

A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium

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Japan could acquire a 50-year reserve of low-enriched uranium fuel for its nuclear power plants at about half the cost of its plutonium program, providing energy security and major economic and political benefits. Fuel for light-water reactors made with plutonium costs four to eight times as much as conventional uranium fuel. Japan can develop a Strategic Uranium Reserve to address its energy security concerns and eliminate any need to proceed now with plutonium recycling with its many attendant costs and nuclear proliferation risks. Such a reserve could provide as much as a 50-year, energy-secure timeframe within which Japan could develop the commercial breeder reactor later on, if necessary. A discounted cash flow analysis demonstrates that, by developing a 50-year uranium reserve instead of a commercial plutonium and breeder program, Japan could save up to \$22.7 billion. Savings would be greater (up to \$38.4 billion) if an enriched-uranium reserve smaller than the extreme 50-year example or a reserve of natural uranium were acquired. The reserve would also make a major contribution to keeping the Asia-Pacific region free of weapons-usable nuclear materials.

OVERVIEW: WHY A STRATEGIC URANIUM RESERVE?

The original dream of nuclear-generated electricity “too cheap to meter”—fueled forever by plutonium recovered from spent reactor fuel and recycled in fast breeder reactors (FBRs)—has long since faded. Adverse economics, persistent safety and environmental problems, and severe risks of nuclear weapons

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proliferation have led most nations to reject large-scale breeder development.

Japan is the only major industrial state still actively investing in achievement of a commercial breeder program.¹ Japan's motivation for breeding plutonium is based on a real concern about energy security. In 1991, the Japanese Atomic Energy Commission (JAEC) stated, "Nuclear fuel recycling makes nuclear energy a more attractive and stable energy source from a long-range point of view so that the national energy security may be further increased. Japan, being scarce in natural resources, has given particular importance to this point."² The Commission projected that by the year 2010, some 80 to 90 metric tons of fissile plutonium will be combined with uranium in mixed-oxide (MOX) fuel and consumed in Japanese breeder and light-water reactors.³

Our examination of benefits, costs and risks indicates that Japan's goal of developing a secure and stable supply of nuclear energy is ill-served by recycling plutonium for breeder reactors when compared with stockpiling uranium for light water reactors. Plans to recycle and breed plutonium date back over 30 years to an era when global uranium reserves were thought to be low and price projections were high in anticipation of a vast expansion of nuclear power capacity worldwide. Today, natural uranium and uranium enrichment services are abundant on the world market, and prices for both are low as the result of new uranium discoveries and of far less nuclear power development than originally expected. In the meantime, spent-fuel reprocessing, plutonium recycling and breeder-reactor development have proven to be more troublesome and many times more expensive than anticipated.

The world glut in uranium is now compounded by the prospect of hundreds of tons of highly enriched uranium being recovered from dismantled U.S. and Russian nuclear warheads and becoming available as fuel for power reactors in low-enriched form. A minimum of 500 to 700 metric tons of HEU could become available in the former Soviet Union, plus at least another 500 to 600 metric tons of HEU in the United States, through dismantling of thousands of nuclear warheads.⁴ The high-end of these estimates of Russian and U.S. weapons uranium would be sufficient to provide, in blended-down form, nearly a 40-year supply of low-enriched uranium for all reactors now operating and under construction in Japan (see table 4).

However, even without access to this former weapons material, there are adequate natural uranium reserves and enrichment services available to permit Japan to acquire a "Strategic Uranium Reserve" of low-enriched uranium sufficient to provide a 50-year supply of fuel for all of its light-water reactors that could be operating in the year 2030. A 50-year reserve of LEU represents an extreme case and would be the most conservative path to energy security, since Japan could certainly achieve ample security against realistic fuel cut-

off and shortfall scenarios with a reserve of LEU one-half that size, or less. Also, the reserve could be made up of natural uranium, which could be acquired at far less cost and enriched later if needed.

In any event, a set-aside reserve of uranium would provide an energy-security benefit similar in concept but far greater in duration than that provided by the Strategic Petroleum Reserve now maintained by Japan. The extended security provided against an unanticipated uranium shortfall or supply cutoff would eliminate any need to proceed now with plutonium recycling with its many attendant costs and risks.⁵ A Strategic Uranium Reserve would permit Japan to defer construction of the Rokkasho reprocessing plant and commercialization of the fast breeder reactor. Japan's breeder program could continue at its present R&D scale with the assurance that a Strategic Uranium Reserve would carry forward into the future and provide Japan an energy-secure timeframe—up to 50 years, in the extreme case—within which to develop a commercial-scale breeder program later on, if breeders were ever found to be needed.

A Strategic Uranium Reserve also would permit Japan to renegotiate European reprocessing contracts on the basis of obtaining spent-fuel storage plus uranium enrichment instead of immediate recovery and shipment of excess plutonium. This approach—which could be called “storage plus SWU in lieu of Pu”—represents an opportunity for Japanese utilities to avoid a double dilemma: repetition of the international outcry that greeted the 1992 sea shipment of plutonium from France and the likely strong domestic opposition that would result if plutonium were brought into Japan faster than it could be absorbed in light water reactors—a violation of official Japanese policy barring a plutonium surplus.⁶

Indeed, at a time when Japan is seeking support from its neighbors for a seat on the UN Security Council, the Japanese government might welcome a chance to avoid controversy and destabilization in the region associated with renewed sea shipments and stepped-up domestic acquisition of plutonium.⁷ (Were Japan to defer its commercial plutonium reprocessing and recycling program, but subsequently find that because of technical difficulties at the Tokai-mura pilot reprocessing plant one or two additional sea shipments were needed to ensure enough plutonium for the present R&D program, such limited shipments might not draw strong opposition if they proceeded with greater consideration of en-route countries' safety and security concerns.)

Further, by means of a Strategic Uranium Reserve, Japan would be in a position to support the ailing uranium mining and enrichment industries worldwide and to put to work the emerging Japanese enrichment industry. Perhaps most significant, building a Strategic Uranium Reserve would be a

Table 1: Comparative costs of Japan's plutonium program and a 50-year reserve of low-enriched uranium.

Reactor status	Plutonium program	Uranium reserve	Net savings
billions of discounted 1993 dollars			
Reference case			
Operable & under construction (42,205 MW _e)	50.6	33.8	16.9 (33%)
Operable, under construction, & projected to 2030 (72,000 MW _e)	53.2	39.5	13.8 (26%)
Best case for uranium reserve			
Operable & under construction (42,205 MW _e)	51.9	29.2	22.7 (44%)
Operable, under construction & projected to 2030 (72,000 MW _e)	54.9	34.0	20.9 (38%)
Worst case for uranium reserve			
Operable & under construction (42,205 MW _e)	50.1	38.6	11.4 (23%)
Operable, under construction, & projected to 2030 (72,000 MW _e)	52.9	46.1	6.8 (13%)

major opportunity to assist Russia. In providing such assistance, Japan could obtain a direct and tangible dividend in the form of huge amounts of inexpensive natural uranium and enrichment services—not to mention good will that could help contribute to settlement of the Kurile Islands dispute.

We will show that benefits to Japan from a strategic reserve of low-enriched or natural uranium are available at far less economic cost than proceeding with a commercial-scale plutonium and breeder program at this time. Even in the most expensive case of a 50-year reserve of LEU, there would be savings of as much as \$22.7 billion, or 44 percent, for all reactors now operable and under construction (see table 1). In addition, these benefits are obtainable without adverse effect on Japanese utilities' existing uranium-supply and enrichment contracts, and without undermining ongoing U.S. plans to absorb blended-down Russian bomb-grade uranium in the course of meeting existing Japanese and other enrichment contracts for LEU.

Table 2: Estimated capital costs of Japan's commercial plutonium program through the year 2030.^a

	billions of constant 1993 dollars ^b
LWR fuel reprocessing plant (Rokkasho)	16.3
Successor LWR fuel reprocessing plant	16.3
MOX fuel reprocessing plant	22.9
LWR MOX fuel fabrication plant	0.4
FBR MOX fuel fabrication plant	0.6
Ohma ATR	4.7
Demonstration FBR	3.3
2 pre-commercial FBRs by the year 2030	6.7
Total	71.2

a. Does not include costs of Joyo and Monju FBRs, Fugen ATR, or Tokai reprocessing plant, which this study treats as part of

b. Cost estimates are undiscounted and rounded to nearest hundred million U.S. dollars.

JAPAN'S PLANNED COMMERCIAL PLUTONIUM PROGRAM

Plutonium-Fueled Reactors

Monju, an experimental 280 MW_e fast breeder reactor scheduled to go critical in the spring of 1994, is treated in this study as part of Japan's plutonium R&D program, rather than as a part of the commercialization effort. Therefore, the costs and MOX fuel requirements of Monju are not included in this analysis of the costs of Japan's commercial plutonium program.

Japan plans to construct Ohma, a 606 MW_e MOX-fueled advanced thermal reactor. Ohma is currently scheduled to begin operation by March 2001.⁸ Japan's Electric Power Development Company Ltd. (EPD), the company developing Ohma, recently estimated its capital cost as 470 billion yen (about \$4.7 billion).⁹

Official plans for the Demonstration Fast Breeder Reactor (DFBR) and follow-on pre-commercial FBRs are still quite vague because the DFBR's capac-

Table 3: Cost components of fuel cycles.^a

Reprocessing/Recycle	
European reprocessing services (based on contracts)	\$1,600 kg ⁻¹
Japanese reprocessing services (minus capital costs)	\$1,000 kg ⁻¹
Storage of separated plutonium	\$2 per gram Pu per year
LWR MOX fuel fabrication	\$948–\$1,300 kg ⁻¹ MOX
FBR MOX fuel fabrication	\$1,822–\$2,250 kg ⁻¹ MOX
MOX security and transportation costs	\$300 kg ⁻¹ MOX
Away-from-reactor storage of spent fuel:	
Capital costs	\$202–\$246 kg ⁻¹
O&M costs	\$55 kg ⁻¹
Once-through	
Uranium	\$26–\$47 kg ⁻¹ U
Uranium conversion services	\$4.75–\$6 kg ⁻¹ U
Uranium enrichment	\$70–\$119 per SWU
LEU transportation to Japan	\$3 kg ⁻¹ U
LEU storage in Japan	\$0.67 kgU per year
U ₃ O ₈ transportation to Japan	\$1.30 kg ⁻¹ U
U ₃ O ₈ storage in Japan	\$0.42 kg ⁻¹ U per year
Away-from-reactor storage of spent fuel	(same as Pu cycle)

a. See text for explanation of cost assumptions.

ity and annual fuel demand have yet to be made public. This study assumes that the DFBR will have a capacity of 600 MW_e,¹⁰ and estimates the DFBR's capital costs at about \$3.3 billion, based upon Japan Atomic Power Company's estimate that the DFBR will cost about 1.5 times the cost of a light-water reactor.¹¹ The schedule for the DFBR has been pushed back several times; it is now scheduled to be completed by 2010.¹²

This study assumes that two follow-up reactors to the DFBR will be con-

Table 4: A Japanese strategic uranium reserve of LEU acquired in part from blended-down military HEU^a (number of years of reserve provided by HEU).

Reactor status	LEU fuel from Russian HEU only (500 MT HEU)	LEU fuel from Russian & U.S. HEU (1,000 MT HEU) ^b
Reactors operable & under construction (42,205 MW _e)	18.7 years	37.3 years
Reactors operable, under construction, & projected to 2030 (72,000 MW _e)	10.9 years	21.9 years

a. Assumes 90% U-235 content weapons HEU.
b. Zachary Davis et al., "Swords Into Energy: Nuclear Weapons Materials After the Cold War," Congressional Research Service, Washington, DC, 29 September 1992, p. 4. Though estimates of total amounts of HEU produced in both the U.S. and former Soviet Union have recently increased substantially (see note 4), the amounts in this chart still represent realistic estimates of amounts of HEU that might become available for redirection from military to civil purposes.

structed by the year 2030.¹³ It is also assumed that, as part of the commercial demonstration, the size (i.e., capacity in MW_e) of the FBRs will gradually be scaled up. Thus, FBR 2 is assumed to have a capacity of 800 MW_e, and FBR 3 a capacity of 1,200 MW_e.¹⁴ It is the hope of FBR proponents that the economics of scale will narrow the capital cost gap between light-water reactors and breeders as larger FBRs are built. This study conservatively assumes that FBR 2 will cost 1.3 times, and FBR 3 1.1 times, the price of an equivalent light-water reactor. If this holds true, FBR 2 would cost about \$2.9 billion, and FBR 3 about \$3.8 billion. Both plutonium-fueled reactors and light-water reactors are assumed to have an operational life of 30 years. Annual operation and maintenance (O&M) costs for both types of reactors are assumed to amount to five percent of the original capital costs of the reactor.¹⁵

Capital Costs of Reprocessing Plants

Japan currently plans to reprocess all of its spent fuel, for both plutonium recovery and waste management purposes.¹⁶ However, its ability to do so is limited by, among other factors, the amount of reprocessing capacity available in Japan and abroad. This study assumes in its reprocessing scenarios that Japan reprocesses as much spent fuel per year as available domestic capacity and current contracts with Britain and France permit, and places the rest of the spent fuel it generates into long-term interim away-from-reactor storage.

Nikkei, an authoritative Japanese financial newspaper, recently reported

that the official cost estimate for the first commercial-scale reprocessing plant, to be built at Rokkasho-mura, has been raised to 1.7 trillion yen, nearly double the earlier estimate of 840 billion yen.¹⁷ Therefore, we assume that the Rokkasho light-water reactor reprocessing plant will cost some \$16.3 billion in constant 1993 dollars.¹⁸

A light-water reactor fuel reprocessing plant will be required, at an estimated cost of \$16.3 billion to replace Rokkasho at the end of its operational life (assumed to be 2030, 30 years after Rokkasho is scheduled to begin operation). There are no official plans yet to build either this plant or a commercial-scale FBR MOX fuel reprocessing plant (see below), but both facilities will be necessary if Japan is to continue its commercial plutonium program during the time frame of our study, and all indications are that they plan to do so. In the absence of any official cost estimates, this study conservatively assumes that the replacement plant for Rokkasho will cost the same as the original plant in real terms (\$16.3 billion in constant 1993 dollars).

At some point in the first half of the next century, Japan will require a plant to reprocess MOX fuel from light-water reactors and FBRs, as well as the blanket material from breeders.¹⁹ This study assumes that a commercial-scale MOX reprocessing facility will be operational in the year 2020. No cost estimates are available for this facility, and direct extrapolation of RETF cost projections is problematic, due to their extreme uncertainty and the difficulty of quantifying the relevant economies of scale. MOX fuel facilities require more extensive and costly worker and environmental protection because of the greater plutonium content of MOX fuel relative to LEU fuel from light-water reactors. This study assumes the MOX reprocessing plant will cost 1.4 times as much as Rokkasho, or about \$22.9 billion in constant 1993 dollars.²⁰

Operation and Maintenance Costs of Reprocessing Plants

Japan currently operates a pilot reprocessing plant at Tokai, with a current annual capacity of 100 metric tons of spent fuel. Based on recently achieved annual throughputs, this study assumes that Tokai will reprocess 90 metric tons of spent fuel per year between now and the end of the century.²¹ The Tokai plant is assumed to cease operation in the year 2000 when Rokkasho becomes operational. The Rokkasho reprocessing plant, with an annual capacity of 800 metric tons, is scheduled to begin operation in the year 2000.

Our study assigns a cost of \$1,000 kg⁻¹ to Japanese reprocessing services (half of the \$2,000 kg⁻¹ total cost estimate for Japanese reprocessing). (See “Response to Criticism by British Nuclear Fuels” below). The estimated value of the uranium recovered during reprocessing is deducted from the cost of reprocessing services to determine a net price for reprocessing.²²

Overseas Reprocessing Services

Japan has contracted with BNFL to reprocess 2,680 metric tons of spent fuel at the THORP plant from 1994 to 2002,²³ and with Cogema to reprocess 2,718 metric tons of spent fuel from 1990 to 2000,²⁴ for a total of 5,398 metric tons to be reprocessed overseas by the year 2002. The price of British and French reprocessing services already contracted by Japan for one kilogram of spent fuel is assumed to be \$1,600 kg⁻¹ in constant 1993 dollars.²⁵

MOX Fuel Fabrication Plants

Japan plans to complete its first commercial-scale fabrication plant for light-water reactor MOX around the year 2000, though there may be a few years of slippage. Construction will take about three years. A senior Japanese nuclear official estimated the cost of the plant as somewhat more than 50 billion yen (about \$400 million in 1993 dollars).²⁶

No plans have yet been publicly announced to build a commercial-scale fabrication plant for FBR MOX, but commercial development of the breeder will require it at some point. No official cost estimates are publicly available. Absent more specific information, this study uses the U.S. Department of Energy's estimate that FBR MOX fabrication plants cost about 40 percent more than light-water reactor MOX facilities of equivalent capacity,²⁷ and assigns this facility a price of \$559 million. It is assumed to become operational in the year 2020.²⁸

MOX Fuel

The price of fabricating one kilogram of light-water reactor or ATR MOX fuel is assumed to be \$1,300 kg⁻¹ MOX in the period 1994 to 2003.²⁹ FBR MOX fabrication is substantially more expensive; this study assumes that fabrication costs \$2,250 kg⁻¹ FBR MOX in the period 1994 to 2010.³⁰ Germany's experience suggests that costs may run even higher—at the small Hanau plant (now shut down), MOX fabrication costs of about \$3,100 kg⁻¹ MOX have recently been reported.³¹ Because of its plutonium content, MOX fuel incurs additional security and transportation expenses. This study assigns a surcharge of \$300 kg⁻¹ MOX for these expenses. This charge is surely too low, as it is based solely on ground transportation of MOX within Western Europe.³²

By the year 2000, Japan plans to have 12 light-water reactors, each with a capacity of about 1,000 MW_e, loaded with one-third core MOX. This study assumes 120 metric tons of MOX containing three percent fissile plutonium are consumed annually.³³

The Ohma ATR will require annual reloads of 19 metric tons of MOX with

a fissile plutonium content of 3.1 percent throughout its operational lifetime (assumed to be 2001–2030).³⁴ The capacity and fueling requirements of the DFBR and subsequent FBRs have not been published. Based on extrapolations from Monju's annual reload requirements, we estimate the following annual MOX requirements: DFBR, about 6.8 metric tons (2010–2030); FBR 2, about 9.1 metric tons (2020–2030); FBR 3, about 13.7 metric tons (2030).³⁵

Fuel Cycle Back-end Costs

This category includes costs of storing separated plutonium and interim away-from-reactor storage for spent fuel cooling prior to reprocessing and spent fuel in excess of reprocessing requirements.

The “carryover” of separated plutonium, i.e., the amount of fissile plutonium remaining each year after that year's MOX requirements are met, must be stored. The price assigned by this study to storage of excess plutonium is \$2 per gram (total plutonium) per year of storage. Various sources cite price estimates for plutonium storage ranging from \$1 to \$2 per gram (total plutonium) per year³⁶ to as high as \$4 per gram (total plutonium) per year.³⁷

Japan will generate considerably more spent fuel annually than it will need to reprocess to meet projected plutonium requirements, or than it has annual capacity available to reprocess. While it awaits reprocessing, this fuel must be placed in interim storage. As at-reactor storage capacity will not be sufficient over the long term, away-from-reactor storage will need to be built. The model calculates the number of metric tons of spent fuel in away-from-reactor storage in a given year. Away-from-reactor storage is assumed to have a capital cost of \$202 to \$246 kg⁻¹, and an O&M cost of \$55 kg⁻¹.³⁸

ELEMENTS OF THE PROPOSED JAPANESE STRATEGIC URANIUM RESERVE

Calculating the Size of the Reserve

To calculate the size of the proposed Japanese Strategic Uranium Reserve, the annual LEU requirement for the 48 Japanese light-water reactors operable or under construction as of early 1993, and for additional projected future light-water reactor capacity, is calculated.³⁹ Japanese light-water reactors operable and under construction as of early 1993 have a total capacity of 42,205 gross MW_e.⁴⁰ Fifty years' LEU requirement is 39,983 metric tons of LEU.

Estimating future nuclear capacity is a very uncertain exercise. Official Japanese projections in the new long-term plan for 70,500 MW_e by 2010 and

approximately 100,000 MW_e by 2030⁴¹ are overly ambitious and unrealistic. This study assumes a robust Japanese nuclear capacity of 60,000 MW_e by 2010.⁴² Capacity is assumed to grow at a rate of 600 MW_e annually thereafter,⁴³ reaching 72,000 MW_e by the year 2030. Fifty years' LEU requirement for 72,000 MW_e of light-water reactor capacity is 68,210 metric tons of LEU.⁴⁴

Uranium Costs

This study uses as the real price of U₃O₈ the median price of ranges projected in a 1993 report by Energy Resources International Inc.: \$10 per pound in 1994; \$14 per pound in 1995–1999; and \$18 per pound in 2000–2030 (in constant 1993 dollars).⁴⁵

It is important to note that the cost comparisons used in the revised JSUR study do not assume the use of any blended-down weapons HEU. Should some of this material become available for Japan for a Strategic Uranium Reserve, the cost of the JSUR would be substantially lower than our current estimates.

Conversion Services

To assign a price for conversion services for one kilogram of uranium, this study uses Energy Resources International's projection: \$4.75 kg⁻¹ U as uranium hexafluoride (UF₆) in 1993; \$5.50 by 1995; and \$6 in 2000 and beyond (in 1993 constant dollars).⁴⁶

Uranium Enrichment Services

This study assumes that LEU fuel for Japanese light-water reactors will average 3.7 percent enrichment.⁴⁷ Based on this study's calculations of annual Japanese demand for LEU (see above), annual Japanese SWU demand for light-water reactors currently operable and under construction (42,205 MW_e) is calculated to be 4.7 million SWU. Total SWU requirements for 50 years' LEU would therefore be 234.5 million SWU. Annual Japanese SWU demand for all light-water reactors projected to 2030 (72,000 MW_e) is calculated to be eight million SWU. Total SWU requirements for fifty years' LEU would therefore be 400 million SWU.⁴⁸

The real price of enrichment services assumed in this study for the period 1994 to 2000 (\$119 per SWU) represents the U.S. Enrichment Corporation's "composite price" of \$119 per SWU for customers that purchase 100 percent of their SWU from the U.S. Enrichment Corporation (USEC). This price may be too high; Russia has a large excess enrichment capacity (as discussed later in this report), and would probably be willing to make much of this capacity available for about \$75 per SWU.⁴⁹ Over the long term, this study assumes

that real SWU prices will drop to \$100 per SWU by the year 2000, then decline by \$10 per SWU per decade.⁵⁰

LEU Transportation and Storage

For transportation of LEU to Japan, this study assumes a cost of slightly more than \$3 kg⁻¹ U as UF₆. Storage of LEU is assumed to cost \$0.67 kg⁻¹ U as UF₆. If the uranium is shipped and stored in the Strategic Uranium Reserve as unenriched U₃O₈, transportation is assumed to cost \$1.30 kg⁻¹ U, and storage as yellowcake is assumed to cost \$0.42 kg⁻¹ U per year.⁵¹

Alternative Light-Water Reactor Capacity

If Japan defers plutonium commercialization, we assume that alternative generating capacity will be required in lieu of plutonium-fueled reactors, and that presumably this capacity will take the form of conventional light-water reactors fueled by LEU. This study assumes that each light-water reactor would have the same capacity as the plutonium-fueled reactor for which it substitutes. LWR 1 (the substitute for the Ohma ATR), with a capacity of 606 MW_e, would cost about \$2.2 billion to construct. LWR 2 (the substitute for the DFBR), at 600 MW_e, would cost about \$2.2 billion to construct. LWR 3 (the substitute for FBR 2), at 800 MW_e, would cost about \$2.9 billion. LWR 4 (the substitute for FBR 3), at 1,200 MW_e, would cost about \$3.8 billion.⁵² Costs for LEU fuel for these LWRs, and for LEU fuel to substitute for MOX that Japan plans to burn in light-water reactors, are calculated in the same way as costs for LEU for the reserve (see discussion above).

Fuel Cycle Back-end Costs

This category includes costs of long-term away-from-reactor storage for all spent fuel generated during the timeframe of the study. The only back-end costs incurred in the once-through scenario within the time frame of this study are those associated with interim spent fuel storage. The relevant cost figure is the incremental difference between away-from-reactor storage costs in the reprocessing and once-through scenarios: i.e., how much more would away-from-reactor storage cost each year with a once-through cycle than it would cost with reprocessing? This incremental annual difference is calculated and assigned as a cost of the uranium reserve/once-through scenario. The same estimates of capital and O&M costs per kilogram of spent fuel in away-from-reactor storage are used here as were used for the plutonium program (see discussion above).

In the once-through scenario, all spent fuel is assumed to be placed in

long-term interim away-from-reactor storage pending disposal in a repository. A permanent geological depository will not be completed in Japan until at least the year 2045.⁵³ Therefore, ultimate repository disposal of both once-through spent fuel and high-level waste from reprocessing lies beyond the time horizon of this study (2030). For this reason, final costs of repository disposal for spent fuel (and for high-level reprocessing waste in the reprocessing scenario) are not included in either the once-through or reprocessing scenarios. Also, in the once-through scenario, spent fuel placed in away-from-reactor storage is assumed to remain there until at least the year 2030.

BUILDING A STRATEGIC URANIUM RESERVE

Japan would need to acquire a large amount of natural uranium or LEU over a period of several years to complete a Strategic Uranium Reserve. Some portion of this material could become available in the form of HEU recovered from dismantled nuclear weapons and diluted with natural or depleted uranium into low-enriched fuel.⁵⁴ Some 1,300 metric tons of U.S. and Russian HEU would, if blended down to LEU, provide a 22-year reserve of LEU for all reactors projected to the year 2030 and nearly a 40-year reserve for all reactors now operating and under construction.⁵⁵ The 500 metric tons of HEU that the United States has agreed to purchase from Russia⁵⁶ is equivalent to enough LEU to fuel all reactors projected to 2030 for over a decade. Though cost estimates vary, it is clear that LEU blended down from HEU is far cheaper than LEU obtained from new enrichment of natural uranium.⁵⁷ If Japan were to arrange to purchase as much blended-down HEU as possible, it could get a good running start on building a Strategic Uranium Reserve.

However, since no such arrangements have been made or are anticipated, this study assumes that none of the warhead uranium is made available to Japan and that the proposed 50-year reserve is obtained exclusively through Japanese government purchases of excess natural uranium and enrichment services over a number of years. Table 5 shows the large surplus of uranium enrichment capacity currently projected on the world market.

Over 19 million separative work units (SWU) per year are expected to be available in excess of annual demand for uranium enrichment services until the year 2000, and over 16 million excess SWU per year are projected to be available between 2000 and 2010.⁵⁸ Japan could purchase a moderate amount of the worldwide excess enrichment capacity—we conservatively use 10 million SWU per year in this study—until its Strategic Uranium Reserve is completed. However, a reserve far smaller than 50 years' supply certainly would

Table 5: Excess enrichment capacity (million SWU per year).^a

Year	Enrichment capacity	Enrichment demand	Excess capacity
1991	46.9	26–27	20.9–21.9
1995	48.6	29.4–29.5	19.2–19.3
2000	51.7	31.7–32.4	19.3–20.0
2010	51.7	34.1–34.8	16.9–17.6
		Western only	
1991	32.9	23.0	9.9
1995	34.6	25.8	8.8
2000	37.7	27.6	10.1
2010	37.7	30.0	7.7

a. Sources: Western enrichment supply and demand: Uranium Institute, Uranium in the New World Market: A Statistical Update of Supply and Demand 1991–2010, October 1992, table 3, “Forecast Western Enrichment Services Requirements to 2010,” p. 15, and table VIII, “Fuel Cycle Services: Enrichment Capacity,” p. 46.

Russian and C.I.S. enrichment supply and demand: U.S. Department of Energy, Energy Information Administration, World Nuclear Capacity and Fuel Cycle Requirements 1992, December 1992, “Potential Impact of Uranium and Enrichment Services from the C.I.S.,” p. 39. All known uranium enrichment capacity in the C.I.S. is located in Russia.

be sufficient to deal with any foreseeable uranium supply disruption, including a war. Table 6 shows the cost of various-sized reserves that would provide 10 to 50 years’ supply, and the savings these reserves represent in relation to Japan’s plutonium/breeder program.

Although Japan might want to have the uranium enriched before placing it in a reserve, there is no reason why a reserve could not be composed of natural uranium acquired abroad and stored in Japan, rather than enriched uranium. If the natural uranium were ever needed, it could be enriched by Japan at that time, using its indigenous centrifuge facilities. If necessary, the capacity of centrifuge enrichment plants could be expanded by adding additional cascades. A reserve composed of natural uranium rather than LEU would offer even greater savings by avoiding the up-front expenses of uranium conversion and enrichment services. Table 7 shows the savings that would be realized by maintaining natural uranium reserves of various sizes.

Table 6: Cost comparison of LEU reserves of various sizes.^a

Reactors operable and under construction (42,205 MW _e) cost of plutonium program: \$50.6 billion		
Size of reserve	Cost of reserve	Savings over Pu program
10 years	\$18.1 billion	\$32.6 billion (64%)
20 years	\$23.4 billion	\$27.2 billion (54%)
30 years	\$27.8 billion	\$22.9 billion (45%)
50 years	\$33.8 billion	\$16.9 billion (33%)
All reactors projected to 2030 (72,000 MW _e) cost of plutonium program: \$53.2 billion		
10 years	\$22.2 billion	\$31.0 billion (58%)
20 years	\$29.6 billion	\$23.6 billion (44%)
30 years	\$34.4 billion	\$18.9 billion (36%)
50 years	\$20.5 billion	\$12.8 billion (26%)

a. All costs and savings calculated using the reference case, and expressed in discounted 1993 dollars, rounded to the nearest hundred million. Figures may not add due to rounding.

ADEQUACY OF WORLD URANIUM SUPPLIES

Advocates of plutonium recycling often claim that world uranium reserves will prove insufficient, perhaps facing total depletion within a few decades.⁵⁹ Such predictions are based on the narrowest estimates of total uranium reserves, those defined jointly by OECD's Nuclear Energy Agency and the International Atomic Energy Agency (OECD/NEA-IAEA) as Reasonably Assured Resources (RAR) recoverable at a cost below \$80 kg⁻¹ U.⁶⁰ However, RAR includes only well-known, completely explored deposits. If Estimated Additional Resources, Category I (EAR-I)—known resources in deposits that have not been completely explored—are also included, estimates of world reserves increase by more than half.⁶¹ Further, according to the OECD/NEA-IAEA study, "There remains very good potential for the discovery of additional uranium resources of conventional type, as reflected by estimates of EAR-II and Speculative

Table 7: Cost comparison of natural uranium reserves.^a

Reactors operable and under construction (42,205 MW _e) cost of plutonium program: \$50.6 billion		
Size of reserve	Cost of reserve	Savings over Pu program
10 years	\$12.2 billion	\$38.4 billion (76%)
20 years	\$14.2 billion	\$36.4 billion (72%)
30 years	\$15.9 billion	\$34.7 billion (69%)
50 years	\$18.3 billion	\$32.3 billion (64%)
All Japanese LWRs projected to 2030 (72,000 MW _e) cost of plutonium program: \$53.2 billion		
10 years	\$13.8 billion	\$39.5 billion (74%)
20 years	\$16.6 billion	\$36.6 billion (69%)
30 years	\$18.5 billion	\$34.7 billion (65%)
50 years	\$20.7 billion	\$32.6 billion (61%)

a. All costs and savings calculated using the reference case, and expressed in discounted 1993 dollars, rounded to the nearest hundred million. Figures may not add due to rounding.

Resources.⁶² Even if Speculative Resources are excluded, and even if the amount of uranium needed to build the Strategic Uranium Reserve is deducted from estimated reserves, uranium reserves would still suffice to fulfill world demand until 2054 from resources recoverable up to \$80 kg⁻¹ U—or until the year 2067 from resources recoverable up to \$130 kg⁻¹ U.⁶³ Ample uranium exists both to build a Japanese Strategic Uranium Reserve and to fulfill world demand far into the future.⁶⁴

Japan could purchase from Russia a substantial portion of the uranium required to produce the Strategic Uranium Reserve. An enormous amount of previously mined natural uranium (U₃O₈) and low-enriched uranium is currently in Russian civilian stockpiles—460 million pounds U₃O₈-equivalent, according to one recent estimate,⁶⁵ enough to provide over 18 years of LEU for all Japanese light-water reactors projected to 2030. Uranium industry sources suggest that if Japan proposed an off-market, government-to-government deal with Russia to purchase some or all of this stockpile, Russia very likely would accept such an offer, particularly if Japan paid slightly more than recent average spot market prices—perhaps \$10 per pound U₃O₈-equivalent.⁶⁶

Japan also could offer to purchase a certain annual amount of newly produced uranium from former Soviet republics to complete the Strategic Uranium Reserve. As in other sectors of the economy, investment in the uranium industry in former Soviet republics has ground to a halt. Absent a large infusion of outside capital, uranium production capacity can be expected to decline precipitously—by 20 to 30 percent a year.⁶⁷ If this capacity is maintained, however, it could supply a major portion of the natural uranium required for the Strategic Uranium Reserve.

The U.S. Department of Energy estimates that “the C.I.S. or its republics could market around 20 million pounds of natural uranium per year from their uranium concentrate production capability.”⁶⁸ This translates to over 23.5 million pounds U_3O_8 annually, enough to provide, even without any additional purchases from the Russian stockpile, more than three quarters of the entire 30.8 million pounds U_3O_8 a year Japan would need to build a Strategic Uranium Reserve at the assumed rate of 10 million SWU per year.⁶⁹

Such a deal would benefit both Japan and Russia. Japan would acquire a windfall of uranium to build its reserve at a moderate price. Russia would receive a windfall of hard currency for many years. Such a deal could help stabilize the situation in Russia and improve Japanese-Russian relations.

Thus, in just a few years, Japan could acquire from Russian and other sources a reserve equivalent to several years’ supply of LEU as a cushion against near-term contingencies, and eventually a reserve that could last half a century. Acquisition of such a reserve would cost far less than Japan’s commercial plutonium and breeder development program.

Each major element in the plutonium fuel cycle costs considerably more than its counterpart in the LEU fuel cycle. The capital costs of plutonium-fueled reactors and fuel cycle facilities are much higher than those of LEU-fueled reactors because plutonium requires more extensive arrangements for environmental, safety and worker protection than LEU, as well as greater physical security and safeguards. Further, MOX fuel is decidedly more expensive than LEU, even assuming major increases in uranium prices. As shown in table 8, when reprocessing costs are included, MOX fuel is shown to be four to eight times more expensive than LEU.

ECONOMIC COMPARISON OF THE JAPANESE PLUTONIUM PROGRAM WITH THE PROPOSED JAPANESE STRATEGIC URANIUM RESERVE

Discounted cash flow analysis is used to determine the net present value

Table 8: Price penalty of plutonium recycle in LWRs.^a

	Annual price penalty ^b	
	Low price MOX ("free" Pu)	High price MOX (Pu price assigned)
Reference case	LEU: \$1,000–1,200 kg ⁻¹ MOX: \$1,300–1,600 kg ⁻¹	LEU: \$1,000–1,200 kg ⁻¹ MOX: \$5,300–6,000 kg ⁻¹
Price penalty	\$31 million–\$77 million	\$507 million– \$600 million
Worst case for uranium reserve	LEU: \$1,100–1,300 kg ⁻¹ MOX: \$1,100–1,600 kg ⁻¹	LEU: \$1,100–1,300 kg ⁻¹ MOX: \$5,100–\$6,000 kg ⁻¹
Price penalty	–\$28 million–\$50 million	\$449 million– \$577 million
Best case for uranium reserve	LEU: \$900–1,000 kg ⁻¹ MOX: \$1,800–2,300 kg ⁻¹	LEU: \$900–1,000 kg ⁻¹ MOX: \$5,800–\$6,800 kg ⁻¹
Price penalty	\$104 million– \$173 million	\$588 million–\$708 million
	Cumulative price penalty, 2000–2030 ^c	
Reference case	\$600 million	\$6.9 billion
Worst case for uranium reserve	–\$295 million	\$6.0 billion
Best case for uranium reserve	\$1.7 billion	\$8.1 billion

a. "Price penalty" is the estimated difference in price between the use of MOX fuel in Japan's light-water reactors and the LEU fuel that would be consumed in the absence of a plutonium recycle program. This study assumes that 12 1,000 MW_e Japanese light-water reactors, each loaded with one-third core of MOX, consume an annual total of 120 metric tons of MOX, averaging three percent fissile plutonium, beginning shortly after 2000.

b. Constant 1993 dollars (undiscounted), rounded to nearest million or hundred million. Fuel prices rounded to nearest

c. Discounted 1993 dollars, rounded to the nearest hundred million.

(NPV) costs of both the Japanese commercial plutonium program and the proposed Japanese Strategic Uranium Reserve. A four percent annual inflation rate is assumed for the entire time frame of the study. Following OECD-NEA's economic analyses of the nuclear fuel cycle, a five percent real discount rate is used.⁷⁰

"Reference," "worst case" and "best case" scenarios have been constructed for the JSUR, and model runs have been performed using their respective price assumptions. The reference case scenario uses all the price assumptions explained above. The worst case scenario for the Strategic Uranium Reserve

assumes that high prices prevail for both SWU and uranium, and that reprocessing and MOX fabrication are considerably cheaper than assumed in the reference case. The best case scenario for the Strategic Uranium Reserve assumes somewhat lower prices for uranium and SWU, and higher prices for MOX fabrication and reprocessing services. The results of these analyses are displayed, along with those for the reference case, in table 1.

RESULTS OF THE ECONOMIC COMPARISON

The economics of a Strategic Uranium Reserve are quite favorable when the price tag of the reserve is compared with that of Japan's commercial plutonium program. Our basic finding is that a 50-year reserve of LEU for all Japanese light-water reactors projected to 2030, including those built in lieu of breeders and ATRs—the most extreme and expensive case for a Japanese Strategic Uranium Reserve—would be less expensive than the commercial plutonium program projected to 2030 across a broad range of price assumptions.⁷¹ Table 1 shows the substantial economic advantage of such a strategic uranium reserve over the plutonium program under three sets of assumptions—reference case, worst case and best case for the reserve.

In the reference-case comparison of the 50-year LEU reserve and the commercial plutonium program, based on best estimates of future prices for uranium acquisition and enrichment and for spent-fuel reprocessing and MOX fuel fabrication, the reserve represents savings of more than \$16.9 billion,⁷² or 33 percent, for reactors operating and under construction, and \$13.7 billion (26 percent) for all reactors projected to 2030. Even in the worst-case comparison for the reserve, assuming high-end prices for uranium and enrichment services and low-end prices for the plutonium program, a 50-year Strategic Uranium Reserve would still represent savings of over \$11.3 billion, or 23 percent, for reactors now operating and under construction, and \$6.8 billion, or 13 percent, for all reactors projected to 2030. In the best-case comparison for the reserve, comparing the low-price estimate for the reserve with the high-price estimate for the plutonium program, the reserve represents a savings of over \$22.7 billion (44 percent) for reactors now operating and under construction and \$20.9 billion (38 percent) for all reactors projected to 2030.

Savings would be even greater if a smaller reserve of low-enriched uranium were acquired. As noted in table 6, a 10-year reserve for all reactors projected to 2030 would cost less than half as much as the plutonium program, saving some \$31 billion. A 20-year reserve for all reactors now operable and under construction would save over \$27 billion (54 percent).

The most economical option would be a reserve of natural uranium. As

noted in table 7, if this path were chosen, a 50-year reserve could be acquired for all reactors projected to 2030 at a savings of \$32.6 billion (61 percent), or for reactors operable and under construction at a savings of \$32.3 billion (64 percent). If Japan chose to stay with the once-through uranium cycle and acquired a 10-year natural uranium reserve for all reactors operable and under construction, this alternative approach to energy security would be over four times cheaper than the plutonium program, saving over \$38 billion.

RESPONSE TO CRITICISMS BY BRITISH NUCLEAR FUELS LTD. (BNFL)

The results of this study were released as a Nuclear Control Institute report in January 1994.⁷³ British Nuclear Fuels Ltd. (BNFL), a corporation providing reprocessing services to Japan and Western Europe, prepared a commentary highly critical of our report.⁷⁴ The BNFL commentary was slightly revised in April.⁷⁵ BNFL's commentary on our study makes three indefensible assumptions:

- ◆ unrealistically low reprocessing costs;
- ◆ extremely high uranium costs; and
- ◆ the farfetched assumption that Japan would have to acquire an entire 50-year reserve over a 10-year period to achieve strategic independence in energy supply.

Only under these assumptions is BNFL able to make reprocessing/recycle of plutonium appear even remotely economic.

Reprocessing Costs

BNFL claims that our study's assumption of a reprocessing O&M cost of \$1,000 kg⁻¹ is excessive for Japan. A Japanese expert familiar with the plutonium program recently estimated the cost of reprocessing in Japan as \$2,000 kg⁻¹ of spent fuel.⁷⁶ This estimate includes capital costs. It is not unreasonable to assume that the capital cost component of this price is about half, or \$1,000 kg⁻¹. A recent Rand Corporation study of fissile materials estimated the capital cost of Rokkasho as \$1,000 kg⁻¹.⁷⁷ The same Rand study calculates that capital costs account for half of the total price in reprocessing contracts for BNFL's Thorp plant.⁷⁸

BNFL claims that \$1,000 kg⁻¹ is too high an estimate of O&M costs, stating that some of this amount "would have to cover decommissioning, financing and profit." Even if true, all these elements contribute to the cost of Japan's

plutonium program and should be included, whether or not they should be strictly defined as “O&M costs.”

Uranium Prices

BNFL assumes that uranium prices will increase at a rate of 1.2 percent per year in real terms. Such a rate of increase is extremely unlikely. Indeed, over the last few years uranium prices have declined substantially in real terms. The price increase which might result from acquisition of uranium for the Japanese reserve is accommodated in our study by using as the real price of U_3O_8 the median of a range of prices projected in a 1993 report by Energy Resources International Inc.—\$10 per pound in 1994; \$14 per pound in 1995 to 1999; and \$18 per pound in 2000–2030 (in constant 1993 dollars).⁴⁶ If anything, ERI’s projections are too high. A close observer of the uranium industry recently predicted that, by the year 2000, uranium would not likely go above \$15 per pound U_3O_8 in constant year 2000 dollars.⁷⁹

As a sensitivity analysis, our study includes a worst case analysis, in which uranium prices reflect the high end of ERI’s projections: \$16 per pound U_3O_8 in 1995–1999; and \$20 per pound U_3O_8 in 2000–2030. Even given these pessimistic assumptions, the once-through cycle and uranium reserve save billions of dollars compared to reprocessing/recycle.

BNFL further claims that purchases for the uranium reserve might increase uranium prices by 50 percent. Absolutely no basis is given for this assertion. BNFL presumably assumes that Japan would contract for all uranium purchases for the reserve up-front, on the open market. There is no reason to believe that Japan would handle such large, long-term uranium purchases in this fashion; indeed, it would not make economic sense to do so.

Instead, a series of off-market, government-to-government deals could be struck with Russia and other major uranium producers. Uranium trading industry experts have advised us that the price effect of such arrangements would be minimal, perhaps an increase of \$1 or \$2 per pound of U_3O_8 . Such a price increase, already provided for in the model as discussed above, would only marginally reduce the economic benefits of a reserve.

Implementation of a Strategic Uranium Reserve

BNFL claims that a uranium reserve, if acquired over 20 or more years, would not assure Japan’s energy security, so the reserve would need to be completed within a decade, increasing the net present value (NPV) cost of the reserve. No reason is given for this claim. Indeed, Japan does not plan to complete plutonium fuel commercialization until the year 2030 or later—nearly 40 years

from now—but BNFL does not criticize the long time frame for Japan’s plutonium/breeder program on the same grounds.

BNFL’s assumption that Japan would need to complete acquisition of a uranium reserve three to four times more quickly than plutonium commercialization is arbitrary, unrealistic, and self-serving. By contrast, the rate of acquisition assumed in our study (10 million SWU per year) is based upon real-world industry projections of excess enrichment capacity.

In discounted cash flow analyses, expenses (expressed in net present value terms) are greater the closer they occur to the present, because they are discounted less heavily. By compressing the acquisition of the uranium reserve into ten years, BNFL unrealistically inflates the NPV cost, suggesting that BNFL is playing a statistical game to make the economics of the uranium reserve appear prohibitive.

Reprocessing and Waste Management

BNFL claims that our study’s reprocessing cost estimates include costs for final disposal of high-level waste from reprocessing, but there is no comparable cost for final disposal of spent fuel included on the once-through side of the ledger. In fact, the reprocessing costs in our study do not include storage, transportation or final disposal of high-level waste from reprocessing. This is because all such final disposal will take place in Japan after the year 2045, when a geological repository is scheduled to be completed. The time horizon for our study is the year 2030. Thus, final disposal costs are not included on either side of the ledger.

A few additional points should be noted. First, final disposal costs, because they occur so far in the future, would be heavily discounted in a net present value analysis. Thus, even if they are large in real terms, their net effect on the overall analysis would be minimal. Second, there is no reason to assume that final disposal of high-level waste from reprocessing will be substantially cheaper than direct disposal of spent fuel. Indeed, the cost may be considerably higher. Third, our study does not include decommissioning and disposal costs for plutonium fuel cycle facilities because they also occur beyond the study’s time horizon—costs which may be as much as the total original capital cost of the facility. These costs are likely to outweigh any marginal cost advantage of final disposal of high-level waste from reprocessing, even if such a cost advantage does exist.

BNFL further claims that “the Strategic Uranium Reserve option assumes Japan will have a politically acceptable domestic location to store the very large volumes of fuel to be disposed of in a once-through cycle regime. This is far from certain.” What BNFL does not acknowledge is that the same political

difficulty confronts the reprocessing/recycle option. There is no indication that Japanese citizens will be more willing to accept reprocessed high-level waste in their backyards than spent fuel.

BNFL implies that siting a high-level waste repository would be less difficult politically because it would contain smaller volumes of waste. However, size requirements of repositories are also affected by the total heat generated by the waste. As a report by the U.K. Department of Energy recognized, "The excavated capacity required in a repository for high-level waste or spent fuel would also need to cope with the heat generation. As this is similar for both high-level waste and spent fuel, the repository capacity required for either high-level waste or spent fuel disposal would be similar."⁸⁰

BNFL also ignores the fact that reprocessing generates enormous amounts of intermediate- and low-level radioactive waste—dozens if not hundreds of times more than direct disposal of spent fuel. Given the much greater volume, final disposal of such enormous amounts of waste could present a much greater political problem for Japan than a spent fuel repository.

BNFL claims that a once-through cycle generates more uranium mining and milling waste than reprocessing/recycle. This claim is irrelevant to BNFL's argument that it would be more difficult politically to site a spent fuel repository in Japan than to site a high-level waste repository. Unlike reprocessing wastes, uranium mining and milling wastes are not sent to the country that consumes the uranium fuel. Therefore, Japan will not have to dispose of these wastes in its repository, and their large volume is irrelevant to the repository siting issue.

CONCLUSION: GIVE URANIUM A CHANCE

The basic point of our study, despite BNFL's attempt to knock it down, has proven to be irrefutable: both economically and politically, across a wide range of price assumptions, plutonium reprocessing/recycle is a bad bargain. For Japan, its plutonium program is considerably more expensive and riskier than a once-through uranium cycle, even when this cycle is supplemented by a 50-year Strategic Uranium Reserve. The only significant challenge to the results of this study has come from BNFL, a vested interest that expects to make billions of dollars from reprocessing Japanese spent fuel. Plutonium is not economical, but BNFL obviously expects it to be profitable. Objective analysis, however, reveals the folly of the plutonium path being pursued by Japan and advocated by BNFL.

It should now be apparent that a Strategic Uranium Reserve makes economic and energy-security sense for Japan. Nuclear policymakers in the

United States and Russia should be prepared to offer to sell Japan some blended-down HEU for a Strategic Uranium Reserve both as a means of satisfying Japan's legitimate energy-security concerns and of drawing down large surpluses of this unneeded material. Such an offer would provide Japan a viable, cost-effective alternative to plutonium and a means to avoid proliferation and terrorism risks associated with plutonium commerce.

Yet, even if present marketing plans make it impractical to offer demilitarized uranium to Japan for a reserve of LEU, the U.S. and the former Soviet Union have enormous, under-utilized uranium resources and production and enrichment capacity that they could make available to Japan with great potential benefit to their ailing uranium industries. At the same time, Japanese reprocessing contracts with Britain and France could be renegotiated to provide spent-fuel storage plus uranium enrichment services instead of unnecessary recovery and shipment of plutonium ("storage plus SWU in lieu of Pu"). At the same time, Japan could suspend plans to construct a commercial reprocessing plant at Rokkasho-mura and to recycle surplus plutonium in light-water reactors. The existing pilot reprocessing plant at Tokai-mura could continue to be utilized to provide plutonium for a limited R&D program involving the pilot Monju and experimental Joyo breeder reactors.

With a Strategic Uranium Reserve, Japan could rest assured that as much as a half-century of energy security provided by an LEU stockpile would be available to be carried forward into the future. Japan need not go beyond the limits of its present breeder R&D program because the reserve would establish a timeframe within which Japan could develop a commercial-scale breeder program if uranium shortages ever occurred that necessitated a move toward commercial-scale recovery and recycling of plutonium.

Stockpiling petroleum is an internationally recognized form of insurance against supply and price instabilities. Japanese stockpiling of natural or low-enriched uranium is long overdue. It would present far fewer political and security problems for Japan than proceeding with additional sea shipments of plutonium and attempting to avoid a plutonium surplus that may prove unavoidable due to delays in the FBR and MOX programs. Continuing along the plutonium path could have serious repercussions for Japan both on the Korean Peninsula and in its bid for a seat on the U.N. Security Council.

Efficient utilization of nuclear power does not require Japan or any other nation to shoulder the substantial costs and risks of a plutonium economy. Ensuring a secure fuel supply—the objective of Japan's present plan to acquire nearly 100 metric tons of plutonium by 2010—can be achieved at substantially less cost and risk by means of a Strategic Uranium Reserve.

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NOTES AND REFERENCES

1. Fast breeder programs have been canceled or scaled back in the United States, Germany, France and the United Kingdom. Russia and Kazakhstan still maintain breeder programs but lack the capital to proceed with them. Only India actively pursues commercial breeder development, albeit with limited resources.

In June 1994, after this study was completed, the Japanese Atomic Energy Commission (JAEC) Advisory Committee for the Long-Term Program released its revised long-term plan for nuclear energy through the year 2010. The revision delays construction of some fuel cycle facilities, and delays slightly development of the fast breeder reactor and of the LWR MOX recycle program, but does not fundamentally change Japan's long-term commitment to reprocessing and plutonium recycle. See "AEC's Revised Long-term Program Stresses Slow, Steady Promotion of Fuel Cycle Projects," *Atoms in Japan*, June 1994, pp. 4–9.

2. Japanese Atomic Energy Commission, Advisory Committee on Nuclear Fuel Recycling, "Nuclear Fuel Recycling in Japan," August 1991, p. 5. The two other reasons JAEC gave for plutonium recycling, "preserving natural resources and environment" and "making the radioactive waste management in Japan more appropriate," are beyond the scope of this paper. However, both rationales have been subjected to serious challenge. See, for instance, Frans Berkhout and William Walker, "THORP and the Economics of Reprocessing," Science Policy Research Unit, University of Sussex, November 1990; and Paul Eavis, "The Case Against Reprocessing," in Frank Barnaby, editor, *Plutonium and Security*, 1992.

3. *Ibid.*, p. 2. Official Japanese data refer only to fissile isotopes of plutonium and understate by about 30 percent the total amount of plutonium actually recovered, shipped and used. Thus, the JAEC recycling plan involves more than 100 metric tons of plutonium by the year 2010. The revised long-term plan released in June 1994 scaled back this estimate to between 65 and 75 MT of fissile plutonium (about 85 to 98 MT total plutonium). "Outlook for plutonium supply and demand in Japan," *Atoms in Japan*, May 1994, p. 7.

4. Zachary Davis, et al., "Swords into Energy: Nuclear Weapons Materials After the Cold War," Congressional Research Service, Washington, DC, 29 September 1992, p. 4. These estimates of total HEU production have proven to be too low for the U.S., and possibly for the former Soviet Union. U.S. Energy Secretary Hazel O'Leary recently disclosed that the U.S. produced 994 MT of HEU between 1945 and 1992, 258.8 MT of which is stockpiled in the United States. "258.8 Metric Tons of HEU Now Stored at 12 Sites Around the U.S., DOE Says," *NuclearFuel*, 4 July 1994, p. 1. It is also possible that the former Soviet HEU stockpile is even larger, exceeding 1,000 MT by some estimates. Viktor Mikhailov, head of the Russian Ministry of Atomic Energy (Minatom), recently claimed that the inventory of former Soviet HEU totals more than 1,200 MT. The credibility of this figure has been disputed. William Broad, "Russian Says Soviet

Atom Arsenal Was Larger than West Estimated," *New York Times*, 26 September 1993, p. 1.

5. Though not the focus of this report, the nuclear weapons proliferation risks associated with civilian plutonium programs are of particular concern. Recent Nuclear Control Institute papers on this subject include "The Impact of Japan's Plutonium Program on Global Proliferation and Nuclear Terrorism," *Asia-Pacific Forum on Sea Shipments of Japanese Plutonium*, Tokyo, 4 October 1992; "The Spread of Nuclear Weapons in the 1990s," *Medicine and War*, 8(4), October–December 1992; "Plutonium and the NPT," Conference on Nuclear Non-Proliferation, Carnegie Endowment for International Peace, Washington, DC, 18 November 1993; Testimony of Paul Leventhal, President, Nuclear Control Institute, before the Joint Economic Committee, U.S. Congress, 6 June 1994; "The New Nuclear Threat," *Wall Street Journal*, 8 June 1994; Paul Leventhal, "The JAEA's Inability to Detect Diversions of Bomb Quantities of Plutonium: JAEA Safeguards Shortcomings—A Critique," (Washington, DC: Nuclear Control Institute, 12 September 1994).

6. David Sanger, "Japan Says Technical Problems Will Force Storage of Plutonium," *New York Times*, 29 November 1992.

7. "S. Korea Fears Japanese Nuclear Capability: South Questions Tokyo's Stockpiles of Plutonium, Anticipates Arms Race," *Defense News*, 13–19 December 1993, p. 6.

8. David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, SIPRI/Oxford University Press, 1993, p. 125. In December 1993, the Demonstration ATR Construction Promotion Committee postponed Ohma start-up to March 2003. "Ohma ATR Construction Plan to be Postponed One Year," *Atoms in Japan*, December 1993, p. 18.

9. *Nikkei Sangyo Shimbun*, 11 October 1993.

10. Tatsujiro Suzuki, MIT, personal communication, July 1993.

11. Tatsutoshi Inagaki, "Present Status of DFBR Design in Japan," *Atoms in Japan*, July 1993, p. 10. Japanese government officials advised the authors that the DFBR is likely to cost much more than this—approximately 500 to 600 billion yen. Personal communication, April 1994.

12. "Project Delays Would Lead Japan to Slow Down Reprocessing Pace," *NuclearFuel*, 12 April 1993, p. 7.

13. "Japanese Utility Leader Pledges Building of Three FBRs by 2030," *Nucleonics Week*, 23 April 1992, p. 8. After completion of this study, the JAEC released its revised long-term plan, which only calls for two FBRs—the DFBR and one follow-on FBR—by 2030. "Key Points in New Long-Term Program for Development and Utilization of Nuclear Energy," *Atoms in Japan*, June 1994, p. 7. Even given this revision, our study's aggregate capital cost estimates for the FBR program are, if anything too low, given our extremely conservative estimate of the cost of each FBR. See note 11.

14. Tatsujiro Suzuki, MIT, personal communication, July 1993.

15. K. Nagano and K. Yamaji, "A Study on the Needs and Economics of Spent Fuel Storage in Japan," in S.C. Slate et al. (editors), *High Level Radioactive Waste and Spent Fuel Management*, Vol. II, American Society of Mechanical Engineers, 1989, p. 475.

16. Japan Atomic Energy Commission, Advisory Committee on Nuclear Fuel Recycling, *Nuclear Fuel Recycling in Japan*, August 1991.

17. Nikkei Shimbun, evening edition, 24 August 1993.
18. This estimate may still be too low. Japanese nuclear industry sources report that the Rokkasho plant is now expected to cost between 1.8 and 2 trillion yen (\$18 to \$20 billion). "Japan AEC Looking at Delay in Startup of Reprocessing Plants," *NuclearFuel*, 14 February 1994, p. 10.
19. A pilot-scale MOX reprocessing plant, the Recycle Equipment Test Facility (RETF), is planned for Tokai. The RETF is scheduled to be operational in 1998, and projected to cost about 120 billion yen (\$1.2 billion). "PNC's FBR-spent-fuel Reprocessing Test-facility Plan Approved," *Atoms in Japan*, August 1993, p. 19. This study does not include the cost of the RETF in its total cost estimates for the plutonium program.
20. The U.S. Department of Energy's standard nuclear plant cost estimation methodology projects that capital costs for a MOX reprocessing plant would run about 40 percent higher than those for an equivalent LWR reprocessing plant. U.S. Department of Energy, Nuclear Energy Cost Data Base, DE89-000407, December 1988 [cited hereafter as DOE, 1988], "Recycle facility costs," table 4.16, p. 43.
21. "PNC, with Figures in Hand, Argues Impending Need to Ship Plutonium," *NuclearFuel*, 3 August 1992, p. 6. The Tokai pilot reprocessing plant has never attained its design capacity of 210 metric tons of spent fuel per year.
22. This credit is calculated as the price of natural uranium in the year the reprocessing takes place, minus a \$10/lb U penalty. This penalty reflects the fact that, due to contamination with U-236 and gamma radiation, recovered uranium is more expensive to use and thus not worth as much as fresh uranium. NEA, 1989, pp. 124-130.
23. Albright et al., 1993, p. 94.
24. *Ibid.*, p. 99.
25. This is probably an underestimate, as it does not include high-level reprocessing waste (HLW) storage, transportation, and final disposal costs. Frans Berkhout and William Walker, "Are Current Back-end Policies Sustainable?," paper presented to the conference "The Management of Spent Fuel," London, 29-30 April 1991, p. 4. A recent analysis of reprocessing by the Karlsruhe Nuclear Research Center in Germany estimates the cost of reprocessing under German utilities' cost-plus-fee contracts with Cogema and BNFL signed in the late 1970s as DM 2,750 (\$1,660) per kgHM. "Direct Disposal Route Will Retain Cost Advantage, KFK Official Says," *NuclearFuel*, 22 November 1993, p. 7.
26. "Japanese Accelerate Plan to Build Commercial MOX Fabrication Plant," *Nucleonics Week*, 18 February 1993, p. 16.
27. DOE, 1988, p. 43.
28. Capital costs of MOX fabrication facilities are calculated in this study in order to document fully the cost of the plutonium program. However, these capital costs are not included in the final spreadsheets to avoid double-counting, because the MOX fabrication prices used in this study (see below) already incorporate capital costs.
29. Frans Berkhout, Princeton University, personal communication, March 1993; based on Berkhout et al., 1992.
30. DOE, 1988, p. 43.
31. "Court Says Hesse Must Pay Siemens for Costs of Shutting MOX Plant," *NuclearFuel*, 26 April 1993, p. 9. Claims by major European reprocessors that LWR MOX will

be economically competitive with LEU by the turn of the century or shortly thereafter are impossible to substantiate, given that these companies refuse to disclose the assumptions underlying their claims (most particularly their projected per-kilogram MOX fabrication costs). However, this study conservatively assumes that fabrication prices for all three types of MOX (LWR, ATR, and FBR) will be 10 percent lower in each successive decade. NUEXCO Information Services, personal communication, September 1993.

32. Frans Berkhout, Princeton University, personal communication, September 1993.
33. STA estimates that each of these 12 LWRs will consume 0.3 MT of fissile plutonium annually. STA, private communication to H. Seki, member of the Japanese Diet, 8 February 1993. Assuming a three percent fissile (4.1 percent total) plutonium content for this MOX (based on Berkhout et al., 1992, table A-4, p. 37), these 12 LWRs would require about 120 MT of MOX annually.
34. Albright et al., 1993, p. 125.
35. Ibid. FBR MOX fuel is assumed to contain 18.5 percent fissile plutonium, a slightly higher enrichment than Monju's fuel.
36. OECD Nuclear Energy Agency, *Plutonium Fuel: An Assessment* NEA, 1989, p. 64.
37. Frans Berkhout et al., "Disposition of Separated Plutonium," *Science & Global Security* 3 (3-4) 1992, p. 9.
38. Based on estimates in Nagano and Yamaji, 1989, table 4.2, p. 475, adjusted for inflation.
39. Tokai Japco, Japan's only Magnox reactor, is not included because it is fueled with natural uranium. The Joyo and Monju FBRs, and Fugen and Ohma ATRs, are not included because they are fueled with MOX rather than LEU fuel. Unless otherwise noted, all data on the individual reactors are taken from *Nuclear Engineering International, World Nuclear Industry Handbook 1993* (NEI, 1993). Annual LEU demand for Japanese LWRs is calculated using the formula:
Total capacity (gross MW_e), multiplied by 365, multiplied by capacity factor, divided by thermal efficiency, divided by fuel burn-up.
40. NEI, 1993, p. 34.
41. "Key Points in New Long-Term Program for Development and Utilization of Nuclear Energy," *Atoms in Japan*, June 1994, p. 7.
42. Atsuyuki Suzuki, University of Tokyo, "Implications of Civilian Plutonium Programs—A Japanese Perspective," paper presented at International Workshop on Nuclear Disarmament and Non-Proliferation: Issues for International Actions, Tokyo, 15-16 March 1993, p. 6. The Japanese Institute of Energy Economics released a report in December 1992 postulating a number of scenarios for Japanese nuclear capacity in 2010, the highest estimate being 60,500 MW_e and the lowest 55,000 MW_e. *Nuclear News*, February 1993, pp. 51-52.
43. Tatsujiro Suzuki, MIT, personal communication, September 1993.
44. This study assumes an average 75 percent capacity factor will be achieved. MITI reports an average 1992 capacity factor of 73.5 percent for PWRs and 73.6 percent for BWRs in Japan. *Nucleonics Week*, 21 January 1993, p. 5. Thermal efficiency is assumed to be 33.6 percent, the average thermal efficiency of Japanese LWRs operable or under construction as of early 1993. NEI, 1993, p. 34. Fuel burn-up is assumed to average

43,000 megawatt-days per metric ton of LEU (MW-d MT^{-1}). OECD's plutonium fuel study assumed this burn-up level in its LEU reference case based on annual replacement of one-quarter core in PWRs. NEA, 1989, p. 48.

45. "ERI Publishes its 1993 Report," *NuclearFuel*, 7 June 1993, p. 15.

46. "ERI publishes its 1993 report," *NuclearFuel*, 7 June 1993, p. 15. Neither ERI nor OECD projects that real prices for uranium conversion services will change much over the long term.

47. Average LEU enrichments in Japan are near this level currently, averaging about 3.4 percent for BWRs and 3.8 percent for PWRs, according to MITI. Public Service Department, MITI, *Nuclear Power Handbook 1993* [in Japanese], pp. 604–605, 618–619. OECD's plutonium fuel study assumed 3.7 percent enrichment in its LEU reference case based on annual replacement of one-fourth core in PWRs. NEA, 1989, p. 48. OECD's reference case suggests that this enrichment level is sufficient to sustain the future fuel burn-up of 43,000 MW-d MT^{-1} assumed in this study. A 0.2 percent tails assay is assumed in all calculations. This is slightly higher than the assay in current contracts, but represents a reasonable mid-point estimate for the post-2000 period. DOE, 1988, p. 14.

48. All estimates rounded to the nearest hundred thousand SWU.

49. NUEXCO Information Services, personal communication, April 1993.

50. NUEXCO Information Services, personal communication, September 1993.

51. Based on personal communications with nuclear industry experts familiar with uranium storage and transportation costs.

52. These estimates are based on the ten Japanese LWRs most recently completed or under construction as of September 1993, the capital costs of which range from \$3 billion to \$4.3 billion. The smallest of these reactors is 825 MW_e ; the largest, 1,360 MW_e . Japan Electric Power Industry Council (JEPIC), Washington, DC, personal communication, September 1993. Based on these costs, this study assigns a capital cost estimate of \$3,636 kw^{-1} to LWR 1, LWR 2, and LWR 3, and \$3,162 kw^{-1} to the larger LWR 4, to account for economies of scale of larger reactors.

53. Toichi Sakata, former head of the nuclear fuel division, STA, quoted in "Project Delays Would Lead Japan to Slow Down Reprocessing Pace," *NuclearFuel*, 12 April 1993, p. 6.

54. Thomas Neff, "A Grand Uranium Bargain," *New York Times*, 24 October 1991, p. A25.

55. See table 4 for calculations of how much Japanese LEU demand could be met by blended-down weapons HEU. Estimates of the amount of HEU stockpiled in the U.S. and Russia are discussed in note 4.

56. Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons, 18 February 1993, reprinted in "Russian-U.S. HEU Agreement," *NuclearFuel*, 1 March 1993, pp. 3–5.

57. See, for example, Thomas Neff, "Integrating Uranium from Weapons into the Civil Fuel Cycle," *Science & Global Security* 3 (3–4), 1992, pp. 59–60. However, the total cost of the Strategic Uranium Reserve would be higher if large amounts of HEU were purchased up-front, instead of being stretched out over a longer acquisition schedule.

58. This projection may substantially underestimate future excess enrichment capacity. Russian Ministry of Atomic Energy chief Viktor Mikhailov is understood to have stated during a recent visit to the United States that Russian enrichment capacity is 20 million SWU per year, considerably more than the known Russian capacity of 14 million SWU per year. However, some of this additional capacity may not be presently operable.
59. Hiroshi Kurihara (PNC), "A Japanese Perspective on Storage of Nuclear Materials from Dismantled Nuclear Warheads," paper presented at The International Workshop on Nuclear Disarmament and Non-Proliferation: Issues for International Actions, Tokyo, 15–16 March 1993. See addendum and figure 1.
60. OECD-NEA/IAEA, *Uranium 1991: Resources, Production and Demand, 1992*, table 1, "Reasonably Assured Resources," p. 21. This frequently cited study is also known as the "red book." See, for example, Kurihara, *op. cit.*
61. *Ibid.*, table 2, "Estimated Additional Resources—Category I," p. 24.
62. *Ibid.*, p. 10.
63. Calculations are based on OECD/NEA-IAEA uranium reserve estimates (*ibid.*), and the Uranium Institute's projections of future world uranium requirements. Uranium Institute, *Uranium in the New World Market: A Statistical Update of Supply and Demand 1991–2010*, October 1992, table II, "Uranium Requirements," p. 39.
64. Moreover, these estimates do not account for the stimulus effect of higher uranium prices on exploration, which leads to discoveries that substantially boost estimated reserves. See, for instance, David Schramm, "The Effect of Uranium Prices on Uranium Exploration," NUEXCO Nuclear Fuel Market Analyses and Price Trend Projections, October 1989.
65. NUEXCO Information Services, Denver, Colorado, personal communication, March 1993. This estimate does not include military uranium stockpiles or HEU in nuclear weapons.
66. Russia should be all the more willing to sell large amounts of uranium to Japan at reasonable prices given the European Community's refusal to open its nuclear markets to Russian contracts at 25–50 percent below what the European Supply Agency believes is a normal market price. "EC in Discord Over Russian Nuclear Fuel," *Wall Street Journal*, 5 April 1993, p. A11B.
67. NUEXCO Information Services, Denver, Colorado, personal communication, March 1993.
68. Energy Information Administration, U.S. Department of Energy, *World Nuclear Capacity and Fuel Cycle Requirements 1992*, December 1992, "Nuclear Industry of the Commonwealth of Independent States," p. 39.
69. This estimated annual requirement assumes the Strategic Uranium Reserve is acquired at a rate of 10 million SWU per year.
70. OECD's most recent study on electricity generation costs uses a five percent discount rate as its reference case, noting that "five percent remains the most frequently used value for OECD countries." Nuclear Energy Agency/International Energy Agency, *Projected Costs of Generating Electricity: Update 1992*, December 1993, p. 24. The same study reported that, in Japanese electricity generation cost estimates provided to OECD by MITI, "a five percent discount rate is used base on prevailing real interest rates." *Ibid.*, p. 118.

71. The only case in which this might not be true is when one assumes that plutonium is a completely “free good”—that is, when none of the costs of reprocessing are reflected in economic comparisons between plutonium recycle and LEU. Such a comparison is clearly unrealistic: reprocessing always costs something, even if the plant’s capital costs have been completely written off. Yet, even if one assumes plutonium is “free,” MOX fuel would still be more expensive than LEU (about \$1,300–1,600 kg⁻¹ MOX, compared to about \$1,000–1,200 kg⁻¹-LEU, in constant 1993 dollars).
72. All savings estimates in discounted 1993 dollars, rounded to the nearest hundred million dollars.
73. Paul Leventhal and Steven Dolley, “A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium,” Updated and Expanded Report, Nuclear Control Institute, 14 January 1994.
74. British Nuclear Fuels Ltd., “Should Japan Reprocess or Build a Strategic U Reserve?,” *Nuclear Engineering International*, April 1994, pp. 28–29. Our rebuttal is presented in Steven Dolley, “Japanese Strategic Uranium Reserve: A Response to BNEL,” *Nuclear Engineering International*, September 1994, pp. 50–51.
75. British Nuclear Fuels Ltd., “Review of the Paper ‘A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium’ by Paul Leventhal and Steven Dolley of the Nuclear Control Institute,” April 1994.
76. Atsuyuki Suzuki, University of Tokyo, Atlantic Council meeting, Washington, DC, 14 September 1993.
77. Brian Chow and Kenneth Solomon, *Limiting the Spread of Weapon-Usable Fissile Materials*, Rand Corporation, November 1993, p. 35.
78. *Ibid.*, p. 34.
79. Michael Knapik, McGraw-Hill Nuclear Publications, personal communication, September 1993.
80. Quoted in Paul Eavis, “The Case Against Reprocessing,” *Plutonium and Security*, Frank Barnaby (editor), 1992, p. 20.