Report

The German Plutonium Balance, 1968-1999

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To date, publicly available information has not provided a clear and full picture of German plutonium stockpiles.[2] Rather, published data have been limited to discrete summaries of certain activities and of the quantities of plutonium these have generated. The most comprehensive unclassified estimate of world-wide plutonium balances was presented by a group of non-governmental researchers in the spring of 1997.[3] It presented figures as of 1996, but, especially in the case of Germany, this analysis lacked detail.

Nine plutonium producing and employing countries presented common guidelines for the handling of plutonium production and use information at the end of 1997. Known as the International Plutonium Management Group, these countries—Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom, and the United States—agreed within the framework of these guidelines to publish inventories of civilian plutonium annually. This is an important step towards the establishment of transparency. [4] Unfortunately, the chosen format for these yearly balance reports is unsatisfactory. It contains only a few aggregated summaries of plutonium holdings, data which do not allow for attribution to facilities or owners and which are not required to be more precise than plus or minus 50 kg—enough for six nuclear weapons according to the International Atomic Energy Agency (IAEA) standard of eight kg per weapon.[5] So far, Germany has increased reporting accuracy to plus or minus five kg, but it has not completely followed the self-imposed obligations of the plutonium holding group. (See Tables 1 and 2). Moreover, separate data on German plutonium held outside Germany and on "foreign" material held in Germany are not made available under the guidelines of the group. The annual reports merely state that all this material is the property of the EU nuclear organization, EURATOM.[6]

The relevant data for Germany on plutonium separation within the country and abroad, on the import and export of plutonium, on processing of separated plutonium into mixed plutonium-uranium oxide (MOX) fuel, and on the use of MOX, as well as accounts of current plutonium inventories were collected by the authors of this paper in a study which relies both on published material and on original, research and calculations.[7] This report contains a summary of the results of that analysis. Now that Germany has discontinued the reprocessing of spent fuel domestically, as well as the production of MOX within the country, it should be possible to compile a conclusive plutonium balance report for these sectors.

In reviewing the data below, it is important to remember that so-called reactor-grade plutonium, which is obtained from spent power reactor fuel with its typically high levels of burn-up, can be used for the production of nuclear weapons, even if such material is of lower quality than the plutonium used by nuclear weapon states for their nuclear arsenals. All German plutonium stocks, it should be added, are under the nuclear safeguards both of the IAEA and EURATOM inspections and audits designed to detect diversions of nuclear materials by national governments. In addition, the material is subject to physical protection and other security measures in the countries where it is stored. These measures are intended to prevent theft or seizure of such materials. Nonetheless, because of the continuing and widely recognized proliferation risks of plutonium, it is essential to develop a strategy for the secure, long-term disposal of German plutonium stocks. Understanding current German plutonium balances and the whereabouts of this material is a critical first step towards the development of such a strategy.

SUMMARY OF REPROCESSING

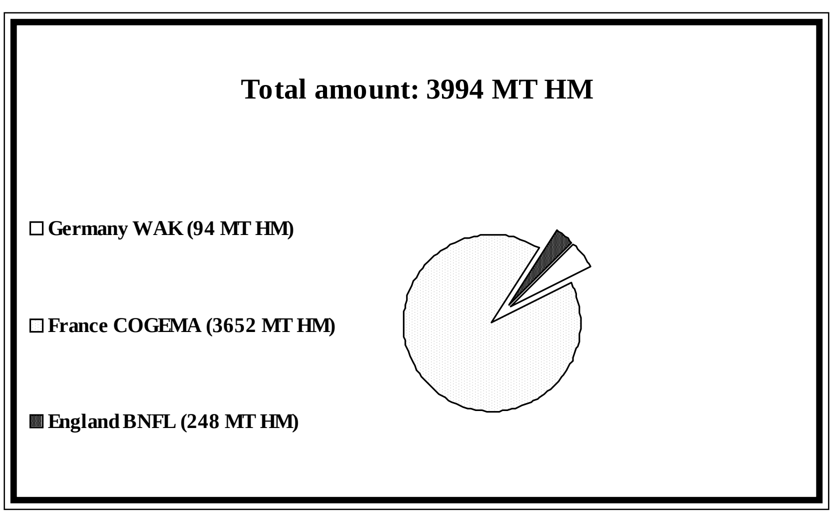
Through February 1999, spent fuel elements weighing a total of 6,253 metric tons (MT) HM (metric tons of heavy metal, that is, uranium and plutonium)[8] had been removed from German power reactors and shipped to other locations. Out of that, 5,279 MT HM (84 percent) was transported to reprocessing facilities and 628 MT HM (10 percent) were brought to a German central interim "away-from-reactor" storage facilities. Again, as of February 1999, an additional 2,641 MT HM were stored in the spent fuel storage pools of German nuclear power reactors.

Of the 5,279 MT HM shipped to reprocessing plants, 4,540 MT HM—more than 86 percent of the total—was transported to the La Hague reprocessing plant, operated by the French concern, COGEMA, illustrating the central importance of German-French cooperation in this sphere. Of the remaining material shipped to reprocessing plants, 94 MT HM (1.7 percent) was delivered to the German reprocessing facility *Wiederaufbereitungsanlage Karlsruhe* (WAK); 645 MT HM (12 percent) was sent to the THORP reprocessing plant in Sellafield, United Kingdom, operated by the British Nuclear Fuels, plc (BNFL); and 28 MT HM was shipped to the reprocessing plant in Mol, Belgium, operated by the firm Eurochemic.[9] In addition, the WAK plant received 110 MT HM from German research and prototype reactors.

Figure 1 shows that as of February 1999, 3,994 MT HM of the 6,253 MT HM delivered by Germany to these facilities had been reprocessed, roughly 64 percent of the material.[10] This reprocessing activity resulted in the separation of a total of between 32 and 38 MT of plutonium (enough for 4,000 to 4,750 nuclear weapons, using the IAEA standard).[11]

At La Hague and Sellafield, this reprocessing was undertaken pursuant to contracts German utilities signed with COGEMA and BNFL prior to the abandonment, in 1989,

Figure 1: Power Reactor Fuel Reprocessed for German Customers as of February 1999



Note: This chart does not include the reprocessing in Belgium of less than 28 MT HM of the planned German reprocessing plant at Wackersdorf. These contracts provided for the reprocessing of a total of 5,641 MT HM at the two foreign facilities and are known as the so-called “old” contracts, or *Altverträge*, in contrast to the “new” contracts, or *Neuverträge*, signed after that date. When Figure 1 (completed reprocessing) is read in conjunction with Figure 2 (all contracts for reprocessing), it appears that as of February 1999 about 70 percent (3,900 MT HM) of the old contracts for reprocessing in France and the United Kingdom had been fulfilled, leaving 30 percent (1,741MT HM) to be fulfilled in the future.[12]

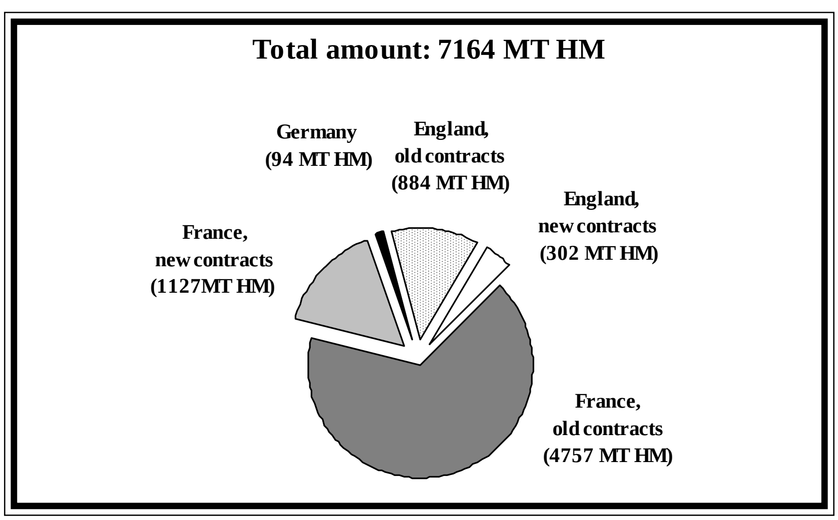
The total amount of spent fuel covered by the new, post-1989 contracts with COGEMA and BNFL is not precisely known, in part because the new contracts are based on demand (in contrast to the old contracts, which were based on fixed amounts). Overall, however, it is believed that the new contracts signed in the 1989 timeframe provided for the reprocessing of roughly 3,010 tonnes of spent fuel. Since that time, however, German utilities have cancelled contracts providing for reprocessing of 1,581 MT of spent fuel, leaving 1,429 MT to be reprocessed under the new contracts.[13] The reprocessing of the remaining 3,170 MT of spent fuel yet to be reprocessed in 1999 under the old and new contracts together, would result in 28-33 MT of separated plutonium (enough for 3,500 to 4,000 weapons), in addition to the 32-38 MT of plutonium already separated from German spent fuel at all facilities as of 1999.[14]

German utilities and the German government have agreed that the last shipment of spent fuel to a reprocessing facility will take place by July 1, 2005. All quantities delivered by that time may be reprocessed.[15] It remains unclear how much spent fuel will eventually be reprocessed. According to current planning data, as shown in Figure 2, the largest share of reprocessing for German customers will continue to take place in France, while the British contribution is expected to increase substantially.

Reprocessing in Germany

The German WAK pilot reprocessing facility operated between 1971 and 1991. According to the information given by WAK managers,[16] roughly one MT (1,189 kg) of plutonium was separated in 32 separation campaigns from 204 MT of HM (see Figure 3). Detailed information on the material processed in these campaigns is available, which permits conclusions to be drawn about the isotopic composition of the plutonium obtained from these activities.[17] Of the nine reprocessing campaigns that processed fuel from the MZFR (*Mehrzweck-Forschungsreaktor*) reactor, seven campaigns treated spent fuel with a burn-up below 10,000 MWd/t. This is of particular interest from the standpoint of proliferation because this low burn-up rate means that the 250 kg of plutonium separated in these campaigns had a high proportion of Pu-239, making the material particularly attractive for use in nuclear weapons. Assuming that eight

Figure 2: German Reactor Fuel Reprocessing Contracts Completed or in Place as of mid-1999



Note: This chart does not include the reprocessing in Belgium of less than 28 MT HM kilograms of plutonium are needed for a nuclear device, this material would be sufficient for more than 30 nuclear weapons. A second, smaller experimental plutonium separation facility, called MILLI, was once operated in the *Kernforschungszentrum* in Karlsruhe. This plant was able to reprocess fuel elements from fast breeder reactors. Sufficient high-quality plutonium for one or more nuclear weapons may have been produced at this facility, but detailed information is lacking.

Reprocessing in France

The total volume of German contracts with the French reprocessing concern COGEMA, which operates the La Hague facility, originally amounted to 6402 MT HM, and currently amounts to 5884 MT HM of spent fuel. New contracts for 598 MT HM have been cancelled. By February 1999, about 4,540 MT HM of spent nuclear power plant fuel elements had been shipped from Germany to France containing between 38 and 45 MT of plutonium. Of this spent fuel, 3,652 MT HM had been reprocessed in France as of February 1999,[18] resulting in between 28 and 35 MT of separated plutonium.[19] By the beginning of 1999, between 9 and 14 MT of separated plutonium had been re-imported into Germany, mainly contained in fresh mixed uranium-plutonium oxide (MOX) fuel.[20] Using these figures, 14 to 21 MT of separated plutonium would still have been stored in France at that time. This amount could be assessed with greater accuracy only if the particular fuel elements that had been reprocessed and their composition and burn-up profile were known. Separation efficiency at the La Hague plant would also play a role in the assessment of the amount of separated plutonium.

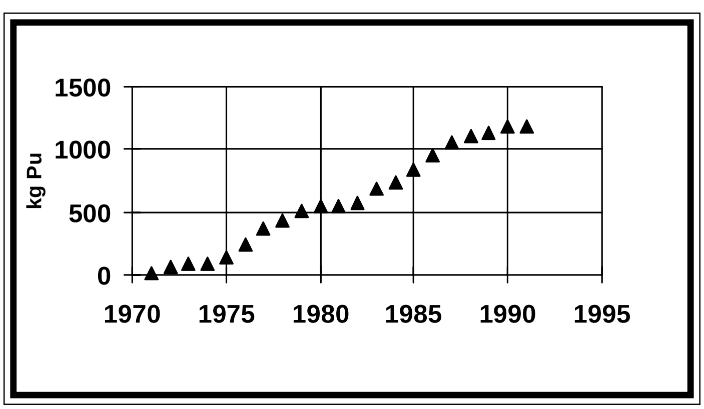
This analysis also indicates that as of February 1999, no more than 9 to 10 MT of plutonium remained in spent fuel awaiting reprocessing in France. According to past experience, an annual separation rate of 3 to 3.5 MT of plutonium from German spent fuel can be expected.

French practice is not to strictly separate civilian and military nuclear activities. Plutonium of different origins can be mixed and even deliberately exchanged, if this satisfies the requirements of its end-users.[21] Therefore plutonium from German reactors could have found its way into the French nuclear weapons program, assuming the addition of equivalent plutonium into German stocks, which would have made the transaction effectively neutral. Such substitutions are not uncommon under international practice. The cores of the KNK I and II research reactors at the *Kernforschungszentrum* Karlsruhe, for example, were reprocessed at France's Marcoule nuclear center in 1976 and 1993-94. The exact amount of plutonium separated during the second campaign (estimated to be about 100 kg), its isotopic composition, and its whereabouts are not known to the authors.[22] The whereabouts of the plutonium that was separated during the reprocessing of fuel elements of the KKN research reactor (Niederaichbach) is also unknown to the authors. This material is of special proliferation relevance since the reactor only achieved 18 days of full power operation, and the purity of Pu-239 should therefore be especially high, although the quantity is likely to be quite small.[23]

Reprocessing in Great Britain

Old and new German nuclear power plant contracts with BNFL provide for the reprocessing of a total of 2,250 MT HM of spent fuel. At the end of 1994, two new contracts

Figure 3: Cumulative Amounts of Separated Plutonium at the Karlsruhe Pilot Reprocessing Facility



with a total of 545 MT HM were cancelled by the German energy utilities HEW and RWE and contracts for a further 518 MT HM were cancelled between 1994 and 1999.

From 1969 to 1973, only 12 MT of German spent fuel were reprocessed in Sellafield at the B204 facility. The amount of separated plutonium should be about 100 kg. By February 1999, 645 MT HM spent fuel had been transferred from Germany to BNFL, an amount that is small compared to the quantity shipped to France. The plutonium content can be estimated as about five to six MT. The new reprocessing plant for light water reactor (LWR) fuel, THORP, became operational in Sellafield in March 1994. Therefore, it appears that only a part of the German fuel has been reprocessed up to now. By February 1999, a total of 248 MT HM with a plutonium content of about 2.0 to 2.3 MT had been reprocessed.[24]

Between 1969 and 1982, a total of 351 kg unirradiated plutonium was imported into Germany from the United Kingdom. This quantity exceeds what was separated for German clients in England at the beginning of the 1970s, implying that Britain provided additional material of its own to Germany for various peaceful purposes. There were no more plutonium deliveries until 1995.[25] It remains an open question how much plutonium that was separated for German nuclear power plant spent fuel has been brought back to Germany since 1994.

Reprocessing in Belgium

More than 28 MT HM from two German power reactors as well as from various research reactors were reprocessed in the reprocessing plant Eurochemic in Mol, Belgium, which was operational from 1966 to 1974. An estimated quantity of at least 110 to 150 kg of plutonium has been separated.[26] German imports of unirradiated plutonium from Belgium, all believed to be in the form of MOX, exceed this amount. It is not clear whether the imports above 150 kg involve German-origin plutonium separated outside of Belgium or plutonium provided by other countries that was fabricated into MOX fuel in Belgium.

Reprocessing in Russia

Russia may have reprocessed spent fuel from reactors in the former GDR. This issue is not covered here, however. As noted earlier, under GDR-Soviet fuel contracts, no plutonium was to be returned to the GDR and, today, any plutonium recovered by the Soviets is considered to be the property of Russia and is not part of German plutonium stocks. With the reunification of Germany in 1990, the FRG and GDR nuclear programs were merged and a decision was made to close the six operating Soviet-designed nuclear reactors in the former GDR. No spent fuel from those plants remains at the six reactor sites. A portion of this material has been shipped abroad (to Russia and Hungary, see below) and the remainder was sent to the German central interim storage facility ZAB, at Greifswald. (See Table 3). There are no existing contracts for reprocessing with Russia.

IMPORTS AND EXPORTS

Data from the German Federal Export Office (*Bundesausfuhramt* or BAFA) are available on the amounts of exported spent fuel, as well as of unirradiated plutonium exported and imported between 1968 and 1994. The figures show the importation of 11 MT of unirradiated plutonium, and the export of five MT of unirradiated plutonium. (See Figures 4, 5, and 6.)[27] The importation of the 11 MT of this material consisted in large part of the return of plutonium from German-origin spent fuel that was separated in foreign reprocessing plants. The export of three MT represents the exportation of plutonium in fresh mixed oxide (MOX) fuel elements fabricated for foreign customers in the Siemens facility (formerly the Alkem facility) at Hanau. In addition to that, two MT of irradiated plutonium (in spent fuel) were exported. The first one-half MT consisted of the transfer of more than 100 MOX fuel elements of the decommissioned VAK experimental nuclear power plant facility, in Kahl, (total mass six MT HM) for direct final storage in Sweden.[28]

A portion of the spent fuel inherited from the former GDR was exported to Russia (293 MT HM) and to Hungary (28 MT HM). The latter contained almost no plutonium because the fuel consisted of an almost fresh reactor core for re-use in the Hungarian reactor at Paks.

MOX Production in Germany

In June 1965, the processing of plutonium into mixed oxide fuel began in Germany with the production of fuel pellets for the SNEAK (*Schnelle Nullenergie Anordnung Karlsruhe*) facility. The company responsible for the project, Alkem GmbH, moved in the early 1970s from the *Kernforschungszentrum Karlsruhe* to Hanau. Alkem was taken over in 1988 by Siemens AG.

Figure 4: Export of Spent Fuel from Germany by Receiving State (According to BAFA)

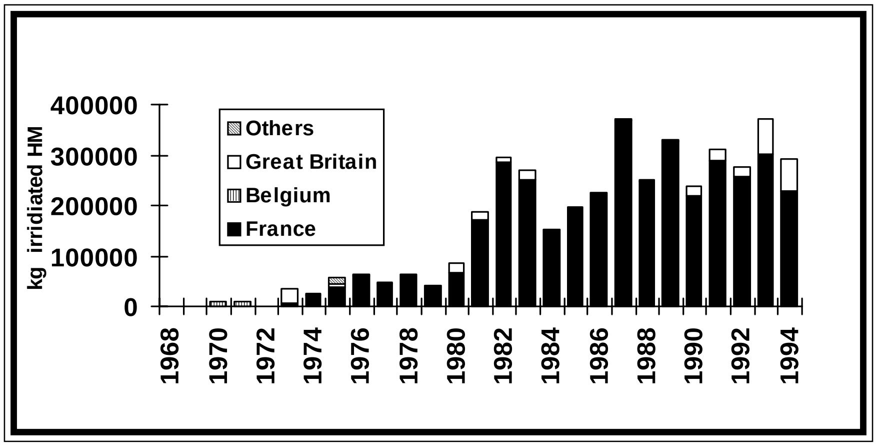


Figure 5: Import of Unirradiated Plutonium to Germany by Originating State (According to BAFA)

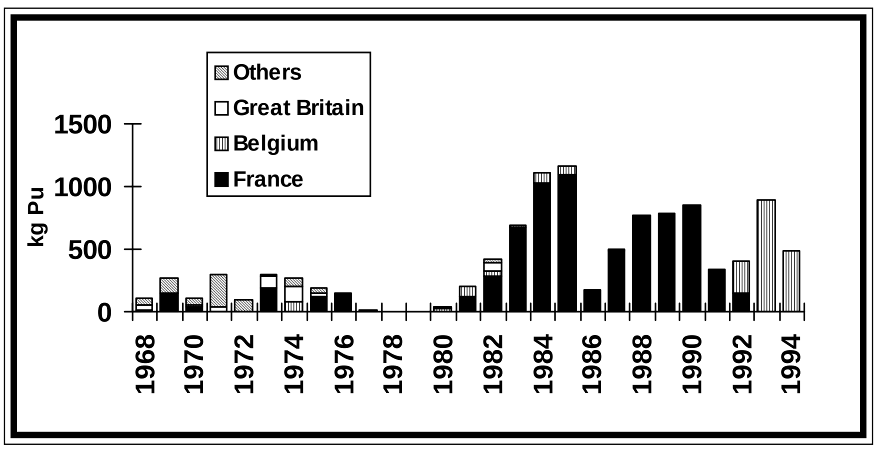
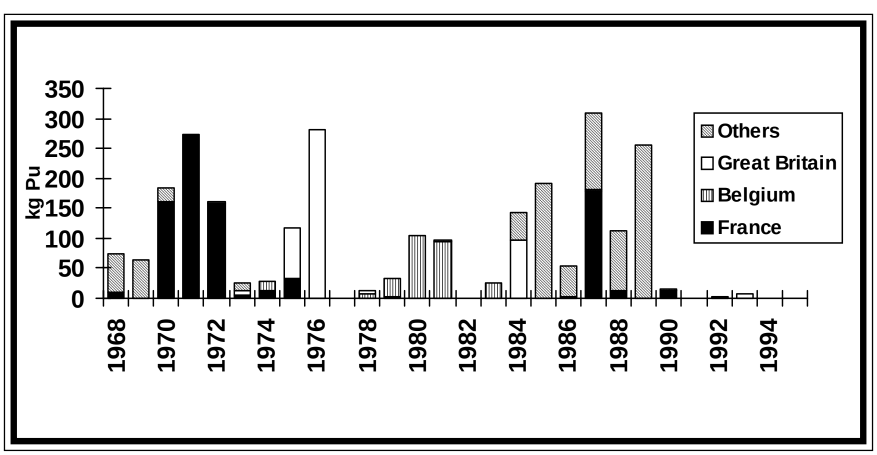


Figure 6: Export of Unirradiated Plutonium from Germany by Receiving State (According to BAFA)



For SNEAK, 600 kg of plutonium was fabricated into fuel rods in Karlsruhe. The plutonium was supplied principally by the United States, most likely before 1972. As for the quantity of plutonium-bearing fuel elements produced by Alkem in its Hanau plant, the only data found in the open literature are contained in a bar chart showing the annual amounts of heavy metal processed at the facility.[29] The bar chart in Figure 7 is a reconstruction of this data, showing the annual output of fresh plutonium-bearing fuel, measured by actual havy metal content, and indicating the proportion of fuel intended for use in fast breeder reactors (FBR) and in commercial nuclear power plants (light water reactors or LWR).[30]

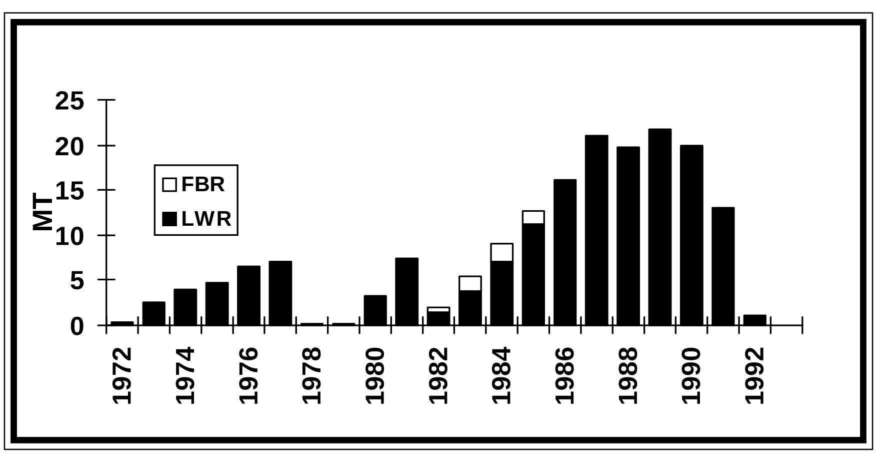
In the years 1968 to 1992, the Alkem (later Siemens) fuel element plant at Hanau processed a total of 8,553 kg of plutonium into 164 MT HM.[31] Of this plutonium, 77 percent was processed for commercial nuclear power plant MOX fuel elements, and another significant portion for research and prototype reactors like the SNR 300 fast breeder reactor. A small remainder was incompletely processed or retained as scrap held in storage. Foreign customers received 13 percent of the MOX fuel elements. The Alkem/Siemens MOX fuel fabrication facility has since been shut down, and an almost completed new facility, also built in Hanau, never became operational. Thus there is no capacity to produce MOX fuel in Germany at this time, and none is expected to be built for the forseeable future. Siemens has continued to act as contractor of MOX fuel elements for German power supply companies by outsourcing orders to other European production facilities.

MOX Usage in Germany

As of February 1999, twelve of Germany's twenty nuclear power stations had received licenses permitting them to use MOX fuel elements, and all but three of those possessing such licenses were using MOX fuel at that time.[32] Another three of the remaining nuclear power stations had requests pending for MOX licenses. The content of fissile plutonium in MOX fuel is typically limited to five percent to protect against neutron embrittlement of the reactor vessel, and only a quarter or a third of the core is allowed to be loaded with MOX elements. One reactor (Isar 2) has an authorization for 50 percent MOX in its core.

Details have never been published concerning how much plutonium has been incorporated into the MOX fuel used in specific reactors each year. Nor has it been disclosed how many fresh MOX fuel elements have actually been loaded in reactor cores at individual German nuclear power plants. However, the aggregate amount of heavy metal in MOX that was employed in German reactors through the end of 1996 has been disclosed in some detail.[33] At that time, 38 MT HM of MOX fuel were in reactor cores; 78 MT HM of MOX were in fuel element storage at reactor sites, whether in the form of spent or fresh fuel has not been specified; and 85 MT HM of MOX fuel had been removed as spent fuel and transferred to a reprocessing facility or a central storage site. By early 1999, at least 123 MT HM of MOX containing 4.3 to 6.2 MT of plutonium were in spent form and an additional two MT were probably irradiated in power reactor cores. The total of irradiated plutonium in this MOX is likley to be six to eight MT.

Figure 7: Fabrrication of LBR and FWR MOX Fuel Elements in Germany



Another area of uncertainty is the proportion of unirradiated plutonium contained in fresh MOX fuel used in German reactors. The fuel ranges from 2.9 percent to 4.4 percent fissile plutonium content ("fissile" meaning isotopes Pu-239 and Pu-241). Since less than 3.5 percent fissile plutonium content can be assumed on the average, a maximum of seven MT of fissile plutonium could have been delivered to LWR reactors in MOX fuel. The amount of total plutonium, *i.e.* including the non-fissile, even isotopes, such as Pu-240, can be estimated to be 10 MT. (All other plutonium quantities used herein include all isotopes of plutonium.) According to Siemens, about six MT

Table 1: Annual Holdings of Civil Unirradiated Plutonium as Reported by Germany to the IAEA (MT)

Type	12/31/96	12/31/97	12/31/98	12/31/99
1. Unirradiated separated plutonium in product stores at reprocessing plants.	0.0	0.0	0.0	not applicable
2. Unirradiated separated plutonium in the course of manufacture or fabrication and plutonium contained in unirradiated semi-fabricated or unfinished products at fuel or other fabrication plants or elsewhere.	0.4	0.3	0.41	0.58
3. Plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere.	2.7	3.9	4.84	5.48
4. Unirradiated separated plutonium held elsewhere.	1.8	1.8	1.31	1.13
(i) Plutonium in lines 1-4 above belonging to foreign bodies.	not available	not available	not available	not available
(ii) Plutonium in any of the forms in lines 1-4 above held in locations in other countries and therefore not included above.	not available	not available	not available	not available
(iii) Plutonium in lines 1-4 above which is in international shipment prior to its arrival in the recipient State.	0.0	0.0	0.0	0.0

of total plutonium were recycled in the production of MOX elements for German light water reactors and roughly one MT for foreign reactors at the Siemens Hanau facility.[34] Additional MOX fuel elements for German customers were produced at MOX fuel fabrication facilities in Cadarache, France, and Mol, Belgium.

At the end of 1996, about two MT of plutonium were held in German LWR reactor cores. Assuming a time-in-core of three years, then about 0.6 MT of plutonium was loaded into the reactor cores as fresh LWR-MOX during 1996.[35] In the past few years, the MOX usage in German reactors has increased. In 1999, MOX elements with a total plutonium content of three MT (1.96 MT Pu-fissile), were delivered to reactor operators.[36]

Stocks of unirradiated plutonium contained in fresh MOX fuel elements awaiting use at the reactor sites are also increasing. At the end of 1996, three MT of plutonium are said to have been in "uniradiated MOX fuel or other fabricated products at reactor sites or elsewhere in Germany." This amount increased to four MT by the end of 1997, to five MT by the end of 1998, and to 5.5 MT by the end of 1999.[37] From the end of 1996 to the end of 1999, the average annual increase of plutonium under this category was 0.93 MT. However, the annual increase of plutonium in unirradiated MOX fuel at reactor sites is somewhat larger, because some plutonium covered by the quoted numbers was removed from the MOX fabrication facility in Hanau during this time, reducing the reported inventory change for this category.

Estimates of Current Inventories

Tables 1 and 2 list the plutonium inventories as reported by Germany to the IAEA according to the Guidelines for the Management of Plutonium, also known as INFCIRC/549.[38]

Table 3 summarizes current German plutonium inventories, as assessed in this paper.[39] Since this is an independent assessment based on incomplete data, there may be discrepancies between the authors' estimates and the amounts officially published (as seen in an example below).

As of February 1999, a total of 70 to 89 MT of plutonium is estimated to have remained from reactor operations in Germany. The largest part remained under German control and responsibility. About 47 to 59 MT of this material was still contained in spent fuel elements, including spent MOX fuel. About half of the latter amount (26 to 32 MT) is estimated to have been in the storage pools of nuclear power plants in Germany at that time, while 11 to 13 MT of plutonium in spent fuel was in France and 3.5 to 5 MT was in the United Kingdom, awaiting reprocessing.[40] The amount of plutonium in spent fuel at reactor sites is reported to be 31.5 MT according to the official report provided to the International Plutonium

Table 2: Estimated Plutonium in Spent Civil Reactor Fuel as Reported by Germany to the IAEA (MT)

Type	12/31/96	12/31/97	12/31/98	12/31/99
1. Plutonium contained in spent fuel at civil reactor sites.	not available	not available	31.5	36.75
2. Plutonium contained in spent fuel at reprocessing plants.	not available	not available	0.0	not applicable
3. Plutonium contained in spent fuel held elsewhere.	not available	not available	5.90	5.90
Note iii) Plutonium contained in spent fuel sent for reprocessing and held in locations in other countries.	not available	not available	not available	not available

Table 3: Estimated Plutonium at and Originating from German Facilities as of Early 1999

Location	Quantity	Appearance	as of
Hanau (Siemens and Bundeslager)	1.093 MT	Fuel elements for the fast breeder reactor SNR 300 in Kalkar	
	0.554 MT	MOX powder and ceramic	
	0.455 MT	Plutonium dioxide as powder (shipped back to France)	
	0.105 MT	complete fuel rods (some to Dounreay)	
	0.070 MT	in nitrate solution (has been precipitated)	
	2.268 MT	*Subtotal*	early 1997
Karlsruhe (WAK)	16.5 kg	in 70 m^3 liquid waste	mid 1999
Kernforschungszentrum MILLI	Unknown	Plutonium separated with the PUREX process from fast breeder fuel	
Cadarache (COGEMA)	Varying	Plutonium dioxide and MOX fuel rods	
Dessel (Belgonucleaire)	Varying	MOX fuel rods and MOX fuel elements	
La Hague (COGEMA)	14 - 21 MT	separated plutonium	Feb. 1999
	9 - 10 MT (in 888 MT HM)	in spent UOX fuel	Feb. 1999
	2.0 -2.8 MT (in 56 MT HM)	in spent MOX fuel	
Marcoule	About 100 kg	separated plutonium	1994
	5 - 10 kg (from 46.3 MT HM)	separated plutonium (only 18 fuel power days in KKN)	
Sellafield (BNFL)	2.0 - 2.3 MT	separated plutonium	Feb. 1999
	3 - 4 MT (in 397 MT HM)	in spent UOX fuel	Feb. 1999
	0.5 - 0.7 (in 14.4 MT HM)	in spent MOX fuel	
Dounreay (UKAEA)	Few grams	HEU fuel elements of research reactor Braunschweig	end 1998
	59 kg	in unirradiated KNK fuel rods (from Hanau)	end 1997
	?	SNR 300 fuel elements (?)	end 1998
	?	further fuel residues (Alkem)	
Power reactors, Germany	4.7 MT	in unirradiated MOX fuel	Feb. 1999
	25 -30 MT (in 2,641 MT HM)	in spent UOX fuel	Feb. 1999
	1.4 -2.0 MT (in 40 MT HM)	in spent MOX fuel	
Greifswald (ZAB)	3.0 - 4.4 MT (in 532 MT HM)	in spent UOX fuel	early 1999
Gorleben	0.26 - 0.37 MT (in 38.4 MT HM)	in spent LWR UOX fuel elements	Feb. 1999
Ahaus	0.5 - 0.6 MT (in 57.8 MT HM)	in spent LWR UOX fuel	Feb. 1999
Sweden (CLAB)	0.83 - 1.19 MT (in 23.8 MT HM)	in spent MOX fuel	early 1999
Russia	1.8 - 2.3 MT (in 293 MT HM)	in spent UOX fuel	early 1999
Hungary	<0.1 MT (in 28.2 MT HM)	in spent UOX fuel (very low burn-up)	early 1999
SUM	70.4 - 88.8 MT	total	early 1999
Out of Which	47.4 - 58.5 MT	in spent fuel	early 1999
	23.0 - 30.3 MT	unirradiated	early 1999

Management Group, (see Table 2). This official estimate is at the higher end of the estimate made in this paper, suggesting that the historical calculations used here are generally consistent with officially published aggregate figures and are conservative in estimating German plutonium stocks.

According to the estimate given in Table 3, about 23 to 30 MT of plutonium were in unirradiated form at the beginning of 1999. The largest part of this material (about 14 to 21 MT) was located in France. In spite of the large uncertainty ranges, this estimate compares well with the 24 to 32 MT of plutonium that remain after subtracting the estimated six to eight MT irradiated in MOX fuel from the total amount of separated plutonium (32 to 38 MT). If all "old" reprocessing contracts with COGEMA and BNFL and all "new" contracts with them that are still in force were completely fulfilled, about 28 to 32 MT of separated plutonium would be added to existing stocks. To what extent the plutonium surplus can be limited depends on whether additional "new" reprocessing contracts are cancelled before being completely worked through.

The Hanau Vault

A significant portion of the unirradiated plutonium that is stored on German territory was located in the so-called plutonium bunker in Hanau. A part of the vault is controlled by Siemens, which had a handling license for 460 kg of plutonium. Stockpiles beyond that were transferred by Siemens to the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz - BfS) for federal storage. This amount is stored in the part of the vault that is called "federal storage space" (*Bundeslager*). SBK, the operating company for the now closed Kalkar SNR 300 fast breeder reactor, has usage rights for plutonium that is stored in Hanau in the Bundeslager.

For a long time, no detailed information on plutonium inventories in Hanau was made public. The standard response of the German government to questions on the subject was that more than two MT of plutonium were stored at Hanau.[41]

At the beginning of 1996, in the license application for the phase-out and shutdown of the Siemens MOX fuel element facility at Hanau, more detailed data were made public.[42] The application revealed that a total of about 2.2 MT of plutonium were then still in the Hanau vault. The largest part of this material consisted of 123 fuel elements, which were produced in Hanau for the SNR 300 fast breeder reactor. These contain one MT of plutonium. About one-half MT of plutonium (554 kg) was at that time stored as bulk MOX fuel powder and is currently being fabricated into MOX *storage* rods. These are fuel rods in which the plutonium, in oxide form, is blended and sintered with large quantities of uranium oxide to dilute it and complicate its future recovery. The rods will not, however, meet regulatory and commercial standards, making the storage rods unusable in nuclear reactors. At the end of 2000, 430 kg of plutonium was stored at Hanau in the form of MOX storage elements.[43]

Returning to the 1996 data, at that time almost one-half MT (455 kg) of unirradiated plutonium was in the form of plutonium-oxide powder that has since been transported in several shipments to France to be used in MOX fuel fabrication. An additional105 kg of plutonium was in the form of complete fuel rods, and at least part of this, consisting of KNK fuel rods, was later sent to a reprocessing facility at Dounreay, Scotland, a transfer completed by the end of 1997. Another 70 kg of plutonium was in a nitrate solution, which was received from the WAK facility, where further processing of the material was no longer permitted. The plutonium in this solution has been precipitated, since it cannot be safely stored as a liquid solution for a longer time, and requires maintenance.

Other Plutonium Stored in Germany

Especially sensitive from the perspective of proliferation are the 277 kg of plutonium that were separated from Magnox fuel elements (i.e., fuel clad in a special magnesium alloy that is used in a unique reactor design employed in the United Kingdom) because the burn-up reaches only about 3000 Megawatt days per MT in Magnox reactors, about a tenth of that for light water reactors. Therefore, the material has a far higher concentration of fissile Pu-239 than the plutonium produced in typical nuclear power plant spent fuel, an attribute that makes Magnox plutonium especially attractive for the production of nuclear weapons. The authors have been unable to determine whether this plutonium is still stored in Hanau or whether it has been returned to the country of origin, presumably the United Kingdom, which is the only country to use Magnox reactors extensively. The authors have also been unable to learn whether additional plutonium with a high Pu-239 content is stored in Hanau (e.g., from MZFR, KKN and the super-heated steam reactor in Karlstein).

Separately, in early 1999, there were 16.5 kg of plutonium stored in two containers with 70 cubic meters of liquid high-level waste in the former WAK reprocessing plant in Karlsruhe.[44] All other plutonium stored there earlier has been removed to other locations, according to the WAK management. The remaining 16.5 kg are believed to have been removed during 1999.

Given the numbers for unirradiated plutonium provided to the International Plutonium Management Group that are quoted in Table 1 for end of 1998 (6.6 MT) and taking into account plutonium stored at Hanau (no more than two MT left in early 1999), it can be concluded that roughly 5 MT of plutonium was stored in unirradiated MOX fuel at power reactors in early 1999.

PROJECTING THE FUTURE CONSUMPTION OF SEPARATED PLUTONIUM

A projection of current trends implies that the existing plutonium surplus will grow further. The plutonium quantity discharged every year from all German LWR reactors is about five MT contained in about 450 MT HM. With a continued annual separation of three to four MT and a plutonium reuse rate of one to two MT per year, the surplus of unirradiated plutonium might possibly grow by two MT per year through 2005, when all spent fuel shipments to reprocessing plants are scheduled to end. Looking from the perspective of the beginning of the year 2000, a total of roughly 50 to 60 MT of plutonium would then have to be reused in future years, unless there are additional cancellations of new reprocessing contracts.[45]

Existing licenses for the use of MOX fuel in German reactors would theoretically permit approximately 130 MT HM, containing about 6.5 MT of plutonium (equivalent to a concentration of plutonium of five percent) to be loaded each year in German LWRs. If it were possible to burn plutonium at this rate, the total projected plutonium inventory looking forward from 2000 could be readily consumed by 2010. The actual annual reuse of plutonium in MOX fuel in German reactors, however, does not come close to reaching this theoretical capacity; the authors estimate that only between one and two MT of plutonium is burned as MOX annually. Assuming 2 MT of plutonium were consumed annually, projected stocks of German plutonium could not be consumed until sometime between 2025 and 2030. Even if the rate of consumption were increased by 50 percent above this level, to three MT per year, stocks of German plutonium would not be consumed until sometime between 2016 and 2020.

The current German government, however, has agreed to a gradual phase out of nuclear power production, with the last nuclear power reactors to be closed in 2021. This decision means that even if all reactors continued to operate until that date, Germany would not be able to work off its projected plutonium stocks at the two MT/year consumption rate and would be left with an excess of 8 to 18 MT of plutonium. Whether Germany could successfully consume the projected 2000 surplus at the rate of three MT/year would depend, in part, on the details of the phase-out.

An exact calculation of the size of the potential plutonium excess is not feasible for many reasons. Uncertainties remain as to the size of the projected plutonium surplus as of 2000 and as to the reactor phase-out. In addition, the expected end of operation of the French MOX fabrication facility in Cadarache will have a strong impact on the amount of MOX that can be produced for German customers, as will continuing delays in licensing new MOX fuel rod fabrication capacity at Sellafield in the United Kingdom. Moreover, the loading of fresh MOX fuel into German reactors appears, in itself, to be a bottleneck, for reasons that are not well understood. Thus, stockpiles of unused MOX continue to accumulate at German reactor sites.

CONCLUSIONS FOR THE HANDLING OF SEPARATED PLUTONIUM

Gaps and inconsistencies remain in this attempt to compile a comprehensive plutonium balance for Germany.[46] These can only be closed and clarified by the plant operators and government officials who have first-hand data. At a minimum, however, the quantity and quality of German plutonium stocks are of significant proliferation concern and represent a substantial responsibility for Germany. A complete clarification of the relevant stockpiles would make the proliferation significance of these materials more evident and help in the development of an appropriate plutonium disposal strategy.

A particular proliferation concern arises from the surplus of separated plutonium oxide, the form of the material that can be fabricated into weapons with minimal additional processing. In early 1999, 6.6 MT of unirradiated plutonium was stored in Germany. France and the United Kingdom have followed the policy of returning plutonium to Germany only as fabricated MOX fuel. Avoiding unnecessary transportation of the material as separated plutonium oxide somewhat reduces the risks of theft or diversion, although the transportation and use of fresh MOX fuel also poses proliferation dangers because its plutonium content can be separated far more easily than plutonium contained in spent fuel, where it is mixed with highly radioactive materials. Another unresolved matter is speculation that plutonium of German origin might have been used in the French nuclear weapons program in exchange for equivalent quantities of plutonium of a different quality. Although this exchange has reportedly been an option, no evidence known to the authors would substantiate speculation that this option had been used.

As noted earlier, German plutonium, both at home and abroad is subject to IAEA and EURATOM monitoring to detect any possible diversion of the material by national governments. It is also subject to physical protection, control, and accounting measures to reduce the risk of unauthorized access by sub-national groups.

For the next several years, the use of plutonium in MOX fuel elements in light water reactor nuclear power plants in Germany does not appear be on a large enough scale to reduce Germany's surplus plutonium stocks. Through 2005, when shipments to reprocessing plants will cease, more plutonium will be added to the surplus annually, as a result of reprocessing in France and the United Kingdom, than will be eliminated by the production and burning of MOX fuel in German reactors. Only after this date will reductions in the surplus begin.

Apart from using separated plutonium as LWR MOX fuel, there are no practical alternatives for significantly reducing the inherent proliferation risks that the material poses. The use of separated plutonium in fast reactors has become obsolete in Germany after the Kalkar fast breeder reactor project was abandoned in 1991. The transfer of German plutonium to foreign customers is also problematic and unrealistic, because the countries potentially interested in using plutonium for LWR MOX or as breeder reactor fuel have accumulated their own surplus stocks of separated plutonium. Late in the Clinton administration there were discussions about selling the bulk of the plutonium contained in the 123 unused SNR 300 fast breeder reactor fuel elements to the U.S. company Advanced Nuclear Medical Services. The intention was to use this material for the production of medical isotopes and tritium at the Fast Flux Test Facility (FFTF) in Hanford, Washington. The tritium was to be used for the U.S. nuclear weapons program. These plans were abandoned in December 2001, however, when the U.S. Department of Energy decided to permanently close FFTF.

For many years, the policy of separating plutonium from nuclear power plant spent fuel has been controversial. Critics argue that it creates unnecessary proliferation risks and environmental burdens, that burning MOX in LWRs raises safety issues, and that the activity is considerably more costly than the traditional "once-through" fuel cycle, in which spent uranium fuel is stored rather than reprocessed. In recent years, German nuclear power operators have echoed the point that plutonium recycle in LWRs has proven to be economically inefficient.

Since 1994, when a new law (*"Artikelgesetz"*) amending the German nuclear energy act was passed, the direct disposal of spent fuel elements has been officially recognized as an acceptable approach for managing spent nuclear power plant fuel. In spring 1997, the German energy utilities declared that in the future they would send only 60 percent of their spent fuel abroad for reprocessing and that 40 percent would be designated for direct final disposal.[47] The latter option could be applied to a larger extent, ideally to 100 percent of spent fuel discharges, in order to facilitate the reduction of the plutonium surplus.

The prospect of an enduring surplus of separated plutonium raises the question of how this material can be processed and safely stored for the long term. One area needing investigation is the possibility of treating separated plutonium as radioactive waste and conditioning it for final disposal. This approach is likely to be required, at a minimum, for those plutonium stocks that are not suitable for use as LWR MOX. Additional options are receiving attention internationally, e.g., the immobilization of plutonium mixed together with liquid high-level radioactive waste, or the production of MOX storage elements and storing these with highly radioactive spent fuel in sealed storage containers.[48] Unfortunately, since none of the approaches currently under discussion for the disposal of plutonium is completely free of problems and since the plutonium itself would remain in existence, additional technical options for the elimination of plutonium need to be investigated.[49]

Germany is not alone in confronting a possible multi-MT surplus of separated plutonium, while lacking an assured plan for the future disposal of this dangerous material. Japan, Russia, and the United Kingdom are known to confront significant plutonium surpluses, while Spain, Italy, and the Netherlands must also address such surpluses, though on a more modest scale. It seems logical that the plutonium problem should be dealt with through an internationally coordinated approach.[50] With surpluses continuing to grow for many of the participating states, a wise first step would surely be to halt additional reprocessing at the earliest time possible, or at least to adopt a temporary moratorium on further plutonium separation until long-term plutonium disposal strategies can be devised.

[1] The views expressed in this article are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

[2] Prior to the reunification of Germany in 1990, the Federal Republic of Germany (FRG) and the German Democratic Republic (GDR) operated separate civil nuclear programs. The nuclear research and power activities of the FRG were closely tied to those of other Western states, while those of the GDR were closely linked to the Soviet Union. The programs of both the FRG and the GDR were subject to comprehensive international inspection by the International Atomic Energy Agency (IAEA) and, in the case of the FRG, also by the European Atomic Energy Community (EURATOM). For the period prior to 1990, this article focuses on plutonium separation and use for peaceful purposes on the part of the FRG; to the authors' knowledge, the GDR did not engage in similar activities. Rather the GDR shipped all of its spent nuclear power reactor fuel to the Soviet Union, where the spent fuel was either kept in storage or "reprocessed," i.e., its plutonium and uranium were separated by chemical processing from other spent fuel constituents, for possible future use. Under GDR-Soviet fuel contracts, no plutonium was expected to be returned to the GDR and, today, any plutonium recovered by the Soviets is considered to be the property of Russia and is not part of Germany's plutonium stocks. With the reunification of Germany in 1990, the FRG and GDR nuclear programs were merged and a decision was made to close the six operating Soviet-designed nuclear reactors in the former GDR. No spent fuel from those plants remains at the six reactor sites. It has partly been shipped abroad (to Russia and Hungary) or to the German central interim storage facility ZAB at Greifswald (see Table 3). The material inherited by the unified Germany, but not spent fuel sent to the Soviet Union before the unification, is included in overall estimates of German spent fuel accumulations since 1990 and of German plutonium contained in spent fuel. In sum, for the purposes of this article, references to "German" nuclear activities prior to 1990 should be considered as the activities of the FRG and after 1990 as those of the reunified German state. The views expressed in this article are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

[3] David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996. World Inventories, Capabilities and Policies* (New York: Oxford University Press, 1997).

[4] International Atomic Energy Agency, *INFCIRC* 549, May 28, 1998, December 23, 1999, December 4, 2000.

[5] M.B. Kalinowski, "Internationale Richtlinien für das Management von Plutonium. Eine Bewertung aus Sicht der Interdisziplinären Arbeitsgruppe Naturwissenschaft, Technik und Sicherheit (IANUS), " [International Guidelines for the Management of Plutonium. An Evaluation by the Mixed Working Group of Science, Technology and Security (IANUS)], *Physikalische Blätter* 54 (1998), p. 206/7.

[6] It should be noted that the first official U.S. plutonium balance, which was presented in February 1996, was not able to fully satisfy the demand for complete accountancy of all plutonium stocks. The report, for example, had to acknowledge inventory discrepancies (material unaccounted for - MUF) of 2.8 MT of plutonium, i.e., 2.5 percent of the total production, potentially enough material for 350 nuclear weapons, using the IAEA standard of 8 kg per nuclear weapon. U.S. Department of Energy, *Plutonium: The First 50 Years*(Washington D.C., U.S. Department of Energy, February 1996). The authors' interest in German plutonium balances, it should be stressed, is not driven by concern that the government of Germany, might misuse this material, but rather by concern that, through theft or diversion, stocks of separated German plutonium might fall into the hands of terrorist organizations or proliferant states.

[7] This paper is based on a detailed study by the authors that was supported by funds from the Federation of German Scientists (Vereinigung Deutscher Wissenschaftler e.V. VDW, Berlin) and Greenpeace Germany. The publication of the report entitled "Deutsche Plutoniumbilanz für die Jahre 1968-1999" with many tables and figures, and a complete list of references is forthcoming in the series "VDW-Materialien", Berlin 2002. It can be ordered from VDW, Schopenhauerstr. 26, D-14129 Berlin, Germany. See also, Martin B. Kalinowski, Wolfgang Liebert and Silke Aumann, "German Plutonium Balances for the Years 1968-1999," INESAP Technical Report No. 2, English version, forthcoming Darmstadt 2002.

[8] A metric ton (MT) is 1,000 kilograms, or 2,200 pounds. Figures in this article over one MT have generally been rounded to the nearest MT.

[9] "Response of the German government to a Parliamentarian Request," *Bundestags-Drucksache* 14/523; "Stand der Entsorgung der Kernkraftwerke," [Status of the Disposal of Nuclear Power Plants], *Bundestags-Drucksache* 14/747 (April 12, 1999).

[10] Ibid.

[11] This estimate was made by the authors under the assumption that over the years the burn-up had been increased and as a result the plutonium content went up. The following assumptions were made for the plutonium content by weight percent of heavy metal: for 1968-1979 0.6-0.8 percent, for 1980-1989 0.7-0.9 percent, for 1990-1994 0.85-0.95 percent, for 1995-1999 0.95-1.15 percent. For spent MOX fuel the plutonium content is estimated to be 3.5-5.0 percent.

[12] In January 2000, COGEMA released information on contracts and on amounts of spent fuel reprocessed, which are slightly higher than the data quoted here from a German source.

[13] There are no "new contracts" with the WAK or Eurochemic plants because these are closed.

[14] This estimate is consistent with a statement in January 2000 by a representative of the energy utility Preussen-Elektra (now E.ON Energie AG), quoting figures indicating that additional withdrawals from new contracts with COGEMA and BNFL might result in the separation of no more than 27 MT of plutonium beyond the accumulations of 1999. M. Etzmuß and H. Bröskamp, "Status und Perspektiven der Plutoniumverwertung in Deutschland durch den Einsatz von MOX-Brennelementen," Workshop of the German Ministry for Environment and Reactor Safety on Options for the Use and Final Disposition of Plutonium, January 13-14, 2000, in *Tagungsbericht Workshop zu Optionen bei der Verwertung und Entsorgung von Plutonium* (Jülich, FRG: Research Center Jülich GmbH, October 2000).

[15] Agreement between the Federal Government of Germany and the utility companies, June 14, 2000, <www.bmu.de/english/download/nuclear/files/atom_agreement.pdf>.

[16] WAK, correspondence with the authors, July 27, 1992.

[17] Baden-Württemberg Parliament, "Stellungnahme des Ministeriums für Umwelt: Ablauf und Risiken der bisherigen und zukünftigen Arbeit der Wiederaufarbeitungsanlage Karlsruhe," [Opinion of the Environmental Ministry: Procedures and Risks of the Current and Future Operation of the Reprocessing Plant Karlsruhe], *Landtags-Drucksache* 10/6223 (November 15, 1991); W. Schüller, "Betriebserfahrungen mit der Wiederaufarbeitungsanlage Karlsruhe," [Operational Experience with the Reprocessing Plant Karlsruhe], atw 8-9/1984, p. 438-444; H.-O. Willax, and K.-D. Kuhn, "Betriebliche Erprobung neuer Verfahren und Komponenten in der WAK," ["Operational Testing of New Systems and Components in WAK]", atw 2/1987, p. 90.94.

[18] "Response of the German Government."

[19] This estimate was made by the authors using the assumptions explained in footnote 9.

[20] Bundesausfuhramt [Federal Office of Exports] (BAFA), Annual Import and Export balance for the Years 1982 to 1995 (correspondence with the authors, July 27, 1992, October 17, 1995, and December 22, 1995); annual import-export statistics of nuclear materials, first published in *Atomwirtschaft* in November 1968.

[21] M.Pavageau, M.Schneider, and J.Schulz, *Deutsches Plutonium und das*

französische Atomprogramm, [German Plutonium and the French Nuclear Program], (Paris: WISE, June 1996).

[22] Response of BMBF Secretary of State B. Neumann to the request 8/352 of the representative S. Probst, MdB dated April 18, 1996.

[23] W. Marth, *The History of the Construction and Operation of the German KNKII Fast Breeder Power Plant*, Kernforschungszentrum Karlsruhe, Report KfK 5456, November 1994.

[24] U.K. Department of Trade and Industry, "Annual Plutonium Figures Through 1987." Correspondence with the authors.

[25] Bundesausfuhramt [Federal Office of Exports] (BAFA), "Annual Import- and Export balance for the years 1982 to 1995: Annual Import-Export Statistics of Nuclear Materials."

[26] Jean-Marc Wolff, *Eurochemic (1956-1990)*, (Paris: OECD Historical Series, 1996).

[27] Bundesausfuhramt [Federal Office of Exports] (BAFA), "Annual Import and Export Balance for the years 1982 to 1995."

[28] There are a number of discrepancies between the annual total of approved exports according to BAFA and the export balance compiled by the Federal Office of Statistics. Since 1981, the Federal Office of Statistics, in Wiesbaden, has compiled a nuclear materials export and import balance, sorted by sending and receiving states and based on customs declarations. See, Statistisches Bundesamt [Federal Office of Statistics], "Auszug aus der Außenhandelsstatistik, unterteilt nach Ursprungs- und Bestimmungsländern in den Berichtszeiten 1970 bis 1995" ["Excerpt from the Statistics of Foreign Trade Classified According to States of Origin and States of Destination for the Time Period 1970-1995], correspondence with the authors, November 3, 1995. A comparison of the data from this office with those of the German Federal Export Office is somewhat difficult, partly because the statistical office considered the given amounts of all fissile isotopes, not only those for plutonium. However, significant discrepancies between the balances can nonetheless be noted.

A series of inconsistencies can be traced back to the apparent fact that plutonium quantities appear in the trade balances of the Statistics Office for which no export or import license was apparently granted by the export authority. One example involves the export of two kg of unirradiated fissile plutonium to Pakistan in 1983, which appears in the export statistics of the Wiesbaden Statistical Office. The Export Office denies knowledge of such a large transfer and speaks of a mistake (a "transcription error") in the statistics of the Wiesbaden office. It asserts that the amount of the real transfer of plutonium was many orders of magnitude smaller than the Statistics Office records show. Export Office records show that the export of 2.36 microgram (not kilogram) Pu-239 was approved on April 19, 1983, and was carried out seven days later. Bundesausfuhramt (BAFA), telephone conversation with the authors, June 4, 1996.

[29] Reiner Jend, "Das Brennelementewerk Hanau," [Fuel Element Facility Hanau], *Jahrbuch der Atomwirtschaft* 1996 [Yearbook on Nuclear Commerce 1996], pp. 40-50.

[30] The original graph in Jend, "Das Brennelementewerk Hanau," translates the data into "LWR equivalents," that is, it shows bars for fast breeder reactor (FBR) and LWR-MOX fuel that are as long as they would be if the same amount of plutonium were be used for LWR-MOX fuel. The following example demonstrates this point. Assume LWR-MOX fuel contains three percent Pu and FBR-MOX contains 30 percent Pu. Let us assume FBR-MOX weighting ten MT HM has been produced. This contains seven MT uranium and three MT plutonium. The LWR equivalent for this amount of FBR-MOX is defined to contain three MT Pu as well and, therefore, would weigh 100 MT HM. Consequently, the bar chart in Figure 7 would show for this amount of FBR-MOX a bar that is as long as the bar for 100 MT LWR-MOX would be, though, in fact, the true weight is just ten MT. In our Fig. 7, the histogram bars for FBR-MOX fuel are corrected to indicate the true amount of heavy metal in the FBR fuel, since these are the units of the y-axis.

[31] Jend, "Das Brennelementewerk Hanau."`

[32] Response of the German Government. The Gundremmingen power station was the latest to employ MOX in its reactors B and C. The reactors at Grohnde, Lingen, and Neckarwestheim I were the three that did not use MOX fuel, despite being licensed to do so since the early 1990s.

[33] Gesellschaft für Reaktorsicherheit [Association for Reactor Security], "Entsorgung abgebrannter Brennelemente aus Kernkraftwerken der Bundesrepublik Deutschland" [Disposal of Used Fuel Rods from Nuclear Power Plants in the Federal Republic of Germany], Ergebnisse der Länderumfrage zum December 31, 1996 [Findings of the Regions Poll, as of December 12, 1996], May 20, 1997.

[34] Jend, "Das Brennelementewerk Hanau."

[35] Estimated by the authors.

[36] Etzmuss and Bröskamp, "Status und Perspektiven der Plutoniumverwertung."

[37] *INFCIRC*/549

[38] Ibid.

[39] As many data as possible are presented here as of February 1999, using information from "Response of the German Government." For other numbers given in this table that are not referenced anywhere else in this paper, author estimates and further references can be found in Kalinowski, et al., *German Plutonium Balance for the Years 1968-1999*.

[40] Estimated by the authors.

[41] See, for example, *Bundestags-Drucksache* BT 12/7472, (May 2, 1994).

[42] Siemens Brennelementewerk Hanau [Siemens Fuel Element Facility Hanau], Antragsunterlagen zum Leerfahrprogramm [License Applications for Phase-out and Shut-down Programs], Auslage im Hessischen Umweltministerium [Display in the Environmental Ministry in Hessen], Wiesbaden, Germany,1996.

[43] *Bundestags-Drucksache* BT 14/5861, (April 5, 2001).

[44] Dieter Balle, "Die heisse Atomsuppe aus Karlsruhe," [The Hot Atomic Soup from Karlsruhe], *Frankfurter Rundschau* (July 14, 1998); S. Reker, "Verkehrte Welt – Um Transporte nach Gorleben hinauszuschieben, billigt die SPD sogar die Wiederaufarbeitung," [Preposterous World: In Order to Defer Transport to Gorleben, the SPD Charges Even for Reprocessing], *FOCUS* Nr. 20/1997 (May 20, 1997), p. 84.

[45] This figure represents unirradiated plutonium from three sources: (1) unirradiated plutonium in the form of oxide and MOX fuel, 23 to 30 MT, as of February 1999, see Table 3; (2) German spent fuel covered by "old" contracts but not yet reprocessed, 14 to 17 MT, as of February 1999; and (3) plutonium from reprocessing under new contracts that were still in force, roughly 14 to 16 MT, for a range of 51 to 63 MT, rounded here to 50 to 60 MT.

[46] Kalinowski, et al., *German Plutonium Balance for the Years 1968-1999*

[47] S. Reker, "Verkehrte Welt."

[48] C. Küppers, W. Liebert, and M. Sailer, "Realisierbarkeit der Verglasung von Plutonium zusammen mit hochradioaktiven Abfällen sowie der Fertigung von MOX-Lagerstäben zur Direkten Endlagerung als Alternative zum Einsatz von MOX-Brennelementen," [Feasability of the Vitrification of Plutonium with Highly Radioative Waste and the Production of MOX-Storage Rods for Direct and Ultimate Waste Disposal as an Alternative to the Use of MOX-Fuel Rods], Study by the Öko-Instituts, Darmstadt, on request of the Freie und Hansestadt Hamburg, Germany,April 1999.

[49] W. Liebert, A. Glaser, and C. Pistner, "Elimination Versus Disposal Options for Plutonium," in G.Neuneck et al. (Hrsg.), *Tagungsbeiträge der DPG-Frühjahrstagungen in München (1997) und Regensburg (1998)*, [*Conference Articles from the DPG-Early Year Conference in Munich (1997) and Regensburg (1998)*], (Bad Honnef: Deutsche Physikalische Gesellschaft (DPG), 1998), pp. 111-120; W. Liebert and C. Pistner, "Disposition of Plutonium Stockpiles", Proceedings of the XIII International Amaldi Conference on Problems of Global Security, Accademia Nazionale dei Lencei, Rome, Italy, November 30-December 2, 2000, pp.155-182; C. Pistner and W. Liebert, "Beseitigung von Plutoniumbeständen," [Disposal of Plutonium Stockpiles], *Physik in unserer Zeit* 32 (2001), pp. 18-25.

[50] A possible forum for the cooperative investigation of future solutions to this dilemma would be the International Plutonium Management Group, where participating states have previously agreed on the desirability of seeking to balance plutonium supply and demand. Negotiations on a fissile material production cutoff would be another forum where civilian plutonium stocks might be involved. In March 1995, the mandate for negotiating a ban on the production of fissile materials for nuclear weapons was agreed at the Geneva-based Conference on Disarmament. In August 1998, an ad-hoc committee was established on the basis of this mandate. However, no progress had been made since then. It has been suggested by various states and non-governmental organizations to extend the mandate to civilian nuclear-weapons-usable materials and to stocks from past production (often referred to as a Comprehensive Cutoff Convention).