Shipments of Weapons-Usable Plutonium in the Commercial Nuclear Industry

David Albright
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The Institute for Science and International Security (ISIS)

International commerce in civil unirradiated, or weapon-usable, plutonium is now well established. Plutonium commerce is centered currently in Europe but is expected to increase in Japan and India, and perhaps in Russia and the United States. Each year, there are roughly 100 commercial shipments, each often containing well over 100 kilograms of weapons-usable plutonium. The next 15 years will see about 1,500 commercial shipments containing about 500 tonnes of unirradiated plutonium. Eight kilograms of plutonium, commonly called a significant quantity of plutonium, is enough to make a nuclear weapon. Thus, over 60,000 significant quantities will be transported through 2020. Stringent security over these shipments will need to be maintained consistently to prevent theft.

The vast majority of the civil plutonium shipments are the result of large, interconnected civil reprocessing and recycling programs in Europe and Japan. India has a nationally self-contained program separating plutonium and using MOX fuel in a breeder reactor research and development program. Additional countries may follow suit. Russia and the United States have declared a large amount of plutonium excess to defense requirements and have committed to build MOX fabrication plants to recycle their excess plutonium into their civil reactors. If these efforts are successful, Russia may opt to recycle its large civil stock of unirradiated plutonium.

Civil plutonium shipments occur by truck, rail, and ship. Air shipments are rarely used anymore, because of health and safety concerns. Information about specific shipments is usually secret in order to better protect the shipments of these dangerous materials from attack or diversion. However, some public information exists about the amount and types of shipments. In addition, ISIS has produced a number of reports and maintains several databases tracking the production, separation, and recycling of plutonium.[1] With this information, it is possible to assess the number of shipments occurring now and expected to occur in the future in the commercial plutonium industries and the amount of unirradiated plutonium that will be transported. In general, the numbers of plutonium

[1] ISIS studies on civil unirradiated plutonium can be found at www.isis-online.org, under the heading "Global Stocks of Nuclear Explosive Materials." See in particular, David Albright and Kimberly Kramer, "Separated Plutonium Inventories: Current Status and Future Directions," June 10, 2005, revised July 8, 2005.

shipments required for civil research and development programs are much harder to estimate and are outside the scope of this report.

Because this study is meant for public dissemination, it focuses on aggregate shipments rather than specific ones or their routes. It also focuses on the commercial power industry that is using plutonium fuels. Because of uncertainties in the scope and timing of US and Russian programs to recycle excess defense plutonium, this report does not analyze those future shipments. One exception to note is that the total quantities of excess defense plutonium currently expected to be transported will be about one quarter the amount transported in the commercial industry during the next 15 years.

Civil Reprocessing and Recycling

Currently, about 15-20 tonnes of plutonium are separated each year in Britain, France, India, Japan, and Russia. Much of this separated plutonium is transported to mixed oxide (MOX) fuel fabrication plants, where it is made into fuel, and then sent to reactors.

Most of the separated plutonium is owned by the British and French governments or utilities in those countries. However, British and French reprocessing plants also separate plutonium from power reactor fuel that is owned by utilities in Belgium, Germany, Italy, Japan, Netherlands, Spain, Sweden, and Switzerland. In addition, India has civil reprocessing plants large enough to separate hundreds of kilograms of plutonium each year.

In the next five to six years, the British reprocessing plants are expected to shut down, and the recently completed Japanese commercial reprocessing plant should reach full capacity. In addition, India wants to increase significantly its capacity to separate plutonium. The net effect is that the annual amount of civil plutonium separated is expected to remain steady at roughly current levels well into the next decade.

Each year, about 11-15 tonnes of separated plutonium are converted into MOX fuel for light water reactors (LWRs), the principal reactor using plutonium fuel. As of the end of 2006, four countries are making MOX fuel: Britain, France, India, and Japan.[2] In the future, the amount of plutonium converted into MOX fuel for LWRs is expected to increase to almost 25 tonnes per year.

A relatively small amount of plutonium is converted into MOX fuel for fast reactors in France and Japan.[3] This amount is expected to grow once Japan brings the Monju reactor back into operation in a few years and India finishes a prototype breeder reactor in about 2010.

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[2] In the summer of 2006, the Dessel MOX fabrication plant in Belgium shut down, because of a lack of orders.

[3] Russia and Kazakhstan have breeder reactors, but these reactors have so far depended on enriched uranium fuel.

After fabrication, the MOX fuel is shipped to power reactors where it is inserted into the reactors. Currently, about 35 power reactors use MOX fuel in France, Germany, Japan, Switzerland, and possibly Belgium. The number of reactors using MOX fuel is expected to increase to over 50 reactors after 2010 and then decrease to roughly 40 reactors by 2020. The increase will result from Japanese LWRs using MOX fuel, a step that has been delayed by years because of domestic opposition to loading MOX fuel. The decrease will occur as Belgium, Switzerland, and Germany use up their remaining stocks of unirradiated plutonium.

Because more plutonium is currently separated than converted into MOX fuel and inserted into reactors, the net amount of separated plutonium has continued to increase, reaching about 240 tonnes by the end of 2003, the latest year for which ISIS has compiled detailed data. Much of this inventory of separated plutonium is stored at reprocessing plants in Britain and France. The net amount of separated plutonium is expected to remain about the same over the next 15 years, or possibly increase somewhat. Table 1 lists the projected inventory of unirradiated civil plutonium owned by a country through 2020. If MOX use programs are expanded to reduce this large excess amount of civil unirradiated plutonium, the number of transports would increase even more than currently expected.

Transport of Separated Plutonium

The vast majority of off-site shipments of unirradiated plutonium occur between reprocessing plants and MOX fuel fabrication plants as well as between the fabrication plants and individual reactors. Because of the amount of unirradiated plutonium in these shipments, physical security requirements are stringent. The plutonium itself is typically in specialized casks or flasks and carried by specialized trucks and ships accompanied by a substantial guard force. As far as could be ascertained, air shipments are no longer being used to transport civil separated plutonium from the La Hague or Sellafield reprocessing plants.

The truck carrying the plutonium, often called a high security vehicle (HSV) or a specially adapted road vehicle (SIFA) is an armored tractor-trailer combination. It is accompanied by multiple other vehicles dedicated to protecting the shipment, supporting the convoy, and maintaining communications among vehicles, a control center, and police. In addition, the control center receives frequent reports of the HSA's location.

The ships used for transporting unirradiated plutonium are modified to either permit the HSV's to roll-on and roll-off or carry specialized shipping casks in their holds. The roll-on and roll-off ships are used for shipments within Europe, allowing the same HSV to travel the entire route. Shipments to Japan from Europe involve truck shipments to the ports and then the transfer of the heavy canisters into the hold of the ship. While at sea, these ships are also subject to substantial physical security.

Reprocessing plants to MOX plants

After separation from irradiated power reactor fuel at civil reprocessing plants, plutonium is converted into plutonium oxide and stored in high-security vaults in individual, criticality-safe canisters. Table A1 in appendix 1 lists the major civil reprocessing plants in the world that are operating, undergoing commissioning, or under construction. Table A2 lists major civil reprocessing facilities that are undergoing decommissioning. Unirradiated plutonium may still be stored at some of these sites and may be shipped elsewhere for recovery or disposal.

A significant fraction of the amount of plutonium separated each year is currently sent to MOX fabrication plants in Britain, France, India, and Japan. Table A3 in appendix 1 contains a list of the major MOX fuel fabrication plants in the world that are operating, under construction, or planned. Table A4 lists those plutonium fabrication facilities that are being decommissioned.

In the case of Britain and Japan, the MOX fabrication plants are located on the same site as the reprocessing plants. The Sellafield site houses the B205 and Thorp reprocessing plants, collectively responsible for the separation of roughly 5 tonnes of plutonium each year when both plants are operating.[4] The Sellafield MOX plant (SMP) is also located at the Sellafield site. The same arrangement applies for the Tokai reprocessing plant and associated MOX fuel fabrication plants. The recently completed commercial-scale Rokkasho reprocessing facility will also send its separated plutonium to an adjacent MOX fuel production plant, slated for construction soon.

One exception to the British situation resulted from the problems SMP has had in filling its customers' orders. As a result, SMP subcontracted five of its European customers' MOX fabrication orders to the Melox and Dessel fabrication plants.[5] These MOX fabricators have used their existing stocks of plutonium to make the MOX fuel, a process called a "plutonium loan." Later, Sellafield must ship plutonium oxide to the fabricators to repay this loan.

France's reprocessing plants and MOX plant are on opposite sides of France. Flasks of plutonium oxide regularly leave the La Hague reprocessing site, near Cherbourg in the northeast of France, and are transported about 800 kilometers on public roads by armored truck to the Melox plant in southern France.

Based on a review of open sources, shipments of separated plutonium, or plutonium oxide, to Melox from La Hague have been in specialized flasks, each typically holding about 15 kilograms of plutonium oxide. These shipments are reported to be in high-security convoys including 2 trucks, each containing about 9-10 flasks or a total of about 270-300 kilograms of plutonium oxide per shipment.[6] The amounts of plutonium oxide transported by Britain may involve smaller amounts of plutonium per shipment.

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[4] For over a year, the Thorp plant has been closed following an accident. It is expected to restart soon.
[5] Pearl Marshall, "First SMP-Made MOX Assemblies Delivered to NOK," *Nuclear Fuel*, June 6, 2005.
[6] Yves Marignac, Xavier Coeytaux, and John H. Large, *Plutonium Transports in France: Safety and Security Concerns over the FS47 Transportation Cask*, Wise Paris, September 21, 2004.

The current agreement among Britain and France and its customers is that plutonium should be returned to the customers in the form of MOX fuel. In the past, for example, Japan planned to receive its separated plutonium directly from reprocessing plants in Britain and France, but shipments are now expected to be in the form of MOX fuel. Thus, foreign-owned plutonium is expected to be transported from reprocessing plants in France and Britain to MOX fabrication plants and not to be sent back to the contracting country for storage, MOX fabrication, or retransfer.

Although Russia is separating plutonium each year and has accumulated a large stock of separated plutonium, it has not yet built any MOX plants to recycle this stock of plutonium. It may do so eventually, particularly given its national commitment to the recycling of plutonium. It may utilize the MOX fabrication plant slated to be built under an agreement between the United States and Russia to convert excess weapons plutonium into MOX fuel. After using up the excess plutonium, Russia has indicated an interest in feeding the plant with its civil separated plutonium. However, this project has slowed down, and the completion date of the MOX plant remains unknown.

India separates civil plutonium at two sites, one at Tarapur north of Mumbai and another one at Kalpakkam, on the east coast. India has an ambitious plan to expand its reprocessing program at Kalpakkam over the 10-15 years, build a new plutonium fabrication plant at Kalpakkam, and build a series of breeder reactors to use plutonium fuels. An Indian official stated in 2003 that the goal was to increase Kalpakkam's capability to reprocess spent fuel from about 150 tonnes annually up to 550 tonnes each year by 2010 and up to 850 tonnes annually by 2014.[7] Most of the plutonium being separated currently is slated for fuel for the Prototype Fast Breeder reactor (PFBR), currently under construction near the Kalpakkam reprocessing plant and scheduled for completion in 2010. Plutonium pellets and rods for the PFBR are reportedly currently being fabricated at the Advanced Fuel Fabrication Facility (AFFF) at Tarapur.[8] India has broken ground on a new plutonium fabrication plant for the PFBR at Kalpakkam which is expected to replace AFFF's role in making pellets and rods for the PFBR.

Little is known publicly about India's shipments of plutonium oxide and plutonium fuel. A 1993 unpublished report on the Indian Atomic Energy Commission by a US official in New Delhi stated that some of the plutonium separated at Tarapur was stored there and the rest was shipped to BARC in Mumbai. Plutonium separated at Kalpakkam is likely shipped both to the AFFF at Tarapur and BARC in Mumbai.

China has announced plans to reprocess power reactor spent fuel and recycle plutonium into breeder reactors. However, these programs are progressing slowly.

From MOX plants to reactors

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[7] P. K. Dey, "Spent Fuel Reprocessing: An Overview," BARC, Indian Nuclear Soceity, 2003. He also stated that at that time PREFRE at Tarapur reprocessed KAPS fuel and Kalpakkam reprocessed MAPS fuel.

[8] H. S. Kamath and A. Kumar," Development of Plutonium fuel for Thermal and Fast Reactors," IANCAS Bulletin, July 2005, pg. 224.

At the MOX plants, the plutonium oxide is manufactured into ceramic pellets and then rods, before being gathered into fuel assemblies. After fabrication, the fuel assemblies are sent to individual reactors, almost all of which are LWRs.

The process of making MOX fuel results in scraps that are recycled. In France, for example, the scraps are transported back to La Hague for recycling. In addition, several tonnes of plutonium in MOX fuel was manufactured in Belgium, France, and Germany and never used. This material is also slated for recycle at La Hague.

Appendix 2 lists by country the reactors using or planning to use MOX fuel in LWRs. In addition, a few fast reactors are included, although this type of reactors will use far less plutonium than LWRs for at least a few decades.

France has the greatest number of LWRs using MOX fuel. For the last two decades, twenty of its 900-MWe-class PWRs have been loading MOX fuel. Each PWR is permitted to load up to 30 percent of its total core of the reactor with MOX fuel. Currently, French LWRs load annually about 100 tonnes of MOX fuel made at the Melox plant. Each assembly contains about 6.9 percent plutonium, or a total of 6.9 tonnes of plutonium per year. The French utility, EdF, has asked French regulators to permit the fraction of plutonium in each fuel assembly to be increased to 8.65 percent, permitting the MOX fuel to remain in the reactor longer. In that case, the total amount of plutonium in the 100 tonnes of MOX would reach 8.65 tonnes, which is the amount of plutonium separated from spent EdF fuel each year at La Hague. Once this license is granted, EdF may consider putting MOX in more reactors, which would permit the reduction of the total stock of French unirradiated plutonium. In addition, EdF plans to build an advanced reactor during the next decade that has been designed to load a core of 100 percent MOX fuel.

Belgium, Germany, and Switzerland have been loading MOX fuel for many years in about 15 reactors. The fraction of the MOX in the various reactor cores has varied between 20 and 50 percent of the core. All three countries have decided not to sign any new reprocessing contracts, and thus, they will continue to use MOX fuel until their supply of separated plutonium from existing contracts is exhausted or the plutonium can no longer be used in reactors. For example, a utility in northern Germany for years experienced difficulty in acquiring a license from a state government to use MOX in its reactors. It is unclear if this utility will be able to recycle its several tonnes of separated plutonium.

Japan has ambitious plans to use MOX fuel in 18-20 LWRs and the Monju demonstration fast reactor, using plutonium separated in Britain and France and at the Rokkasho reprocessing plant. Local opposition and a series of nuclear accidents have delayed this MOX use plan by years. As a result, Japanese utilities have been delayed in recycling MOX fuel into LWRs. Japanese utilities are expected to load about one-third of the LWR's core with MOX fuel. Japan has also decided to build an advanced LWR that will be fueled by a full core of MOX fuel.

India has loaded small quantities of plutonium fuel into its boiling water reactors at Tarapur and a test breeder at Kalpakkam. This fuel was shipped from the fuel fabricator to the reactors. India plans to start the PFBR in 2010 and build several more breeders and an advanced heavy water reactor in the following decade that would use tons of plutonium each year. It hopes to also recycle plutonium into both its BWRs and at least one pressurized heavy water reactor.

Britain and Russia have no concrete plans to recycle civil plutonium into their reactors. With the poor performance of the SMP, Britain has few options to use the plant to make MOX fuel for domestic use, even if the government decided to do so. Russia is expected to eventually seek a way to recycle its plutonium in LWRs and fast reactors.

The United States is planning to recycle excess defense plutonium in LWRs. It is expected to recycle much of this plutonium in a several LWRs. To test four lead test assemblies of MOX fuel in Duke Power's Catawba PWR, the United States shipped 140 kilograms of plutonium to France by sea. After landing in Cherbourg in northwestern France, the separated plutonium was shipped by truck to the Cardarche MOX fabrication plant in southern France. After the four assemblies were made, the MOX fuel was trucked back Cherbourg and then loaded on a ship that sailed to the United States.

Illustrative shipments of MOX fuel MOX fuel is transported to reactors in specialized shipping containers that can hold from one to over ten fuel assemblies. The mass of a MOX fuel assembly varies based on the type of reactor. PWR fuel assemblies are more massive and contain more plutonium per assembly than BWRs. As a result, transport casks usually hold fewer PWR than BWR fuel assemblies.

The annual amount of MOX fuel transported to a specific reactor depends on several factors. Larger reactors will need more fuel assemblies each year. The fraction of plutonium in each assembly varies, with the trend toward increasing the plutonium fraction as the fuel is able to achieve a higher "burn-up," or irradiation time in the reactor. However, with higher burn-up of the fuel, fewer MOX assemblies are needed each year. In addition, the reactor owner may not be able to obtain enough MOX assemblies each year to load the reactor to its maximum permitted level, particularly given the uncertainties that have affected the ability of the major MOX fabrication plants to reach their design throughputs.

A MOX fuel assembly in a 1,000 MWe PWR has a mass of about 500 kilograms and would typically contain about 5-7 percent of plutonium or 25-35 kilograms of plutonium. The core would have 30 percent MOX assemblies and refuel on a three year cycle. [9]

[9] Because many PWRS are moving toward longer operating cycles, the fraction of plutonium in the MOX fuel is being increased to permit a four-year cycle, although the movement in this direction has been relatively slow. For example, the French utility, EdF, has been trying since 1999 to obtain approval from its regulatory authorities to permit MOX fuel to achieve higher burnups in line with those achieved by conventional LEU fuel. Currently, the MOX fuel is loaded and discharged under a three year cycle while the LEU fuel uses a four year cycle.

Under these assumptions, a 1,000 MWe PWR would require annually roughly 15 fuel assemblies, containing in total about 375-525 kilograms of plutonium. One or two shipments could transport this number of assemblies to a reactor from a MOX fabrication plant. In practice, more shipments may occur.

Over the last several years, the nuclear industry has developed shipping casks that can carry more fuel assemblies. Older shipping casks used to transport fuel assemblies by truck in France and Germany could carry only one or two PWR fuel assemblies or perhaps two to four times as many BWR fuel assemblies. These casks were designed to permit them to be sent individually or stacked in sets of two or four. In practice, trucks are believed to have carried only one or two of these casks to reactor sites. Currently, Melox can ship in a new cask (MX 8) that can carry eight PWR assemblies. SMP has reportedly also been developing a new cask able to carry more assemblies.

For sea shipments from Europe to Japan, the casks are heavier although the ones used by Melox still carry a maximum of 8 PWR fuel assemblies. However, the number of casks on a ship can be considerably greater than the number carried by one or two trucks in a convoy. A shipment to Japan for example could contain PWR and BWR assemblies containing 500-1,000 kilograms of plutonium, while a truck convoy would typically carry fuel assemblies with less than 500 kilograms of plutonium.

After irradiation in the reactor, the MOX fuel is scheduled for long-term storage. Eventually, this irradiated fuel may be reprocessed and the plutonium recycled, although such plans are currently vague and excluded from this analysis.

The Number of Shipments of Civil Unirradiated Plutonium in Europe and Japan

There is little public information that gives the number of civil plutonium transports in the world today or expected in the future. To develop a sense of the number occurring, it is useful to consider two crude estimates. The first estimate extrapolates from an old International Atomic Energy Agency (IAEA) study, and the second one involves a scoping calculation.

IAEA Transport Study

An unpublished, undated summary of a study by the IAEA's Division of Systems Studies in the mid-to-late 1980s about the number of plutonium shipments can be used to provide a useful comparison to the present situation. This study estimated the total number of unirradiated plutonium shipments expected in 1990 and in 1995 in non-nuclear weapons states (NNWS). This study did not include the transfers of unirradiated plutonium expected in the nuclear weapon states or states that had not signed the NPT such as India.

The Division of Systems Studies estimated that in 1990 the number of foreign and domestic transfers of unirradiated plutonium in non-nuclear weapon states in amounts exceeding one kilogram would be on order of 200 per year. In 1995, the study estimated that number would double to about 400 per year.[10]

The basis for the estimate of 200 shipments per year is not explained in the summary, but it likely includes a considerable number of facilities involved in the research and development of reprocessing, breeder reactors, and MOX use in LWRs. These facilities and activities required the shipment of a large number of relatively small shipments of separated plutonium or MOX fuel. The facilities that existed then and would have likely been included in the estimate included three mid-sized MOX fuel fabrication plants in Belgium, Germany, and Japan, a certain level of use of MOX fuel in LWRs, two small reprocessing plants in Germany and Japan, a few small breeder reactors, and several research reactors or critical facilities. Many of these shipments would have been relatively small. Most of these types of activities are no longer occurring.

The basis for the increase of 200 to 400 shipments annually by 1995 was explained more thoroughly in the summary. It was based on assuming that between 1990 and 1995 the NNWS would start two new large reprocessing plants, one and perhaps two large MOX fabrication plants, a 300 MWe breeder reactor, and a 700 MWe advanced thermal reactor, and would load more LWRs with MOX fuel. To derive its estimates, the IAEA evaluated the quantities of plutonium expected to be shipped between facilities. It used then existing patterns in the amount of plutonium per shipment to derive a total number of annual shipments.

However, the first half of the 1990s turned out far differently. Several of the facilities were cancelled or delayed. For example, the German Wackersdorf reprocessing facility and the 300 MWe breeder were cancelled, and MOX use in LWRs grew far more slowly during that period than expected.

The amount and type of new facilities and activities expected to materialize by 1995 in the NNWS are roughly comparable to the total number of such facilities and activities currently in both the NNWS and nuclear weapons states. There are now two large reprocessing plants, two large MOX fabrication plants, a mid-size breeder reactor in France, and a steady use of MOX fuel.

Based on this comparison, no more than 200 shipments per year would be expected to occur today from these facilities and activities. The actual number would be expected to be significantly less. More plutonium is likely contained in each shipment now than in the 1980s, and shipments between the Thorp reprocessing plant and the SMP are counted as intra-site shipments and not counted in this study.

Based on the IAEA study, it is reasonable to expect up to another 100 shipments of unirradiated plutonium per year in amounts greater than one kilogram but far less than the shipments associated with major commercial operations. These shipments would be

[10] Undated Answer to a Question, Division of Systems Studies, IAEA. Shipments of unirradiated plutonium then included plutonium oxide, plutonium nitrate, mixed oxide powders, and fresh fuel containing plutonium. Civil plutonium nitrate is no longer shipped.

likely associated with residual research and development activities or clean-up of decommissioned pilot or demonstration facilities.

Scoping Calculation

Although great uncertainty surrounds estimates of the number of off-site shipments of unirradiated plutonium each year, a scoping calculation can estimate the rough number of shipments occurring in Europe and Japan associated with commercial activities. This calculation rests on estimating the annual amount of plutonium being separated commercially and the annual amount of plutonium fabricated into MOX fuel for LWRs and a few fast reactors. This latter amount is then assumed to be used in these reactors.

This estimate does not include plutonium shipments associated with research and development activities or most decommissioning activities. Because the number of shipments occurring in India is difficult to estimate on an annual basis, it is not included in this scoping calculation. Shipments in India will be discussed in the next section.

In the case of reprocessing, only the La Hague reprocessing plant needs to be considered, because the other major reprocessing plants are not shipping separated plutonium off-site. In this scoping calculation, each shipment from La Hague is assumed to hold about 300 kilograms of plutonium, as discussed above. Enough plutonium is assumed to be shipped each year to match the amount of plutonium fabricated into MOX fuel at Melox and in 2005 at Dessel.

The variability of MOX use in reactors is great. Some LWRs may need fewer fuel assemblies than expected; sometimes more may be transported to a LWR. The maximum value for a large LWR could be an annual requirement of roughly 500-600 kilograms of plutonium in two or more shipments. At the other extreme, a LWR may only receive a few fuel assemblies per year, containing less than 100 kilograms of plutonium. Given the wide variability, each shipment of MOX fuel in this scoping calculation is assumed to have on average 300 kilograms of plutonium.

Table 2 shows that about 92-97 shipments containing about 25.0-26.5 tonnes of unirradiated plutonium are estimated to be currently occurring each year in Europe and Japan. As can be seen, there are an estimated 39-43 shipments per year of plutonium oxide from the La Hague reprocessing plants to Melox. About 43-44 shipments of MOX fuel are transported from the fabrication plants to reactors.

Table 2 also projects the number of shipments through 2020.[11] The annual number of shipments increases, mainly because of the start of the Rokkasho reprocessing plant and

[11] This projection makes several reasonable assumptions about the future output of several key reprocessing and MOX fabrication plants. The Melox plant is assumed to reach a capacity of 195 tonnes of MOX fuel per year by 2010, the SMP reaches a capacity of only 40 tonnes of MOX fuel per year by 2010, the Rokkasho reprocessing plant achieves its nominal capacity in 2010, and the Rokkasho MOX fabrication

MOX fabrication plant. By 2015, there will be about 141 shipments per year containing almost 41 tonnes of unirradiated plutonium.

In total, there are projected to be about 1,635-1,865 shipments from the end of 2006 through 2020, containing about 463-570 tonnes of weapons-usable plutonium. Averaging these numbers gives about 1850 shipments containing 499 tonnes of unirradiated plutonium, or about 62,300 significant quantities of plutonium.

Unirradiated Commercial Plutonium Transports in Key Countries

This section evaluates the expected number of commercial plutonium transports in countries using significant quantities of MOX fuel. Specifically, it discusses countries, or utilities in those countries that own a significant amount of unirradiated plutonium and that will or could reasonably be expected to fabricate this plutonium into MOX fuel and insert it into LWRs.

This section does not evaluate the number of unirradiated plutonium shipments related to research and development efforts, most decommissioning efforts, and plutonium recovery operations in France involving the shipment of materials between sites. The last two efforts can require a large number of shipments, but each shipment tends to have relatively small quantities of plutonium.

The main results of this section are summarized in Table 3. Using this methodology, which uses Crystal Ball® software, from the end of 2006 through 2020, the median number of shipments is 1,404 with a range of 1,136-1,873 shipments, containing about 486-527 tonnes of plutonium.

France

France's electricity utility, EdF, has been recycling 100 tonnes of MOX fuel into 20 PWRs. It may decide to recycle MOX fuel into more PWRs, although such additional MOX use remains uncertain. France also operates the demonstration Phenix fast reactor that uses plutonium as fuel. The lifetime of the reactor has been extended, although it remains unclear how much longer the reactor will operate.

One hundred tonnes of MOX fuel would correspond to about 215 fuel assemblies of the type used in the French PWRs of the 900 MWe-class.[12] If the MOX fuel achieves scheduled burnups and up to 30 percent of the core use MOX, each reactor would load up to about 15 MOX fuel assemblies each year, where each fuel assembly would contain about 32 kilograms of plutonium.

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plant starts in 2012 and ramps up to full capacity by 2015. A related key assumption is that the MOX fuel from the Rokkasho MOX plant can be utilized, which ultimately depends on Japanese LWRs starting to use MOX fuel.

[12] Each fuel assembly is assumed to have a mass of about 0.465 tonnes.

In total, the 100 tonnes of MOX fuel currently contains about 6.9 tonnes of plutonium. Assuming each shipment from the La Hague reprocessing plant to the Melox plant contains about 300 kilograms, about 23 shipments per year are needed.

For French PWRs, Melox is likely using the MX 8 shipping cask, and each reactor would be expected to receive one to two shipments per year, or equivalently 8-15 fuel assemblies per year, containing roughly 250-480 kilograms of plutonium. If each reactor received its full potential allocation of MOX fuel each year, or 15 fuel assemblies, then about 14 reactors could be fueled annually. Such a scenario would require about 14-28 shipments per year, assuming that each cask contained 8 fuel assemblies and each shipment had 1-2 casks. If all 20 reactors receive at least some MOX fuel, about 20-30 shipments would be required, assuming that as many reactors as possible receive a full allotment of 15 fuel assemblies.[13] If each reactor received an equal number of fuel elements, about 10-11 elements, then about 20-40 shipments per year could be required. However, an upper bound of 40 shipments seems impractical and overly expensive, particularly given the cost of transporting unirradiated plutonium.

An alternative calculation uses Crystal Ball® software, where the number of transports is estimated by dividing the total amount of plutonium made into MOX fuel by the estimated amount of plutonium per shipment, about 256-480 kilograms of plutonium per shipment in the French case. This calculation results in a median of 20 shipments a year with a range of 15-30 shipments each year.[14]

Although the more accurate estimate is likely based on knowing the total number of reactors scheduled to use MOX fuel and the number of fuel assemblies slated for each reactor, the estimate based on using a range of plutonium appears to produce similar results. The one exception is that the Crystal Ball® estimate does not appear to capture the upper bound of 40 shipments that was derived above. Despite this limitation, the methodology using the Crystal Ball® software is used in this section. As will be discussed below, often information about which particular reactor is loaded each year with MOX fuel is not known. In addition, most countries do not have one type of reactor using MOX fuel as in the case of France. This lack of reliable information complicates efforts to estimate the number of transports based on knowing the number of MOX fuel assemblies sent to specific reactors.

EdF has asked the government to allow it to increase the fraction of plutonium in each fuel assembly to 8.65 percent. If this request is approved, EdF would achieve a rough parity between the amount of EdF plutonium separated each year at La Hague and the amount turned into MOX fuel. In this case, up to about 12 MOX fuel assemblies could be loaded each year into a reactor, where each fuel assembly would contain about 40

[13] Assume that a reactor receives either 8 or 15 fuel assemblies. In this illustrative case, about 12 reactors would receive 8 fuel assemblies, requiring 12 shipments. Another 8 reactors would receive 15 fuel assemblies, requiring 8-16 shipments. In total, about 20-28 shipments per year would be needed in this scenario.

[14] The range is technically the values from the 0^{th} to the 100^{th} percentile. In each calculation, there will exist a small number of outliers which are not included in this range.

kilograms of plutonium. Each year, most reactors would receive 12 fuel assemblies, or 480 kilograms of plutonium. However, some would receive fewer fuel assemblies. Assuming that EdF's request is approved and each reactor receives 8-12 assemblies per year, or 320-480 kilograms of plutonium each year, the median is 22 shipments a year with a range of 18-29 shipments each year. From the end of 2006 through the end of 2020, the total estimated number of shipments to French PWRs has a median of about 305 and a range of 240-395 shipments each year. The total amount of plutonium transported in MOX fuel would be about 121 tonnes.

At a plutonium fraction of 8.65 percent in MOX fuel, about 8.65 tonnes of plutonium must be moved to Melox each year from La Hague. This would require about 29 shipments, where each shipment is assumed to contain about 300 kilograms of plutonium. From the end of 2006 through 2020, the Melox plant would receive about 406 shipments containing about 121 tonnes of plutonium.

France has a large inventory of separated plutonium, over 48 tonnes at the end of 2003 (see Table 1). This excess civil stock is projected under current plan to remain roughly the same through 2020. If France decided to increase its use of MOX fuel, such as loading MOX in additional reactors, it could work down this excess stock, but it would encounter more shipments. Assuming that 25 tonnes of this plutonium were used in MOX and assuming the above conditions, the median is 63 shipments to reactors, with range of 52-79 shipments. In addition, another 83 shipments from the La Hague reprocessing plant to the Melox facility would be required, where each shipment is assumed to contain 300 kilograms of plutonium.

Germany

German utilities have been receiving shipments of MOX fuel from Belgium, British, and French MOX fabrication plants for many years. Germany used to operate its own MOX fabrication plant, but this facility closed over a decade ago. Currently, about 11 reactors are licensed to use MOX fuel, although it is difficult to know which reactors are scheduled to receive fresh MOX fuel during any particular year. In addition, the reactors do not have a uniform policy on the fraction of MOX fuel used in an individual reactor. As a result, the quantities of MOX fuel vary from reactor to reactor and year to year, making estimates based on the annual usage of fuel assemblies impossible to do. Further complicating an estimate, the number of MOX fuel assemblies in a shipment has varied.

Because of these uncertainties, the number of transports is estimated from total unirradiated plutonium stocks used annually in MOX fuel. This estimate assumes that each year German utilities have about 35-60 tonnes of MOX fuel fabricated containing about 5-6 percent plutonium. The amount of plutonium per shipment is taken as 150-500 kilograms. In this case, the median of the average number of MOX shipments in Germany each year is 8 shipments per year with a range of 4-20 shipments per year. This number of shipments is expected to continue over the next 10-15 years and then end as Germany uses up or decides not to recycle its supply of separated plutonium from British and French reprocessing plants.

Germany's plutonium has been separated in Britain and France. Most of the MOX fuel in recent years has depended on plutonium separated at La Hague, because of operational problems at SMP in Britain. Assuming that all of Germany's MOX fuel has been fabricated in recent years at Dessel or Melox, these plants would have required about 6-12 shipments per year of plutonium oxide, where each shipment is assumed to hold 300 kilograms of plutonium.

Extrapolating the calculation of annual MOX shipments, the number of MOX shipments to German reactors from Melox and SMP from the end of 2006 though 2020 would have a median of 104 and a range of 45-285. These shipments would contain about 22-46 tonnes of plutonium.

About half of the German plutonium used in MOX is estimated to have been separated at La Hague. In this case, about 37-77 shipments of plutonium oxide to Melox would be required, containing 22-46 tonnes of plutonium. German plutonium separated at Thorp in Britain is assumed to be converted into MOX at the adjacent SMP.

Germany also has had leftover unirradiated plutonium, mostly in the form of MOX or scraps at decommissioned fuel cycle facilities. Much of this material is being transported to La Hague for processing. However, the total number of shipments is difficult to determine but is crudely estimated to be on order of ten and contain one tonne of plutonium.

Switzerland

Switzerland contracted to have a major portion of its spent fuel reprocessed in Britain and France and to recycle the separated plutonium in three of its LWRs. It has steadily been recycling plutonium into these reactors. The number and type of transports to Swiss reactors has varied and been dependent on the supply of MOX fuel. In June 2005, the Beznau PWRs received a shipment of four MOX fuel assemblies from SMP, and in April 2006, these reactors received another four assemblies from SMP.[15] SMP was supposed to have sent 12 MOX assemblies in the spring, but it could not manufacture them in time for the second shipment. The other eight fuel assemblies are expected to be sent to Beznau later. In addition, Swiss utilities have contracted with France for MOX assemblies.

Each Beznau fuel assembly has a mass of about 0.38 tonnes, so each MOX fuel assembly would contain about 27 kilograms of plutonium, assuming the plutonium is about 7 percent by mass. Thus, four fuel assemblies would contain about 110 kilograms of plutonium. An individual shipment is likely to contain 4-8 fuel assemblies, or about 110-215 kilograms of plutonium. The Gosgen PWR is the third Swiss reactor using MOX, and its fuel assemblies have about the same mass as the Beznau reactors. As a result, shipments to the Gosgen reactor should be similar in size as those to the Beznau reactors.

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[15] Pearl Marshall, "BNG's German MOX Contract Marks its First Supply Deal in Four Years," *Nuclear Fuel*, May 22, 2006.

At the end of 2004, according to its last official declaration to the IAEA, Switzerland had in separated form or in spent fuel awaiting reprocessing, about 3 tonnes of plutonium in Britain and France. Over the next several years, Swiss utilities are expected to use the recovered plutonium in their LWRs. Assuming that all this plutonium is used and 110-215 kilograms per shipment, the median of the total number of shipments is 18 with a range of 13-28. The vast bulk of these shipments are expected to occur after the end of 2006.

Given the delays in the operation of SMP, much of the Swiss plutonium is likely in Britain. Swiss utilities are likely to have recycled much of their plutonium separated at La Hague. Assuming that one quarter remains at the La Hague plant, about 3 shipments of plutonium oxide to Melox will be needed. The rest of this plutonium is expected to be converted into MOX at SMP.

Belgium

Belgium separated in total about 4.8 tonnes of plutonium at the La Hague reprocessing plant. It decided several years ago not to reprocess any more of its spent power reactor fuel. Its plutonium has been made into MOX fuel and most, if not all, of this MOX has been put into two Belgian reactors. Although some MOX shipments to Belgian reactors may still be occurring, it is reasonable to conclude that they will soon end.

The closure of the MOX fabrication plant in Dessel, Belgium in the summer of 2006 will result in shipments of residual plutonium, which are reportedly being fabricated into "dummy" rods. The rods are expected to be sent to La Hague for plutonium and uranium recovery. The number of shipments is unknown. If Dessel was storing unirradiated MOX fuel intended for the never-finished Kalkar reactor (SNR 300), it may also send such MOX fuel to La Hague for processing.

As of the end of 2004, according to Belgian's declaration to the IAEA, about 2.1 tonnes of unirradiated plutonium were in unfinished or semi-fabricated fuel at fuel fabrication plants in Belgium, essentially at Dessel. Another 1.2 tonnes were in finished unirradiated MOX fuel at reactor sites or at fabrication plants. Most of the latter is thought to be at Dessel. Much of the former should have been fabricated into finished fuel prior to Dessel's closure. A crude estimate is that about one tonne of unirradiated plutonium will be sent to La Hague for recovery. The number of shipments to La Hague is expected to be on order of ten. Subsequent shipments of the plutonium recovered at La Hague plutonium are not considered here because of a lack of information about the owners of the plutonium.

Sweden

Although Sweden is opposed to reprocessing or recycling plutonium from its power reactors, a Swedish utility, OKG, years ago contracted for the separation of 830 kilograms of plutonium at Sellafield. To utilize the plutonium, OKG contracted with

SMP to make 80 MOX fuel assemblies for the Oskashamn-3 BWR from this plutonium.[16,17] This material will be transported by ship to the reactor site, which is located on the Swedish east coast. *Nuclear Fuel* reported on May 8, 2006 that SMP was expected to make MOX fuel for Oskashamn in late 2006 or 2007. Only two shipments are expected to occur.[18] According to the *Nuclear Fuel,* one shipment of the MOX fuel is expected to be sent to Oskarshanm in 2007 and a second one in 2008, according to the *Nuclear Fuel* report.

Netherlands, Italy, and Spain

Netherlands, Italy, and Spain have had or will have plutonium separated in Britain and France, but they do not have any reactors to recycle MOX fuel. As a result, they are trying to sell their plutonium. In addition, they may also try to have their plutonium converted into MOX fuel and irradiated in other countries' reactors.

Combined, these three countries will need to sell, recycle, or dispose of almost 8 tonnes of separated plutonium.[19] Despite the utter lack of need for the plutonium, Italy may contract to have another two tonnes of plutonium separated in Britain or France. Using Crystal Ball® and ignoring the possibility of additional plutonium, an upper bound on the possible number of shipments of MOX fuel can be derived, assuming that each shipment will contain about 150-500 kilograms of plutonium. The maximum number of shipments has a median of 25 with a range of 16-54.

Italian and Spanish plutonium is in Britain, so shipments to SMP would be within the same site. About 75 percent of the four tonnes of Dutch plutonium slated for recovery is separated in France. Transporting three tonnes of plutonium oxide to the Melox plant would require about 10 shipments.

Britain

Britain has a large and growing stock of civil separated plutonium, but no plans to use the plutonium in MOX fuel. Thus, few, if any, shipments of British owned plutonium in the form of MOX fuel are expected during the next decade.

Russia

Russia has no concrete plans to use the bulk of its growing stock of civil separated plutonium. The one exception is that Russia plans to blend several tonnes of civil separated plutonium with excess weapons plutonium to disguise the original isotopic composition of the weapons plutonium. This plutonium would be blended at a

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[16] OKG Aktiebolag, private communication.

[17] A fuel assembly in Oskarshamn 3 has a mass of about 0.17 tonnes of heavy metal. Assuming no losses of plutonium, each assembly would contain about 10.4 kilograms of plutonium, or about 6.1 percent plutonium by mass.

[18] OKG, private communication.

[19] "Separated Plutonium Inventories: Current Status and Future Directions," op. cit.

conversion facility at Mayak, where the civil plutonium is stored, and then transported in a blended product to a MOX fabrication plant slated to be build at Seversk (Tomsk-7).

Japan

Japan has extensive plans to use MOX fuel in 18-20 LWRs and the Monju demonstration breeder reactor. Public and local government opposition has dramatically slowed down utilities' plans to insert MOX fuel into LWRs, but the utilities are determined to overcome the opposition. Few believe that Japan can reach its stated goal of having MOX fuel in 18-20 LWRs in 2010, but its use of MOX fuel should gradually increase over the next several years. MOX fuel will come from two main sources: European MOX fabrication plants and the Rokkasho MOX fabrication plants.

As of the end of 2004, Japan had about 37.4 tonnes of plutonium oxide stored in Britain and France. Another 5.6 tonnes is estimated to be in spent fuel scheduled for separation at the Thorp plant after 2004. Thus, in total Japan will have about 43 tonnes of plutonium oxide in Europe. It is not currently expected to take back this plutonium as plutonium oxide; instead, it is expected to contract in Europe to convert the separated plutonium into MOX fuel before it is transported back to Japan. The European-made MOX fuel will be transported to Japan in casks on ships, off-loading the casks at reactor sites on the coast or onto trucks for overland transport to inland reactors. The average amount of plutonium in each ship is expected to be larger than in overland shipments to individual reactors. Each ship is also likely to carry fuel for more than one reactor. The MOX fuel in each shipment is estimated to contain about 500-1,000 kilograms of plutonium. The median number of estimated sea shipments is 57 shipments with a range of 43-86 shipments.

Associated with these sea shipments will also be overland truck shipments in Europe to the ship and, in some cases, from the ship to reactors in Japan. The MOX fuel made in France will require overland shipments of plutonium oxide from the La Hague plant to the Melox plant. About 21.5 tonnes of Japanese plutonium are slated for separation at the La Hague reprocessing plant. About 72 shipments of plutonium oxide from La Hague to Melox will be needed, where each shipment is estimate to contain about 300 kilograms of plutonium oxide. In addition, assuming each MOX fuel shipment contains about 250-500 kilograms of plutonium, the median number of overland shipments of MOX fuel from Melox back to La Hague is 57 shipments with a range of 43-86 shipments.

In Britain, overland shipments of MOX fuel will be required from SMP to a port. Shipments of plutonium oxide from Thorp to SMP will occur within the Sellafield site and are not counted in this report. In total, about 21.5 tonnes of Japanese plutonium in MOX will be transported to a port. Each shipment is assumed to contain about 250-500 kilograms of plutonium. The median number of overland shipments is 57 shipments with a range of 43-86 shipments.

In these estimates, two overland shipments of MOX fuel on average will be necessary for each sea shipment from Europe. After docking in Japan, the number of overland shipments to reactors is arbitrarily taken as equal to zero, because the reactors are located on the coast and the MOX fuel can be off-loaded in the vicinity of the reactors.

Plutonium separated and converted into MOX fuel at the Rokkasho-mura reprocessing plant will likely be sent to reactors by ship or truck. The shipments of MOX fuel assemblies are estimated to contain about 250-500 kilograms of plutonium. Projecting the amount of plutonium that will be separated and converted into MOX at Rokkasho-mura is very uncertain. However, if the plant works as designed, then from 2007 through 2020, about 87 tonnes of plutonium are estimated to be separated and converted into MOX fuel. A lower bound is taken as 70 tonnes of plutonium, which is still on the high side but achievable. From 2007 through 2020, the median of the number of domestic shipments from the Rokkasho-mura fabrication plant to domestic reactors has a median of 212 and a range of 142-347.

The total number of shipments involving Japanese plutonium is summarized in Table 3. In total, 512 shipments will occur from the end of 2006 through 2020.

India

India has maintained a small research and development MOX fuel program that requires a small number of plutonium shipments between fuel fabrication plants at BARC and Tarapur and the Tarapur BWRs and a Fast Test Breeder reactor at Kalpakkam. These shipments have been sporadic and have involved relatively small quantities of plutonium.

India plans to expand dramatically its use of plutonium bearing fuels. The bulk of its separated plutonium is slated for use in large breeder reactors, the first of which will be the 500 MWe Prototype Fast Breeder reactor at Kalpakkam scheduled for completion in about 2010. The reactor's core contains about 1.9 tonnes of plutonium and will require a reload of about 800 kilograms of plutonium per year. The fuel pins and rods for the first few cores of the PFBR are scheduled to be made at the Advanced Fuel Fabrication facility (AFFF) at Tarapur.[20] Subsequent cores are expected to be made at a co-located fuel fabrication plant being built at Kalpakkam. Thus, if the first two cores are made at AFFF, India will need to transport fuel containing 3.8 tonnes of plutonium from Tarapur on the west coast near Mumbai to Kalpakkam on the east coast. Each shipment of fuel is assumed to contain about 100-300 kilograms of plutonium. The median number of shipments is 19 with a range of 13-38. After these first two cores are fabricated, the plutonium should be separated, fabricated, and used on the same site at Kalpakkam.

In addition, India separates plutonium at the Tarapur and Kalpakkam reprocessing plants, where the latter is located near the PFBR on the same site. As a result, some fraction of the plutonium for the first two cores of the PFBR will need to be transported from the Kalpakkam reprocessing plant to the Tarapur fuel fabrication plant. Assuming that one-half the plutonium fabricated at the AFFF comes from the Kalpakkam reprocessing plant and each shipment contains about 100-300 kilograms of plutonium oxide, the median number of shipments is 10 with a range of 7-19.

[20] "Development of Plutonium fuel for Thermal and Fast Reactors," op. cit.

It is possible that MOX fuel could be made at the AFFF for use in the Tarapur boiling water reactors. However, these sites are co-located.

India has ambitious plans to build more breeder reactors and advanced heavy water reactors that would use plutonium fuels. Indian officials have said that the Kalpakkam reprocessing plant could be expanded to process by 2014 about 850 tonnes of spent fuel a year, separating about 3 tonnes of plutonium per year, enough to permit the fueling of additional breeder reactors and an advanced heavy water reactor.[21] If the reprocessing plant, fuel fabrication plant, and reactors are co-located, off-site shipments would be kept to a minimum. However, if the reactors are sited elsewhere, as would be expected, the number of shipments would increase accordingly. Each 500 MWe breeder reactor would require several shipments per year of plutonium fuel.

Findings

During the next 15 years, roughly 1,500 shipments of unirradiated commercial plutonium containing about 500 tonnes of plutonium will be shipped in Europe, Japan, and India. The estimated number of shipments varies widely between 1,100 and 1,900 shipments, depending mainly on the amount of plutonium in each shipment. However, the amount of plutonium in these expected shipments varies relatively little, and those shipments will contain over 60,000 significant quantities of unirradiated plutonium. Table 4 compares the results of the three methods used to estimate the number of shipments.

Over half of the shipments will occur completely within France. They will go from the La Hague reprocessing plant to the Melox fuel fabrication plant, back to La Hague prior to sea shipment to Japan, or from Melox to twenty French LWRs.

In addition to these shipments, there will likely be on order of 100 shipments involving smaller quantities of unirradiated plutonium transported as a result of decommissioning of facilities, research and development activities, and recycle operations.

By 2020, Germany and Switzerland are expected to have discontinued the use of MOX fuel. France, India, and Japan are expected to have largely self-contained national programs with few shipments happening internationally among European countries and Japan. Russia and the United States may have started their own plutonium recycling programs, using excess defense plutonium. Countries with large stocks of civil unirradiated plutonium, in particular Britain and Russia, may have decided to recycle their material rather than dispose of it. Other countries may have started commercial reprocessing and recycling programs.

Annual shipments of unirradiated plutonium are likely to remain at projected levels past 2020. If more countries move to recycle plutonium, the numbers of shipments could increase further.

[21] "Spent Fuel Reprocessing: An Overview," op. cit.

Conclusion

The transportation of unirradiated plutonium is widely recognized as one of the most vulnerable parts of the fuel cycle to the threat of terrorist or subnational attack. Thus, these shipments will require extraordinary physical protection. Even the theft of a single shipment could provide enough plutonium for tens of nuclear weapons.

It is unlikely that events will fundamentally alter the amount of civil unirradiated plutonium expected to be transported during the next 15 years, principally in Europe and Japan but also in India. As a result, a continuing, rigorous review of national and international physical protection standards and practices for plutonium transports will be required well into the future. If new plutonium separation and fabrication facilities are built, they should be located within the same secure site. If feasible, reactors using the plutonium should also be sited with those facilities. One example is India's decision to co-locate its first demonstration breeder reactor with a reprocessing plant and a fuel fabrication plant, eliminating the need for off-site shipments of unirradiated plutonium.

Another approach is to reduce the number of shipments and increase the security of these larger shipments. This approach would require that each shipment contain as much plutonium as feasible, for example by using multiple high security trucks to carry the plutonium in a single, heavily protected convoy. This approach could cause greater health and safety concerns that would need to be addressed, but these concerns should be manageable. Another concern is that shipments should not cause large amounts of MOX fuel to build up in storage at reactors, where physical protection may be less than at fabrication plants. But a policy to reduce the number of shipments while not causing physical security problems in other parts of the fuel cycle would help to decrease the threat of theft.

In the longer term, a more effective strategy would be to move away from plutonium fuel cycles entirely. That day appears to be at least two decades away, and even then, the world may inherit large stocks of unirradiated plutonium that will require disposition. As a result, the maximum effort should be made to ensure that terrorists cannot steal unirradiated plutonium and that additional nations do not acquire the underlying technologies and use them to obtain nuclear weapons.

Table 1 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	38.8	50[n]	58[n]	66[n]
Total (rounded)	**238 (236-240)**	**286 (266-297)**	**277 (227-325)**	**263 (214-321)**

Source: David Albright and Kimberly Kramer, "Separated Plutonium Inventories: Current Status and Future Directions," June 10, 2005, revised July 8, 2005, www.isis-online.org.

Table 2 Estimated Annual Off-Site Shipments of Civil Unirradiated Plutonium, number (#) and quantities of weapons-usable plutonium in tonnes (t)

	2005		2010		2015		2020	
	Shipments	**Plutonium**	**Ship.**	**Pu**	**Ship.**	**Pu**	**Ship.**	**Pu**
	(#)	**(t)**	**(#)**	**(t)**	**(#)**	**(t)**	**(#)**	**(t)**
Reprocessing Plants to MOX Plants								
LaHague to Melox and Dessel(a)	39-43	11.7-12.9	46	13.8	46	13.8	46	13.8
MOX plants to La Hague (rejects, unused rods)(b)	10?	0.5?	10	0.5	10	0.5	10	0.5
Sellafield and Thorp to SMP	0	0	0	0	0	0	0	0
Sellafield (SMP) to other MOX plants	0	0	3-4	1	0	0	0	0
Tokai to MOX fabrication plants	0	0	0	0	0	0	0	0
From MOX Plants to Reactors								
Dessel(a)	9	2.7	0	0	0	0	0	0
Melox	33	9.9	46	13.8	46	13.8	46	13.8
SMP	1-2	0.3-0.6	7	2.1	9	3.6	9	3.6
Rokkasho MOX plant	0	0	0	0	28	8.4	28	8.4
Tokai MOX plants to Monju	0	0	2	0.6	2	0.6	2	0.6
Total	**92-97**	**25.1-26.6**	**115(d)**	**31.8**	**141**	**40.7**	**141**	**40.7**

Comments

(a) The Dessel facility closed in the summer of 2006.

(b) Shipments from MOX plants to La Hague reprocessing plants include material generated routinely at Melox fabrication plant and material sent from closed facilities, including Cardarache, Dessel, and Hanau MOX fabrication plants. The estimated value is uncertain.

(c) SMP owes plutonium to other MOX fabrication plants, mainly Melox, that it must eventually repay (see text). The estimated number and quantity owed is arbitrarily assigned to 2010.

(d) Rounded.

Table 3 Estimated Planned and Reasonably Expected Annual Off-Site Commercial Shipments of Unirradiated Plutonium in Europe, Japan, and India, End 2006 through 2020, number of shipments and quantities of plutonium in tonnes (t)

	Separated Plutonium(a)		**Unirradiated Plutonium in MOX Fuel**	
	(shipments)	**(tonnes)**	**(shipments)**	**(tonnes)**
France	406	121	305 (240-395)	121
Germany(b)	37-77	22-46	104 (45-285)	22-46
Switzerland(b)	3	0.75	18 (13-28)	3
Belgium			~10	1
Sweden			2	0.83
Netherlands, Italy, and Spain(b)	<10	<3	<25 (16-54)	<8
Japan				
From Europe to Japan				
Overland portion in Europe				
To Melox	72	21.5		
To ports	--		114 (86-172)	43
By Sea to Japan			57 (43-86)	43
Overland to reactors			0	0
From Rokkasho			212 (142-347)	70-87
India	10 (7-19)	1.9	19 (13-38)	3.8
Totals	**538**	**170.15**	**923 (641-1441)**	**337-378**

Comments and Notes

(a) All shipments in this column, except for India, are from the La Hague reprocessing plant to the Melox plant in France.
(b) All shipments are by an high security vehicle, although a portion of the trip could be on a specialized roll-on, roll-off ship.

Table 4 Summary and Comparison of Estimates of Commercial Shipments of Unirradiated Plutonium

	Annual Shipments		**Cumulative,**
	Current	**2020**	**from end of 2006 through 2020**
IAEA Transport Study	<200	not estimated	not estimated
Scoping Calculation	92-97	141	1,850 with a range of 1,635-1,865
Key Countries Estimate	average of 100 per year		1,404 with a range of 1,136-1,873

Appendix I Civil Reprocessing and Fuel Fabrication Facilities (a)

Table I.1 Civil Reprocessing Plants, Operating and Planned

	Plant	Scale	Design Capacity (t HM/yr)	Feed Material
China:	1. Lanzhou (RPP) * Under construction	Pilot Plant	0.1	PWR, HWRR
France:	1. La Hague - UP2-800	Commercial	1000	LWR
	2. La Hague - UP3	Commercial	1000	LWR
India:	1. Kalpakkam Reprocessing Plant (KARP)	Commercial	100	PHWR
	2. Lead Minicell Facility (LMC)	Pilot Plant	n/a	FBTR
	3. Power Reactor Fuel Reprocessing Plant (PREFRE), Tarapur	Commercial	100	PHWR, LWR
	4. Fast Reactor Fuel Reprocessing Plant (FRFRP) * Under construction	Commercial	n/a	FBTR
Japan:	1. Rokkasho Reprocessing Plant * Under commissioning	Commercial	800	LWR
	2. JNC Tokai Reprocessing Plant	Commercial	210	LWR
Russia:	1. Research Institute of Atomic Reactors (RIAR)	Pilot Plant	1	n/a
	2. RT-1, Combined Mayak	Commercial	400	WWER-440
UK:	1. BNFL B205 Magnox Reprocessing	Commercial	1500	U Metal
	2. BNFL Thorp	Commercial	900	LWR, AGR Oxide

(a) Plants are in operational status unless otherwise noted. The source of the information is the IAEA's Nuclear Fuel Cycle Information System.

Table I.2 Decommissioned Civil Reprocessing Plants

		Plant	Scale	Design Capacity (t HM/yr)	Feed Material
France:	1.	Experimental Reprocessing Facility	Pilot Plant	5	
	2.	La Hague - AT1	Pilot Plant	0.365	
	3.	Laboratory RM2	Laboratory	0	
	4.	Marcoule - UP1	Commercial	600	
Germany:	1.	Wiederaufarbeitungsanlage (WAK)	Pilot Plant	35	MOX, LWR
Italy:	1.	Eurex SFRE (Pu Nitrate Line) • Stand by •	Pilot Plant	0.1	PUO2-UO2
Japan:	1.	JAERI's Reprocessing Test Facility (JRTF)	Laboratory	0	Pu (NO3)4
U.K.	1.	BNFL B204 Reprocessing Plant	Commercial	0	
	2.	BNFL B207 Uranium Purification Plant	Commercial	0	
	3.	BNFL Thorp Miniature Pilot Plant (TMPP)	Pilot Plant	0	
	4.	UKAEA Reprocessing Plant, MTR	Commercial	.02	MTR
	5.	UKAEA Reprocessing Plant, MOX * Stand By	Commercial		

Note: Plants are in decommissioned status unless otherwise noted. Not all decommissioned facilities are listed. For example, US facilities closed in the 1970s are omitted. Eurochemic is also omitted. The source of the information is the IAEA's Nuclear Fuel Cycle Information System.

Table I.3 Operating MOX Fuel Fabrication Plants

Country	No.	Plant	Scale	Design Capacity (t HM/yr)	Product Material
France:	1.	Melox	Commercial	145	MOX for LWRs
India:	1.	Advanced Fuel Fabrication Facility (AFFF)	Commercial	100 (nominal)	MOX for BWR,PFBR
	2.	Kalpakkam MOX Breeder Fuel Fabrication * Under Construction	Commercial	?	MOX for PFBR
Japan:	1.	JNC Tokai (PFDF-MOX)	Laboratory	.03	MOX fuel pin
	2.	JNC Tokai (PFFF-ATR)	Pilot Plant	10	MOX fuel assembly
	3.	JNC Tokai (PFPF-FBR)	Pilot Plant	5	MOX fuel assembly
	4.	Rokkasho MOX Plant *Planned	Commercial	120	MOX for LWRs
Russia:	1.	Mayak – Paket	Pilot Plant	0.5	FBR, RR MOX fuel
	2.	Research Institute of Atomic Reactors	Pilot Plant	1	FBR (Vibropack)
UK:	1.	Sellafield Mox Plant (SMP) *Commissioning	Pilot Plant	likely 40	MOX for LWR

Note: Plants are in operational status unless otherwise noted. The source of the information is the IAEA's Nuclear Fuel Cycle Information System.

Table I.4 Decommissioned and Closed MOX Fuel Fabrication Plants

		Plant	Scale	Design Capacity (t HM/yr)	Product Material
Belgium:	1.	Belgonucleaire PO Plant	Commercial	40	LWR MOX
	2.	FBFC International – MOX	Commercial	100	BWR, PWR MOX
Germany:	1.	Betriebsteil MOX Commercial (Siemens)	Commercial	120	BWR, PWR MOX
	2.	Betriebsteil MOX Demo (Siemens)	Pilot Plant	30	FBR / LWR MOX
UK:	1.	BNFL Coprecipitation Plant	Commercial	0	
	2.	Sellafield MDF (MOX Demonstration Facility) *On Stand By	Pilot Plant		LWR MOX
US:	1.	Fuels and Materials Examination Facility * On Stand By	Laboratory	0	MOX for Pu Disp.

Note: Plants are in decommissioned status unless otherwise noted. The source of the information is the IAEA's Nuclear Fuel Cycle Information System.

Appendix II: List of Reactors Using, Expected to, or Possibly Using MOX Fuel

Country	Name	Type	Power	Comments
Belgium	Tihange-2	PWR	1056	Stopped MOX use?
	Doel-3	PWR	412	Stopped MOX use?
France	Blayais-1	PWR	951	
	Blayais-2	PWR	951	
	Dampierre-1	PWR	937	
	Dampierre-2	PWR	937	
	Dampierre-3	PWR	937	
	Dampierre-4	PWR	937	
	Gravelines-1	PWR	951	
	Gravelines-2	PWR	951	
	Gravelines-3	PWR	951	
	Gravelines-4	PWR	951	
	Saint-Laurent-B1	PWR	956	
	Saint-Laurent-B2	PWR	921	
	Tricastin-1	PWR	955	
	Tricastin-2	PWR	955	
	Tricastin-3	PWR	955	
	Tricastin-4	PWR	955	
	Chinon-B1	PWR	954	
	Chinon-B2	PWR	919	
	Chinon-B3	PWR	954	
	Chinon-B4	PWR	954	
	Phenix	Fast	250	Shutdown in 2008?
	Blayais-3	PWR	951	Possible MOX use
	Blayais-4	PWR	951	Possible MOX use
	Gravelines-5	PWR	951	Possible MOX use
	Gravelines-5	PWR	951	Possible MOX use
	EPR	APWR		Start in 2012 and load full core of MOX?
Germany	Brokdorf	PWR	1395	
	Grafenrheinfeld	PWR	1345	
	Gundremmingen-B	BWR	1300	
	Gundremmingen-C	BWR	1308	
	Isar-2	PWR	1475	
	Philipsburg-2	PWR	1390	
	Unterweser	PWR	1320	
	Emsland	PWR	1363	
	Grohnde	PWR	1394	
	Neckarwestheim-1	PWR	840	

	Neckarwestheim-2	PWR	1365	
	Obrigheim	PWR	357	Closed
	Brunbuettel	BWR	806	License?
	Kruemmel	BWR	1316	applied for license?
Switzerland	Beznau-1	PWR	364	
	Beznau-2	PWR	364	
	Gosgen	PWR	990	

Japan (no LWRs using MOX currently; actual LWRs could vary; utilities plan to have 18-20 LWRs using MOX fuel)

Tepco	Fukushima-3	BWR	784	
	Kashiwazaki-Kariwa-1	BWR	1100	
	Kashiwazaki-Kariwa-2	BWR	1100	
	Kashiwazaki-Kariwa-3	BWR	1100	
Kansai	Takahama-3	PWR	870	
	Takahama-4	PWR	870	
	Ohi-3	PWR	1180	
	Ohi-4	PWR	1180	
Chubu	Hamaoka-4	BWR	1137	
Kyushu	Genkai-3	PWR	1180	
Japco	Tokai-2	BWR	1100	
	Tsuruga-?	PWR		
Hokuriku	Shika-1	BWR	540	
Tohoku	Onagawa-?	BWR		
Chugoku	Shimane-2	BWR	820	
Shikoku	Ikata-3	PWR	890	
Hokkaido	Tomari-?	PWR	?	
EPDC	Ohma	ABWR	1350	Start in 2012
JAEA	Joyo	Fast	0	
JAEA	Monju	Fast	280	Restart in 2007-08

India	Tarapur-1	BWR	160	Possible use of MOX
	Tarapur-2	BWR	160	Possible use of MOX
	KAPS?	PHWR		Possible use of MOX
	PFBR	Fast	500	under construction
	AHWR	HWR	300	planned