ELSEVIER

Journal of Hazardous Materials 44 (1995) 1–23

JOURNAL OF HAZARDOUS MATERIALS

Report

How much plutonium do we need: A case study – Japan

Kenneth Alvin Solomon*

Institute of Risk and Safety Analyses, Woodland Hills, CA 91364, USA

Received 1 June 1994; accepted 1 April 1995

Abstract

This report is one of several produced within RAND's project on Avoiding Nuclear War, sponsored by the Carnegie Corporation of New York. The Carnegie Corporation made the original grant in 1985, when the issue of avoiding nuclear war, and the Cold War, was still very much alive. The grant initially supported a wide range of papers, Ph.D. dissertations, conferences, and "crisis games", but when the Warsaw Pact crumbled in 1990 and the Soviet Union itself collapsed in 1991, it was decided to use the remaining funds to explore the new issues facing the world without a Cold War but still with nuclear weapons.

The present study investigates some of the technical, economic, and political issues that would surround a Japanese decision to convert to plutonium fuel in its nuclear power industry. It should interest senior policymakers involved in controlling nuclear proliferation.

The other reports in the series cover other aspects of controlling nuclear proliferation and potential use of nuclear weapons.

Keywords: Plutonium; Japan; Hazardous waste; Nonproliferation; Nuclear weapons

1. Introduction

1.1. Background

Throughout its industrial history, Japan has been preoccupied with the problem of competing in the world economy while having few indigenous natural resources. Its position in the international economy has been characterized as that of a "fragile blossom" [1] that can survive only if supply security is accepted as a basic principle of industrial policy.

Adequate supplies of electricity have allowed Japan to make impressive economic advances in the 20th century. Japan has attempted to assure its supply first through

* Tel.: (818) 348-1133.

0304-3894/95/$09.50
SSDI 0304-3894(95)00046-1

exploiting hydroelectric and coal resources, and later through developing independent nuclear power technologies. By the beginning of 1992, Japan had roughly 31 gigawatts net of its electricity (GWe) delivered by nuclear power. This accounted for nearly 30% of Japan's total demand for electricity and about 10% of the world demand for nuclear power. A further 14.5 GWe of nuclear power is under construction in Japan (see Fig. A.1 [2]) so by the year 2000 about 40% of Japan's electricity is expected to come from nuclear power. As in all nuclear power programs worldwide, Japan's present use of thermal reactors is a transitional step toward the use of breeder reactors.

Almost all worldwide nuclear reactors producing energy for civilian use are thermal (i.e., nonbreeding) reactors. Thermal reactors – also called present generation reactors in this report – are fueled primarily with low enriched uranium (LEU). LEU typically contains about 3 to 4% of the fissile isotope U-235 and 96–97% of the fertile isotope U-238. Fissile content of a few percent (U-235) is definitely unsuitable for weapons production. The fertile isotope U-238, when bombarded with neutrons in a reactor, produces fissile isotopes of plutonium (Pu-239 and Pu-241). So, although a thermal reactor does not initially contain fissile plutonium when it is first fueled, it produces fissile plutonium in its spent fuel. This fissile plutonium could be separated out of the spent fuel at some cost. Separated fissile plutonium could be used to fuel other thermal reactors, future generation breeder reactors, or nuclear weapons. Although thermal reactors can be fueled with either plutonium or uranium, breeders depend upon plutonium as a fuel. Breeders, as their name implies, produce more plutonium than they consume.

Thermal reactors are considered a transitional step to breeder reactors because for breeders to survive economically, the excess plutonium they produce needs to be recycled in thermal reactors, since the breeder could not use all of the plutonium fuel it generates. Typically, it is assumed that one breeder could support two to three thermal reactors.

Only small quantities of fuel are needed to run a nuclear power plant, compared to fuel requirements for hydroelectric and coal-fired power plants. For example, one pound of uranium ore (also known as yellow cake) contains about 20 to 25 times the heat content of lignite, sub-bituminous, bituminous, or anthracite coals. One pound of uranium fuel (also known as low enriched uranium) used in a light water reactor contains nearly 1000 times the heat capacity of a pound of coal. Thus, nuclear power plants become attractive because a country where land is scarce (such as Japan) could easily store the fuel needed to power them for many years. Hence, nuclear power could assure Japan a significant level of energy, provided it could also be assured an adequate supply of uranium fuel.

Over 100 uranium deposits have been identified in Japan by the Geological Survey of Japan, the principal ones being at Tono and Nongyo; the deposits are not large and are widely variable in composition and host rock formations [3]. Japan has only 10 000 MTU (metric ton of uranium) domestically and 230 000 MTU will be required by the year 2000 to supply its nuclear power industry; the rest of its yellow cake must be imported.

As of April 1991 [4] Japan is committed to yellow cake purchases of 63 400 MTU between 1988 and 2000, from Nambia (24%), Central Africa (19%), South Africa (4%), Canada (31%), Australia (20%), and the US (2%).

Reactors need not be fueled solely with uranium. The supply of uranium fuel could be extended if it were mixed with plutonium, which is generated along with energy in a nuclear reactor. Present generation reactors can be fueled either exclusively with uranium or with a mixture of uranium and plutonium, called MOX. Thermal reactors, whether fueled with uranium or with MOX, convert their fuel to both energy and plutonium. If Japan were to obtain plutonium by recycling its spent fuel or from dismantled nuclear weapons, it could mix it with uranium and extend its supply of reactor fuel.

Supplies of plutonium might also foster the next generation of reactors. Breeder reactors are typically fueled only with plutonium, and, as they operate, they produce energy and also more fissile plutonium. Breeder reactors, unlike thermal reactors, produce or *breed* more plutonium than they consume.

However, introducing plutonium as a fuel for present generation nuclear reactors may increase the risk of nuclear weapons proliferation. Plutonium, like uranium, has two uses: It can fuel reactors or nuclear weapons. Plutonium differs from uranium, however, in that when it is used to fuel a reactor, its fissile[1] content is very high – high enough to serve as fuel in a nuclear weapon. Uranium must be highly enriched (greater than 90% fissile or U-235 content) before it can be used in a weapon. Reactor-grade uranium is typically low enriched (less than 3 to 4% U-235 or fissile content). Therefore, reactor-grade uranium is strictly unsuitable for weapons.

Plutonium does not occur naturally and is available only when recycled from spent reactor fuel. The spent fuel may be either a by-product of energy production in a civilian reactor or a by-product of plutonium production in a military reactor. Leaving plutonium unseparated in spent fuel makes it much harder to use in a weapon because it requires reprocessing. Even though the plutonium generated in a civilian reactor is of lower fissile content than that generated specifically for weapons production in a military reactor, both types are suitable for either weapons production or reactor fuel. However, weapons-grade plutonium is somewhat more concentrated in its fissile content. The Japanese are not interested only in plutonium generated in Japanese nuclear reactors and contained in Japanese spent fuel.[2] As thousands of former Soviet and American nuclear weapons are being dismantled, the supply of raw plutonium is increasing substantially and the Japanese are interested in the more than 100 metric tons (tonnes) of plutonium that will be available from these weapons.

1.2. Objective of this report

This report attempts to place in perspective Japan's perceived need for energy security. Although we do not arrive at a solution to Japan's energy security needs, we

[1] Material is considered fissile if it spontaneously generates neutrons that can be used to fission (or split) radioactive isotopes to release large quantities of energy.

[2] Japan is not the only country interested in extending nuclear fuel materials by obtaining plutonium. Taiwan and South Korea, for example, have expressed the same interest.

do offer some thoughts and policy directions upon which a future study might focus more intensely. We begin to address three broad issues in this report:
- What are the technical and economic considerations surrounding a conversion of Japan's nuclear industry to plutonium?
- What benefits might accrue from such a step, and what costs would Japan incur?
- What might be a reasonable alternative?

1.3. How this report is organized

In the next section, we consider the technical and economic arguments in favor of and against using a mix of plutonium and uranium. Then, we discuss the resource assurance arguments. In Section 4, we offer some preliminary thoughts on the concept of an international fuel bank as a way to assure nuclear fuel supplies while reducing the risks of weapons proliferation.

An appendix presents some detailed figures.

2. The technical and economic arguments for using plutonium to assure energy for Japan

Japan has two ready sources of plutonium: reprocessed spent fuel from its own reactors and from dismantled nuclear weapons. Either source could provide substantial amounts of reactor fuel. Some view the transition to plutonium as an essential step in the transition to the next generation of reactors. The economic issue devolves primarily to one of cost.

2.1. Plutonium from spent fuel

Japan can convert its reactors to plutonium fuel by reprocessing the spent fuel from its own reactors. During the 1970s, Japan's first reprocessing plant was constructed at Tokai with technology supplied by France. This plant has had a troubled history. The United States initially obstructed its operation when the Carter Administration, in 1977, launched an international campaign to halt reprocessing of civilian spent fuel. US concern, aroused by India's 1974 detonation of a nuclear weapon that used plutonium from civilian reactors, was that a worldwide expansion of reprocessing would increase the risks of nuclear proliferation. The Carter policy's main effect was to strengthen Japan's desire to achieve fuel cycle independence. Japan saw its energy assurance as hostage to decisions made in the United States [5].

From 1977 to 1979, Japan took no major, public actions to establish a new reprocessing plant. In 1979, Japan amended the law regulating nuclear reactors and materials to allow private industry to operate reprocessing plants. After the Reagan Administration's 1981 reversal of the 1977 Carter policy banning the construction of new reprocessing facilities, Japan set plans in motion to build a facility capable of reprocessing 800 tonnes of spent fuel per year. Japan intends to start operating this plant (located at Rokkasho-Mura in northern Honshu) in 1997.

By the 1970s, the Japanese utilities were facing spent fuel storage limitations at reactor sites and a long wait before substantial reprocessing capacity could be available in Japan. Contracts were signed which committed Japan to sending to Europe close to 80% of its spent fuel produced in power reactors before 1990 [4].

Since then, spent fuel from Japan's commercial nuclear power stations (See Fig. A.2 for a summary of spent fuel generated by Japan. The information in this figure was extracted from Tsuboya et al. [5, 6]. (the first of which was one of only two British Magnox reactors to be exported) has been sent to Sellafield, England, and Cap La Hague, France, for reprocessing into plutonium. The pace is picking up as we approach the mid-1990s and as new plants at Sellafield and Cap La Hague come on line to handle fuel from light water reactors. The reprocessing plant to be run by British Nuclear Fuels will handle 700 tonnes of fuel a year at full capacity; the UP-3 and UP-2800 plants at Cap La Hague, to be run by Cogema, will handle 800 tonnes each. Japanese electric companies will be the largest customers. (The annual generation of spent fuel in Japan is shown in Fig. A.2.) Each tonne of spent fuel contains 9 kg of plutonium, which includes fissile as well as nonfissile isotopes (Fig. A.4 illustrates the concentration of plutonium isotopes with and without spent fuel reprocessing and recycling).

Japan has always intended to bring home both its plutonium and its waste [5]. The original plan was to transport plutonium in specially built containers carried on board Boeing 747s. To do so, however, required permission from the US government because the raw uranium originated in the United States. The United States denied air transport of plutonium but did agree to oceanic transport [5]. On 7 November 1992, Japan began transporting 1.7 tonnes of plutonium (originally from Japanese spent reactor fuel) from France on board the *Akatsuki Maru*, escorted by Japanese naval ships. This shipment was met by a storm of protests from environmental groups and more than a dozen governments insisted that the cargo ship be kept out of their territorial waters.

2.2. Plutonium from dismantled nuclear weapons[3]

At present, Japan has an additional opportunity to fuel its thermal reactors with MOX (a blend of about one-third fissile plutonium with about two-thirds fissile uranium imbedded in about a 97% blend of (U-238)). The opportunity is to utilize the 75 or more tonnes of plutonium extracted from dismantled nuclear weapons in the former Soviet Union as reactor fuel.

The expected amount of uranium and plutonium available from dismantled former Soviet and US warheads has been estimated in J. Styne [4] The estimates are as shown in Table 1.

[3] This question is being addressed by a number of ongoing proposals. Specifically, late in 1992 representatives of Japanese energy interests presented Department of Energy (DoE) officials with a proposal. The broader question (beyond Japanese interest) of what to do with the plutonium is discussed in Berkhout et al. [7].

Table 1

Dismantled warhead Material	Material quantity (Tonnes)
Former Soviet Union	
HEU	400
Pu-239	75
United States	
HEU	300
Pu-239	56

However, this opportunity is not without cost, which could be significant, both financially and in terms of setting the precedent of allowing a nonnuclear weapons state to obtain weapons-grade material.

2.3. *How much plutonium does Japan need?*

Assuming no weapons interest, plutonium has two specific uses: as fuel in a breeder reactor or as a blend with uranium to form MOX to burn in an existing thermal reactor. Thermal reactors can use either MOX or LEU fuel. MOX could be economically desirable only if it were cheaper than conventional, LEU fuel. However, unlike a thermal reactor, a breeder reactor (also known as an advanced reactor) requires plutonium to operate, not low enriched uranium fuel.

Below we will show that MOX fuel, regardless of the source of the plutonium, costs substantially more than fuel for thermal reactors under current and near-term projected prices for uranium ore (or yellow cake). (See Fig. A.6 for a summary of yellow cake prices from 1982 to 1989. During this period, the average price went to less than half its original price and the marginal selling price dropped even more.) Further, if MOX-fueled thermal reactors are not economical, then breeders are most certainly not economical either, since the capital and operating costs of breeders are higher than for thermal reactors. However, one could argue that a breeder need not be "economical" to be brought on line if its purpose is merely to demonstrate technical feasibility and not to generate cheap electric energy and more plutonium fuel. It is beyond the scope of this report to demonstrate the technical feasibility of the breeder.

How much plutonium would Japan need over the next 20 years to operate its planned breeder reactors? How much plutonium would be available from reprocessing Japan's spent fuel and purchasing the plutonium from dismantled nuclear weapons? Japan's advanced reactor program was viewed in the 1970s as a prelude to the adoption of advanced reactors in the 1990s and beyond. However, in all countries building up a nuclear power program, the time scale for bringing advanced reactors on line has lengthened substantially. During the 1990s, Japan will need plutonium for two different types of advanced reactors: the Joyo and Fugen advanced thermal reactors and the Monju prototype fast breeder reactor.

Depending on operational and fueling protocol, the Joyo and Fugen reactors could require an annual load of from 130 to 290 kg [1]. The 280 megawatt electric (MWe)

Monju reactor will likely be commissioned within a year. Its startup will require around 1800 kg of plutonium. Its annual requirement will be about 600 kg of plutonium. Assuming a 1993 startup date, then up to 6 tonnes of plutonium will be needed to fuel Monju through the end of this century. Its requirements together with those of Joyo and Fugen will amount to about 8 tonnes through the end of the century.

Japan is planning both an advanced thermal and a demonstration fast reactor beyond the three just mentioned. Japan has chosen a site at Ohma for its demonstration advanced thermal reactor (fuel fabrication for this reactor is being installed at Tokai). Plans for a demonstration fast reactor are somewhat less developed. The design is not yet agreed upon, so the official startup date of 2003 may be optimistic. Given the history of startup delays in the worldwide nuclear industry as a whole, one might add five years to this startup date to bring it to 2008.

Fig. 1 contrasts the range of cumulative plutonium demands (solid lines) for the Joyo, Monju, and Tokai reactors likely to be operational in Japan during the rest of this decade and in the first decade of the 21st century (These projections are extrapolated from Berkhout et al. [1, 9, 10].) with the anticipated, cumulative plutonium available from Japan's spent reactor fuel, assuming that all of the spent fuel is

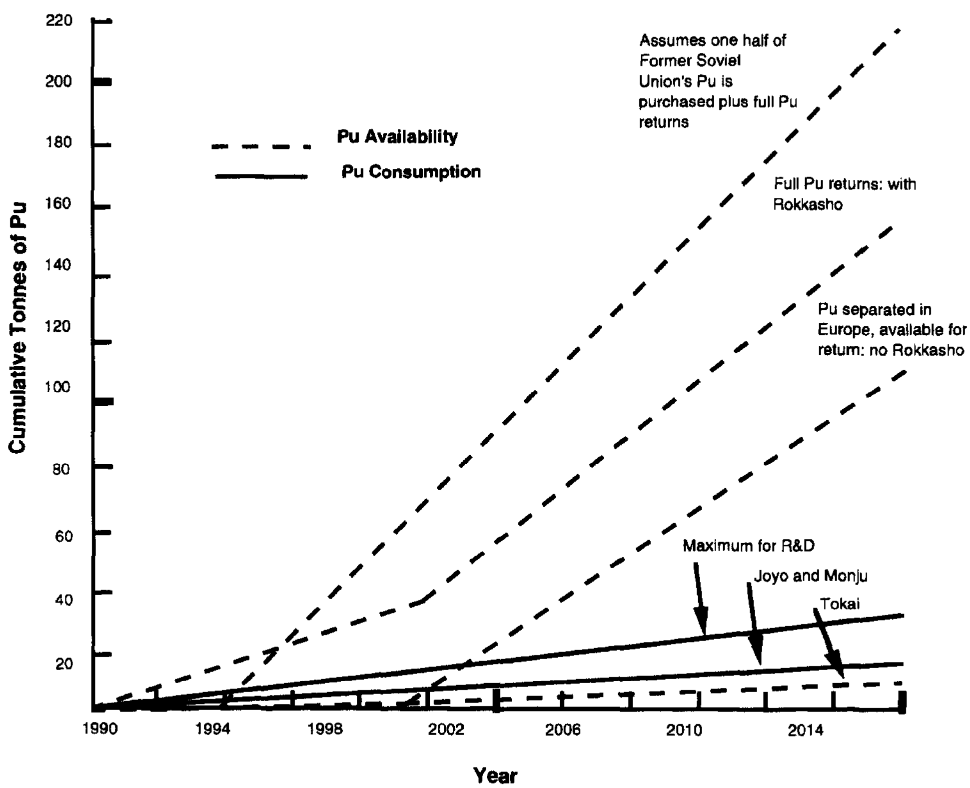

Fig. 1. Availability of Pu far exceeds potential demand.

reprocessed (dashed lines). Fig. 2 demonstrates plutonium availability under three scenarios:

- All Pu separated from Japan's spent fuel in Europe is available for return to Japan, and Japanese Rokkasho reprocessing facility is assumed not operable.
- All Pu separated from Japan's spent fuel in Europe is available for return to Japan, and Rokkasho is operable.
- All Pu separated from Japan's spent fuel in Europe is available for return to Japan, Rokkasho is operable, and half the Pu from dismantled weapons is also available.

Fig. 1 demonstrates clearly that the Pu available from any one of these scenarios far exceeds any demand that Japan may have for its advanced reactors. Fig. 1 argues further that only a small fraction of the Japanese spent fuel needs to be reprocessed to meet the demand for plutonium by Japanese advanced reactors.

Another technical argument supporting the transition to plutonium fuel is that it also supports the transition to the next generation of reactors. Perspectives may differ about *when* a switch to breeders would be possible. According to current RAND and recent studies by others, breeders are not expected to be economical until well into the 21st century. Whether or not the Japanese perceive breeders to become economical earlier, their interest in assuring energy independence is causing them to push for both plutonium recycle into thermal reactors and an earlier breeder program (see [1]).

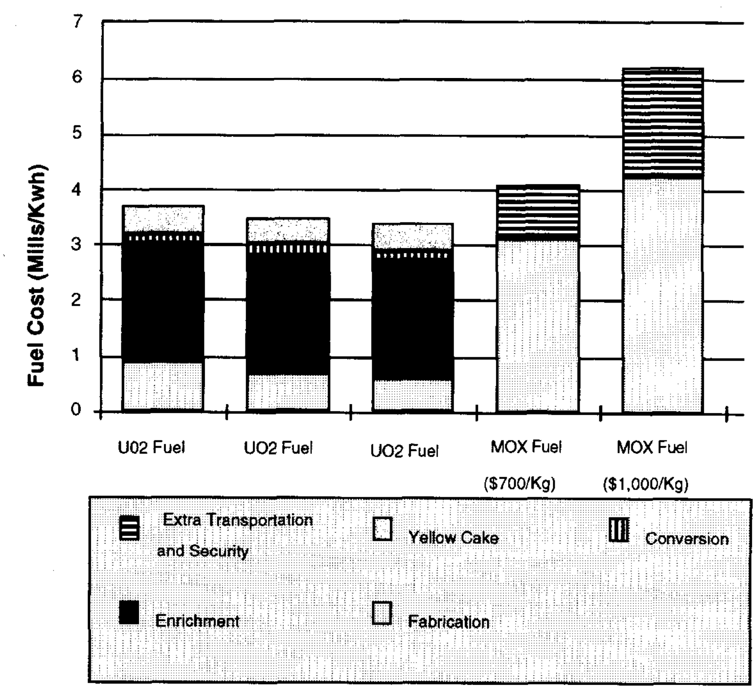

Fig. 2. Uranium is a preferred fuel for PWRs.

The perception of *when* a breeder would be economical is fundamental to the argument: *At what earlier time would spent fuel reprocessing and plutonium recycle from thermal reactors be economical?*[4] The thermal reactors currently in use worldwide are fueled with LEU or natural uranium. They generate plutonium. Only a few countries, including Japan, reprocess their spent fuel to extract the plutonium – the primary fuel for the breeder.[5] The breeder, as its name implies, generates additional quantities of plutonium, which in turn must be reprocessed and recycled as fuel in both breeder and thermal reactors to recover the plutonium's value. In an economy dependent on thermal reactors, no spent fuel reprocessing is required and no plutonium separation is needed. However, a premise of breeders is that spent fuel be reprocessed and plutonium be recycled.

2.4. Economic aspects of using plutonium

The technical argument provides some support for converting fuels. The economic argument is less persuasive. Judging by current yellow cake spot prices of $7.10 per pound, plutonium is not a cost-effective fuel for either thermal or breeder reactors. Fig. 2[6] contrasts the pressurized water reactor (PWR)[7] fuel costs (inclusive of plutonium purification costs and extra plutonium security and transportation costs) for

[4] For a breeder reactor to be self sustaining and economical, it must be able to generate enough plutonium to fuel two to three thermal reactors and itself. This is because the breeder reactor is more expensive to build than a thermal reactor. Thus, the reason for even having breeders is that they are designed to generate more plutonium than they consume. While the breeder also produces energy, it is primarily a fuel-producing reactor. Because thermal reactors can use either LEU fuel or fuel that contains plutonium, thermal reactors (unlike the breeder) need not reprocess their spent fuel and recycle their plutonium. In fact, at present, plutonium-fueled thermal reactors are more expensive to operate than those fueled with LEU. Before it would be cost effective for a thermal reactor to use plutonium generated by a breeder, it must be cost effective for the thermal reactor to use plutonium generated by other thermal reactors.

[5] See Fig. A.2 for a summary of present and expected world reprocessing capacities and activities in the years 1995 and 2000. At present, Japan has no reprocessing capabilities in-country. By 1995 it should be able to reprocess 750 MTU/year, and by 2000 about 1500 MTU/year.

[6] The information contained in this figure has been adapted from Fig. 18 in [10]. The values used are taken in part from Table 14 of this report; average yellow cake cost of $10.00 per pound is assumed. The values are:

	Low	Average	High
Yellow cake ($/ lb)	—	10.00	—
Conversion to UF6 ($/lb)	—	3.00	—
Enrichment ($/SWU)	—	90.00	—
UO_2 fuel fabrication ($/kg)	700	800	1000
Pu purification ($/g)	10	18	28
Pu security/transportation ($/g)	0	1	2

[7] A pressurized water reactor is the most common type of thermal reactor. Other types of thermal reactors include a BWR (boiling water reactor), HTGR (high-temperature gas cooled reactor), and a CANDU (a natural uranium, heavy water reactor).

uranium oxide (UO_2) fuel and MOX fuels. The three values shown for UO_2 fuel reflect differing assumptions with regard to fuel fabrication costs. The two values shown for MOX reflect different MOX fabrication costs ($700 and $1000 kg).[8] We observe, from Fig. 3, that MOX costs between one-half mill to three mills per kilowatt-hour more to use than uranium oxide.[9] This translates to an annual cost increase of between $135 and $800 million. Of course, these numbers are subject to significant uncertainties.

This wide range in the premium paid for using MOX instead of uranium results from two principal uncertainties in our estimates. The first arises from the unknown costs of MOX fabrication. According to the 1989 OCDE publication, "Plutonium Fuel", fabrication costs are expected to vary between $700 and $1000/kg. The second uncertainty comes from the costs of safeguarding, securing, and transporting plutonium. Again, according to the same OCDE publication, safeguard and storage costs for plutonium may be between $1 and $3/g per year, depending both on the quantity stored and other factors.

Separating plutonium and storing it for future use has other costs besides the transportation, security, and storage dollar costs.

Plutonium might make more sense from a cost point of view if uranium were to get more expensive. It does not seem likely that will occur any time soon. Fig. A.6 illustrates that from 1982 to 1989, yellow cake prices fell to half their 1982 value. Yellow cake ores are available from many countries, and it is reasonable to expect that ore prices will not rise significantly or at all over the next several years. Beyond the year 2010 or 2020, the price of yellow cake becomes more difficult to predict.

Finally, a quasi-economic argument could be made that to pursue the plutonium option could reopen the entire question of Japan's stake in a growing nuclear power industry and threaten its political base of support. Hence, it is argued, it is better to proceed despite uncertainties about benefits and technical limitations than to risk undermining the political viability of the Japanese nuclear power industry.

2.5. *Plutonium is hard to justify on either technical or economic grounds*

We have shown that:

- The amount of plutonium available from reprocessing Japanese spent fuel – to say nothing of that available from dismantled weapons – far exceeds the amount needed to fuel Japanese advanced reactors.

---

[8] MOX fabrication costs above $1000/kg may also be realistic. However, we use $750 and $1000/kg for the purpose of our examples..

[9] A one mill per kilowatt-hour difference in cost translates to about $270 million when 31 GW of MOX fueling is used in place of uranium oxide. Japan at present generates 31 GW of energy via nuclear power and by the year 2000 will generate perhaps 40 GW. A one-half to three mill differential would correspond to between $135 million and $800 million per year as the premium paid for replacing uranium oxide fuels with MOX.

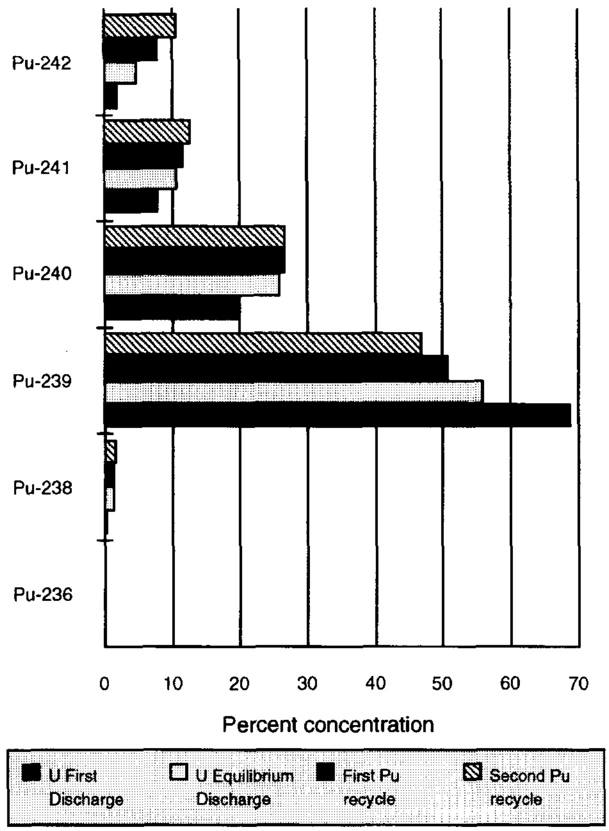

Fig. 3. Reactor-grade plutonium is far more fissile than reactor-grade uranium.

- It is more expensive for the Japanese to fuel their reactors with MOX than LEU.
- Storing plutonium separated from either spent fuel or dismantled nuclear weapons is expensive.

The next section investigates the value of maintaining a plutonium option to provide extended fuel assurance.

3. The energy assurance arguments

At least two arguments relating to energy assurance explain why Japan may wish to keep its plutonium option open. First, even if plutonium costs more, it offers some degree of nuclear fuel assurance to its owner. Second, even if Japan does not hold the plutonium, a plutonium economy does provide the world nuclear market with more potential fuel supplies so that Japan would spread its fuel dependency among a larger number of countries. But converting to a plutonium economy has substantial technical and political drawbacks.

3.1. Plutonium available from the world's dismantled weapons could extend Japan's fuel supply significantly

The arguments previously made suggest that on economic grounds it makes no sense to use MOX in thermal reactors whether the plutonium comes from recycled Japanese spent fuel or from dismantled nuclear weapons. Even though these calculations are subject to at least the usual uncertainties, the conclusion is clear.

On the basis of resources, the total amount of plutonium in the former Soviet Union's dismantled weapons would extend the world fuel supply only by about 75 reactor-years (or by about one-quarter of a calendar year considering the roughly 300 GW of world nuclear energy). If, however, the plutonium were used exclusively by Japan, it would be assured roughly an extra two and a half years of fuel supply for its thermal reactors over and above whatever fuel assurances it had with regard to uranium supply.[10] If US dismantled weapons are also considered, this two and a half years of fuel supply would roughly double (Table 2). Combining the weapons-grade plutonium with the excess reactor spent fuel plutonium production capacity (above that needed for its advanced reactors), Japan might extend its fuel reserves by perhaps 10 years.[11]

3.2. Technical drawbacks

Plutonium cannot be stored indefinitely and still maintain its nuclear worth. Plutonium isotopes differ significantly. Only the uneven isotopes (that is, Pu-239 and Pu-241) are fissile. And although Pu-241 is fissile, it decays (with a fourteen and a half year half life) to Americium-241 (Am-241). Americium-241 is a neutron poison, and as it builds up, the equivalent worth of the plutonium drops. (For typical concentrations of Am-241 in plutonium, the reader is referred to Figs. A.8 and A.9 in the appendix.)

The Am-241 buildup problem is far more significant in reprocessed spent fuel than it is in weapons-grade plutonium because the latter has only a small amount of Pu-241 compared to plutonium separated from spent fuel (see the discussion in the appendix).

3.3. The political cost of plutonium

In addition to the technical difficulties of storage, any decision to switch to a plutonium-based fuel would have political drawbacks. Transporting plutonium generates negative reactions both domestically and internationally. It also raises the specter of proliferation.

---

[10] At present, Japan's nuclear power industry generates about 10% of the world's nuclear power. A one-quarter year extension of world fuel supply would translate to a 2.5-year extension of Japanese fuel supply. Extending the fuel supply means that the Japanese would either hold the plutonium within Japan or hold it outside of Japan, with its delivery guaranteed on demand.

[11] If past trends are a valid indication of the future (see Fig. A.6), yellow cake prices are likely to continue to decline or hold steady over the next few years.

Table 2
HEU provides much more nuclear fuel than Pu

Amount of weapons-grade material available in dismantled weapons (measured in equivalent calendar years of uranium displaced) in order to meet

	Word demand[a]			Japanese demand		
	Soviet	US	Total	Soviet	US	Total
Pu	0.25	0.25	0.50	2.5	2.5	5.0
HEU	3.9–6.4	2.6	6.5–9.0	39.0–64.0	26.0	65.0–90.0
Pu as% HEU	4–6	10	6–8			

[a]World demand is drawn from a forthcoming RAND Report by Brain Chow and Kenneth Solomon.

The transport of separated plutonium from Europe to Japan has generated substantial concern and is likely to continue to do so. The rising international concern over Japan's shipment of 1.7 tonnes of plutonium has surprised the Japanese. Numerous environmental groups and more than a dozen governments lodged formal protests with the Japanese government insisting that the cargo ship (*Akatsuki Maru*) and its military escort be kept out of their territorial waters. According to Tocichi Sakata, Director of the Science and Technology Agency's Nuclear Fuel Division, "Nobody who had been involved in the shipment expected it would get such high public attention." According to a November 14, 1992, *Los Angeles Times* report, a Japanese Foreign Ministry official said that all this reaction will be taken into consideration when Japan makes its regular review of its nuclear policy. Hiriyoki Kishino, Director of the Nuclear Energy Division of Japan's Foreign Ministry, adds that he has doubts about proceeding with Japan's 18-year nuclear power program plan in light of circumstances surrounding the current shipment of plutonium from France. (See the *Washington Post*, November 17, 1992, p. A-28.) Japan had planned to transport about 30 tonnes of plutonium from France and Great Britain in the next two decades as part of its policy to create a complete nuclear fuel cycle. At this writing, Japan's plans are somewhat uncertain.

Conversion to plutonium fuel also raises the issue of proliferation. Fig. 3[12] compares the kilogram quantities of fissile uranium and fissile plutonium needed to form

[12] Extrapolated from Epstein [11]. This figure refers to both weapons-grade plutonium (plutonium generated in weapons reactors and irradiated for relatively short times) and to reactor-grade plutonium. Weapons-grade plutonium is typically irradiated for weeks in a reactor. The resultant plutonium is relatively high in the fissile isotope Pu-239 (above 95% Pu-239). The plutonium generated as a by-product of energy production in a civilian reactor has less Pu-239. If the Pu-239 is generated and not separated and recycled back into MOX, its fissile content is above 70%. If it is extracted from the spent fuel, reprocessed, and recycled into MOX, its fissile content (Pu-239) reduces to below 60% after it is used in the reactor. After a second recycle (i.e., after it is reused twice), the fissile content (i.e., percentage of Pu-239) further depletes.

a critical mass.[13] About 5 kg of weapons-grade plutonium or about 15 kg of weapons-grade uranium are required to form a critical mass. No more than 10 kg of reactor-grade plutonium are required to form a critical mass. As mentioned, reactor-grade uranium cannot form a critical mass.

This conversion increases the proliferation risk in at least two ways. First, a MOX economy would increase and spread the supply of weapons-grade material. Second, Japan's neighbors might possibly be suspicious of Japan's motives and nuclear weapons capability. However irrational, this suspicion could stimulate other countries to develop their own nuclear weapons program.

3.4. Should Japan rely upon a mixed plutonium and uranium economy?

We arrive at conflicting findings. On the one hand, Japan has no present economic justification to use MOX in place of UO_2 in its thermal reactors, whether the plutonium comes from Japan's recycled spent fuel or from dismantled nuclear weapons. Furthermore, storing separated plutonium for an extended time would be costly both in terms of security and, in the case of reactor-grade plutonium, in terms of the Am-241 buildup problem. Still further, the political costs to Japan associated with the transport of separated plutonium across international boundaries could be high. Japan is, of course, developing its own reprocessing capability. But this, in turn, could raise political costs by stimulating concern in some international quarters about proliferation control.

On the other hand, although a mixed plutonium and uranium economy will cost Japan more than a pure uranium economy, a plutonium economy does buy Japan several years of extended fuel assurance for its thermal reactors as well as fuel for its advanced reactors. Extended fuel assurance may further buy Japan a more stable nuclear power program. Because energy assurance is so vital to Japan's future, the increased costs may be well worth the expenditure if the Japanese wish to maintain their industrial leadership. Eliminating plutonium from Japan's nuclear option might be interpreted by some as weakening Japan's future nuclear power program.

4. Assuring energy vs. nonproliferation: The international fuel bank

An alternative method of assuring Japan's nuclear fuel supply might resolve some of the conflicting considerations associated with converting to plutonium fuel. Although a number of options are possible, time constraints permitted examination of only the one we will discuss here.

[13] A critical mass is the quantity of fissile material shaped in the form of a sphere needed to create a self-sustaining chain reaction. A nuclear weapon requires two or more quantities of material that are individually less than a critical mass but are collectively greater than a critical mass. The weapon is activated when these two or more subcritical assemblies are imploded rapidly to form a critical mass, a self-sustaining chain reaction, and the release of large quantities of energy.

First, taking even the most demanding scenario for Japan's advanced reactor program, Japan need not separate more than 10 tonnes of plutonium through the year 2000 for its advanced reactor program.

Second, the argument in favor of the Japanese storing plutonium for future use is weak because of both the high dollar storage and security costs and the Am-241 problem. The present price of yellow cake would have to rise substantially before MOX would be a cost-effective fuel. Historical trends in yellow cake prices over the last ten years show a substantial decline. The Japanese should recognize that the very diverse number of yellow cake suppliers, and the only modest increases in world demand for nuclear power, should keep yellow cake prices well below the threshold at which plutonium recycle becomes cost effective. Storing separated plutonium for years just makes no sense if yellow cake is available. Maintaining plutonium in spent fuel (for commercial-grade plutonium) seems to be a more viable option because (1) it would be more difficult to use it to proliferate weapons and (2) the Am-241 it would generate in spent fuel could be removed if and when the spent fuel were reprocessed. It is less apparent what to do with plutonium from weapons.

Third, while storing separated plutonium is costly, Japan's need for guaranteed, continued fuel supplies argues that considerable thought be given to how best to tie this available plutonium to fuel supply assurance without having to pay all of the proliferation risks and dollar costs such assurance will bring. The concept of an international fuel bank that could store unseparated plutonium in spent fuel and separated quantities of weapons-grade plutonium merits serious study. Although study of such an international fuel bank concept is beyond the scope of this report, we can identify some criteria for such an institution.

1. The primary purpose of an international fuel bank would be to provide safeguarded storage, as well as availability and distribution of uranium or plutonium. It would provide a means of more effectively assuring both a nonproliferation policy and a guaranteed nuclear reactor fuel supply.

2. The international fuel bank must demonstrate long-term stability for it to be acceptable. Multinational operation and perhaps multinational placement of the fuel could provide some degree of assurance.

3. The fuel bank must be able to guarantee delivery of plutonium or the equivalent energy worth of uranium at competitive prices to all countries that can justify a need based on their nuclear power program.

4. Participation in the fuel bank might be limited to states that have ratified the Non-Proliferation Treaty (NPT) and have accepted International Atomic Energy Authority (IAEA) safeguards.

The question of how Japan can further assure its energy, and in particular its nuclear fuel supplies, needs further analysis. Potential paths include, besides storage of plutonium, storage of LEU, establishment of an international fuel bank either in Japan or in several countries, and storage of spent fuel rods in Japan together with gradual buildup of reprocessing capabilities. A comparative analysis of these options in terms of energy security for Japan, costs, proliferation risks, and so on, must await further study.

5. Summary

5.1. Background and objective

Adequate supplies of electricity have allowed Japan to make impressive economic advances. But Japan can sustain this advance only if it has an assured supply of fuel. To this end, it diversifies both its types of power-producing facilities and its sources of fuel. Nuclear power provides a growing source of its energy, accounting for about 30% of Japan's electricity today; that proportion is expected to grow to about 40% by the end of the century. Most of the uranium needed at present to fuel Japan's nuclear power plants is imported.

Japan is facing both an opportunity and a dilemma. Japan's opportunity is to convert its nuclear power industry from uranium fuel to a mix of plutonium and uranium fuel (mixed oxide or MOX fuel). Arms-control agreements between the former Soviet Union and the United States have resulted in the dismantling of thousands of nuclear weapons, making available a substantial amount of weapons-grade plutonium that could fuel nuclear power plants. Japan can also obtain plutonium by reprocessing spent nuclear fuel. The dilemma is that such a conversion brings with it technical, economic, and political drawbacks. This report investigates both sides of this issue and suggests an alternative way to provide plutonium to the world's nuclear power countries.

5.2. The technical and economic arguments

Converting to plutonium fuel in its nuclear industry offers Japan some technical advantages. First, substantial quantities of plutonium are available. Second, the plutonium mixed with uranium could fuel Japan's nuclear power industry. Finally, converting to plutonium fuels would also give the Japanese experience in handling this sensitive material. That experience could prove useful as Japan contemplates using breeder reactors, which are fueled solely by plutonium, in its nuclear power industry.

Economically, the conversion to MOX makes less sense. World uranium prices are stable and appear likely to remain so. It costs more to run reactors using MOX than using only uranium. The amount of the increase is sensitive to a number of assumptions, but it would range between $135 and $800 million annually. Japan could clearly afford the increased cost. The question simply becomes one of whether the benefits justify the cost.

5.3. The energy assurance argument

The most persuasive argument for converting to MOX is that it could extend Japan's nuclear fuel supply for at least a decade. Plutonium available from dismantled former Soviet weapons exceeds 75 metric tons. Japan could also get plutonium from reprocessing spent nuclear fuel. Analysis of Japan's nuclear fuel industry shows that it would need only eight metric tons of fuel to power its advanced reactors through the end of the century. Even the most conservative estimate – one that assumes reprocessing of fuel in Europe and no purchase of plutonium from dismantled weapons – yields more than 20 metric tons by the year 2000. A decade of assured fuel for an industry that supplies 40% of Japan's power needs is a powerful inducement.

That said, converting to MOX has both technical and political drawbacks. On the technical side, plutonium from reprocessed fuel does not store well. It is rich in an isotope that decays into Americium-241, a neutron poison that further limits the plutonium's worth as a fuel. Although weapons-grade plutonium does not generate as much Americium-241, it presents an added security burden because it could be reconverted for use in a weapon.

Furthermore, plutonium is politically controversial. Japan has already generated substantial domestic and international turmoil in its attempts to ship reprocessed plutonium from Europe. Nor it is clear that the international community would welcome the prospect of providing weapons-quality material to a nonnuclear power. Such a step could be perceived as fostering proliferation. Other nations might be nervous about Japan having high-grade plutonium and might attempt to acquire their own supply.

5.4. An alternative: An international fuel bank

Japan will make its own decision about converting to MOX fuel in its nuclear power industry. However, the international community could remove much of the anxiety about such a decision by establishing an international fuel bank. User nations would have to agree to safeguards and inspections. But such an approach might not appeal to Japan because it would still not control its own fuel supply, and would have to share the plutonium with other countries.

Acknowledgements

The author acknowledges the reviews and constructive comments from Professor Michael May of Stanford and from Dr. Arnold Horelick, Dr. Brian Chow and Dr. Robert Levine, RAND.

Appendix: Technical data

Fig. A.1 projects Japan's nuclear power program through the year 2010. Japan at present generates a little over 30 GWe per year by nuclear power. By the year 2010, that amount will more than double. Even in the year 2010, most of Japan's nuclear power will be generated by thermal rather than breeder reactors.

Fig. A.2 contrasts world reprocessing capacity in 1989 with what is projected for 1995 and 2000. Many countries intend to put reprocessing capacity on line by the year 2000.

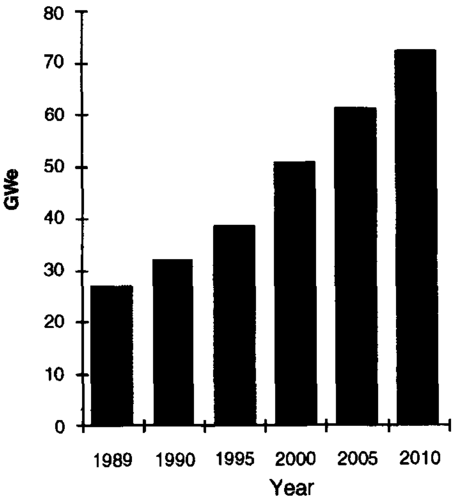

Fig. A.1. Nuclear power projections in Japan for selected years.

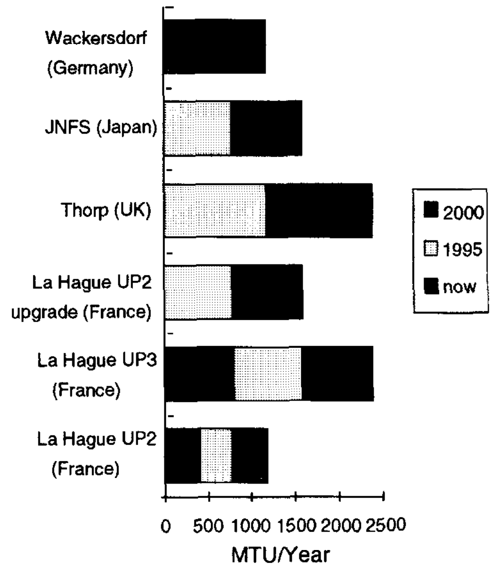

Fig. A.2. Reprocessing facilities in operation and planned, worldwide.

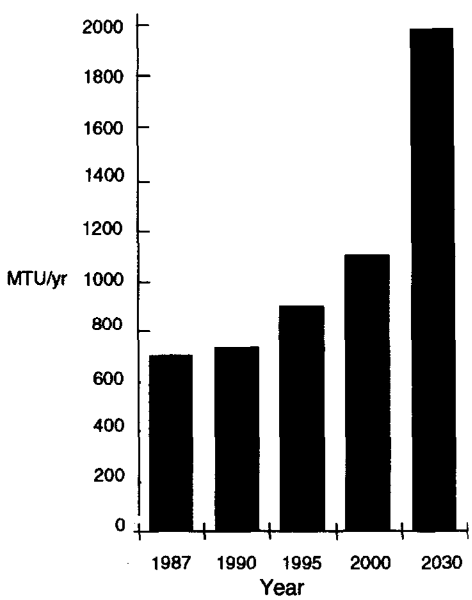

Fig. A.3. Generation of spent fuel in Japan for selected years.

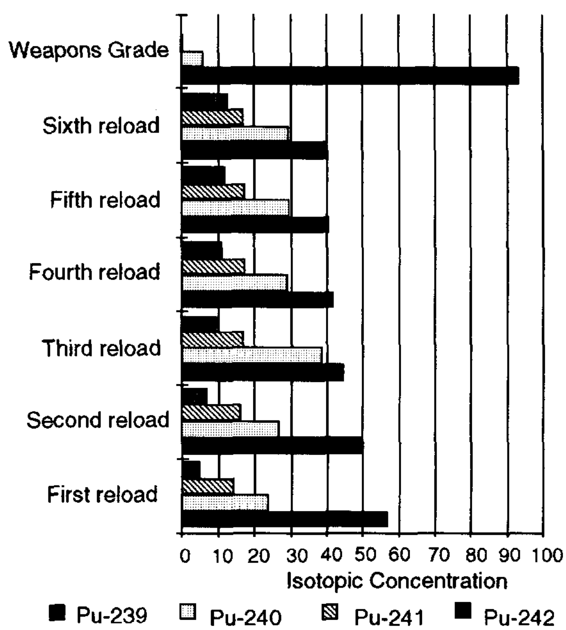

Fig. A.4. Fissile plutonium depletes after reprocessing and recycle.

Japanese spent fuel generation is projected through the year 2030 in Fig. A.3.

Figs. A.4 and A.5 illustrate the changing concentration of fissile plutonium after it has been reprocessed from spent fuel and recycled back into a thermal reactor. Fig. A.3 shows the generation of spent fuel in Japan.

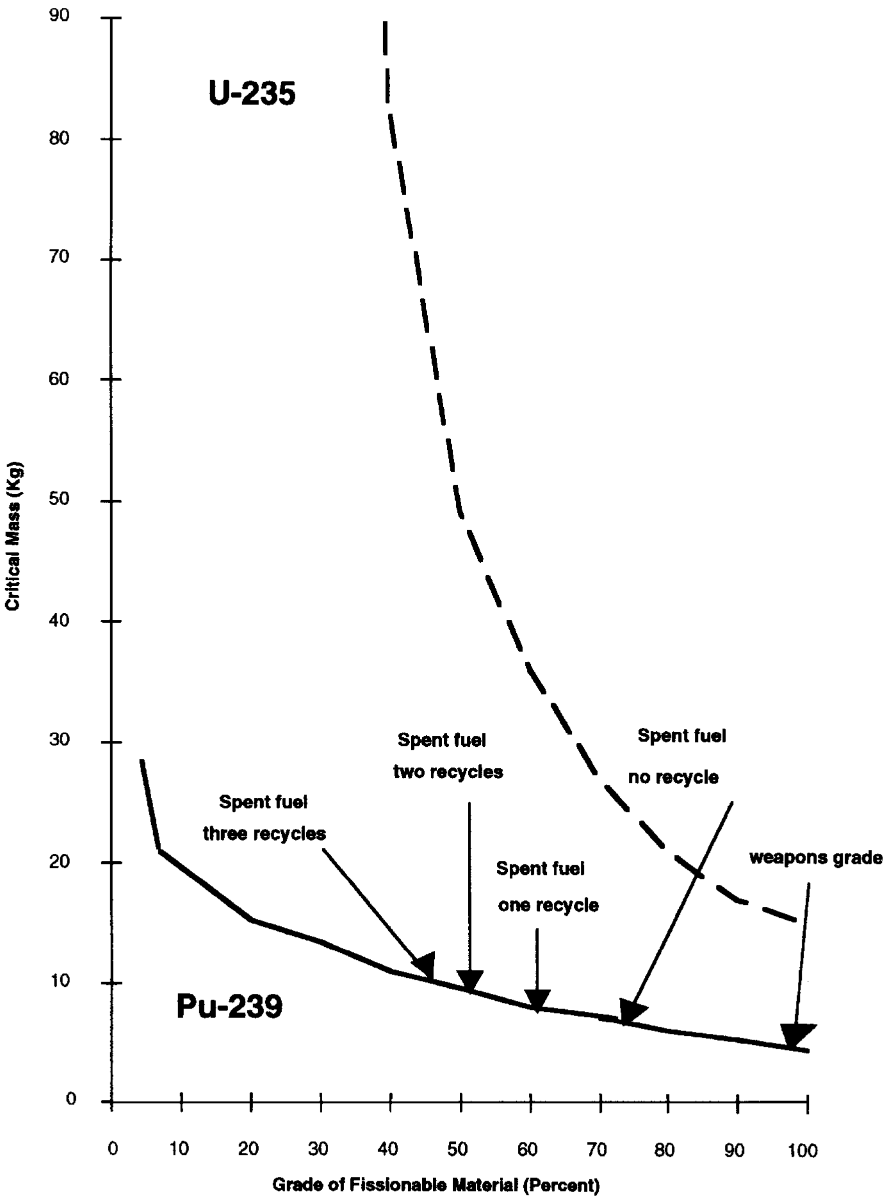

Fig. A.5. Weapons-grade plutonium is 93.5% Pu-239 and only 0.5% Pu-241.

The average delivery price of yellow cake (uranium ore) has decreased substantially through the 1980s, as demonstrated in Fig. A.6.

Weapons contain substantial quantities of plutonium and enriched uranium. Their equivalent values in terms of pounds of uranium yellow cake ore and equivalent enrichment values (measure in separative work units or SWUs) is shown in Fig. A.7.

Plutonium cannot be stored indefinitely and still maintain its nuclear worth.

Not all isotopes of plutonium are equal. Only the uneven isotopes of plutonium (that is, Pu-239 and Pu-241) are fissile. And, although Pu-241 is fissile, it decays (with a fourteen and a half year half life) to Americium-241. Americium-241 is a neutron poison, and as it builds up, the equivalent worth of the plutonium drops.

The Am-241 buildup problem is far more significant in reprocessed spent fuel than it is in weapons-grade plutonium has only a small amount of Pu-241 compared to

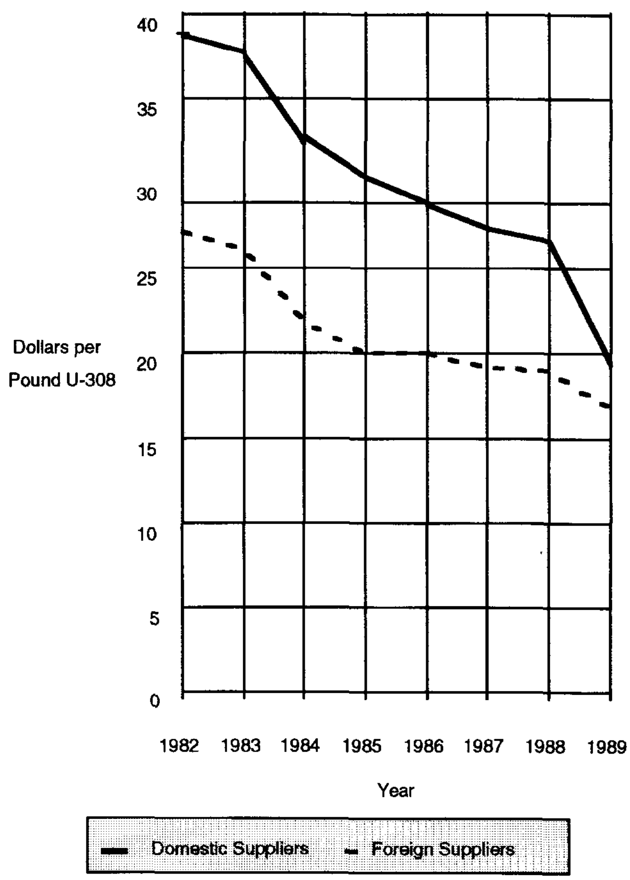

Fig. A.6. Declining price of yellow cake.

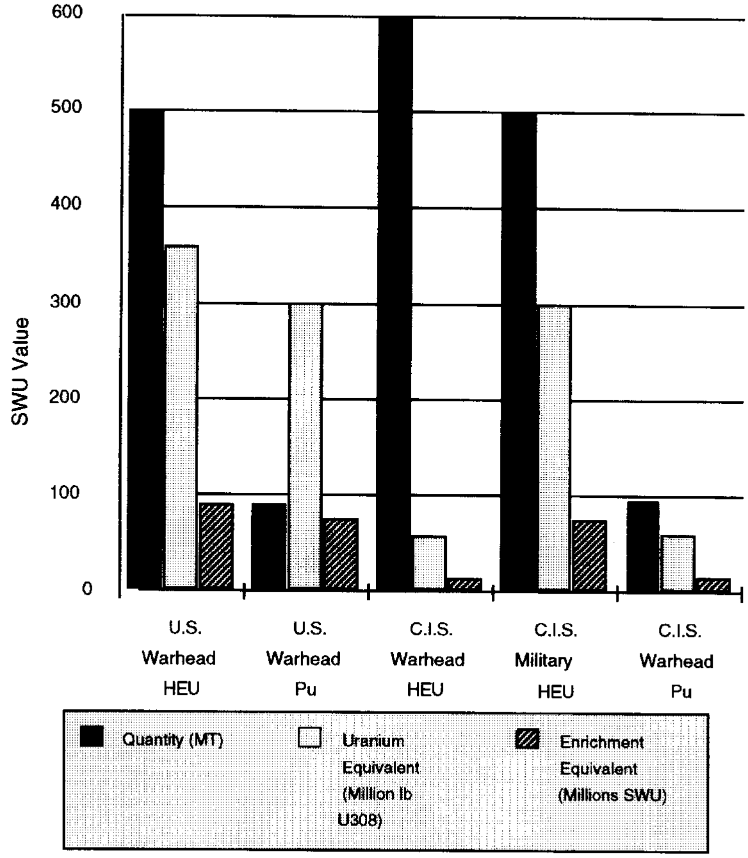

Fig. A.7. Yellow cake and SWU values contained in weapons.

plutonium separated from spent fuel (see Figs. A.4 and A.5). The concentration of Am-241 in plutonium separated from reactor-grade spent fuel – as a function of when the spent fuel was reprocessed and for how long it was stored – is illustrated in Fig. A.8. The decay of Pu-241 and growth of Am-241 from the time the weapons-grade plutonium was separated is illustrated in Fig. A.9. Comparing these two figures, we can see, for example, that 50 years after the plutonium is separated, the concentration of Am-241 is only 0.42% in reactor-grade plutonium and after only one year from separation from spent fuel, the Am-241 concentration is 0.7% and growing rapidly. Fig. A.10 demonstrates the fissile worth of thermal reactors (typically liquid metal fast breeder reactors or LMFBRs), and weapons-grade-originated plutonium as a function of the time it was removed from the reactor.

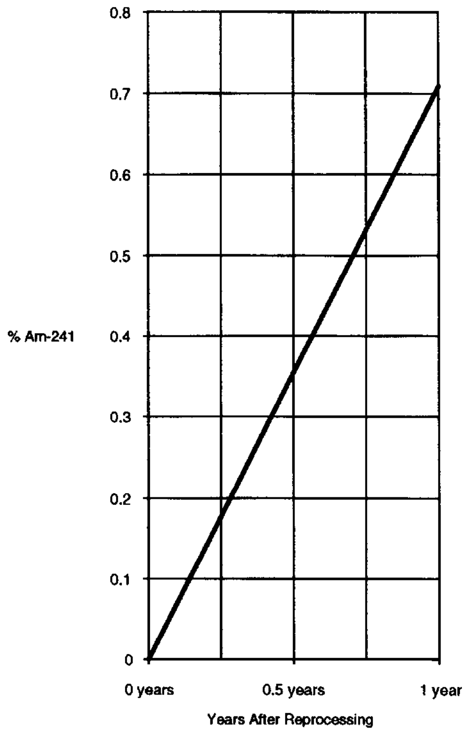

Fig. A.8. Buildup of AM-241 after reprocessing of spent LWR reactor-grade fuel.

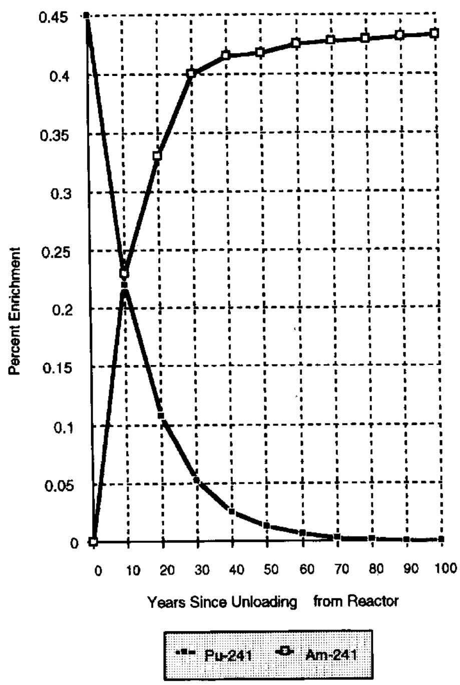

Fig. A.9. Decay of Pu-241 and growth of Am-241 in weapons-grade plutonium.

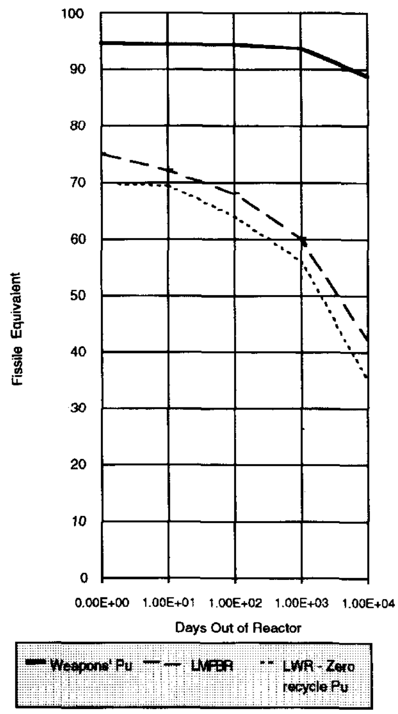

Fig. A.10. Fissile equivalent of plutonium as a function of days out of the reactor (LWR, LMFBR, and weapons-grade).

References

[1] F. Berkhout, T. Suzuki and W. Walker, The approaching plutonium surplus: A Japanese/European Predicament, Int. Affairs, 66(3) (1990) 523–543.
[2] World List of Nuclear Power Plants, Nuclear News, August 1992.
[3] S. Okada et al., Historical review o uranium exploration in Japan, Exploration, IAEA Panel Proc. Ser., 1988, pp. 193–206.
[4] W. Schneider et al., National briefing summaries: Nuclear fuel cycle and waste management, Battelle, Pacific Northwest Laboratory, PNL 6241, Rev. 2, April 1991.
[5] T.S. TSuboya et al., High Level Waste Management, An overview of high level waste management in Japan, Proc. 1989 Joint Int. Waste Conf., Kyoto, Japan, October 22–28, 1989.
[6] T.S. Tsuboya et al., High Level Waste Management, American Society of Mechanical Engineers, New York, Vol. 2, 1989, pp. 105–110.
[7] W. Berkhout et al., Science and Global Security, Vol. 3, 1992, pp. 1–53.
[8] J.J. Styne, The potential impact of arms reduction in LWR fuel cycle: An update, The Uranium Institute Ann. Symp., 1992.
[9] F. Berkhout, T. Suzuki and W. Walker, World Nuclear Industry Handbook, Nuclear Engineering International, 1990, IAEA publication, Vienna.
[10] F. Berkhout, T. Suzuki and W. Walker, Plutonium Fuel: An Assessment, A Nuclear Agency Publication, Paris, 1989.
[11] W. Epstein, A ban on the production of fissionable materials for weapons, Scientific American, 243(1) (1980) 43–51.