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PLUTONIUM END GAME:
Managing Global Stocks of Separated Weapons-Usable Commercial and Surplus Nuclear Weapons Plutonium

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Preface

The high hopes of the 1950s that plutonium would provide a "magical" energy source – one that might even be "too cheap to meter" – have run aground on the shoals of technical problems in the development of breeder reactors, high costs of reprocessing (that is, separation of plutonium from irradiated reactor fuel) and plutonium fuel fabrication, non-proliferation concerns, serious and continuing pollution for plutonium separation plants, and low uranium prices. At the same time, alternative energy sources, notably wind energy, have come of age, with far less public support than they deserve.

Yet, those who fervently hope and believe in the long-term future of plutonium as an energy source have enough muscle in the political and economic arenas to keep the plutonium flame alive. Indeed, they have been able to vastly increase the amount of plutonium being separated and used as a fuel. This mixed plutonium dioxide-depleted uranium dioxide (called mixed oxide or MOX) fuel is being used in light water reactors – the most common kind of commercial reactor – the vast majority of which were not designed for plutonium fuels. Enormous subsidies from electricity ratepayers and taxpayers to the reprocessing and MOX fuel industries have been involved and are continuing.

Even with all these efforts, surplus commercial plutonium stocks have been rising. High costs, unsuitability of several reactor designs for MOX fuel, and environmental and security concerns associated with reprocessing and MOX fuel production has limited the number of countries and reactors in which MOX fuel is being used. Britain faces the most acute crisis with about one-third of the entire world's separated commercial plutonium stock, and at best one nuclear power reactor in which it may be used. In Russia, the stock of commercial plutonium stands at about 30 metric tons – enough to make thousands of nuclear bombs – raising significant security concerns.

On the military side, as the Soviet Union collapsed, large numbers of nuclear warheads not only became superfluous – they turned into short-term security threats because they may have wound up on black markets. The same kind of security concern also arose in relation to separated plutonium and highly enriched uranium. In the ensuing years both the United States and Russia declared significant quantities of plutonium (about fifty tons each) and highly enriched uranium surplus to their security needs.

The United States and Russia have been negotiating ways in which to put their surplus military plutonium into non-weapons usable form. The primary method they have chosen is to use it as MOX fuel in power reactors. In Russia, MOX fuel would also be used in at least one breeder reactor. The US-Russian agreement, formalized on 1 September 2000, would allow Russia to reprocess MOX spent fuel and thereby to re-extract the substantial amount of residual plutonium in it. The agreement has been used by Russian nuclear establishment as a key component for its plan for the re-establishment of the commercial nuclear industry, and specifically its breeder reactor component, which was severely affected by the twin blows of the Chernobyl accident and the economic crisis in Russia.

The objective of this report is to analyze the problem of rising commercial plutonium stocks in the context of the failed hopes for a plutonium based energy future and of the end of the Cold War. I will also discuss surplus military plutonium to the extent necessary to integrate recommendations regarding its management with that of commercial plutonium. IEER has published many articles and one book on the disposition of surplus military weapons usable fissile materials, and hence it is not necessary to discuss these at length here.

In this report, I will take at face value the declaration of governments regarding the extent to which they consider a part of their military plutonium stocks to be in excess of their needs. The questioning of any "need" for military plutonium is, of course, a legitimate area of debate, in the context of nuclear disarmament. Such a discussion is beyond the scope of this report. The reader desiring additional information on the disposition of surplus military plutonium should consult IEER's web site at www.ieer.org. IEER's analysis of issues related to nuclear disarmament, and to the management of nuclear materials in that context, can also be found there.

The issue of alternative energy sources for the long term has also been covered in other IEER publications. For instance, a detailed report published by IEER has shown that wind energy is already far more economical than plutonium as an energy source. Hence the recommendations for the immobilization of commercial plutonium should be viewed not only in the context of the analysis provided here, but also in the context of the overall situation in regard to the development of alternative technologies and the evolution of proliferation risks in the post-Cold-War period.

We use metric units in this report, unless otherwise noted. We have used the conversion rate of 1 dollar = 1 euro for converting present-day European costs into US dollars and vice versa. The euro has been seventeen percent higher than this figure in the past and is over ten percent lower at the time of this writing (early September 2000). These differences are small enough in the context of plutonium costs and their uncertainties that they do not significantly affect the calculations or conclusions of this report. All dollars are expressed in 1999 dollars, unless otherwise specified. Many calculations have been done in terms of 1996 dollars and 1996 dollars have been converted to 1999 dollars by using a factor of 1.05. Financial figures are rounded to one or two significant digits, as implied by the presentation of the amount.

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Summary and recommendations

A huge and unjustifiably large sum – on the order of $100 billion worldwide – has already been spent over the past five decades on attempts to create a plutonium economy. There is no end in sight to the subsidies and there is no reasonable way to resolve the many problems that are still outstanding in the foreseeable future. By any rational economic and security criteria, the commercial plutonium fuel and breeder industries should have made a complete exit from the stage of energy choices at least a decade ago. Yet, commercial plutonium separation continues in several countries, adding to the problem. Plans for breeder reactors also remain in place in some countries. Uneconomical use of plutonium as a fuel (in the form of mixed uranium and plutonium oxide or MOX) in existing reactors grew considerably in the 1990s, creating a new set of subsidies for the plutonium industry.

The prospects for plutonium use received their latest dramatic setback in late 1999, when Japan suspended its purchases of British MOX fuel. The very first shipment sent by British Nuclear Fuels (BNFL) was found to contain fuel whose quality control data had been partly fabricated. This was followed by a finding by the Nuclear Installations Inspectorate (the British government agency that oversees nuclear safety) that BNFL suffered from systemic problems in its management and safety culture. The overall result has been a severe crisis in BNFL that has thrown into question the future of reprocessing and MOX fuel fabrication operations in Britain, the country with the world’s largest commercial separated plutonium stocks. BNFL suffered a loss of $500 million in its 1999-2000 accounting year mainly as a result of the MOX fuel data fabrication scandal. The Japanese MOX fuel crisis was compounded by the criticality accident in a uranium fuel processing plant at Tokai-mura in late September 1999, which resulted in the deaths of two workers from exposure to high levels of radiation, the first such deaths in Japan since the bombing of Nagasaki.

Further, Germany has decided to phase out nuclear power, which will likely mean an end to reprocessing of German spent fuel in France in the next few years. The reverberations of the German decision in France have extended to the publication of the first official report showing that reprocessing of French spent fuel is a huge economic burden on French electricity ratepayers. In a recent interview, Roland Lagarde, Technical Advisor to the French Environment Minister, raised the possibility that France should consider the option of ending reprocessing as early as 2002.

Even if commercial plutonium separation were to stop immediately, there would still remain an immense problem of the management of separated commercial plutonium stocks, which are now beginning to approach the size of military plutonium stocks. But commercial plutonium separation continues in several countries, adding to the problem. It is therefore urgent both to stop commercial reprocessing and to create a plan to put separated commercial plutonium and surplus military plutonium into non-weapons-usable form as expeditiously as is consistent with safety, health, and environmental protection.

Main findings

1. **Attempting to make plutonium a mainstay of electricity supply is a very costly, failed idea.**

   Roughly 70 billion dollars (1999 dollars)[1] have been spent worldwide on building relatively large breeder reactors, commercial reprocessing, and subsidies for MOX fuel use. These costs do not include costs of relatively small breeder reactors, costs of research and development on reprocessing, notably the Japanese reprocessing plant at Rokkasho-mura which is under construction (with a price tag of about $20 billion), the net operating costs of breeder reactors, the costs of extended storage of separated plutonium, and decommissioning and clean-up costs. When these major costs so far are taken into account, the total cost of chasing the dream of a plutonium economy so far comes to about $100 billion. Even if further large-scale efforts to commercialize plutonium were to stop now, the final global price tag for the failed attempt to create a plutonium economy will be well over $100 billion, once future costs such as decommissioning of reprocessing plants and breeder reactors are taken into account.

2. **Reprocessing of spent fuel from commercial nuclear power reactors is uneconomical and is now, by far, the main contributor to the global build-up of weapons-usable materials**

   The major powers have formally stopped producing more plutonium and highly enriched uranium for military purposes. Essentially no highly enriched uranium is being produced for commercial or research applications. The operation of military reprocessing plants, supposedly for non-military fuel management purposes, adds far less to the stock of separated plutonium than the surpluses from commercial reprocessing, even after the use of commercial plutonium as MOX fuel is taken into account.

   The technical and economic failure of breeder reactors overall and the high cost of reprocessing and MOX fuel for light water reactors relative to low-enriched uranium fuel are the principal reasons for a rate of plutonium use far lower than the rate of its separation from commercial spent fuel. The overall stock of separated commercial plutonium is more than 200 metric tons. The continued accumulation of global commercial plutonium stocks is only possible through continued governmental and electric ratepayer subsidies. An official report to the Prime Minister of France, the country with the largest commercial reprocessing complex and MOX fuel use, admits that the plutonium fuel program is far more expensive than uranium fuel.

   Uneconomic reprocessing and MOX fuel use are resulting in huge direct costs as well as in indirect costs such as separated plutonium storage, and discharges of radioactive contaminants into the environment, notably into the Irish Sea and the English Channel, from where they have spread.

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[1] As noted in the preface, all figures are in 1999 dollars, unless otherwise specified.

3. **The huge and growing stock of separated commercial plutonium has created a large new proliferation problem.**

   Plutonium from commercial power plants can be used to make nuclear weapons. Such plutonium is not likely to be used to make nuclear weapons in nuclear weapons states, since they have weapon-grade plutonium, which has a higher plutonium-239 content. But non-weapons states that do not now have nuclear-weapons-usable materials and terrorist groups would not hesitate to use it for such a purpose should they have access to the material and the desire to build nuclear weapons. It takes about 7 or 8 kilograms of reactor grade plutonium to make a relatively crude nuclear weapon. On this basis, the current separated commercial plutonium stock is equivalent to over 25,000 nuclear bombs.

4. **Converting surplus military weapon-grade plutonium into a fuel and using it in commercial power reactors raises troubling safety concerns.**

   The vast majority of commercial reactors were designed for uranium, not mixed oxide (MOX) fuel, in which plutonium isotopes provide the fissile material. Modifications to these reactors to accommodate more control elements may be needed. Weapon-grade plutonium has never been used as a commercial fuel in reactors, though plutonium derived from commercial spent fuel is now being used in commercial power reactors in France, Germany, Belgium, and Switzerland. The computer codes that would be used to evaluate the safety of MOX made from weapon-grade plutonium would be those developed for and tested for reactor-grade plutonium. How safety concerns arising from the different plutonium composition of weapon-grade plutonium and reactor-grade plutonium and the different patterns of loading MOX fuel will be resolved remains unclear.

   The consequences of an accident in a reactor with MOX fuel would be more severe than one with uranium fuel. The regulatory infrastructure in Russia is relatively weak, leading to questions as to how safety concerns would be brought up or resolved. Moreover, new proliferation risks will also be created, since fresh MOX fuel would be transported on highways and stored at commercial nuclear power plants that do not now have military levels of security.

5. **Corporations that participate in the US-Russian program to use surplus weapons plutonium as a fuel in light water reactors face serious unresolved liability questions that could have severe adverse financial implications for them in case of a reactor accident on the scale of Chernobyl.**

   Despite years of negotiations, the United States and Russia have been unable to arrive at an agreement on who would bear the liability for the MOX fuel program. Russian light water reactors are acknowledged in the West not to be up to Western safety standards. Moreover, there is no realistic prospect that the serious liabilities arising from the program, notably compensation in case of a severe accident, can be realistically resolved. Even though Russia and the United States have signed an agreement on MOX fuel use as a method of plutonium disposition, they have been unable to agree on liability provisions. MOX use in LWRs, as a method of plutonium disposition, is being pursued at Western, rather than Russian, insistence. Hence, Western corporations and governments participating in the program could face substantial liabilities in case of a severe accident.

6. Russia sees the joint US-Russian weapons disposition program, agreed to in September 2000, as a way to establish a plutonium-fuel economy based on MOX fuel use in breeder reactors. Unresolved liability issues are particularly troubling in this regard.

Minatom has explicitly stated that the US-Russian weapons plutonium disposition program "must be seen as the first step in developing a technology for a future closed nuclear fuel cycle…" This would involve "the use of mixed uranium–plutonium fuel of fast reactors," also known as breeder reactors. The United States has agreed to such a system in Russia in the context of weapons plutonium, even though it was rejected in the United States in the 1970s as too proliferation prone. Moreover, Minatom does not appear to care whether MOX fuel use in thermal light water reactors is carried out abroad or in Russia, so long as the West is the responsible party for the program. "The disposition of a limited amount of weapons plutonium in thermal reactors, if this requires political approval, can be carried out under the financial and technological cooperation of the world community." [2] The lack of a liability agreement for the U.S.-Russian disposition program is particularly troubling in this context.

7. France, the country with the largest plutonium infrastructure, has spent a total of almost $20 billion so far on its plutonium program since about 1960, not including several important cost elements or future liabilities from the past program. It continues to spend on the order of $1 billion per year on its MOX fuel program.

France has built the largest single breeder reactor, it has the largest capacity for reprocessing commercial spent fuel, has reprocessed more commercial spent fuel (its own plus that of other countries) than any other country, and overall, has the largest plutonium infrastructure. The net costs of the French plutonium program so far amount to about $20 billion. These costs do not include R&D costs for breeder reactors, the net operating costs of breeder reactors, and the costs of modification of light water reactors to use MOX fuel. Future costs, including future reprocessing and decommissioning costs of existing reprocessing plants and breeder reactors will also add to this total. France continues to spend on the order of $1 billion per year (net) on its plutonium program, not including many research and infrastructure costs. These are net cost estimates, which take into account the fact that MOX fuel use reduces the uranium fuel needed to operate nuclear power plants.

8. Achieving the spent fuel standard is not as crucial as creating sufficient barriers to theft and re-extraction by non-nuclear weapons states and non-state groups.

The choice of the "spent fuel standard" for plutonium disposition has restricted disposition policy greatly without corresponding benefit in non-proliferation. (The standard requires that the difficulty of stealing and re-extracting plutonium after it has been processed for disposition should be equivalent to that for light water reactor spent fuel.) This is because neither the United States nor Russia is likely to re-extract plutonium that is immobilized or in spent reactor fuel for weapons purposes. Both countries already have large surpluses of separated weapon-grade plutonium that would be faster and cheaper to use to make more

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[2] Minatom 2000, pp. 17-18.

weapons, should they decide to so. Further, Russia plans to re-extract the plutonium from MOX spent fuel in the next few decades. It also plans to use fast neutron reactors for plutonium disposition, which adds to the proliferation potential of the U.S.-Russian disposition plan. Both reprocessing and fast reactor use by Russia make an insistence on the spent fuel standard even less meaningful. This is because separated plutonium is weapons-usable and hence the farthest one can get from the spent fuel standard. Interestingly, the DOE, in its recent request to the National Academy of Sciences to examine the spent-fuel did not ask the NAS to consider the implications of the Russian fast reactor plan for this standard. [3]

9. Immobilization of commercial plutonium in one of several ways would be a safer, faster, and cheaper way to put separated plutonium into non-weapons-usable form.

The use of plutonium as a fuel will not be economical in the foreseeable future. In other words, its management must be seen mainly with a view to ensuring that safety, non-proliferation, and environmental goals are met both in the short- and long-term. Immobilization represents a far safer, faster, and more economical approach to the management of separated plutonium than its use as MOX fuel.

10. Corporations, such as Cogéma of France, with an expertise in reprocessing, radioactive waste management, and MOX fuel fabrication could apply their expertise and experience in plutonium immobilization instead.

Plutonium immobilization technologies have a great deal in common with MOX fuel fabrication and vitrification technologies. The processing steps needed for immobilization are, in some cases, close to those needed for MOX fuel fabrication. The ideological commitment to a plutonium economy of corporations, such as Cogéma and British Nuclear Fuels, as well as nuclear ministries, such as Russia's Minatom, is hindering recognition of the non-proliferation, environmental and economic realities, all of which point to plutonium immobilization. Workers' fears of job losses have been a major factor in preventing a halt to reprocessing. However, this problem would be considerably alleviated or possibly eliminated by the construction and operation of plutonium immobilization facilities for all commercial separated plutonium as well as surplus military plutonium and by the implementation of better clean-up plans for contaminated sites.

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[3] NAS 2000, p. 2 and Appendix A.

Recommendations

Our main overall recommendation is that all direct and indirect attempts to create a plutonium fuel economy or an infrastructure for that economy should be halted. Existing plutonium stocks should be managed in ways that minimize proliferation, environmental, and health risks.

Our specific recommendations are as follows:

1. **All commercial reprocessing should be halted.**

   It is crucial that commercial reprocessing be halted for non-proliferation, cost, and environmental reasons. It is necessary to put an end to the build-up of separated commercial plutonium that will cost further large sums of money to store, safeguard, and put again into non-weapons usable form.

2. **The use of separated commercial plutonium as a reactor fuel should be halted. The proposed use of surplus Russian and U.S. military plutonium as MOX fuel should not be pursued.**

   MOX fuel use is the economic fig leaf that rationalizes continued commercial reprocessing. Halting MOX fuel use will provide the needed impetus to stop reprocessing. Such a step is economically justified since there is a huge economic penalty to reprocessing spent reactor fuel and fabricating the plutonium into MOX fuel, relative to using low-enriched uranium fuel.

   France, the country that provides the inspiration to advocates of plutonium fuel, is using MOX fuel in 20 power reactors despite the 1989 opinion of its nationalized electric utility, Eléctricité de France (EDF), that MOX fuel would cost an extra 2.3 billion francs (discounted to 1990 francs) compared to uranium fuel over a decade. EDF went along with its use because it had already signed the contracts to use MOX, to keep long-term economic options open, and because renouncing MOX would have "detrimental consequences for the nuclear option as a whole."[4]

   MOX fuel use for the purpose of military plutonium disposition is being justified as the way to convince Russia to put some of its military plutonium into non-weapons usable form (MOX spent fuel). However, Russia has made it clear that it will use the plutonium disposition program to further its aims for creating a commercial plutonium infrastructure, defeating the stated aim of putting surplus weapons plutonium into non-weapons usable form. Hence both commercial MOX fuel use and plans for MOX fuel use for military plutonium disposition should be abandoned.

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[4] EDF 1989, Section 3, translated from the French by Annie Makhijani.

3. **All commercial plutonium as well as surplus military plutonium should be put under the safeguards system of the International Atomic Energy Agency (IAEA).**

   Putting weapons-usable plutonium, whether of commercial or military provenance, under IAEA safeguards is an essential institutional step for reducing the likelihood of diversion for weapons purposes by third parties or by the country in which the plutonium is located. Some military plutonium is in shapes that may reveal some aspects of nuclear weapons design. Such plutonium pits should be put in storage containers that can be verified without revealing design data. Further, such plutonium should be converted into non-classified shapes expeditiously and put under IAEA safeguards.

   Like many national agencies responsible for nuclear matters, the IAEA both promotes nuclear energy and serves as a non-proliferation watchdog. The safeguards function is at odds with its promotion function. This conflict of interest should be addressed by removing the promotion functions from its charter.

4. **Commercial and military plutonium disposition should be planned as part of an overall immobilization and storage program.**

   Commercial and surplus military plutonium should be put into non-weapons-usable forms, since both can be used to make nuclear weapons and represent significant proliferation risks. The immobilization of both will greatly reduce these risks.

5. **The approach to immobilization should suit the situation in the particular country within the context of overall proliferation-resistance.**

   There are a number of immobilization approaches to making plutonium proliferation-resistant. The specific approach chosen is likely to depend on the circumstances in any particular country, such as the size of the plutonium stock to be immobilized, the amount of liquid high-level waste available for mixing with plutonium, the existing technological infrastructure, etc. The main criteria for proliferation resistance should relate to the prevention of theft and the degree of difficulty for non-nuclear-capable states or terrorist organizations to re-extract plutonium from immobilized forms.

6. **Corporations that now have reprocessing and MOX programs should put their expertise to use for plutonium immobilization instead.**

   A halt to reprocessing and MOX fuel use is needed to focus the attention of corporations, notably Cogéma and British Nuclear Fuels, as well as the Russian nuclear ministry, Minatom, on immobilization. Continued reprocessing and MOX reinforce the inertia and the utterly unrealistic hopes of the past half-century for plutonium fuel use.[5]

   A halt to reprocessing and MOX fuel use, coupled with a program for maintaining jobs, can result in an early creation of immobilization programs at the same places that are now reprocessing centers.

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[5] See, instance, IEER's study *Wind Versus Plutonium*, which shows that wind-generated electricity is already far cheaper than MOX fuel use in existing nuclear reactors or breeder reactors (Fioravanti 1999).

7. **The spent fuel standard, while desirable as a goal for disposition, should not be a primary goal; such a standard unduly restricts the choice of disposition approaches.**

   The main goals of disposition should be the prevention of theft and the creation of significant barriers to re-extraction by third parties that do not now possess large stocks of plutonium. The spent fuel standard biases policy in favor of MOX fuel use, especially in Russia. The irony is that Russia plans to reprocess the MOX spent fuel, a step that would defeat the goal of the spent fuel standard by recreating separated plutonium. Even though this separated plutonium would be under the safeguards of the International Atomic Energy Agency, it would be in a form far inferior to immobilized plutonium, so far as non-proliferation criteria are concerned. Hence, the achievement of the spent fuel standard should be regarded as a very secondary goal that should not be allowed to compromise otherwise satisfactory plutonium disposition schemes.

8. **Before Japan, Canada, and wealthy European countries agree to provide funds for the US-Russian military plutonium disposition, they should initiate a detailed study and a broad public debate of its risks.**

   The United States and Russia intend to ask Japan, Canada, and the European member of the Group of Seven countries (France, Germany, Britain, and Italy) to fund a large portion of the costs of the Russian MOX program. These countries should not accept the US-Russian program as a *fait accompli*, but initiate their own assessments, including evaluations of the regional proliferation dangers that the agreement might pose as well as the financial liabilities they might incur in case of an accident, especially in a Russian light water reactor, as a result of MOX fuel use. They should make no commitments of funds until such assessments have been completed and publicly debated.

9. **The West should offer to purchase all separated commercial and all surplus military plutonium from Russia for immobilization and storage under international safeguards there. The West should also pay for the immobilization. The United States should undertake a parallel commitment for immobilization of its own commercial and surplus military plutonium.**

   Were plutonium valued in the most generous theoretical way for its fuel value, the amount of money that would be needed to purchase Russian commercial and surplus military plutonium would amount to at most $2 billion – a pittance compared to the security benefits to be derived from such a move. An additional similar sum would be needed for immobilization of the plutonium. Existing cooperative nuclear security arrangements indicate a Russian willingness to consider programs that it would not otherwise have undertaken. Yet no Western offer to purchase Russian surplus plutonium for immobilization has officially been made to the Russian government. Such an approach deserves urgent consideration.

Chapter 1: Nature of the problem of commercial plutonium

Plutonium is one of the most important links between the commercial and military nuclear industries. Plutonium is made by irradiating relatively abundant, naturally-occurring uranium-238 in a nuclear reactor. This can be done for military purposes, whereby the plutonium is extracted from the fuel and targets rods irradiated in a nuclear reactor (called irradiated reactor fuel, or spent fuel). Plutonium is also created in commercial nuclear reactors, since uranium-238 is present in large amounts in commercial nuclear reactor fuel. Since there are a large number of such reactors (more than 400 worldwide), the total quantity of plutonium that has been generated in the commercial nuclear power industry has been far greater than that produced in military nuclear weapons programs. By the end of 1999, the total plutonium created in commercial power reactors amounted to over 1,400 metric tons, compared to about 270 to 300 metric tons in military programs.

Commercial plutonium can be used to make nuclear weapons. It does not have the same isotopic composition as weapon-grade plutonium – that is, it does not contain as much plutonium-239, the fissile isotope of plutonium that is the most suited for making nuclear bombs. But any grade of commercial plutonium – that is essentially any isotopic composition of plutonium derived from a nuclear reactor – can be used to make nuclear bombs.

One metric ton of weapon-grade plutonium could be used to make about 200 nuclear bombs – more, if sophisticated bomb designs are used. It takes roughly 40 percent more commercial-grade plutonium to make a similar bomb. Commercial reactor spent fuel contains enough plutonium to make hundreds of thousands of nuclear bombs, if it were first separated from the other radioactive material in the spent fuel. An Interagency Working Group of the US government on plutonium disposition has clearly stated that:

> "Virtually any combination of plutonium isotopes – the different forms of an element having different numbers of neutrons in their nuclei – can be used to make a nuclear weapon. Not all combinations, however, are equally convenient or efficient."[6]

The main physical barrier to the use of commercial plutonium in nuclear bombs is that when it is in reactor spent fuel, it is mixed up with a far larger quantity of uranium and with highly radioactive fission products generated in the course of the nuclear chain reaction. In order to be usable for making nuclear bombs, the plutonium must first be separated from the uranium and fission products. Further, the spent fuel is so radioactive that approaching it in an unshielded state even for a few minutes would result in a lethal radiation dose.[7] Hence plutonium in spent fuel is secure because spent fuel is resistant to theft and the plutonium in it would be very difficult to re-extract should the spent fuel be stolen.

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[6] U.S. DOE 1997, p. 37.

[7] In discussions of plutonium disposition, a matrix, which is the material and physical form into which plutonium has been incorporated, that is as resistant to theft and to re-extraction of plutonium as spent fuel is called meeting the "spent fuel standard." The NAS report defines this as making weapons plutonium "roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel." NAS 1994, p.34. The concentration of plutonium in typical commercial reactor spent fuel is about one percent or less (except MOX spent fuel, in which it is generally considerably higher).

Commercial plutonium is less attractive as a nuclear weapons material for designers in the nuclear weapons states since it contains far less plutonium-239 than weapon-grade plutonium. However, the larger amount of plutonium-240 in commercial plutonium could actually make it less difficult to design a weapon. This is because the higher rate of spontaneous fission of plutonium-240 provides a source of neutrons that helps trigger the nuclear weapon. This same property also makes the yield less predictable in relatively crude bomb designs.

Plutonium extraction from commercial spent fuel is a chemical process, known as reprocessing. Commercial reprocessing plants are large and result in large amounts of liquid radioactive waste, some of which is highly radioactive and must be stored in special tanks. They also emit large amounts of radioactive krypton-85 gas into the atmosphere, which can be detected offsite. As a result, reprocessing plants are easily detectable.[8] It would be difficult for non-state parties, such as terrorist groups, to construct and operate reprocessing plants, even if they somehow got access to spent fuel. Hence, officially sanctioned commercial reprocessing plants are among the principal potential sources of proliferation risk arising from separated plutonium.[9] Commercial reprocessing plants are still operating in France, Britain, Russia, Japan, and India. Table 1 shows the operating commercial reprocessing plants and their capacities. The incomplete Rokkasho-mura reprocessing plant in Japan is not shown. It will be the most expensive reprocessing plant ever built.

Table 1: Operating commercial reprocessing plants

Country	Location and name	Nominal Capacity: metric tons heavy metal per year	Comments
France	Two plants at La Hague: UP2 and UP3	800 each	Light water reactor fuel. UP2 is for French fuel; UP3 for foreign fuel
Britain	Sellafield: THORP	700	For foreign light water reactor fuel and British Advanced Gas Reactor (AGR) fuel
Britain	Sellafield: B205	1500	Magnox reactor fuel
Russia	Mayak: RT-1	600	VVER-1000 light water reactor fuel
Japan	Tokaimura: PNC	100	shut since 1997 waste accident except for a test run during June/July 2000.
India	Tarapur: PREFRE	100	
India	Kalpakkam: KARP	100 to 200	

Source: Albright et. al. 1997, table 6.2. For Tokai status, personal e-mail communication from Citizen's Nuclear Information Center, Tokyo, 15 August 2000. For British AGR fuel, Martin Forwood, personal telephone communication, November 22, 2000. For France, Davis 1997.

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[8] The DOE is developing a new reprocessing technique called "pyroprocessing" or "electrometallurgical processing" that can be done in relatively compact facilities. While the plutonium separated as a result of this process is relatively impure (70 percent plutonium), it can still be used to make nuclear weapons, though such fabrication would be more difficult and involve larger radiation doses – see OTA 1994, pp. 33-36. While such facilities would still emit krypton-85, they would be far easier to hide because of their compactness. It would be difficult to pinpoint the location of the krypton source without some idea of where the pyroprocessing plant is located, since the atmosphere already contains large amounts of that radionuclide, mainly from commercial and military spent fuel reprocessing and secondarily, from nuclear weapons testing.

[9] The other sources are military separated plutonium and highly enriched uranium (HEU). Most HEU is used in the military sector (in nuclear weapons and as a fuel in naval reactors), but some of it is also used in research reactors.

The United States operates two military reprocessing plants at its Savannah River Site in South Carolina, ostensibly for the purpose of "environmental management." In any case the result of the operation of these plants is an increase in the stock of weapon-usable separated plutonium.[10] Russia also operates two military reprocessing plants in Siberia, one at its Tomsk-7 plant near the city of Tomsk, and the other at Krasnoyarsk-26, near the city of Krasnoyarsk, also ostensibly for the purpose of managing spent fuel.

Once plutonium has been separated from spent fuel, the main barrier to proliferation has been overcome. Many of the principles and some of the details of nuclear weapons technology were first published in an unclassified report by the United States government as long ago as 1945.[11] There are so many details publicly known by now, that it is widely considered that if the materials have been acquired by a party determined to make nuclear weapons clandestinely, it could do so. According to a US National Academy of Sciences report,

> "These two materials [plutonium and highly enriched uranium] are the essential ingredients of nuclear weapons, *and limits on access to them are the primary technical barrier* to acquisition of nuclear weapons capability in the world today."[12]

The main current use of plutonium separated from commercial spent fuel is the fabrication of the plutonium into mixed oxide, or MOX, fuel for use in light water reactors. MOX is a mixture of a few percent (generally 5 to 7 percent total plutonium) plutonium dioxide (PuO_2) with the rest being depleted uranium dioxide (UO_2), which consists almost entirely of uranium-238. The MOX fuel is used in some of the same light water nuclear power reactors that now use uranium oxide fuel, containing 3 to 5 percent uranium-235, which is the fissile isotope of uranium. Essentially, the plutonium-239 and plutonium-241, both fissile isotopes of plutonium, replace the uranium-235 as the fuel.[13] Both uranium and MOX fuel contain mostly uranium-238.[14] In both cases, some of the uranium-238 is converted to plutonium-239 (and higher isotopes) during reactor operation. Some of this new Pu-239 is fissioned during reactor operation and the rest remains in the spent fuel. Spent fuel derived from uranium-fueled light water reactors contains about 1 percent plutonium, while that derived from MOX-fueled light water reactors would contain 1.6 to 3.9 percent plutonium depending on the length of irradiation of the fuel, the reactor type and the percentage of MOX fuel loading.[15]

Fresh MOX fuel is a far greater proliferation risk than fresh uranium fuel for commercial reactors. In the latter case, the low-enriched uranium, if stolen, would have to be further enriched in huge, costly and complex uranium enrichment plants, present in only a few countries. In the case of MOX, the plutonium and uranium in the fuel, being different elements with differing chemical

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[10] See Sachs 1996 for a detailed analysis of the official decision-making on this subject.

[11] Smyth 1945.

[12] NAS 1994, p. 1, emphasis added.

[13] Because of the different characteristics the mixture of isotopes of plutonium that is used to make MOX and the performance of MOX fuel compared to low enriched uranium fuel, the percentage of fissile isotopes of plutonium in MOX fuel has to be considerably greater than in LEU fuel. Eléctricité de France considers MOX fuel having 5.3 percent Pu fissile content as being the equivalent of 3.25 percent LEU. EdF 1989, Section 2.1. The uranium in MOX fuel is presumed to be depleted uranium.

[14] For a table showing types of reactors, see Makhijani and Saleska 1999, pp. 46-47. This table is also posted on IEER's web page www.ieer.org.

[15] NAS 1995, Table 6-1, p. 252. Based on MOX made with weapon-grade plutonium.

properties, can be chemically separated with relative ease in smaller scale facilities that would be difficult to detect. Since the principal uranium and plutonium isotopes are alpha-emitting radionuclides, with weak gamma rays, thick shielding and remote operation are not necessary for processing fresh MOX fuel so as to separate the plutonium from the uranium in it. While glove boxes and complex worker protection are desirable, this is unlikely to be a significant restraint on plutonium recovery from fresh MOX fuel, should non-weapons states or terrorist organizations acquire it for the purpose of acquiring sufficient plutonium for making nuclear weapons.

The chemical separation of the components of fresh MOX fuel yields relatively pure plutonium that can be used to make nuclear weapons. Assuming that commercial MOX fuel would have five percent plutonium, about 140 kilograms of MOX fuel (about 14 liters volume) would be needed to get enough commercial plutonium to make a relatively simple nuclear bomb.[16]

By contrast, commercial reactor uranium fuel is a mixture of uranium isotopes, which are chemically essentially identical. The concentration of the fissile isotope is 3 to 5 percent by weight for light water reactors (less for other types). Nuclear weapons cannot be made with this uranium without further enrichment. The minimum enrichment needed is at least 20 percent, but deliverable weapons require 50 percent or more uranium-235 content. Nuclear weapons states use uranium enriched to over 90 percent uranium-235 in their weapons, in which case 10 to 20 kilograms is required.

Uranium enrichment is a difficult and expensive process done in very large plants. Hence, fresh low-enriched uranium fuel is far more proliferation-resistant than MOX fuel, even though both contain comparable concentrations of fissile material (a few percent). Since MOX fuel is only a few relatively simple chemical processing steps away from yielding nuclear weapons-usable material, it must be safeguarded in facilities that are as secure as those that would be used for nuclear weapons. Failure to do so invites increased proliferation risks.

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[16] MOX pellet density is about 10 grams per cc. NAS 1994, Figure 6-2, p. 155. For MOX made with weapon-grade plutonium, the corresponding figures would be 100 kilograms and 10 liters.

Chapter 2: A Brief History of Commercial Plutonium

Plutonium separation for use in nuclear reactors began in a small way during the 1960s. The two premises of the commercial plutonium program in the United States and elsewhere were:

- Uranium was a scarce resource that would become increasingly expensive, necessitating the use of plutonium as fuel.
- The rapid growth of nuclear power, which would become the primary source of electricity by the end of the century. In the United States alone, the expectation of the nuclear industry in 1970 was that there would be 1,000 nuclear power plants of 1,000 megawatts each by the turn of the century (the actual number was about 10 percent of the projection).

The rapid increase of oil prices during 1973-74 seemed to confirm the prognosis of those who believed that plutonium would be the main energy source of the future. Uranium prices rose along with oil prices. France and Japan in particular, both dependent on oil imports to a far greater extent than the United States, intensified and expanded their light water reactor and reprocessing programs. These programs were complemented by costly breeder reactor programs. Breeder reactors are designed to produce more fissile material than they consume during reactor operation by conversion of non-fissile uranium-238 into fissile plutonium-239.[17] The aim was to replace light water reactors by breeder reactors, which would use at first the plutonium created in light water reactors and separated in commercial reprocessing plants. Eventually, an all-breeder-reactor electricity sector was envisaged. In such an economy, plutonium would fuel the reactors and plutonium produced in the "blankets" of the reactors from uranium-238 would be the source of further fuel supply. However, the hoped-for era of a plutonium-fuelled economy did not materialize. Five crucial problems confronted it that have steadily grown worse over the past 25 years:

1. Uranium turned out to be far more plentiful than anticipated, and the price of uranium declined rapidly (with an upward blip in the 1970s). It is currently at or near historic lows. Table 2 shows some data on historical uranium prices.
2. Sodium-cooled breeder reactors, the technology of choice for creating a plutonium economy, and the one in which the greatest efforts and money have been invested, has turned out to be a very difficult technology to master and make economical. Despite over $20 billion in construction expenditures over more than four decades for just the large completed plants, the technology continues to be plagued by technical problems and high costs. Table 3 shows the approximate worldwide capital expenditures on major sodium-cooled breeder reactors, and the current status of the various reactors.
3. Separated commercial plutonium can be used to make nuclear weapons, so that the development of a plutonium economy incurs considerably increased proliferation risks compared to those posed by uranium-fueled nuclear power reactors.
4. Reprocessing proved to be a costly technology, thereby increasing costs of plutonium relative to uranium.

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[17] Net fissile material output can also be produced in breeder reactors that convert non-fissile thorium-232 to fissile uranium-233, which does not occur in nature other than in trace amounts. This approach to breeding nuclear fuel is much farther from commercialization than plutonium-239 breeder reactors and we shall not discuss it in this report. We should note that stocks of uranium-233 created in reactor and reprocessing programs also present a disposition issue, though of a far smaller magnitude than that of plutonium-239.

5. Reprocessing results in discharges of large amounts of liquid radioactive waste and also creates other radioactive wastes that pose environmental problems and create safety and health risks.

Table 2: Historical prices for natural uranium, 1995 dollars (rounded)

Year	Price $/kilogram U
1960	100
1970	50
1980	90
1990	60
2000	30

Source: IEER's newsletter, *Energy and Security* No. 1, and US Energy Information Administration. *Spot market prices of uranium* can be found at http://www.eia.doe.gov/cneaf/nuclear/special/uranproj.html

The cost and proliferation factors have been the most decisive. The United States abandoned commercial reprocessing in the mid-1970s for non-proliferation reasons, as a result of decisions by Presidents Ford and Carter. By the time President Reagan tried to revive commercial reprocessing in the early 1980s, there were no private sector takers, since the economic prospects of reprocessing no longer appeared favorable. Indeed, by the early 1980s, nuclear power itself began to fall out of favor on Wall Street. In France, Britain, Japan, Russia, and India, where the governments subsidize commercial plutonium development, either directly or through policies that cause ratepayers to pay for the added costs, reprocessing has continued. France in particular put two large commercial reprocessing plants into operation. The reprocessing facilities at La Hague in France are now the center of the world's commercial reprocessing industry.

The growth of commercial reprocessing and of global stocks of separated plutonium in the 1970s and 1980s was accompanied by the increasingly insistent reality: breeder reactor technology would be costly and difficult to master. It could not, in the foreseeable future, use the stocks of plutonium that were growing rapidly as a result of putting commercial reprocessing into operation.

The reprocessing plant owners and the governments that supported a plutonium economy confronted a serious dilemma in the mid-1980s. At the very time that reprocessing plants were beginning to generate large amounts of separated plutonium on a consistent basis, the technology designed to use that plutonium – the sodium-cooled breeder reactor – was escalating in cost, with no definitive resolution to the technical problems. Smooth operation of large breeder reactors with plutonium fuel had still not been achieved. France had built a large 1,250 MW (electrical) demonstration breeder reactor, the Superphénix, which was about the same size as the uranium-fueled commercial nuclear power plants it was putting into operation in the 1980s. But the Superphénix was not only expensive; it never operated at high capacity for any substantial length of time. Its total output from 1986 to 1998, when it was permanently shut, equaled less than one year of output at rated capacity. An operating commercial nuclear power plant would put out almost ten times as much in the same period.

Table 3 shows the relatively large breeder reactors that have been built and their approximate costs. Over 20 billion dollars have been spent on large breeder reactor construction alone for the reactors that have been completed. Roughly $3 billion were spent on the US Clinch River Breeder Reactor, abandoned in the early 1980s. In all, about $25 billion have been spent on large breeder reactor construction worldwide. Significant sums have also been spent on smaller breeder reactors, and on breeder reactor operation. There has been a low return in terms of electricity output, overall, since many breeder reactors have operated far below rated capacity and many reactors operate for a decade or less. While we have not attempted to make a detailed estimate of operating costs versus revenues from electricity, the poor operating record of breeder reactors, including the largest among them, the Superphénix, makes it likely that operating and fuel costs have far exceeded the sales of electricity. In addition, billions of dollars will have to be spent to decommission breeder reactors and manage the wastes. Finally, we have not included research and development costs or the costs of the many reactors under 100 megawatts thermal. Were all these factors to be taken into account, the net costs of the global breeder reactor program would likely exceed the estimates in Table 3 by billions of dollars.

Rather than admit failure and move on to renewable energy sources, advocates of a plutonium economy resorted to the idea of using plutonium as a fuel in existing light water reactors. Plutonium was to be mixed with depleted uranium dioxide to create mixed oxide (MOX fuel, with about five to seven percent total plutonium content. About a third of the reactor core is loaded with MOX fuel; the rest is conventional low-enriched uranium (LEU) fuel.

However, the use of MOX fuel in light water reactors is a technical dead-end so far as a plutonium economy is concerned, since the quality of plutonium in spent MOX fuel from light water reactors deteriorates with each pass through the reactor and soon becomes too low for further use. Moreover, most light water reactors were not designed for plutonium fuel use, since plutonium fuel requires more control elements that uranium fuel, other things being equal. Some reactors do have the room for modifications. In France, for instance, only the first generation of 28 nuclear reactors has been deemed suitable for MOX fuel use. Subsequent designs cannot be modified to accommodate the needed additional control elements.

The large-scale use of MOX fuel, it was hoped, would use up the growing plutonium stocks and allow more time for the development of breeder reactors. In France, the government-owned utility, Eléctricité de France (EDF), arrived at an agreement in the mid-1980s with Cogéma, the government-owned reprocessing company (now 19 percent privately owned) to the use of MOX in its reactors, assuming that it would be economical. But by 1989, the situation had changed and EDF had concluded that MOX was "not competitive" with uranium fuel and that its use could impose additional costs on EDF of billions of francs during the 1990s. EDF estimated that the additional cost of using MOX fuel over the decade of the 1990s would amount to 2.3 billion francs (discounted to 1990) compared to uranium fuel. But EDF felt that it was necessary to go ahead nonetheless, since it had already signed the contracts with Cogéma, since continuing with reprocessing would keep options open for what types of reactors might be built to replace the existing generation of light water reactors, and because abandoning MOX would have "detrimental consequences for the nuclear option as a whole."[18]

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[18] EDF 1989, Section 3, translated from the French by Annie Makhijani.

Table 3: Capital Costs of Breeder Reactors Larger Than 100 megawatts-thermal (MWt)

Name and country	Capacity, MWt	Construction period	Operation dates	Capital cost, million local units, current	Currency Type	Exchange rate, $/local unit	Exchange rate date	Capital cost, $, million current	Deflator	Capital cost, $ million (1996 $)
Fermi 1, USA	300	1956-66	1966-72	~100	USD	1.00	1960	100	4.03	403
BN350, Kazakhstan	1,000	1964-72	1972-	180	Soviet rubles	~1.20	1970	216	3.35	724
Phénix, France	560	1968-73	1973-	650	FF	0.18	1970	118	3.35	395
Dounreay PFR, Britain	600	1966-74	1974-94	?	Brit. Pound	2.40	1970	?	3.35	395
Joyo, Japan	100	??-77	1977-	19,500	yen	0.0034	1975	66	2.19	144
KNK-2, Germany	~100	1974-77	1977-91	120	DM	0.41	1975	49	2.19	107
BN600, Russia	1,470	1969-80	1980-	350	Soviet rubles	~1.20	1975	420	2.19	918
FFTF, USA	400	1970-80	1980-1993	639	USD	1.00	1975	639	2.19	1397
Superphénix, France	2,900	1976-85	1985-98	26,000	FF	0.16	1977-85	4239	1.42	6028
Monju, Japan	714	1985-94	1994-1995	590,000	yen	0.0075	1989	4436	1.16	5134
SNR-300, Kalkar, Germany	762	1972-91	Did not open	7,000	DM	0.43	1972-91	3004	1.42	4272
Total	**8,906**									**19,917**

Sources: For starting dates and capacities: Albright, Berkhout, and Walker 1997, p. 196 and IAEA 1999. Exchange rate and producer price index data from the *U.S. Statistical Abstract*, (1990, 97, and 98). For cost data: Phénix: *Le Monde*, 8 September 1983. "Phénix a fourni 11 milliards de kilowattheures : En dix ans de fonctionnement." For Kalkar: Richard Donderer, personal communication, e-mail, 16 June 2000 and No Nukes Inforesource webpage www.ecology.at/db/nni/country/sites/stgerman/kalkar.htm. The same source is used for Kalkar end of construction date. For KNK-2: Heike Prietzel of Öko-Institut e.V. Nuclear Technologie and Plant Safety Division, Darmstadt, Germany, personal communication, which refers to *ATW Internationale Zeitschrift für Kernenergie*, For Monju and Joyo: Mika Ohbayashi, personal communication, e-mail 10-9-99 and Satoshi Fujino, personal communication e-mail, 11 September and 12 September 2000; for FFTF: Westinghouse 1979 and for FFTF construction start date: GAO 1975, p. 9. For Fermi 1, estimated from Fuller 1976, p. 195 and Elward 1979. pp. 81-91. For BN-600 and BN-350, Lee Kotchekov, personal communication, e-mail 23 November 1999. For Superphénix: *Revue Générale Nucléaire (RGN) Actualités*, Issue No. 4, July-August 1997.

Notes:

1. The total does not include about $1.6 billion (current dollars) spent on the incomplete and abandoned Clinch River breeder reactor (about $3 billion in 1996 dollars) or the costs of other incomplete reactors. United States Senate 1983, p. S-14644.
2. Start of operation corresponds to achievement of criticality.
3. Local currencies USD = US dollars, FF= French francs, DM = German marks. The method of conversion to constant 1996 dollars is as follows. The cost of construction is converted into US dollars at the exchange rate prevailing at about the mid-point of construction. If the exchange rate varied a great deal, as it did in the 1980s, an average rate was calculated. The deflator for US dollars between the mid-point of construction and 1996 is then used to obtain 1996 constant dollars. We have used the deflator for the producer price index. This gives a very approximate, internally consistent estimate of capital costs of breeder reactor construction.
4. The Fast Flux Test Facility was on standby between 1993 and November 2000, when the DOE announced that it would be permanently shut. "Energy Department Announces Preferred Alternative for Nuclear Infrastructure," DOE News, Washington, D.C., November 21, 2000.
5. Monju is not officially shut permanently. It suffered a severe sodium leak accident in December 1995 (MacLachlan 1995). Its re-opening appears unlikely.
6. According to Bagdasarov et al. 1985, the cost of the two BN type Soviet breeder reactors was between 1.5 and 1.6 times that of thermal reactors.
7. Dounreay cost data not available. We have assumed the cost of the Dounreay breeder to be equal to the cost of the French Phénix due to the similar size and construction dates.

Japan embarked on a similar course. Some other countries, notably Germany, not wanting to store growing stocks of spent fuel at their reactor sites, also saw advantages in simply exporting their spent fuel to France, and in the 1990s, to Britain for reprocessing. In this way, Japan and Germany have become the largest foreign customers of the French and British reprocessing and MOX industries. (Belgium also has a small plant, which exports MOX fuel.)

Global MOX fuel use has not grown enough to consume the plutonium separated as a result of commercial reprocessing of light water reactor spent fuel. This has resulted in a rapidly growing stock of separated commercial plutonium stocks. The other major factor in the rise of global plutonium stocks has been the continued reprocessing by Britain of the spent fuel from its Magnox reactors and its Advanced Gas Reactors (AGRs), neither of which use MOX fuel. The ostensible reason for reprocessing Magnox spent fuel is that it is in metal form and corrodes when stored wet. However, Britain failed to develop dry storage for its Magnox spent fuel, preferring to reprocess it.

The net result of failure in, and cancellation of, breeder reactor projects and of insufficient MOX fuel use due to high cost and other factors in light reactors has been a rise in commercial separated plutonium stocks. The total amount of plutonium separated from commercial spent fuel and breeder reactor fuel projected to the end of the year 2000 has been about 280 metric tons, with about 15 to 20 metric tons of additional plutonium being separated per year, mostly at La Hague and Sellafield. The inventory of commercial separated plutonium, excluding the separated plutonium used as MOX fuel, at the end of the year 2000, is over 210 metric tons (see Table 4).

The rise of commercial separated plutonium stocks is now about 10 metric tons per year after accounting for MOX fuel use. This far outstrips the growth of military stocks. The growth of military stocks for military purposes is presumably occurring in India and probably Israel. There is possibly a small nascent program in Pakistan. Both the United States and Russia are operating military reprocessing plants as part of management of irradiated fuels and (in the case of the US) target rods. While they claim that these operations are needed for safety and materials management, the end result is a growth in separated plutonium stocks in the military sector. However, even when all of these elements of the growth of military stocks are taken into account, the growth of plutonium stocks in the commercial sector far exceeds that in the military sector. We estimate that the global growth of plutonium stocks in the military sector (independent of the purpose of plutonium separation and grade of separated plutonium) is on the order of a 1 metric ton per year.[19]

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[19] Russia is operating three military reactors whose spent fuel is reprocessed, possibly yielding on the order of a metric ton per year. The United States is recovering some plutonium from previously irradiated target and fuel rods at the Savannah River Site. The amount of plutonium is likely to be quite small, probably under one hundred kilograms per year. Estimate for Russia based on reactor capacity estimates in Cochran and Norris 1993, pp. 87, 99, and 100. Estimate for the United States based on target irradiation data in Cochran et al. 1987a, p. 109.

Table 4: **Estimated separated commercial plutonium stocks in country of storage, metric tons (see note)**

Country	Separated Plutonium	Date of stock	Comments
France	~80	end of 1999	Includes foreign Pu stored in France
Britain	78.5	31 March 2000	Includes foreign Pu stored in Britain
Russia	30	2000	
Japan	5.3	End of 1999	
USA	1.5	2000	
Other	11	end of 1998	Germany, Belgium, India
Total	~206		Total will exceed 210 metric tons by the end of 2000.

Sources: Estimated from various sources, including Walker and Berkhout 1999 and Albright, Berkhout, and Walker 1997. British data are from Barker and Sadnicki 2000. The French estimate was made using information from the Plutonium Investigation web site, www.pu-investigation.org and a personal e-mail communication, Xavier Coeytaux, of WISE-Paris, 11 Sep 2000, for the end of 1998 French plutonium stock of 75.9 metric tons. Japanese data are from the Science and Technology Agency (STA) of Japan for the plutonium inventory of Japan at the end of 1999 (see http://www.sta.go.jp/genshi/nuclear/pu_kanri.html or http://www.cmc.jca.apc.org/english/data/pu_inv..html) , forwarded by Satoshi Fujino (CNIC, Tokyo). Data for the other category are from Albright 2000, Table1.
Note: All figures include separated plutonium that has been fabricated into fuel but not yet irradiated.

The total worldwide separation of commercial as well as breeder reactor plutonium amounts to about 280 metric tons, including all plutonium that has been used as a fuel in commercial, demonstration, and research reactors.[20] While there are no official figures for total military plutonium production worldwide (only the United States and Britain have declared their production and/or inventories)[21], it is estimated to be between 270 and 300 metric tons. Of this, some has been expended in over 2,000 nuclear weapons tests, and a considerable amount is present in radioactive waste. The current global military stock of all grades of plutonium is about 250 metric tons, which is modestly larger than the commercial stock of about 210 metric tons. [22] If commercial reprocessing continues

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[20] Estimated from Albright, Berkhout, and Walker 1997 and Walker and Berkhout 1999.

[21] US production and acquisition of plutonium in the military sector, including all grades of plutonium and a small amount of unseparated plutonium was 111.4 metric tons. The current inventory is 99.5 metric tons. U.S. DOE 1996, p.1. The difference of about 12 metric tons between production and current inventory was used in nuclear weapons tests, discharged as waste or into the environment, and is part of materials “inventory differences” (also known as “material unaccounted for”). The British inventory of plutonium in the military sector is 3.5 metric tons of weapon-grade material and 4.1 metric tons of fuel-grade and reactor grade material. Walker and Berkhout 1999, pp. 12-14.

[22] This figure includes all grades of separated plutonium that are in military stocks, including those portions of military stocks slated for being brought under international safeguards. Of this figure about 230 metric tons is weapon-grade plutonium (Walker and Berkhout 1999 Table 2). This does not include the plutonium used in nuclear weapons tests or that discharged into the environment.

unabated, total separated plutonium stocks for commercial reprocessing are set to surpass those resulting from all military programs in the next few years.

Roughly $40 billion or so has been spent on reprocessing of commercial spent fuel and fast reactor spent fuel.[23] Reprocessing should be considered a net cost of development of the plutonium economy. The US National Academy of Sciences' study of military plutonium disposition concluded that MOX fuel use in existing reactors is more costly than low enriched uranium light water reactor fuel even if the plutonium were free.[24] Even the Russian ministry of atomic energy, Minatom, which is arguably the most determined agency in the world to want to create a plutonium economy, acknowledges that plutonium is currently uneconomical as a fuel:

> “At the same time, under current conditions in Russia - the availability of reliable reserves of relatively low–cost uranium, the absence of plants for the fabrication of fuel with plutonium (MOX–fuel) and the absence of nuclear reactors licensed to fabricate fuel - significant additional costs are required in order to being [sic] to use plutonium in the nuclear fuel cycle.”[25]

In the context of MOX fuel production from separated commercial plutonium, the processing steps are fewer since the plutonium is available in oxide form at the end of the reprocessing line, but the cost of MOX fuel fabrication still appears to be somewhat higher than that of acquiring LEU fuel.[26] As a first approximation, we have assumed that

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[23] Only a small percentage (less than five percent) of the total commercial reprocessing has been breeder-reactor-related reprocessing. Cumulative amounts of reprocessing over time were obtained from Albright, Berkhout, and Walker 1997, Table 6.8, p.184. The $40 billion figure should be viewed as a rough estimate. The actual historical contract figures for reprocessing are not public. Estimates for current dollar costs of reprocessing have varied a great deal. A discussion of estimated costs, actual prices, and projections for reprocessing costs can be found in the 1996 study on transmutation by the National Research Council of the U.S. National Academy of Sciences (NAS-NRC 1996, Appendix J). Brian Chow and Kenneth Solomon of RAND has also presented a summary discussion of the issue (Chow and Solomon 1993, pp. 30-38). Estimates of costs vary a great deal. One confirmed price charged by Cogéma in the early 1990s were reported to be in the $1,250 per kilogram of heavy metal (kgHM) (NAS-NRC 1996). Chow and Solomon 1993 report that British Nuclear Fuels and Cogéma were charging their customers $1,400 to $1,800 per kgHM. Low estimates ranging from $670 to $720 per kgHM have also been reported (NAS-NRC 1996, p. 433). These estimates are for light water reactor spent fuel using the PUREX process. Estimates for Magnox and other reactors are not available. We have used a price of $1,000 per kgHM, in current dollars, for light water reactor spent fuel containing 0.9 percent plutonium and used the per-kilogram plutonium cost derived from that to estimate reprocessing costs of spent fuel from other types of reactors. Producer price index deflators were applied to the current dollar amounts to arrive at a rough estimate of $40 billion cumulative expenses on reprocessing in constant 1999 dollars (rounded to one significant figure). The deflator for the middle of the decade was applied to the current dollar cost total for plutonium separated during that decade. In the estimates of the costs of the attempt to develop a plutonium economy to date discussed in this report, these reprocessing costs are counted as net costs. See text above.

[24] The range of best estimates of net costs of MOX fuel use in existing reactors estimated in the NAS 1995 was $0.5 to $5 billion for 50 metric tons of plutonium (1992 dollars). NAS 1995, pp. 11-12 and pp. 280-329.

[25] Minatom 2000, p. 17.

[26] The actual relative costs depend on a number of factors, including the price of natural uranium (currently near historic lows), the number of years for which the separated plutonium has been stored (see below), and the costs of reactor modification. The recent report to the French Prime Minister indicates the net costs of the use of MOX fuel over the entire life of present nuclear power plants in France to be about 164 billion francs (1999 francs), including the cost of reprocessing. Considering that only 28 reactors will use MOX

the costs of MOX fuel fabrication after reprocessing has recovered the plutonium would approximately offset the costs of LEU acquisition in order to estimate the net worldwide costs of the attempts to use plutonium fuels.

It should be noted that much separated stored plutonium cannot be used for MOX fuel fabrication without being reprocessed again. This is because the build-up of americium-241 (due to the decay of plutonium-241) renders it unfit for MOX fuel fabrication.[27] Hence, this plutonium must either be immobilized and stored as transuranic waste, or it must be reprocessed again, at considerable cost, to be made fit for MOX fuel production. Until then, the plutonium must be stored, the costs of which are estimated to be on the order of two million dollars per metric ton per year.[28] Hence, many billions of dollars will have to be spent in any case on management of surplus commercial plutonium. The overall cost will depend on what management methods are chosen. The more spent fuel that is reprocessed, the larger will be the costs for plutonium management, whether or not the separated plutonium is used as a fuel.

Overall, roughly $70 billion have been spent on the attempt to develop a plutonium economy so far by the time most of the direct, monetized costs have been taken into account. This estimate does not include many important costs. The single largest element among them is the cost of the still incomplete Rokkasho-mura reprocessing plant in Japan. The plant is scheduled to be completed by 2005, at a total cost of about $20 billion.[29] If we include the cost of this plant, research and development costs, the costs so far of storage of separated but unused plutonium, and the net operating costs of breeder reactors costs,[30] the overall net costs of the plutonium fuel and breeder reactor program can be estimated to be roughly $100 billion. A summary of these costs is shown in Table 5.

The future costs of past plutonium policies will include:

(i) disposition of already separated plutonium but so far unused
(ii) decommissioning of breeder reactors and commercial reprocessing plants,
(iii) breeder reactor waste management

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for part of their operating lives, the costs of MOX fuel per year per reactor using MOX fuel amount to almost $40 million, yielding a total net cost of about $1.1 billion per year for the 28 reactors that can use MOX. Reprocessing costs for French spent fuel are not published but are on the order of $1,000 per kilogram of heavy metal, amounting to a total of roughly $800 million per year.

[27] Americium-241 is a strong gamma emitter. If present in greater than allowable concentrations it would create problems of radiation protection for workers. In general, commercial plutonium separated from light water reactor spent fuel must be fabricated into MOX fuel within two to five years of separation in order that the americium-241 concentrations may be acceptably low. The storage times for plutonium derived from fuel with lower burn-up in some other types of reactors (or in weapons grade plutonium) can be longer since the percentage of initial plutonium-241 in the isotopic mix is lower.

[28] Chebeskov 2000.

[29] Sawai 1999.

[30] Net cost calculations take into account the benefit of electricity sales.

(iv) Extraordinary costs, such as those associated with transoceanic MOX fuel shipment and the costs arising out of the BFNL MOX data fabrication scandal (see Chapter 3). The latter costs alone are estimated to be about $300 million.[31]

Table 5: Summary of the Approximate Net Worldwide Costs of Attempts to Develop Plutonium as a Fuel

Cost category	**Cost, 1999 US $**	**Comments**
Major breeder reactors	~20 billion	Larger than 100 megawatts thermal; completed reactors only
Incomplete breeder reactors, small breeders, net operating costs	~10 billion?	
Reprocessing (counted as a net cost)	~40 billion	See text and footnotes
Rokkasho-mura reprocessing plant construction	20 billion	Incomplete plant, now officially scheduled for completion in 2005
Other past costs (R&D, infrastructure, past decommissioning, long-term commercial plutonium storage)	Many billions (see note)	Includes closed reprocessing plants, (e.g. West Valley, New York), past reprocessing and breeder decommissioning, breeder and reprocessing R&D
Subtotal costs to date	**~100 billion**	
Future continued reprocessing net costs	~2 billion per year	Assuming $1,000 per ton of heavy metal – see text and footnotes. Assumes continued reprocessing at current rates
Storage costs for old plutonium stock	0.4 billion per year	
Future decommissioning and commercial plutonium disposition costs	Billions or tens of billions total	

The largest portion of the world's total expenditures on plutonium is accounted for by Japan, which has the single biggest cost item in the form of the incomplete Rokkasho-mura reprocessing plant. The country with the most ambitious plutonium program, France, has accounted for a significant portion of the rest. When French reprocessing costs and breeder reactor costs to date are added up, considering reprocessing as a net cost, France has spent a total of about $20 billion, or about 130 billion francs (1999 francs)[32] on its plutonium program so far (net costs).[33] They do not include R&D costs

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[31] Michael Harrison , "BNFL reveals £337m loss after series of errors," *The Independent*, 15 September 2000.

[32] As noted in the preface, we use a conversion rate of 1 euro = 1 dollar and the fixed internal conversion rates between the euro and the national currencies that are part of the euro zone. In the case of the franc, 1 euro = 6.55 French francs.

[33] This estimate includes the costs of the two breeder reactors, Phénix and Superphénix and the costs of reprocessing French spent fuel, including light water reactor, Magnox and breeder reactor spent fuel.

for breeder reactors and reprocessing, the net operating costs of breeder reactors, and the costs of modification of light water reactors to use MOX fuel. Future costs, including future reprocessing and decommissioning costs of reprocessing plants and breeder reactors will add to this total.

An official French government report to the Prime Minster of France has now conceded that reprocessing and MOX are imposing huge costs on the French economy. Table 6 summarizes some of the results of the study. The costs are un-discounted costs in constant 1999 French francs. Scenario S7 in the table is a hypothetical one, which calculates the cost of electricity had France never gone down the reprocessing, MOX fuel route. Compared to an entirely non-MOX nuclear power sector, the study estimates that the additional costs of using MOX in 28 reactors over the lifetime of the reactors amount to 164 billion francs (1999 francs), or about $35 billion.

Table 6: Official French scenarios for reprocessing and MOX fuel use

Scenario	S4	S5	S6	S7
Cumulative Electricity Generation, TWhe	20,238	20,238	20,238	20,238
Average reactor lifetime, yrs.	45	45	45	45
MOX fuel use	Until 2012-2013	Partial MOX (20 reactors, current situation)	As much MOX as possible (28 reactors)	No MOX
Reprocessing assumptions	Stop in 2010	65-75% of LEU spent fuel	All LEU spent fuel	No reprocessing (hypothetical case)
Centimes/kWhe	14.27	14.38	14.46	13.65

Source Charpin et al. 2000, pages 34, 35, 59, 60, and Annexe 1.
Note: The three scenarios not shown are basically similar to S4 through S6, except that they assume an average reactor life of 41 years.

By comparing the hypothetical non-MOX scenario, S7, with the maximum MOX scenario, S6, which is the actual current policy, and keeping all other factors constant, it is possible to derive the French government's own estimate of the costs per reactor per year of the MOX program.[34] The total additional costs in scenario S6 compared to S7 amount to 164 billion francs. This entire additional cost is attributable to reprocessing and MOX fuel use. This yields an additional cost per year per reactor using MOX of about 260 million francs. This means that for the twenty reactors now using MOX, the French government's own estimate of additional annual cost is over five billion francs, or about 800 million US dollars. For a program involving 28 reactors using MOX, the annual costs amount to over $1 billion per year.

Dollars have been converted to francs at a rate of $1 = 6.55 francs, which corresponds to a rate of 1 euro = 1 dollar. No other costs are included.

[34] All MOX scenarios assume a 30 percent MOX core loading, with the rest of the fuel being LEU.

Chapter 3: Assessment of the current situation

The commercial plutonium business is in deep trouble. The underlying cause is the economic and technical failure of the breeder reactor strategy as the basis for a plutonium economy. The interim strategy of keeping the plutonium separation business going by using MOX fuel in existing commercial power reactors has also run into grave difficulties due to a combination of structural factors:

- the high costs of MOX fuel (including reprocessing) relative to LEU fuel
- low uranium prices
- a stagnant or declining nuclear power business mainly due to continued relative lack of competitiveness of nuclear-generated electricity
- an increasingly competitive market for electricity
- improvements in wind power that have made wind energy far more economical than plutonium fuel[35]
- widespread public concerns regarding the safety of nuclear power, intensified by the 1986 Chernobyl accident
- potential adverse proliferation consequences of nuclear power, and particularly of a plutonium-based nuclear power sector
- dramatic improvements in the efficiency of combined cycle natural gas fired electricity generation plants.

These structural factors have been accompanied by recent events, all but one of which are highly unfavorable to continued commercial reprocessing and MOX fuel use:

1. After the election of the Social Democratic-Green coalition government in late 1998, Germany decided to phase out nuclear power. This phase-out schedule, as it stands at the present time, will be relatively slow, corresponding approximately to the lifetime of the existing power plants. But the phase-out necessarily includes a stoppage of reprocessing German spent fuel. This will make it even more difficult to rationalize continued operation of UP3 in France (dedicated to foreign spent fuel reprocessing) and BNFL’s THORP plant in Britain, also commissioned to serve foreign customers.
2. The German phase-out decision is causing reverberations in France and elsewhere, where the topic of a phase-out of nuclear power is no longer as politically difficult as before.
3. The Science and Technology Committee of the British House of Lords concluded in 1999 that commercial plutonium was a waste.[36] This was a severe blow to the prospects for plutonium fuel use in Britain.
4. The sodium-fire accident at the Monju breeder reactor in Japan in 1995 and the criticality accident at the Tokaimura plant in September 1999 have increased opposition to Japan’s MOX fuel use plans. The entire future of nuclear power in

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[35] Fioravanti 1999.

[36] House of Lords 1999, pp. 63-66. The report noted that plutonium “is given a zero value in BNFL’s balance sheet” and it recommended that, apart from storage of “a minimum strategic stock,” British commercial plutonium should be declared a waste.

Japan is now far more open to question than seemed possible before the Tokai accident.

5. The revelation that some BNFL MOX fuel quality control data were fabricated, including those relating to some of the fuel shipped to Japan. This has thrown the British MOX program into disarray. BNFL made and exported the fuel to Japan and Germany. Other batches of fuel, including some sent to Germany, were also suspect. The data fabrication scandal has considerably delayed Japan's plans to use MOX fuel and also has caused Japan to suspend further orders of MOX from BNFL. Germany and Switzerland have suspended their MOX contracts with BNFL. Even British Energy, the private company that operates British nuclear power plants, and which is expanding internationally, has stated that it would not use MOX fuel fabricated by BNFL in its reactors. British Energy has also stated that it prefers to store its spent fuel rather than have BNFL reprocess it.[37] BNFL has suffered $500 million in losses in the accounting year 1999-2000, most of it due to the data fabrication scandal.[38] These developments have thrown British reprocessing and MOX plans into disarray.
6. Minatom, the nuclear energy agency with the strongest attachment to a plutonium economy, has been and continues to be strapped for funds and cannot pursue an ambitious breeder reactor program on its own. Russia also lacks a commercial-scale MOX fuel fabrication plant.
7. The sole recent factor favoring MOX fuel use comes from the military sector. The 1 September 2000 US-Russian agreement would fill this gap in its nuclear infrastructure, if it is fully funded by the West and proceeds as envisioned (see below). This agreement is aimed at putting military stocks of plutonium that have been declared surplus by the two countries into non-weapons usable form, mainly by using it as MOX fuel in light water reactors. Russia also wants the MOX fuel fabrication plant to be capable of making MOX fuel for breeder reactors. However, Russia and the United States have not been able to arrive at an agreement about who would bear the liability for the program, including in case of an accident. The agreement leaves that question open for further negotiations (see Chapter 4).[39]

The net result of the historical and current trends and events is that there is now a large policy issue of what should be done with the huge but uneconomical stock of commercial plutonium that is growing rapidly. The problem is exacerbated by the fact that the plutonium stock and facilities are run by institutions that have a declining command of public confidence and respect, not least because of the data fabrication, safety, and environmental scandals that afflict BNFL. These factors have compounded the underlying problems arising from poor economic decision-making by governments and plutonium-related corporations.

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[37] Patrick Wintour and Martin Wainwright , "Fresh blow to nuclear plant Plan to end reprocessing of waste fuel at Sellafield," *The Guardian*, March 27, 2000

[38] Michael Harrison, 15 Sept. 2000, op. cit.

[39] U.S. –Russian Agreement September 1, 2000.

Japan

The attachment of other states and bureaucracies to plutonium fuel subsidies is also a large obstacle. Prominent in this regard are the Japanese, British, and French nuclear reprocessing and plutonium establishments. However, the BNFL data fabrication scandal[40] has had widespread repercussions and added to the growing doubts about the wisdom in continuing with MOX fuel programs. In Japan the fabrication of MOX fuel quality control data by British Nuclear Fuels (BNFL) was revealed just at about the same time that the first MOX fuel shipment from BNFL was arriving in Japan. This scandal came on the heels of the immense international controversy about the safety and environmental appropriateness (or lack thereof) of the shipments. The criticality accident in the uranium fuel fabrication facility at Tokaimura has resulted in the deaths of two workers from high radiation exposure, severe injuries or exposures to other workers, substantial doses of radiation to dozens of people, and the evacuation of over 160 people from their homes. Schools were closed within a 10-kilometer radius of the plant,[41] and about 300,000 people were advised to stay indoors.[42] The accident and data fabrication scandal of 1999 came after the 1997 fire and explosion at a waste bituminization facility in the plutonium processing part of Tokaimura had already resulted in the shut down of the reprocessing plant at that site.[43]

These episodes have given rise to serious doubts about the future of nuclear power in Japan and have dealt another blow to its hopes for a plutonium economy. BNFL's Japanese customers have asked that the fuel with faked quality control data be taken back by BNFL, which it appears set to do at considerable cost. The faked MOX quality control data could therefore set the stage for potential non-fuel disposition strategy to be considered seriously in Japan for the first time.

Britain

Britain has no current plans for MOX fuel use. The output of its B205 reprocessing plant, which reprocesses metal spent fuel from its gas-cooled, graphite moderated Magnox reactors is being stored. The reprocessing is being continued only because Britain has not developed dry storage for this fuel and prolonged wet storage of Magnox

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[40] Some quality control data relating to MOX fuel fabrication at BNFL were falsified. Some MOX with such fabricated quality control data was sent to Japan in the first shipment of MOX fuel from Britain. The discovery of the data falsification followed by the criticality accident in a medium enriched uranium fuel fabrication facility at the Tokai plant in Japan caused Japan's MOX fuel program to grind to a halt. The BNFL MOX data fabrication was first revealed by the British newspaper, *The Independent* on 14 September 1999 in an article by Steve Connor entitled "Inspectors Sent in as Sellafield Admits to Serious Safety Lapses."

[41] IAEA 1999a, p. 27.

[42] CNN news transcript, 1 October 1999.

[43] Citizen's Nuclear Information Center (CNIC) Alert, "Japan Resumes Reprocessing of Spent Fuel," Tokyo, [no date, issued after start of test run in June 2000]. The Tokai reprocessing plant has been shut since 1997 apart from the month-long test run that started on June 29, 2000. The Tokai management plans to restart the facility later in the year 2000 and to reprocess about 40 tons of spent fuel by March 2001, according to the CNIC Alert.

fuel is undesirable from an environmental and safety standpoint. The THORP reprocessing plant processes foreign fuels and British Energy's advanced gas reactor spent fuel. The plutonium from THORP was to be fabricated to MOX on an industrial scale and shipped to foreign customers, chief among them being Germany and Japan.

The data fabrication scandal has seriously jeopardized these plans, which were already marginal at best as a result of the combined effects of high MOX costs, electric power deregulation, the German nuclear power phase-out decision, the BNFL MOX data fabrication scandal, and the Tokaimura criticality accident. Export of plutonium in the form of MOX fuel to other countries had been considered a possibility, but this will be far more unrealistic now, in light of the global crisis of confidence in BNFL.

In this context, the 1999 recommendation of the Science and Technology Committee of the House of Lords that British plutonium be considered a waste raised the insistent question about the fate of separated plutonium stored in Britain.[44] Earlier, in 1998, the Royal Society noted that Britain did not have a strategy for dealing with the accumulating stocks of commercial plutonium and recommended that an independent comprehensive review of the matter be undertaken.[45]

BNFL was to be given a lift as a corporation by a partial privatization. But the privatization has been put off until at least 2002 as a result of multiple factors. These include, the data fabrication scandal (and the $300 million cost directly attributable t it), the distinctly poor prospects of reprocessing, and the loss of a major US clean-up contract (the multi-billion dollar project to vitrify military high-level liquid wastes at the DOE's Hanford, Washington site). Rising US business was to have been a major new source of profits for BNFL. That claim is now viewed with far more skepticism.

The case for an abandonment of reprocessing and MOX and a conversion of BNFL to a decommissioning and plutonium management corporation is now stronger than ever, as is being increasing recognized. For instance, a rising number of parliamentarians have called for an evaluation of immobilization as an option for plutonium disposition.[46]

Germany

Spent fuel from German nuclear reactors is reprocessed at La Hague and at Sellafield. Germany's decision to phase out nuclear power also will mean the phase-out reprocessing of its spent fuel and a phase-out of MOX fuel use there. Prior to the BNFL MOX data fabrication scandal, there was some potential that the plutonium separated from Germany spent fuel might be used as MOX fuel in German reactors as part of the

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[44] House of Lords 1999.

[45] Royal Society 1998.

[46] An Early Day Motion in the British Parliament, "Nuclear and Renewable Energies," on 25 July 2000 deplored BNFL's decision to spend 40 million pounds and possibly 100 million pounds to bring back the defective MOX fuel from Japan, when the budget for renewable energy was only 31 million pounds. Nineteen parliamentarians signed it. Another Early Day Motion on the US-Russian plutonium agreement, signed by 29 parliamentarians, asked Britain's Parliament to oppose the US-Russian military MOX agreement and study the liability issues involved.

disposition process. However, doubts about the quality control and hence safety of the MOX fuel have meant that this option is likely to be ruled out. Germany is suspending its MOX fuel fabrication in Britain.

Issues regarding German spent fuel and its shipment to France are complicated by the fact that French law allows for importation of spent fuel for providing reprocessing services but prohibits the storage of foreign nuclear waste. Hence Germany has the option of continuing to ship spent fuel to France for reprocessing, which generates plutonium that must then be dispositioned, or storing the spent fuel in Germany, for which there is not enough room at present, since German nuclear power plans were based on export of spent fuel. Germany's current decision is to phase out shipments of spent fuel and reprocessing in the next few years, and nuclear power over the longer term.

France

Of all the major economies, France is the most reliant on nuclear power. Between 75 and 80 percent of its electricity is generated in nuclear power plants. France is also the center of the world's reprocessing industry, with two large commercial processing plants operating at full capacity at La Hague.[47] It fabricates most of the MOX fuel that is used in the world. France uses more MOX fuel in its nuclear reactors than any other country. With the deep troubles of BNFL due to the MOX fuel data scandal, the position of France in the commercial plutonium business has become even more central, raising the possibility of even more business in the short-term. These conflicting trends between British and French plutonium industries mask common elements. Cogéma is primarily a government owned corporation (19 percent is privately owned); BNFL is wholly government owned. Both companies have run afoul of their own countries' laws or regulations. In the case of Cogéma, it is being investigated for storing foreign waste in contravention of French waste storage law.[48] Both BNFL and Cogéma are shielded by the secrecy laws of their home countries. Both have discharged and continue to discharge large quantities of liquid radioactive waste into the seas and are under pressure from the European Union to eliminate these discharges. And both la Hague and Sellafield have had elevated levels of childhood leukemia in the vicinity of their reprocessing operations, though both have denied that their facilities are connected to the elevated incidence.

In both countries, utilities face the reality of electricity deregulation, which is creating competitive pressures to reduce or eliminate reprocessing and MOX fuel use. In a few years, German phase out of reprocessing and MOX will affect France even more than Britain, since most German reprocessing is done at La Hague. The pressures in Japan, France's other main foreign customer and BNFL's main foreign customer, to wake up from costly commercial plutonium dreams are now stronger than ever before. In this context, Roland Lagarde, Technical Advisor to the French Environment Minister, raised the idea of France ending reprocessing as early as 2002 by stating that it "is regrettable

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[47] For the operating record of the La Hague reprocessing plants, see the Plutonium investigation web site: www.pu-investigation.org.

[48] Letter from Senator Phil Leventis, South Carolina Senate, to U.S. Senator Strom Thurmond, 4 November 1999.

that the report [to the French Prime Minister] does not examine the possibility of stopping reprocessing in 2002. This will have to be considered one day."[49]

Underlying all these issues is the fact that MOX fuel is uneconomical and that there is no realistic prospect that uranium prices will rise enough to make MOX a competitive fuel. Even the French government now recognizes this reality, as was discussed in Chapter 2.

Given that even France now acknowledges that plutonium fuel is not now economical and is not likely to be for decades, the time is clearly ripe for consideration of non-fuel approaches to both commercial and military plutonium disposition. However, the overall decisions on commercial plutonium will be affected by the approach taken by the United States and Russia for disposition of surplus military plutonium. We will discuss this issue before analyzing plutonium disposition alternatives.

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[49] Lagarde 2000. The report to the French Prime Minister (Charpin, Dessus, and Pellat 2000) considered a phase-out of reprocessing by 2010, but did not consider any earlier phase out options.

Chapter 4: Disposition of US-Russian Surplus Military Plutonium

Having failed in the commercial sector, the plutonium fuel industry may have found a crutch in the military sector. The end of the Cold War raised the issue of surplus plutonium from dismantled nuclear warheads that were no longer required for military purposes by the United States and the Soviet Union/Russia. In turn, the issue of the disposition of surplus plutonium is part of the larger issue of the security of nuclear weapons and weapons-usable materials that achieved some urgency because of economic distress in Russia in the 1990s and the frequent political changes there.

The attempted coup in August 1991 in the Soviet Union dramatized the problem. For several days, no one knew who, if anyone, had operational control of the Soviet nuclear arsenal. Within weeks, President Bush unilaterally withdrew most US tactical nuclear weapons from deployment and from the US arsenal altogether, hoping that President Gorbachev would reciprocate. He did, in about a week. In the same period, the United States and the Soviet Union arrived at the START I agreement to reduce their strategic nuclear arsenals. The dismantlement in both Russia and the United States of thousands of nuclear weapons has occurred simultaneously with the decline in the availability of financial resources to Russian nuclear weapons production and design centers. While the problem of diversion of nuclear weapons materials into black markets has always been a serious security concern, the issue took on greater importance and urgency with the disintegration of the Soviet Union and the decline of its economy.

Between them, the United States and Russia have declared about 100 metric tons of plutonium surplus to their military requirements, of a total stock (in various forms) of about 220 metric tons. Further, the Soviet Union also operates a commercial reprocessing plant, RT-1 within its Mayak nuclear weapons facility near the city of Chelyabinsk in the southern Urals. Commercial spent fuel reprocessing over the last two-and-half decades has created a stock of about 30 metric tons of plutonium that is stored on the Mayak site. Soviet plans, like those in France and Japan, and earlier hopes in the United States, called for an electricity sector based on breeder reactors. But, the two large-scale breeder reactors in the Soviet Union (one is in Russia, the other in Kazakhstan) operate on medium enriched uranium fuel.[50] By the end of the 1980s, Soviet plans for building additional breeder reactors stalled for lack of money and due to increasing public opposition.

In contrast to several western countries and Japan, Russia's nuclear energy ministry Minatom, and its Soviet predecessor did not make plans to use plutonium in the form of MOX fuel in light water reactors during the 1980s. This is because such use degrades the isotopic composition of plutonium, creating increasing amounts of the higher isotopes, plutonium-240, -241, and -242, with each pass through a light water reactor. The presence of increasing amounts of these higher plutonium isotopes makes the plutonium unfit for repeated use as fuel. Moreover, it is uneconomical to reprocess such MOX spent

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[50] Albright, Berkhout, and Walker 1997, p. 196. Both reactors have used plutonium fuel on an experimental basis. The BN-350 breeder reactor in Kazakhstan, built in Soviet times, is to be closed in the near future.

fuel just to re-extract the uranium, since it has little value. Indeed, the uranium recovered from reprocessing plants is increasingly coming to be viewed as an economic liability since it is contaminated with traces of fission products, plutonium, and neptunium as well as undesirable isotopes of uranium that are created in the reactor, uranium-232 and uranium-236.

These technical factors mean that MOX use in light water reactors cannot convert, even in theory, more than a few percent of the uranium-238 resource base into plutonium. By contrast, the use of MOX in fast breeder reactors does not degrade the isotopic composition of the plutonium, since, unlike the thermal neutrons in a light water reactor, the fast neutrons in a breeder reactor also fission the non-fissile isotopes of plutonium, namely plutonium-240 and –242.[51] Moreover, since plutonium-239 of relatively high purity can be made in the breeder reactor "blanket" by putting uranium-238 there, breeder reactors can actually be used to improve the isotopic composition of plutonium (in the sense of increasing the percentage of plutonium-239).

These technical factors underlie Minatom's goal of developing an energy economy in which plutonium-fueled breeder reactors would play a major role. Hence, immobilizing plutonium and treating it as a waste has not been well-regarded by Minatom in its plutonium disposition negotiations with the United States.

From a purely technical point of view, an electricity system based on nuclear reactors that aims to use the uranium resource to the fullest must be based on breeder reactors, and not on the use of MOX in light water reactors. However, the use of most of the uranium-238 resource base, while it may be technically appealing to some, is not necessarily a rational economic goal. The merits of a narrow physical resource-related goal must be compared to other available options in terms of resource use, cost, performance, and environmental criteria, even aside from the safety or non-proliferation related considerations that are unique to plutonium fuel.

The lack of a MOX fuel fabrication plant in Russia and the stalling of its breeder reactor program means that essentially all its commercial separated plutonium is stored, unutilized (a situation similar to that in Britain). Further, while Russia has some experience at the pilot plant level in MOX fuel fabrication, there is no commercial plant for making MOX fuel in Russia. In the absence of a significant number of breeder reactors, the Soviet Union did not build a commercial-scale MOX fuel fabrication facility. Russia is producing small amounts of MOX fuel at a pilot plant in Dmitrovgrad for a small breeder reactor, BOR-60, located there.

The disposition of surplus military plutonium in Russia therefore comes, for Minatom, within the larger context of its own plans and ambitions for a plutonium economy based on breeder reactors. The US disposition approach is more complex. Its fundamental aim has been to create a program that, in the shortest feasible time, would permanently put as

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[51] A fissile material is one that can sustain a chain reaction using neutrons of very low (ideally zero) energy. Heavy non-fissile nuclides, like plutonium-240 and uranium-238, can be fissioned with fast neutrons. Such non-fissile radionuclides are described by the term "fissionable."

large a portion of Russian military plutonium as possible into non-weapons usable forms that cannot be diverted easily. In order to do that, the United States realized that it must propose a program that would also put its own surplus plutonium into non-weapons usable form(s).

The evolution of US-Russian proposals to deal with surplus military plutonium must be seen in light of these conflicting objectives. If Russia were to attain its goal of a plutonium economy, then construction of a MOX plant suitable for breeder reactors would be a principal objective, along with the reprocessing of spent MOX fuel. The US goal meant that spent MOX fuel should not be reprocessed, for to do so would result in the re-separation of weapons usable material. Further, since separated commercial plutonium is also weapons-usable, the same underlying tension applies to any disposition strategy for Russian separated plutonium.

In 1994, the US National Academy of Sciences proposed a two-track approach to plutonium disposition that sought to strike a balance between the US government and Minatom goals. A part of the surplus military plutonium would be fabricated into MOX fuel for light water reactors and used in a once-through mode as a fuel. This would extract some of the fuel value from the plutonium, though at a net cost, since plutonium is far more expensive to fabricate into a fuel that uranium. And a once-through mode of use, that is, without reprocessing, would mean that the plutonium fabricated into MOX would be permanently put into a non-weapons usable form.

This was so far from Minatom's objectives that subsequent negotiations have altered the plan in fundamental ways towards Minatom's goals. The June 4, 2000 US-Russian agreement, which was signed by Vice-President Gore on September 1, 2000,[52] provides for the disposition of 34 metric tons of surplus weapons grade plutonium for each country in the following way:[53]

- MOX fuel plants would be built in Russia and the United States.
- Russia would convert all of its surplus weapons plutonium into MOX fuel, while the United States would use 25.5 metric tons as MOX and immobilize 8.5 metric tons in a ceramic matrix that would then be put into highly radioactive glass logs to provide proliferation resistance.
- At least 2 metric tons per year would be dispositioned, with provision to increase this by another 2 metric tons per year. Hence, once the plants are built (the target date for which is currently 2007), it would take between 8.5 and 17 years for each side to put its 34 metric tons into non-weapons usable form.
- Russia would be allowed to reprocess MOX spent fuel after the 34 metric tons has been used in reactors under international safeguards.

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[52] Unless otherwise mentioned, discussion of the official US-Russian program is based on the agreement text. See US-Russian Agreement September 1, 2000.

[53] Makhijani 2000 and US-Russian Agreement September 1, 2000. See also the editorial in *Energy and Security* number 3, "Will Disposition be the Road to a Plutonium Renaissance," 1997. On IEER's web site at www.ieer.org

- The West would pay for the costs of the plutonium disposition program in Russia, though not all costs would be covered (see below).
- Future surplus plutonium would be dealt with along the same lines.

However, Russia and the United States have not been able to arrive at an agreement on who would bear the liabilities arising from the program. A central question in this regard is the question of who would pay the damages to third parties, such as European countries, in case a severe reactor accident on the scale of Chernobyl were to spew radioactivity over Europe.

The United States and Russia lack only a MOX fuel fabrication plant and some related processing facilities to complete the infrastructure for MOX fuel production. Once that is done, there will be an incentive to continue plutonium separation, which would entrench plutonium use. And, as noted, the US-Russian agreement allows Russia to reprocess MOX spent fuel, after a delay, which may be as short as ten to fifteen years. The US-Russian MOX program will increase proliferation and safety concerns, while also increasing the cost for disposition.

Russia clearly sees the weapons disposition program as a way to establish a plutonium fuel economy. According to Minatom:[54]

> "Disposition of weapons plutonium must be seen as the first step in developing a technology for a future closed nuclear fuel cycle. The basic direction in the disposition of excess weapons plutonium, as with plutonium from spent nuclear fuel, is the use of mixed uranium–plutonium fuel of fast reactors, which forms the basis for future large–scale nuclear power engineering. The disposition of a limited amount of weapons plutonium in thermal reactors, if this requires political approval, can be carried out under the financial and technological cooperation of the world community."

In other words, Minatom does not appear to care whether MOX fuel use in thermal reactors (including light water reactors) is carried out abroad or in Russia, so long as the West is the responsible party for the program. Recently, Atomic Energy Minister Yevgeny Adamov stated that the cost of modifying Russian light water reactors to use MOX would be high because Russia does not use MOX in these reactors. He suggested that Russia would consider selling MOX fabricated in a Russian plant to other countries for irradiation there.[55]

In sum, Minatom's plans make it abundantly clear that its core program is to build, at Western expense, the MOX fuel fabrication infrastructure for breeder reactors. Minatom also hopes to build new breeder reactors at its own expense. Minatom may also want to make some money by selling MOX made in Russia to third countries for irradiation in thermal reactors. However, given the immense and growing surplus of commercial plutonium, it may be difficult to find customers for Russian MOX fuel.

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[54] Minatom 2000, pp. 17-18.

[55] Reuters new wire story "Russia says costs could slow plutonium destruction," Vienna, 20 September 2000.

Non-proliferation

A MOX fuel program would create the infrastructure of facilities and financial interests for continuing “commercial” plutonium use. Once begun for weapons plutonium, the MOX plant is likely to be used for plutonium separated from commercial spent fuel. This intent is explicit in Russia, and currently denied in the United States. But once the plant is there, it will be politically difficult to shut it. As evidence, we point to the fact that two military reprocessing plants are still operating at Savannah River Site in South Carolina, supposedly for reasons of “environmental management.” In the same way, Russia is also operating two military reprocessing plants, one at Tomsk-7 and the other at Krasnoyarsk-26, as a way of managing its spent fuel. In the process, Minatom continues to inject highly radioactive liquid wastes deep underground. Low-level liquid radioactive wastes are discharged into aquatic environment.

A MOX program would put plutonium on the roads and in commercial nuclear power plants. At every step of the MOX process until it is loaded into a reactor and its irradiation has begun, the plutonium would need to be safeguarded with a military level of security. This is because plutonium can be separated from the uranium in MOX fuel by relatively simple steps and facilities compared to reprocessing spent fuel. The MOX production facilities, transport to power plants, and its storage at power plants would all be points of potential theft. Unless steps are taken to militarize security at these facilities, there will be a risk of diversion of weapons-usable, including weapon-grade, plutonium.

Proponents of the current US-Russian MOX plans argue that a moratorium on reprocessing of MOX spent fuel during the disposition program would be a sufficient safeguard against proliferation. But it is irrelevant whether MOX spent fuel is reprocessed now or in one or two decades. There is plenty of other spent fuel to reprocess now. This can keep reprocessing plants going until the moratorium on MOX spent fuel reprocessing expires. MOX spent fuel can conveniently be put at the end of the line. Moreover, the US-Russian plan does not address the 30 metric tons of separated commercial plutonium stored at Mayak in the southern Urals. So the net result will be that first military plutonium will be used in the MOX plant, decreasing the military plutonium stock, while commercial reprocessing increases the commercial plutonium stock. Then the military-origin MOX spent fuel can be reprocessed, while the already separated commercial plutonium is fabricated into MOX fuel. In the meantime, new breeder reactors would be built. All but the last element of the plan would be financed with western money. This seems to be the plan the Minatom is banking on.

Safety

The vast majority of light water reactors were not designed to use plutonium as a fuel. Several specific differences between MOX fuel and low-enriched uranium fuel affect safety:

- The rate of fission of plutonium tends to increase with temperature. This is called a positive temperature coefficient of reactivity and can adversely affect reactor control.

- Reactor control depends on the small fraction of neutrons emitted in the seconds to minutes following fission of uranium or plutonium. These neutrons are called delayed neutrons. On average, plutonium yields about three times fewer delayed neutrons per fission than uranium. This means that provision must be made for increased reactor control if MOX is used. Otherwise, the reactor would become less safe. How many more control elements are needed, where they must be placed and whether any particular reactor can be modified to accommodate MOX fuel, are questions that must be examined with every specific light water reactor design. For instance, only one of the three designs of pressurized water reactors that are being used in France for power production can be modified to accept MOX fuel.
- MOX fuel also causes more irradiation damage to the reactors than traditional fuel, because the neutrons resulting from MOX fuel use in light water reactors have a greater average energy than those resulting from uranium fuel. This is due to differences in the fission cross sections between plutonium and uranium in various parts of the thermal neutron spectrum.
- Irradiated MOX fuel is thermally hotter than uranium fuel. Further, the larger quantities of transuranic elements produced during reactor operation with MOX fuel complicate repository disposal of MOX spent fuel.

The larger quantity of transuranic elements, like americium, present in irradiated MOX fuel means that the consequences of a serious accident would be even more severe than for a reactor fueled with low-enriched uranium. According to a report by the Nuclear Control Institute in Washington, DC, the public health consequences of severe accidents involving light water reactors with MOX cores are likely to be considerably greater than those involving low-enriched uranium (LEU) cores.[56] This is mainly because the higher proportion of plutonium in the fuel would increase the release of plutonium and other transuranic elements to the environment in case of a severe accident.

Historically, VVER-1000 reactors have experienced significant problems in the past, just using the uranium fuel for which they were designed. Vladimir Kuznetsov, a reactor expert, who worked for Gosatomnadzor for many years, Russia's nuclear regulatory agency, has expressed serious concerns about VVER-1000 reactor safety and published a book on the subject.[57] Use of MOX fuel in VVER-1000 reactors would complicate the safety issues associated with the operation of these reactors. It would become more complex to assess the conditions of their safe operation, for example.

The fact that Minatom is not particularly interested in the use of MOX fuel in light water reactors is a further problem. As discussed above, Minatom’s clear and publicly stated goal is to use the weapons plutonium disposition program to further its goal of creating a long-term program for the use of MOX fuel in breeder reactors. This has become an important part of its goal of creating a plutonium-based electricity sector.

Another safety issue specific to weapons grade plutonium is that it has never been used as a commercial fuel. Reactor-grade plutonium has different isotopic characteristics than

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[56] Lyman 1999.

[57] Kuznetsov 1999. See also Lyman 2000.

weapon-grade plutonium. Reactor grade plutonium from light water reactors has roughly 60 percent plutonium-239. Weapon-grade plutonium has about 94 percent plutonium-239. The US Department of Energy is proposing 40 percent MOX fuel in the reactor core,[58] compared to the 30 percent that is normal in the reactors which use MOX fuel in France. This means that in US reactors fueled with MOX, there will be about 38 percent plutonium-239 as fuel, compared to about 20 percent for commercial reactors, which represents almost a doubling of the amount of plutonium-239 in the reactor core compared to French experience. Despite this crucial difference, the US Department of Energy intends to use the computer codes from French reactors using commercial MOX fuel to analyze weapons plutonium MOX performance in reactors. Such large extrapolations from commercial experience will create significant uncertainties about safety.

In Russia, the pressure to increase the MOX fuel loading of the core will be even greater. Achieving the 2 metric tons per year rate disposition rate in Russia has been a concern, because the number of Russian light water reactors is limited. Moreover, all of the existing reactors that are under consideration for MOX will reach the end of their 30-year lifetimes within the next 25 years and many of them much earlier. The pressure to extend the lifetimes of the reactors will be very great. Other possible measures include using a large percentage of MOX in the BN-600 reactor core, using reactors in Ukraine, or using CANDU reactors in Canada. All of these approaches pose additional safety risks that have not been adequately addressed.

In the United States, the DOE may ask for a loading of MOX fuel of as much as 40 percent of the reactor core, even though the experience with MOX in France, whose computer codes would be used to evaluate US reactor operation, is with a 30 percent core. Further, the neutron economy of this 40 percent of the core and hence of the entire reactor will be different from that prevailing in French reactors using MOX. This is because commercial MOX contains reactor-grade plutonium, which has about 60 percent plutonium-239, whereas weapon-grade plutonium contains about 93 percent plutonium-239. The use of French computer codes for evaluating weapon-grade MOX fuel use therefore raises some procedural, technical and safety concerns.

Liability

In order to satisfy US demands, Minatom has agreed to use MOX in light water reactors, rather than breeder reactors as they would prefer. So far as we understand, Minatom had never seriously considered the use of MOX fuel in its light water reactors, until the United States brought the idea to the table as part of the military plutonium disposition plan. This raises some liability questions, such as who will pay for the costs, if an accident should occur in a light water reactor using MOX fuel.

The liability question has not been resolved in the September 2000 US-Russian agreement. This is a principal problem that could have serious implications. Russia does not possess the financial resources to insure the MOX fuel program. Were there to be an

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[58] Eller 2000, p. 4.

accident in a light water reactor using MOX fuel, Russia could, with reason, claim that this was a western idea implemented for western purposes with western money. Even the money for funding the Russian nuclear regulatory agency, Gosatomnadzor, is to come from the West. Hence, whatever agreement is reached about liability, the reality of the situation is that it will be borne by the people of the west and of all those areas in Russia and elsewhere that are at risk of contamination in case of an accident.

Given that the dangers of using MOX fuel in Russian light water reactors are being publicly discussed, parties injured as a result of accidents could reasonably claim that companies such as Cogéma, Siemens, and BNFL, which are all likely to be involved in the implementation of the agreement, knew of the risks but went ahead with the program anyway. Hence, the liability issues associated with the MOX program not only have significant financial implications for the US and Russian governments, but also for the people, governments and corporations of France, Britain, and possibly Belgium. Yet despite the grave safety and economic issues involved, there has been little public discussion of liability issues arising from the US-Russian plutonium disposition agreement.

An independent evaluation of whether the safety standards involving Russian MOX use would be comparable to those in the United States is needed. Even in the United States the regulatory situation in regard to military plutonium disposition is far from satisfactory. The US Nuclear Regulatory Commission has not exercised adequate oversight in the process of selection of which reactors might be suitable or not for MOX fuel use. In fact, it has allowed commercial interests to dominate the process by allowing any reactor owners to bid for MOX fuel contracts. A prudent process would have ruled out some reactors on the basis of design or other safety considerations. It would have allowed only those owners of nuclear power plants to express interest that passed a set of stringent safety and design criteria to express interest in the MOX program.

Further, the Russian regulatory agency Gosatomnadzor appears to have far less authority over actual decision-making in regard to licensing and operation of facilities than the Nuclear Regulatory Commission in the United States. Corresponding to its low political clout, Gosatomnadzor has little money and will likely depend on US money for regulating MOX fuel use. This is a serious vulnerability and shows the relatively weak position of this agency in the Russian nuclear establishment.

The estimated budget for the disposition of Russian military plutonium makes no provision for liability insurance. This implies that Russia will bear the costs, if an accident should occur in a light water reactor using MOX fuel. The state of the Russian economy is such that Russia would not be able to cover such costs. Even the US the provision for liability for its own reactors, $10 billion, is grossly inadequate. Even in better economic times, the resources of the Soviet Union were not adequate to the task of paying for the costs of the Chernobyl accident. Remembering the grave damage that many countries besides Ukraine, Belarus, and Russia have suffered as a result of the Chernobyl accident, the European people might reasonably ask whether or how they would be compensated in case of an accident.

Even if the United States agrees to assume a portion of the liability, it is far from certain that the US Congress would actually provide the money, should it be needed. This could create its own set of political difficulties. In sum, the liability for use of MOX fuel in Russian light water reactors presents a very difficult problem. That would continue to be the case even if the United States and Russia arrive at a formal agreement on the liability question, since it is highly unlikely that such an agreement could designate resources to compensate victims in case of a severe accident.

Costs

The current estimate is that the Russian MOX program will cost $1.7 billion[59] and the US program will cost about $4 billion.[60] These cost estimates do not include many items such as the cost of insurance or the costs of electricity while the reactors are shut down for modifications. These costs could be significant. Who will pay for them is still an unresolved issue. Even though plutonium will be used to generate electricity, the use of MOX fuel will involve net costs. This, because it is more expensive to fabricate MOX fuel even when the military plutonium is free than it is to purchase low-enriched uranium fuel. In addition, the extra security, which will add to the cost of the whole process, has not been adequately considered in the evaluation of the MOX program.

The total amount of the net cost of the MOX plan is a matter of some debate. It will depend on the actual costs of processing weapons grade plutonium into MOX fuel, the costs of reactor modifications, the time it will take to make reactor modifications, the cost of the replacement electricity, and the cost of ensuring and certifying the safety of reactors for MOX fuel use. Any international transport of plutonium, for instance to Canada, would add to the costs and risks.

A considerable amount of discussion has revolved around the financing of the Russian portion of the plutonium disposition plan. In order for the MOX plan to be implemented, the wealthy governments of the West and Japan, called the Group of 7 (or G-7) must agree to finance it. While Russia and the United States are pressing Japan and the European member of the G-7 to help finance the plan, no money has as yet been committed beyond US funding for the design of the Russian MOX plant.

It is also possible that private financing might be developed. One financing plan has been put forward by a US corporation known as the Non-Proliferation Trust, Inc. This would involve importation of up to 10,000 metric tons of foreign spent nuclear power reactor fuel for storage in Russia, a complete halt to commercial reprocessing, and a payment to Russia for building storage facilities, a nuclear waste repository and other purposes. Such a plan is currently illegal under Russian law and hence attempts are being made to amend the law. However, many Russian, US and other non-governmental environmental organizations oppose this plan.

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[59] For the Russian cost estimate, see Joint U.S.-Russian Working Group Report 2000,p. iii.

[60] Holgate 2000.

The commercial plutonium industry is currently uneconomical and could survive only with vast subsidies from taxpayers and electricity ratepayers. The US-Russian disposition agreement would provide MOX fuel use with even more subsidies, which, in Russia’s case, would be used to provide new life to its moribund breeder reactor program. This would renew hopes for a plutonium economy in the nuclear establishments not only in the United States and Russia but also in other countries, notably France, Germany, Japan, and possibly also Britain.

Chapter 5: Alternative Disposition Options

The most detailed investigations regarding the fate of surplus plutonium have been done in the context of the disposition of surplus military plutonium. However in the past couple of years, disposition of commercial surplus plutonium has also become a more pressing issue, as the costs, proliferation risks, environmental liabilities, and management scandals surrounding reprocessing and MOX use have grown and become more evident due to a variety of factors.

Detailed attention has begun to be given to the various options for disposition of commercial plutonium, other that its use as MOX fuel in reactors. Since commercial plutonium is now admitted to be an economic liability even by the US National Academy of Sciences and the British House of Lords Science and Technology Committee,[61] it is only logical that the disposition of commercial plutonium should be considered integrally with that of military plutonium Moreover, US-Russian military plutonium disposition is likely to involve Cogéma and BNFL, the very companies that possess the largest stocks of commercial plutonium.   These companies have, or could develop with greater facility than most others, the expertise needed to immobilize plutonium in order to put it into non-weapons usable forms.

Since the publication of the US National Academy of Sciences study on plutonium disposition in 1994, it has been generally accepted that there will be net costs associated with plutonium disposition, whatever disposition route is taken. In that context, the methods best suited for managing commercial separated plutonium and surplus weapons plutonium should be decided in light of the need to achieve security and environmental goals within a reasonable cost and time.

Since commercial plutonium is a liability rather than an asset in the economic sense of these terms, continued commercial reprocessing only exacerbates the economic burden, besides adding to proliferation concerns. It is a huge waste of resources to continue reprocessing even from the point of view of those who believe that plutonium may be a valuable fuel a few decades hence. Such an eventuality has receded farther from the horizon over the past two decades. Should it appear imminent and desirable a few decades from now, there will be time enough to re-consider the question. Current world uranium resources are large; they are not going to run out overnight. Continued commercial reprocessing is an unacceptable economic and proliferation gamble that is, moreover, harming the environment without providing any concomitant benefit except to entrenched plutonium bureaucracies that refuse to see the writing on the wall.

A halt to reprocessing for a prolonged period or a complete termination of commercial reprocessing programs is an issue that is now more closely linked to plutonium disposition than when the military surplus was the main policy issue under consideration. It is necessary to halt commercial reprocessing immediately. That way the stocks of plutonium will not be growing via reprocessing even as precious resources are being expended to reduce surplus military plutonium stocks.

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[61] NAS 1994, p. 3 and House of Lords 1999, pp. 63-66.

In light of this analysis, the actions needed for sound plutonium management and disposition that are consistent with security, environmental and economic criteria can be enunciated as follows:

- All separation of plutonium for military or commercial reasons should be stopped.
- All separated commercial and all surplus military plutonium should be managed according to a consistent policy that is guided by safety, non-proliferation, and environmental protection objectives, and not by (covert or overt) objectives of promoting a plutonium fuel economy.
- All separated commercial plutonium should be put under IAEA safeguards and all surplus military plutonium under bilateral or multilateral safeguards with a transfer to IAEA safeguards at the earliest possible time.
- Separated plutonium should be put into forms that would make it difficult to steal the plutonium.
- The immobilization matrix for plutonium should be such that it would be difficult for countries that do not now possess significant nuclear capability to re-separate the plutonium. This would also prevent terrorist groups from re-separating it, should they gain possession of the immobilized plutonium.
- The plutonium immobilization matrix should be chosen so that it would be highly durable under a variety of repository disposal conditions.

Three technical issues associated with non-fuel disposition of plutonium impact considerably on how the above general ideas would be put into practice:

- the isotopic composition of the plutonium before and after disposition
- the problem of the "spent fuel standard"
- the choice of the matrix in which the plutonium should be immobilized so that non-proliferation goals are met in a manner that is compatible with repository disposal criteria.

Isotopic composition of plutonium

The only technical advantage of a MOX fuel route for disposition, assuming that reprocessing is halted, is that the isotopic composition of weapon-grade plutonium can be changed to reactor-grade plutonium. But since reactor grade plutonium can also be used to make weapons, if separated, this is not a large advantage in non-proliferation terms. Because immobilization cannot achieve isotopic degradation of weapons grade plutonium, it became an issue in US-Russian negotiations as a point in favor of MOX fuel as the disposition route. However, the problem of the potential re-extraction of plutonium from its immobilized form and its possible re-use by the United States or Russia for weapons purposes can be resolved by simply putting the immobilized plutonium under IAEA safeguards. That would provide a multilateral guarantee that surplus weapons plutonium would never again be re-extracted and used to make nuclear weapons.

Spent fuel standard

In 1994, the US national Academy of Sciences defined the “spent fuel standard” as the desirable goal for plutonium disposition. By this measure, the barriers to theft and reuse of the plutonium would be comparable to that facing the use of plutonium present in nuclear power reactor spent fuel. For practical purposes, light water reactor spent fuel has been the specific reference material.

The spent fuel standard provides measures for:

- the radiation field that should be achieved as a barrier to theft of the spent fuel
- the difficulty of re-extraction of the plutonium should any party decide to do so.
- the isotopic composition of the spent fuel in relation to the weapon-grade or weapon-usable material
- the time for which the non-proliferation barriers would be effective.

It is important to remember that the appeal to the spent fuel standard to provide the yardsticks for assessing plutonium disposition standards is based on a negative argument. Since most of the plutonium in the world is contained in light water reactor spent fuel, methods of plutonium disposition that would provide non-proliferation barriers greater than such spent fuel are not justifiable. Thus, the spent fuel standard represents a practical ceiling for plutonium disposition efforts.

Whether the spent fuel standard should also constitute a practical floor for evaluating plutonium disposition has not been subjected to comparable scrutiny. A number of factors lead to the conclusion that the actual achievement of the spent fuel standard should be a secondary consideration in the current US-Russian program. For instance, the spent fuel standard does not give adequate weight to the fact that nuclear weapons states, notably the United States and Russia, would be highly unlikely to re-use disposition weapon-grade plutonium in weapons. This is because they have huge available surpluses of separated weapon-grade plutonium due to reductions in nuclear weapons stockpiles that will endure for the foreseeable for the future.

Moreover, a principal practical problem that has emerged with the spent fuel standard should be explicitly recognized. The fact that immobilization does not change the isotopic composition of the plutonium has been one of the Russian arguments against immobilization. This has been used to promote the use of plutonium as a reactor fuel in the name of disposition that would meet the spent fuel standard. Had there been no plan to use MOX fuel in breeder reactors and to reprocess MOX spent fuel, this argument would at least have had the merit of consistency. But the US-Russian plutonium agreement allows Russia to reprocess MOX spent fuel after a time as short as ten to fifteen years, re-creating the problem of rising separated plutonium stocks. Further, the agreement also meets the Russian goal of allowing the use of plutonium in breeder reactors.

While breeder reactors may be operated in a mode so as to degrade the isotopic composition of the plutonium, they can also be operated so as to improve it. Since there are no long-term restraints on how these reactors would be operated, Russia could, in the long-term, increase its stocks of weapon-grade plutonium under its civilian nuclear power program. This can be accomplished by putting uranium-238 in the “blanket” surrounding the breeder reactor core. The high purity plutonium-239 that can be created in the blanket can then be mixed with reactor-grade plutonium. With sufficient high-purity (“super-grade”) plutonium, a large amount of reactor grade plutonium can be converted into weapon-grade plutonium.

The practical goal of long-term conversion of weapon-grade plutonium into an immobilized form containing reactor grade plutonium will therefore not be met by the US-Russian plutonium disposition agreement. Unfortunately, the scope of the most recent study of the spent fuel standard by a special panel of the National Academy of Sciences did not include the use of MOX in breeder reactors, even though that is Minatom’s preferred option for the Russian use of MOX made from weapon-grade plutonium. The scope of the study was defined by the Office of Fissile Materials Disposition of the Department of Energy.[62]

A more urgent and realistic goal would be to put plutonium into non-weapons-usable forms for a long period of time in order to:

- prevent the emergence of black markets in plutonium – that is prevent theft or illicit sales of plutonium, and
- prevent the re-extraction and reuse of plutonium, should it be stolen or illicitly sold.

One problem that has emerged is the potential lack of sufficient cesium-137 to provide a large enough radiation barrier to theft if the plutonium is vitrified with high-level waste. In Europe, the potential insufficiency of cesium-137 arises from that fact that much of the high-level waste generated from reprocessing has already been vitrified. In the United States, the failure of the In-Tank-Precipitation process at the Savannah River Site has created an even more acute question in this regard. This process was designed to separate cesium-137 from a large volume of salt crystals and liquid high-level waste. The cesium would have been added to the vitrification process and provided the radiation barrier that would be a central element of the achievement of the spent fuel standard in the immobilization disposition program.

Two broad approaches to address this question have been suggested. One approach, put forward in Germany, is to make non-fuel quality MOX pellets, put them into fuel rods, and then put the fuel rods into canisters together with spent fuel.[63] The whole assembly would then have a high radiation barrier to theft. However, the MOX itself would not provide a significant barrier to re-separation of plutonium from the depleted uranium, were the MOX fuel rods to be removed from the spent fuel canister. Another disadvantage of this approach is that it would keep the MOX plants operating for a

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[62] NAS 2000, p. 2 and Appendix A.

[63] Kueppers et al. 1999.

considerable period of time. It would thereby leave open the possibility of the manufacture of MOX fuel for reactors as well as impure MOX pellets designed for disposition without use as fuel.

From a non-proliferation standpoint, it would be preferable to have an approach that eliminated the manufacture of MOX altogether. This can be done with the ceramic immobilization approach in the United States for part of the surplus weapons plutonium. Since the basic process of pressing and sintering is the same as for MOX, but the size and composition of the immobilized product is different, it may be possible to modify existing MOX plants, especially the Sellafield MOX plant, which has not yet been commissioned, to accomplish this.

It may also be useful to examine another approach to creating a radiation barrier to theft. Immobilized ceramic pucks can be placed in glass logs without fission products. (Thorium-232 may be added to the ceramic. This would make re-separation of the plutonium more difficult because thorium is chemically analogous to plutonium.) The vitrified canisters can then be placed inside another specially manufactured canister that contains a small amount of cesium-137. This container would therefore have high gamma radiation, but the bulk of materials inside the container would not have significant gamma-emitting materials. The elimination of self-absorption of gamma radiation in the glass log allows a reduction of cesium-137 requirements by about an order of magnitude. According to calculations done at the Savannah River Site, 135 grams of cesium-137 (12,000 curies) could provide a radiation barrier of about 5,000 rad per hour.[64] Exposure to such an intense radiation field would result in a lethal radiation dose in about five minutes. Separated cesium-137 is available at the Hanford Site in Washington State.

Our view is that achieving the spent fuel standard in all respects is not as crucial as creating sufficient barriers to theft and re-extraction by non-nuclear weapons states and non-state groups. Early completion of disposition should be a high priority, since timeliness is at least as important as any other single factor in the achievement of non-proliferation goals.

The choice of options will depend on the specific country, decisions regarding the use of existing facilities, availability of storage, the situation regarding the creation of the radiation barrier, and the specific combinations and amounts of commercial and military plutonium that are to be put into non-weapons-usable form. For instance, the options in France and Britain will be affected by their relationships to the US and Russian plutonium disposition programs. This is because BNFL and Cogéma are involved in US surplus plutonium disposition issues directly (in the case of Cogéma) or indirectly, in the case of BNFL, which is the site contractor (via its Westinghouse subsidiary) for the DOE-owned Savannah River Site in South Carolina.

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[64] John Plodinec, personal telephone communication to Noah Sachs, November 28, 1994. See Makhijani and Makhijani 1995.

Immobilization matrix

The current US immobilization plan involves the fabrication of a titanate ceramic into which a small percentage of plutonium as been mixed. The resultant ceramics pucks would be placed in a steel frame and then surrounded by vitrified high-level waste (see below). While the method would accomplish the non-proliferation oriented disposition goals that we have discussed above, there is some question whether it could meet long-term environmental goals. Specifically, glass may disintegrate rather rapidly under the conditions that may prevail in Yucca Mountain, the only repository site now being investigated in the United States.[65]

Secondly, a titanate ceramic waste form appears to be vastly inferior to zirconium-based compounds (either oxides or other compounds). Damage to the structure of the waste matrix is created by the alpha particles emitted by plutonium in the process of radioactive decay. Such damage appears to be far more rapid and complete with titanate than with some zirconium-based matrices. Preliminary findings from recent research, sponsored by the DOE's own Office of Basic Energy Sciences, and done at the University of Michigan and the DOE's Pacific Northwest and Los Alamos National Laboratories shows that zirconium-based compounds may be highly resistant to radiation damage. The results indicate that the present titanate-based ceramic would be "completely damaged by the radiation in less than 1,000 years …[while they] will not sustain damage for periods up to 30 million years." The international research team "included scientists at the Australian Nuclear Science and Technology Organization and the Indira Gandhi Centre for Atomic Research in India."[66] Moreover, earlier work at the University of New Mexico, indicates that zircons, which are stable natural compounds, may provide the route by which to develop waste forms that could contain long-lived radioactive materials far better than presently proposed matrices.

US-Russian plutonium disposition options

The main reason that the United States is pursuing a MOX program, so far as stated policy goes, is Minatom's insistence that plutonium is a long-term energy resource that cannot and should not be discarded today as a waste. This Russian objection to immobilization is somewhat spurious since neither the MOX nor the immobilization option require either side to actually construct a repository or to dispose of MOX spent fuel or immobilized plutonium in it. The main interest in Russia seems to be the financial assistance that would be associated with a light water reactor MOX program (which is not a preferred Minatom program) and the creation of an infrastructure for breeder reactor MOX fuel production.

Of these factors, the financial is probably the strongest, since Russia does not have the money to build an economy that would be even partly run on breeder reactors. It has only one large breeder reactor in operation today. We believe that a far better negotiating

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[65] Makhijani 1991.

[66] August 9, 2000, University of Michigan, College of Engineering press release. Contact Janet C. Harvey-Clark, janethc@engin.umich.ed

approach would be to immobilize Russian plutonium without requiring its disposal. The US should follow a similar program. The main elements of a Russian-US agreement, possibly with partial financing from western Europe and Japan, could be as follows:

1. The same disposition plan in terms of technical details would be carried in parallel in the United States and Russia.

2. It would include all separated commercial and surplus military plutonium.

3. Plutonium would be immobilized. There is some flexibility as regards the specific immobilization method (see below).

4. All commercial plutonium and surplus military plutonium would be stored under bilateral safeguards as soon a possible and transferred to IAEA safeguards at the earliest possible date. All immobilized plutonium would be put under IAEA safeguards as soon as it is immobilized.

5. The West would lease Russia's plutonium for 50 years or would purchase it outright. Since plutonium has no commercial value as a fuel for the foreseeable future, some method needs to be devised to determine the compensation to be paid to Russia to achieve the global non-proliferation benefit. Since Russia regards plutonium as a potentially valuable fuel, the upper limit to the purchase price would be the value of the LEU equivalent of the MOX that could be made out of the plutonium disregarding all fuel fabrication costs or any other additional costs associated with the use of MOX. In other words the maximum amount Russia would be paid would correspond to the LEU fuel value as if the plutonium had already been made into MOX. At the present time, the maximum value for 80 metric tons of surplus Russian plutonium (50 metric tons of which would be military plutonium and the rest commercial plutonium) calculated in this way would be roughly two billion dollars.

6. The payments to Russia could be stretched out over a time period comparable to the purchase of 500 metric tons of highly enriched uranium from Russia by the United States -- that is, about 20 years. Alternatively, payments could be made over the time that it takes to immobilize it and put it under IAEA safeguards. If Russia agrees to put all commercial separated plutonium and all surplus military plutonium under IAEA safeguards prior to immobilization, the United States would do the same and Russia would receive the entire payment at the time that the plutonium is put under IAEA safeguards.

7. The West would also pay for the immobilization. The funding, both for the plutonium purchase and for immobilization, could come from some combination of the following: (1) the G-7, the group of the wealthiest countries, (2) European Union, (3) a small tax on natural gas imported from Russia into Europe. (4) United States, (5) NATO.

The United States has chosen the "can-in-canister" approach as its preferred immobilization strategy. This involves the mixing of plutonium dioxide with depleted uranium dioxide and non-radioactive ceramic titanates, and then pressing the mixtures into hockey-puck-sized elements that are stacked in a stainless steel container – see Figure 1. Apart from the question of the type of matrix used to contain the plutonium, there is the issue of how to provide a strong external radiation field that would be the main barrier to diversion of the immobilized plutonium, and one of the main barriers to its re-extraction.

Under the present DOE plan, a number of these containers would be positioned in a bird-cage arrangement inside the large canisters in which high-level waste is now being vitrified at the Savannah River Site in South Carolina. The plutonium is thus immobilized in a ceramic matrix located in vitrified high-level waste. As we have discussed above, a principal technical hitch in this scheme is that only high-level waste sludge is currently being vitrified, and this fraction of the waste does not contain enough cesium-137 to provide a sufficient radiation barrier.

The options are to:

1. create an external radiation barrier by applying cesium-137 externally to the canister and then placing the assembly in another canister. A sub-option under this would be to adopt a can-in-canister vitrification process with thorium-232 instead of high-level waste (see below);[67]
2. mix already separated cesium-137 from Hanford in the vitrification process at Savannah River site (which would require transportation of cesium-137 capsules from Hanford to Savannah River Site);
3. immobilize plutonium into the ceramic puck forms, store it on site and put it under stringent IAEA safeguards, until the issue of how the radiation barrier is to be created are resolved (the Department of Energy is currently investigating alternatives to the failed In-Tank Precipitation Process)
4. adopt a can-in-canister vitrification strategy, in which plutonium is vitrified in small cans that are placed in larger canisters to which molten glass is then poured (see below).

The Russian approach could parallel that adopted in the United States. Early storage of immobilized plutonium under IAEA safeguards (option 3 above) is highly desirable in Russia. Since Russian high-level wastes at the Mayak facility in the southern Urals are in acidic form, it is possible for Russia to immobilize its plutonium via high-level waste vitrification or by creating an external radiation barrier as described in option 1 above. In the latter case, a calcining facility as well as other special facilities would have to be built. A high-level waste vitrification plant has operated at Mayak. A new plant has been built but has not been completed. Russia's commercial separated plutonium is stored at Mayak, while its main military plutonium store appears to be at Tomsk-7.

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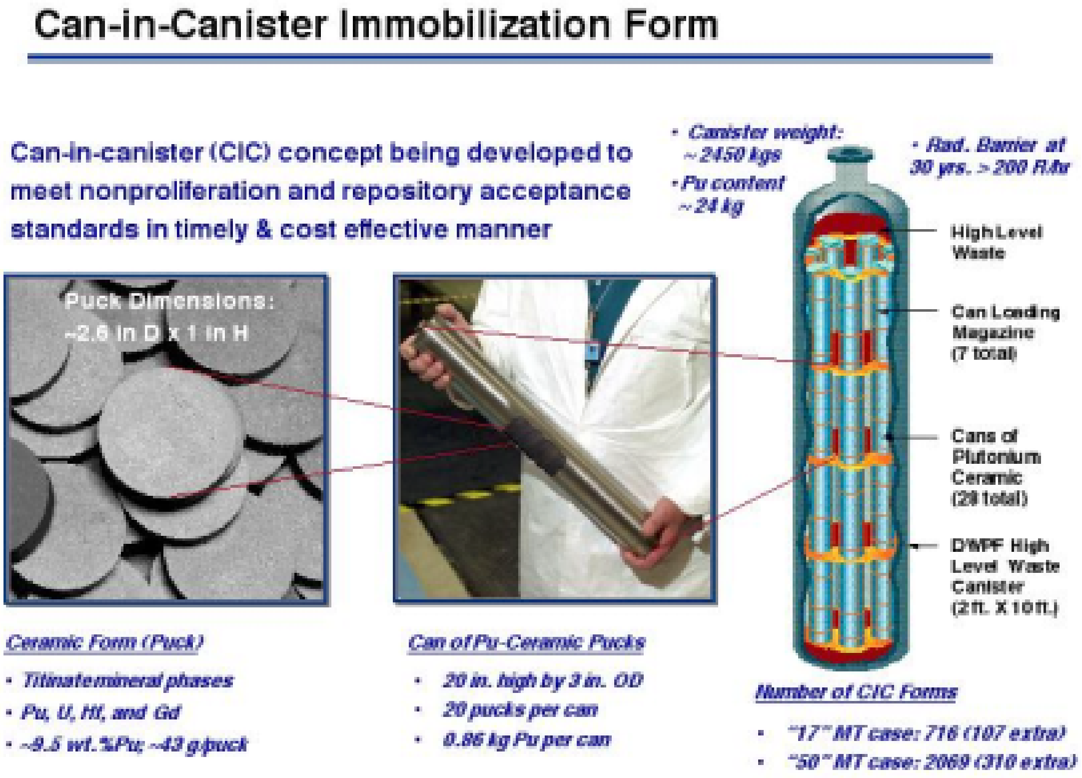
[67] See Makhijani and Makhijani 1995 for details.

Figure 1: Immobilization of Plutonium Using the Can-in-Canister Approach



Can-in-Canister Immobilization Form

Can-in-canister (CIC) concept being developed to meet nonproliferation and repository acceptance standards in timely & cost effective manner

- *Canister weight: ~2450 kgs*
- *Pu content ~24 kg*
- *Rad. Barrier at 30 yrs. > 200 R/hr*

Ceramic Form (Puck)

- *Titinate mineral phases*
- *Pu, U, Hf, and Gd*
- *~9.5 wt.%Pu; ~43 g/puck*

Can of Pu-Ceramic Pucks

- *20 in. high by 3 in. OD*
- *20 pucks per can*
- *0.86 kg Pu per can*

Number of CIC Forms

- *"17" MT case: 716 (107 extra)*
- *"50" MT case: 2069 (310 extra)*

Source: Courtesy of T.H. Gould, Lawrence Livermore National Laboratory, Livermore, California

Making impure MOX that could be put into fuel pins for storage with LEU spent fuel is not an option for the United States or Russia since neither country has a MOX fuel fabrication facility. The option of adding thorium-232 to either the ceramic pucks or to the glass logs needs to be carefully evaluated. Thorium-232 has a decay chain consisting of short-lived decay products that build up to equilibrium in a couple of decades. Thallium-208, one of these decay products, is a very strong gamma emitter. Hence, immobilization with thorium-232 would also provide a durable radiation barrier, though due to technical limitations on thorium loading, it would not physically prevent theft as would be the case with a gamma radiation barrier created by cesium-137. Moreover, thorium is a close chemical analog of plutonium. Hence the addition of thorium would make re-extraction of plutonium from the ceramic pucks far more difficult for non-state groups and for most non-weapons states.

The main disadvantage of adding thorium-232 to the immobilization process is that thorium-processing facilities would have to be built in order to remove the decay products before preparing the ceramic powder mix. Such removal is necessary for worker protection, since the ceramic mix would be prepared in a glove box environment, rather than a heavily shielded, robotically operated facility.

One way around this problem would be to add thorium into the molten-glass and high-level waste mix. Since high-level waste vitrification is carried out entirely remotely, it would not be necessary to mix the plutonium with the thorium in the process of making plutonium-containing ceramic pucks.[68] Yet, the mixing thorium in the glass would add to the complexity of plutonium re-extraction. This strategy may allow for plutonium immobilization in glove box facilities, allowing it to be completed in a relatively short-time. At the same time, shielded facilities could be used for the addition or thorium, making it unnecessary to process thorium solely for the purpose of separating it from its decay products.

The United States and Russia should step up their own as well as joint immobilization efforts to ensure that commercial and surplus military plutonium is immobilized as rapidly as is compatible with health and safety, so that it can be put under IAEA safeguards at an early date. In the meantime, both expeditious completion of the storage facility now being built in Russia as well as arrangements for thorough bilateral safeguards of surplus plutonium in both countries is highly desirable. Finally, it is imperative that both countries stop the operation of their reprocessing plants, so as to prevent an increase in separated plutonium stocks even as they are spending resources to immobilize plutonium.

Britain

The British situation differs from the one in the United States in that Britain has a large scale MOX fuel fabrication facility, the Sellafield MOX Plant (SMP), that could be used

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[68] High-level waste contains gamma-emitting radionuclides and must be processed remotely. Plutonium is mainly an alpha-radiation emitter. Since alpha radiation is not penetrating – a piece of paper can stop it – plutonium processing generally requires only glove box use for worker protection purposes.

for the purpose of disposition. As we have noted, it has been proposed that the SMP facility be used to make impure MOX that could be put in fuel pins. These pins could then be stored with LEU spent fuel, which would provide the radiation barrier. This option has the disadvantage that it would entail the opening of SMP, and enable the production of MOX for use as a fuel, with its attendant adverse non-proliferation consequences.

Another possibility is to investigate the conversion of the SMP to fabrication of hockey-puck size plutonium ceramics like those that are to be produced in the United States. This would entail modifications in the sintering furnace and changes in the presses that are used to compress the oxide powders into pellets. However, such a conversion may enable the use of the structure, glove boxes, powder preparation and mixing equipment and much of the other infrastructure associated with the SMP, without allowing for its use for MOX fuel production. This would have the additional advantage of being compatible with US disposition, so that the two programs could reinforce each other in terms of technical experience, safety, cost, etc. However, a detailed study is needed to establish its technical feasibility. A technical study on plutonium immobilization has been started in Britain. [69]

It may also be possible to combine the option of storing immobilized plutonium with LEU spent fuel with the option of immobilizing it in sizes that are different from those of spent fuel rods. Assemblies of such off-size immobilized plutonium rods could then be stored interspersed with spent fuel assemblies. One advantage of such an approach would be that if existing MOX plants are converted to immobilization, it would be far more difficult technically, politically, and financially, to re-convert them to MOX manufacture. The level of protection against re-extraction would be somewhat lower because the immobilized plutonium assemblies would be more readily distinguishable from the spent fuel assemblies. However, this lowering of the re-extraction barrier would be marginal relative to the high barrier provided by the external gamma radiation emanating from the spent fuel.

Further, as discussed above, the barrier to re-extraction from the ceramic pucks could be increased by the addition of thorium-232 during the immobilization process. In this case, thorium processing facilities would have to be built or existing facilities converted to thorium processing. The overall non-proliferation merit of schemes that avoid the use of MOX facilities *as such* is far greater than that of the fabrication of impure MOX for storage with spent fuel. Plutonium immobilization in forms other than MOX-fuel-type forms would provide further incentive to ending MOX fuel use and to ending commercial reprocessing. Specifically it would decrease the incentive for keeping the THORP and the UP2 and UP3 reprocessing plants.

France

France separates far more commercial plutonium than all other countries combined. It also has the largest MOX fuel fabrication facilities and is the world's principal supplier of

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[69] David Lowry, personal e-mail to Arjun Makhijani, 8 August 2000.

MOX both inside and outside France. However, even the French government now acknowledges that reprocessing MOX fuel use even in a limited number of reactors has raised and will continue to raise the price of electricity compared to the option of LEU fuel only (see Chapter 3).

The financial incentive to shut down reprocessing and MOX fuel production has heretofore been diminished by large foreign reprocessing and MOX fuel fabrication contracts. Further, BNFL's troubles arising from the MOX data fabrication scandal may provide greater business opportunities to Cogéma to make MOX fuel for BNFL's Japanese customers.

The U.S.-Russian MOX fuel agreement also promises to further entrench Cogéma in its course of reprocessing and MOX fuel use, and provides it with additional leverage in the internal economic and political discourse in France. This is because these foreign relationships are a source of export revenues.

However, with the planned phase out of nuclear power in Germany and the high-level of resistance to MOX fuel use in Japan after the BNFL scandal and the Tokaimura criticality accident, France's foreign plutonium business is in some jeopardy, notably in the long-term. France again seems to be at a watershed with respect to plutonium fuel use. Will it continue to spend billions of dollars chasing a plutonium mirage, or will it end reprocessing?

How the La Hague facility would shut down its reprocessing plants and transition into plutonium management and immobilization is more complex than just the problems of technical conversion. French nuclear waste law prohibits the storage of foreign spent fuel in France, but allows its import for reprocessing. The vitrified high-level wastes, as well as intermediate level wastes, are to be sent back. German nuclear power plants do not have enough storage space for spent fuel, complicating the problem of a practical phase out strategy for nuclear power plants, as well as a termination of reprocessing contracts. The present general approach is to build on-site storage, as well as storage for returned vitrified glass logs from France. Further compounding difficulties is the fact that most high-level waste in France has already been vitrified. This presents issues similar to those in the United States and Britain arising from a shortage of gamma-emitting fission products to provide a radiation barrier. Finally, the conversion of existing MOX facilities in France to immobilization will pose greater problems (if it can be done at all) since they have already been commissioned for plutonium fuel fabrication.

Broadly speaking the options for immobilizing plutonium are similar in France, but it is likely that new immobilization facilities will have to be built (as is also the case with the United States and Russia). On the positive side France has far more experience with operation of large scale MOX fuel fabrication that could enable it to design and operate plutonium immobilization facilities more rapidly that other countries.

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