation at the Thorp plant by 2010.

i) The following countries do not currently have any firm plans to use MOX fuel or otherwise dispose of their stocks of unirradiated plutonium through 2020. Some countries have considered selling their stock of plutonium, and Spain has succeeded in selling most of its current stock and may be able to sell the remainder of its expected stock of separated plutonium, despite the shortage of buyers. In general, however, countries with stocks of separated plutonium are expected to encounter difficulty in selling their stocks of unirradiated plutonium. Although Russia has stated it plans to recycle its civil plutonium as MOX, it has not established any firm schedules to do so through 2020.

j) Because of cutbacks in the British nuclear reactor programs, including less AGR spent fuel being committed to reprocessing, less British plutonium is expected to be separated in the future.

k) Italy may seek to have another 235 tonnes of LWR spent fuel reprocessed in France or Britain. This fuel would contain about 2 tonnes of plutonium, which would be returned to Italy after reprocessing, unless Italy is able to make other arrangements for the separated plutonium. This plutonium is not included in the quantity listed in table 2.

l) The Netherlands intends to sell its separated plutonium. It has also contracted to continue reprocessing its spent fuel from the Borssele reactor in France. If the Netherlands does not find buyers for all of its separated plutonium, it may be returned to the Netherlands.

m) Spain is seeking a buyer for the plutonium that has been or will be separated from 97 tonnes of spent fuel contracted for reprocessing at Thorp. It has already sold to BNFL, the owners of Thorp, about 500 kilograms of plutonium recovered from about 57 tonnes of spent fuel also contracted for reprocessing at Thorp. If Spain is unable to sell this separated plutonium, it will be held in Britain until 2008, when it will be returned to Spain.

n) This estimate assumes that Russia will continue reprocessing LWR spent fuel after 2010. A small quantity of this plutonium is scheduled for blending with excess military weapon-grade plutonium. This reduction is not taken in this table, because the total amount of civil plutonium separated is very uncertain.

Table 3 Projected Japanese Plutonium Inventories, in tonnes*

Cases	2010	2015	2020
Case 1-Optimistic	59	59	50
Case 2-Two-year delay	63	75	68
Case 3-Four-year delay	64	91	86
Case 4-European-Stored Plutonium First	51	24	15
Case 5-No Mox Use	64	78	78

Notes

* The cases are defined in the text.

Table 4 Current and Projected US and Russian Stocks of Excess Unirradiated Plutonium Subject to MOX Disposition, in tonnes*

Country	2010	2015	2020	2025	2030
Russia	34	26 (23-28)	16 (11-20)	6 (0-12)	0 (0-5)
United States	34	25 (20-29)	13 (4-22)	1 (0-16)	0 (0-9)

* The estimates for 2015 and 2020 are the median and the range (in parentheses) created by the 5th and 95th percentile in the estimate of the disposition of 34 tonnes of weapon-grade plutonium. These estimates are calculated using the forecasting software Crystal Ball®, which allows a more systematic uncertainty analysis. The lower values in the ranges for 2025 and 2030 are arbitrarily set at 0 for the estimate of the disposition of 34 tonnes of plutonium, because the 5th percentile is negative in the calculation. In 2030, the median in the calculation is also negative and is set at zero.

Table 5 Current Stocks of Excess US and Russian Unirradiated Military Plutonium, Reflecting MOX and Other Firm Disposition Decisions, central estimates, in tonnes*

Country	2010	2015	2020	2025	2030
Russia	50	42	32	22	16
USA	45	36	21**	9	8
Total	**95**	**78**	**53**	**31**	**24**

Notes

* Median values from table 4 are used as the basis for these estimates.

** In 2020, three tonnes of US excess plutonium are projected to be disposed in the WIPP facility and thus removed from the excess stock (see text).

Table 6 Civil Unirradiated Plutonium, from Civil Reactors and Declared Military Excess, in tonnes*

Origin	2003	2010	2015	2020
Civil**	238	286 (266-297)	277 (227-325)	263 (214-271)
US and Russian*** Excess	95	95	78 (70-84)	53 (42-69)
Total (rounded)	**333**	**380 (360-390)**	**355 (295-410)**	**315 (255-340)**

* The values in parentheses are the lower and upper bounds of each estimate, derived from the bounds in tables 2 and 4.
** Taken from table 2. This quantity includes British excess military plutonium.
*** Derived from tables 4 and 5.

Figure 1 Projection of the Global Inventory of Civil Unirradiated Plutonium through 2020