Disposition of Highly-Enriched Uranium from Nuclear Weapons

by

Thomas B. Cochran, Ph.D.

Presented
at the

Conference on
Conversione delle armi in progetti
di sviluppo nel Sud del Mondo

10-11 October 1998

Sacro Convento di S. Francesco
Assisi, Italy

NATURAL RESOURCES DEFENSE COUNCIL, INC
1200 New York Avenue, N.W., Suite 400
Washington D.C. 20005

Voice: 202-289-6868 (main)
202-289-2372 (Cochran)
FAX: 202-289-1060
Internet: TCochran@nrdc.org

Introduction

This report is an addendum to the report "Disposition of Plutonium from Nuclear Weapons" presented by the author at the same conference.

Declarations of Excess Highly-Enriched Uranium

United States. In 1996 the United States declared that 174.3 tonnes (t) of highly-enriched uranium (HEU) were in excess of military requirements (Table 1).[1] Approximately one-half of this was in metal or oxide form and reserved for weapons. The other half was from a variety of sources, including irradiated reactor fuel, uranium hexafluoride (UF_6) which was to be converted into naval reactor fuel but did not meet reactor fuel specifications, and uranium, chemically separated from spent production reactor fuel, containing a high concentration of uranium-236. Moreover at least 98 t of the total has an average enrichment of approximately 40% U-235, so the 174.3 t HEU total is equivalent to less than 115 t of 93.5% enriched HEU.

The United States announced in June 27, 1994, that it had produced 994 t of HEU between 1945 and 1992. This total includes HEU produced for nuclear weapons and fuel for naval reactors and civil research and test reactors. DOE announced its intention to provide an analysis of how the total, now estimated to be a little over 1000 t of HEU, was utilized. To date, however, no breakdown has been provided to indicate what fraction of the approximately 1000 t was for weapons. A reasonable assumption is that 50-75 percent was in weapons or available for weapons.

Russia. In 1992 Russia declared that it was willing to sell to the United States 500 t of HEU from weapons after blending it down (i.e., diluting it with natural or depleted uranium) in Russia into low-enriched uranium (LEU) for use as commercial power reactor fuel.[2] This was codified in a February 18, 1993, U.S.-Russian government-to-government agreement. This, in effect, was the first and only declaration of excess HEU by Russia. Unlike the HEU declared excess by the United States, all of the Russian excess HEU is to be extracted from dismantled weapons, both Russian and Ukrainian. Russia has not declared how much HEU it and its predecessor, the Soviet Union, has produced. Outside experts have estimated the Soviet/Russian HEU inventory is on the order of 1100 to 1300 t.[3]

Disposition of Excess Highly-Enriched Uranium

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[1] Uranium is considered to be "highly-enriched" provided the weight concentration of uranium-235 in the uranium is equal to, or exceeds, 20 percent.

[2] The sale of HEU from weapons was first proposed in 1991 by Thomas L. Neff, a physicist at MIT.

[3] Thomas B. Cochran, Robert S. Norris and Oleg A. Bukharin, *Making the Russian Bomb* (Boulder: Westview Press, 1995), p. 189.

United States. The United States has initiated programs to dispose of most of its excess HEU. Approximately 156 t of the 174.3 t of excess HEU is planned for disposition as commercial nuclear fuel. The United States has transferred to the United States Enrichment Corporation (USEC) 13.2 t (ultimately 14.2 t) of uranium in the form of enriched UF_6 for down blending into LEU, and signed a Memorandum of Agreement to transfer an additional 50 t of HEU (containing about 40 % U-235) over a five year period beginning in FY 1999. Currently this 50 t of HEU consists of 39.1 t of uranium metal and 10.9 t of uranium oxide (UO_2). Another 34.9 to 38 t of HEU, consisting primarily of high U-236 content uranium, will be blended down and used to fuel TVA power reactors over the next 10 to 15 years. In the future another 55 t of HEU will be blended down for use as commercial reactor fuel. The remaining 17.8 t of HEU in irradiated fuel will be disposed of as waste.

Russia. On January 14, 1994, USEC, serving as the Executive Agent for the United States, entered into a contract with the Russian Federation to purchase over a 20 year period the LEU blended from 500 t of HEU extracted from Russian weapons. The contract was estimated in 1994 to be worth $11.9 billion (unadjusted 1993 dollars), based on an initial price of $780 per kilogram (kg) of 4.4% enriched LEU, computed assuming $82.10 per SWU, and $28.50 per kg of uranium feed as UF_6.[4] In 1998 the contract was valued by USEC at $8 billion.[5]

Under the 1994 contract, 10 t of HEU (equivalent to about 310 t of LEU) were to be down blended and shipped to the United States during each of the first five years. Thirty tonnes of HEU (equivalent to about 930 t of LEU) were to be down blended and shipped during each of the subsequent 15 years. As of August 1998, the following shipments had been made:

Year	LEU (t)	Derived from HEU (t)
1995	186	6
1996	371	12
1997	480	18
1998 (thru Aug)	294	8.8[6]
Total	1331	44.8

In December 1991—three weeks before the Soviet Union was dissolved and prior to the HEU agreement—in response to a petition by U.S. (and European) uranium mining interests, the U.S. Department of Commerce initiated an antidumping investigation to determine whether the Soviet Union was exporting uranium to the United States at less than fair market value. A

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[4] LEU is valued in terms of the amount of natural "uranium feed" that must be fed into a uranium enrichment plant and the amount of work or "services" performed by the enrichment plant, the latter being measured in "separative work units" (SWU).

[5] See USEC web site: http://www.usec.com which directs one to: http://frontpage.USEC.inter.net/news_releases/8-24-98p.htm

[6] A total of 723 t of LEU, derived from 24 t of HEU, were ordered by USEC for delivery in 1998.

preliminary ruling by the International Trade Commission went against the Soviet states. Under the trade law the "closest" free market was used to establish "fair value." Thus, even if the Soviet Union and the newly independent states had been selling uranium at a profit, they could have been (and were) found to be in violation of U.S. antidumping trade law. In October 1992, Russia and the other successor states agreed to restrict uranium imports into the United States, and in return the Department of Commerce suspended the antidumping investigations against them. Commerce also ruled that the "Suspension Agreement" between the United States and the newly independent states covered the natural uranium component of HEU.

Over the past six years the U.S. government has been engaged in a lengthy process of privatizing its uranium enrichment enterprise. USEC was established as a government owned corporation in October 1992 and it began operations in July 1993. Just over two months ago, on July 28, 1998, the privatization of USEC was completed with the transfer of the government's entire ownership in USEC to the private sector. USEC currently has approximately a 75% share of the North American uranium enrichment market and a 40% share of the world market. The company supplies enriched uranium to approximately 60 customers to use in 176 nuclear reactors located in 14 countries throughout the world.

As a consequence of all these competing interests, Russia has been unable to receive fair value for the LEU delivered to the United States. Under its contract with Russia, USEC pays for the SWU component of the LEU at the time of delivery. Now operating as a private business—and as a near monopoly, rather than an agent for national security—USEC has insisted that Russia accept a low value for the SWU component.

Under the 1992 Suspension Agreement utility feed, delivered in exchange for the uranium component of the LEU, could not be resold in the United States in amounts in excess of those specified in the Suspension Agreement. This has prompted Russia to complained on numerous occasions that the suspension agreement and the privatization of USEC threaten the HEU deal. In response the U.S. government has pressured USEC into providing Russia with advanced payments against future deliveries of LEU. In mid-1994, $60 million was advanced, and in mid-1995 another $100 million was advanced against deliveries in 1996 and 1997. In December 1996, USEC transferred to the U.S. government the natural uranium equivalent of all the LEU purchases for 1995 and 1996, for which USEC paid Russia $160 million. At the same time USEC advanced Russia another $100 million against deliveries in 1998 and 1999.

On April 26, 1996, President Clinton signs into law the USEC Privatization Act which, among other things, directed USEC to return to the Russian Executive Agent the natural uranium component of shipments. The Act facilitated Russia's disposition of the natural uranium beginning in January 1997. Subsequent legislation gave Russia clear title to the feed component and permitted Russia to sell future deliveries of the uranium component. In 1997 Russia reaches agreement in principle with Cameco, Cogema, and Nukem to sell the natural uranium component associated with LEU deliveries over the next ten years. To date there has been no public announcement indicating completion of natural uranium purchase arrangements between Russia and the Cameco/Cogema/Nukem consortium or any other buyers. Last month the U.S. Department of energy was again seeking arrangements to rescue the troubled HEU deal by promising Russia aid to address falling uranium prices and reduced revenues from its uranium sales.[7]

Summary and Conclusion. In both the United States and Russia, the amount of HEU being removed from military stockpiles for use as commercial use represents a small fraction of their respective military stocks, and therefore the national security impacts of these removals are not particularly significant. To use the "swords into ploughshares" analogy, both countries are retaining vast quantities of "steel" to make new swords should the need arise. The United States and Russia are each hiding the relative magnitude of their respective HEU reductions by refusing to reveal the size of the HEU inventories each is retaining for military purposes.

The U.S. program for blending down its relatively small excess HEU stockpile into reactor fuel is functioning smoothly, albeit slowly. The success of the Russian HEU disposition program is being threatened by Russia inability to receive equitable and prompt value for the LEU delivered to the United States. This is a consequence of the restrictions placed on the sale of the natural uranium component in the United States and the low price for enrichment services offered by USEC.

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[7] "DOE Scrambles to Repair Russian Uranium Deal," *The Energy Daily*, September 28, 1998, pp. 1-2.

[incomplete]

I. Economics.

A. Comparing of Open and Closed Fuel Cycles.

The cost of electricity generated by nuclear power plants can be broken down into three components: a) capital cost, b) fuel cycle cost, and c) operating and maintenance (O&M) cost. The capital cost component represents that portion of the electricity price needed to pay the principal and interest on the money borrowed to pay for the construction of the power plant. Fuel cycle costs include all cost associated with purchasing, processing and transporting the fuel and disposing of the spent fuel. O&M costs are the remaining costs associated with operating the plant on a day-today basis.

Fuel cycle costs depend upon two sets of determinants--one set establishes the amount of fuel or fuel services that are required, and the other set is the unit costs of the various fuel services. The amount of fuel and fuel services required is a function of the type of reactor, its operating parameters, the type of fuel used, and whether the reactor is operating on an open or closed fuel cycle. As a reference case we will be using typical operating parameters of a VVER-1000 reactor. It can be shown that our conclusions would be the same had we chosen an other other light water reactor and the results are also insensitive to the ranger of operating parameters found among operating.

B. Reference VVER-1000 Reactor Parameters.

As our reference reactor we select the VVER-1000, which is designed to operate with a thermal power output of 3000 MWt and a gross electrical power output of 1000 MWe, which implies that the efficiency for converting thermal to electrical energy is 33 percent. After the first couple of refuelings VVER-1000 reactors are typically refueled with 4.4%-enriched uranium.

Fresh Fuel Requirements. The amount of natural uranium required to produce 4.4%-enriched VVER fuel depends on how much U-235 is left in the enrichment plant tailings. Assuming the enrichment plant is operating at 0.2% tails assay, and ignore slight processing losses, in order to produce one kgHM of 4.4%-enriched fuel, one must obtain 9.693 kg of U_3O_8, convert it to uranium hexafloride (UF_6), and then enrich the uranium from its natural level (0.711% U-235) to the 4.4% U-235 level. This last step requires 7.460 kg "separative work units" (kg SWU), where a kg SWU is a measure of the work required to separate the U-235 and the U-238 isotopes at the enrichment plant. The enriched uranium, as UF_6, is then converted to uranium-dioxide (UO_2) and fabricated into fuel rod assemblies. These fuel requirements (per kgHM) of fuel) are summarized in the first two columns of Table 1.

Table 1. VVER-1000 Fresh LEU Fuel Cost ($/kgHM)

	Requirements (per kgHM fuel)	Unit Cost	Cost ($/kgHM)
Yellowcake (U_3O_8)	9.639	$ 39±13/kg	276±48
Conversion (U_3O_8 to UF_6)	8.219 kgHM	9±3/kgHM	74±186
Enrichment	7.460 kg SWU	100±25/kg SWU	746±186
Conversion (UF_6 to UO_2)	1 kgHM	8±2/kgHM	8±2
Fabrication	1 kgHM	225±25/kgHM	225±25
Total			**1330±220**

Fuel burnup. "fuel burnup" is a measure of the amount of thermal energy generated per unit of fuel. The amount of plutonium (and unused uranium) in the spent fuel is a function of the fuel burnup of the discharged fuel. The fuel burnup varies among operating reactors, typically ranging between 35 and 40 MWd/kgHM for VVER-1000 reactors. We will assume for our calculations a burnup of 40 MWd/kgHM. Within this burnup range the content of uranium and plutonium in one tHM of spent fuel is shown in Table 2.

Table 2. Fuel characteristics of a VVER-1000 at different fuel burnups.

	35 MWd/tHM	40 MWd/tHM
Uranium (kg/t)	953.8	947.8
%U-235	1.52	1.26
%U-236	0.554	0.596
Plutonium (kg/t)	9.74	10.49
%Pu-238	1.408	1.829
%Pu-239	62.67	59.34
%Pu-240	20.46	20.96
%Pu-241	12.60	14.02
%Pu-242	2.855	3.848
%fissile Pu (fPu=Pu-239+Pu-241)	75.27	73.36

C. Unit Costs of Various Fuel Cycle Services.

The open and closed fuel cycles are depicted in Table 3. The total cost of either cycle is found by summing up the cost of the various fuel cycle components, each the product of the amount of service required and the unit cost of that service.

Table 3. Components of an open and a closed fuel cycle.

Open Cycle

Front End (Fresh Fuel Production)
Yellowcake (U_3O_8) Purchase
Conversion to UF_6
Uranium Enrichment
Conversion to UO_2
UO_2 Fuel Fabrication

Back End (Spent Fuel Disposition)
Spent Fuel Storage
Spent Fuel Transportation
Spent Fuel Disposal

Closed Cycle

Reprocessing
Plutonium and Uranium Storage
MOX Fuel Fabrication
Low/Intermediate Waste Disposal
High-Level Waste Vitrification
High-Level Waste Transportation
High-Level Disposal

In the case of the closed fuel cycle in order to make a fresh MOX fuel assembly, one must blend the plutonium recovered by reprocessing spent fuel with recovered uranium or uranium from other sources. In either case the amount of uranium recovered from the reprocessed spent fuel will exceed what is required to blend with the plutonium, and consequently credit for the excess uranium must be taken into account.

We describe below our assumptions regarding the unit costs of each fuel cycle service. We rely upon Western price estimates, as there is little reliable Russian price data. Reducing all the costs by approximately the same proportion, of course, would not cange the overall conclusion of the economic analysis.

Yellowcake (U_3O_8) Unit Cost. There are several prices for U_3O_8 that are tracked by NUKEM, a uranium broker:[1]

* U.S. restricted uranium spot market price--i.e., buyer/seller is restricted from receiving CIS product

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[1] See *NUKEM Market Report*, published monthly.

- U.S. unrestricted spot market price--i.e. buyer/seller is restricted from receiving CIS product
- U.S. average contract price (domestic suppliers)
- U.S. average contract price (imports)
- EURATOM medium and long-term price

In 1995 the U.S. spot prices were in the range:

U.S. restricted uranium spot market price:	\$9.50 to \$11.75/lb U_3O_8 (\$24.70 to \$30.50/kgU)
U.S. unrestricted spot market price:	\$7.15 to 7.55/lb U_3O_8 (\$18.60 to 19.60/kgU)

The U.S. average contract prices have been dropping steadily over the past decade to the following in 1993 (the last year for which this price is quoted):

\$13.14/lb U_3O_8 (\$34.20/kgU) from domestic suppliers; and
\$10.53/lb U_3O_8 (\$27.40/kgU) from imports

The EURATOM medium and long-term price has been steadily dropping from \$32.50/lb U_3O_8 (\$84.50/kgU) in 1987 to \$21.17/lb U_3O_8 (\$55.00/kgU) in 1993.

The OECD (1994) fuel cycle cost analysis assumes uranium reference price of \$50/kgU (in 1990) increasing at 1.2% per year, and a sensitivity analysis range of \$40-90/kgU.[2] Given the U.S. prices and the precipitous drop in EURATOM prices since 1987, the OECD reference case assumption appears to be an upper limit for projected uranium prices in the foreseeable future.

Based on the foregoing we believe \$15±5/lb U_3O_8 (\$39±13/kgU) is a reasonable projection of uranium prices in the foreseeable future. While prices may fall outside this range for short periods, historical trends would suggest that any short-term rise in uranium prices due to faster than anticipated growth in nuclear electricity demand will be met by an increase in uranium supply, assuring relative price stability over the long term.

Uranium Conversion (U_3O_8 to UF_6) Unit Cost. Most estimates of the cost to convert U_3O_8 to UF_6 are is in the range of \$6-11/kgU. The U.S. National Academy of Sciences (1994) assumed \$9±1/kgU,[3] while the OECD (1994) assumed \$8/kgU as its reference case and a sensitivity analysis range of \$6-11/kgU.[4] We will assume the same range, \$9±3/kgU.

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[2] *The Economics of the Nuclear Fuel Cycle*, Nuclear Energy Agency, Organization for Economic Co-operation and Development (OECD), (Paris, 1994), pp. 111 and 13.

[3] *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Panel on Reactor-Related Options for Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, National Academy of Sciences (Washington, D.C.: National Academy Press, 1995) p. 285.

[4] OECD (1994) pp. 11 and 13.

Enrichment Unit Cost. The U.S. spot market price for enrichment service has increased from \$53.50-\$55/kgSWU in 1990 to \$75-87/kgSWU in 1995.[5] The OECD (1994) reference case estimate of the enrichment cost is \$110/kgSWU.[6] Due to current excess capacity and likely improvements in technology, the long-term trend in enrichment prices should be downward. We will assume a price in the range of \$100±25/kgSWU.

Conversion (UF_6 to UO_2) Unit Cost. We assume this cost to be in the range \$8±2/kgU. The price for this conversion service, however, is usually included in the price of fuel fabrication.

LEU Fuel Fabrication Unit Cost. The U.S. National Academy of Sciences (1994) estimated LEU fabrication costs to be \$200±30/kgU.[7] The OECD (1994) assumed for its reference case a much higher value, namely \$275/kgU, and its sensitivity range is \$200-350/kg.[8] As we believe the OECD reference estimate is unjustifiably high, we will assume the fabrication prices is in the range \$225±25/kgU.

Fuel Reprocessing Unit Cost. Today in the West estimates of the cost of spent fuel reprocessing (exclusive of charges for long-term high-level waste storage, transportation, and burial) ranges from \$750/kgHM to \$1800/kgHM.[9] Cogema and BNFL reportedly charged their customers about \$1400/kgHM to \$1800/kgHM to subsidize construction of their respective plants at La Hague and Sellafield.[10]

BNFL's Thermal Oxide Reprocessing Plant (THORP) at Sellafield began operating on March 27, 1994, and BNFL projects that it will obtain its full capacity, 700 tHM/y, in two years.[11] BNFL claims THORP represents a total investment of £2.85 billion (\$4.56 billion), and BNFL has secured orders worth £9 billion (\$14.4 billion) covering the first ten years of operation, over half from overseas, and £3 billion (\$4.8 billion) of foreign contracts for reprocessing during the second ten years.[12] NUKEM claims two-thirds of the capital investment in THORP was met by advanced payments by utilities, and that 3300 tHM of of the 7000 tHM second ten year campaign has been committed.[13] BNFL is said to be charging about \$900/kg for

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[5] *NUKEM Market report*, February 1995, p. 36.

[6] OEDC, 1994, p. 11.

[7] US. NAS (1994), p. 285.

[8] OEDC, 1994, pp. 11 and 13.

[9] Brian G. Chow and Kenneth A. Solomon, "Limiting the Spread of Weapon-Usable Fissile Materials," RAND, 1993, pp. 33-34.

[10] Ibid.

[11] BNFL, "Annual Report and Accounts 1994," p. 6 and 19.

[12] Ibid., p. 19.

[13] UKEM Market Report, September 1995, pp. 6-7.

contracts that would cover the second ten year operating period of its THORP plant at Sellafield.[14] As was done in the RAND study by Chow and Solomon, we assumed the cost of reprocessing is $900/kgHM, where one-half of this represents capital costs and one-half represents operating costs.[15] The $450/kgHM capital cost is based on the reported cost of the THORP plant as being $2.8 billion and an average throughput of 700 t/y over 25 year life.

MOX Fuel Fabrication. Chow and Solomon note that there is substantial uncertainty in the cost of MOX fuel fabrication, with some West European estimates ranging from $1,300 to $1,600/kgHM and one estimate as high as $3,000/kgHM.[16] The West European estimates appear reasonable fore a new plant in the West. Seimans invested 1.2 billion DM to construct a 120 tHM/y MOX plant at Hanau, Germany.[17] The plant is unlikely not be completed due to opposition by the Hesse SPD-Green government. The cost to purchase and operate this plant has been estimated to be:

250-300 million DM purchase price (scrap value);
200 million DM to complete the plant;
500 million DM for future decommissioning cost;

and the operating cost of the Hanau plant is estimated to be 800 DM/kg MOX.[18] Thus, had the Hanau plant been completed the cost of MOX would have been about 2500 DM/kg-MOX [$1800/kg-MOX].[19] If purchases at its scrap value and completed the cost of MOX would be about 1700 DM/kg-MOX [$1200/kg-MOX].[20]

Spent Fuel Disposal Cost. In the United States the utilities must pay the Federal Government $0.001 per kilowatt-hour of nuclear energy generated to cover the cost of the geologic disposal of spent fuel. For a 1000 MWe power plant operating at 70 percent of the time (a 70% capacity factor) and discharging 25 tHM spent fuel annually, this amounts to approximately $250/kgHM, or $12.5 billion for storage of 50,000 tHM generated by 100 reactors operating 20 years each. Some have argued that due to mismanagement of the high-level radioactive waste repository, the Government's waste fund will be inadequate. Perhaps the charge should be doubled to $500/kgHM. Waste transportation and interim storage cost are a small fraction of the disposal cost and can be ignored.

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[14] Ibid.

[15] Chow and Solomon, RAND, p. 34.

[16] Ibid., p. 32.

[17] Frank von Hippel, Draft notes summarizing meetings in Germany on reprocessing (May 8-10, 1995), May 14, 1995.

[18] Ibid.

[19] ((1200+200+500)*10^6DM*0.11/(120*10^3 kg-MOX))+800 DM/kg-MOX = 2741 DM/kg-MOX. We have assumed a 25 year amoritization.

[20] ((300+200+500)*10^6 DM*0.11/(120*10^3 kg-MOX))+800 DM/kg-MOX= 1717 DM/kg-MOX.

European estimates of the disposal costs are higher than those in the United States. A 1995 study "Economics Comparison of Various Spent Fuel Disposal Options," by Cologne University Institute of Energy Economics provides the following summary of direct disposal cost estimates in deutsche marks (normalized to a spent fuel burnup of 40 MWd/kgHM):[21]

	DM/kgHM	DM/$	$/kgHM
Karlruhe-Cologne (1984)	1200	3.00	400
OECD/NEA (1985)	6240	3.00	2080
Fichtner (1991)	2000	1.50	1300
German Utilities (1993)	2900	1.68	1700
OECD/NEA (1994)	2700-4000	1.64	1600-2400

We have converted the deutsche marks to dollars assuming the exchange rates given above.

If one switched to MOX fuel, one must still dispose of the fission product waste, which in the MOX case would be in the form of vitrified high-level waste. The amount of waste that can be placed in a geologic repository is limited by the heat loading from the fission products, and not from the physical volume of the individual waste canisters. The difference in the heat loading between MOX and LEU fuel is less than a factor of two. Therefore, regardless of whether the spent fuel disposal cost is $500/kgHM the cost of disposing of the fission product waste from reprocessing will be not less than a factor of two less. Therefore, differences in the cost of waste management and transportation will not alter the conclusion that reprocessing and plutonium recycle is uneconomical.

D. The Cost of LEU Fresh Fuel for VVER-1000.

We are now able to calculate the cost of fresh LEU fuel for the VVER-1000 reactor. As previously indicated the fuel service requirements are summarized in the first two columns in Table 5. The third column gives the unit costs and the last column the product of the two. As seen from Table 5, the cost of fresh VVER-1000 fuel based on U.S. prices is estimated to be in the range $1000/kgHM to $1400/KgHM. A German utility executive is said to have quoted the price of LEU fuel to German utilities as 2500 DM/kgHM, which would be about $1700/kgHM. This higher price in Europe no doubt is a reflection of the fact that the average price for natural uranium under EURATOM contracts is more than 60 percent higher than the average contract prices of U.S. domestically supplied uranium.

E. The Cost of MOX Fuel for VVER-1000.

By reprocessing the VVER-1000 spent fuel, the plutonium and unused uranium can be recovered and used to make fresh fuel. The recovered plutonium can be converted to plutonium-

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[21] Ibid.

dioxide (PuO_2) and blended with UO_2 to form what is called mixed-oxide (MOX) fuel. If plutonium were a free good it would be straight forward to estimate the cost of MOX fuel fabrication in $/kgHM-MOX and compare this against the cost of fresh LEU fuel estimated above. But of course plutonium is not a free good. To compare the cost of the open and closed fuel cycles, one must take into account all of the fuel cycle costs, including the cost of reprocessing the spent fuel to recover the plutonium and unused uranium.

To make VVER-1000 fuel from MOX, a good first approximation is to assume that the MOX must have the same fissile material concentration as the fresh LEU fuel, namely, 4.4 percent. In Table 6 (a) we have assumed that the MOX is made by blending the recovered plutonium with depleted uranium tails from the enrichment plant. In Table 6 (b) we have assumed that the uranium blend stock comes from the uranium recovered by reprocessing VVER-1000 fuel. Actually, more detailed calculations indicate that in order to match the neutronic behavior of the fuel at the end of the burnup period, one must start with a somewhat higher concentration of plutonium--on the order of 7% Pu instead of 5.6% Pu as indicated in Table 6 (a).

The plutonium requirements are lower in Table 6 (b) compared to the requirements in Table 6 (a) because the uranium blend has a higher enrichment. But from Table 6 (b), we see that for every kg of MOX fuel one must reprocess about four kg of VVER-1000 spent fuel in order to recover the needed plutonium [$4*0.00974$ kg $\approx$ 0.0391 kg]. The ratio would be about five if we made a more careful calculation designed to match the neutronic behavior of the fuel at the end of the fuel life in the reactor.

In Table 7 we summarize the cost of VVER-1000 MOX fuel in order to make a direct comparison with the cost of VVER-1000 fresh LEU fuel summarized in Table 5.

F. Comparison of LEU and MOX Fuel Cycle Costs.

As can be seen by comparing the totals in the Tables 5 and 7, MOX fuel costs about three to four times as much as LEU fuel. In our calculations we have ignored fabrication and conversion losses because these are only on the order of 1.5 percent.

So far we have also ignored any differences in managing the back end of the fuel cycle, including managing and disposition of fission product wastes and storage of separated plutonium from reprocessing on the one hand and storage and disposition of spent fuel in the case of the once through fuel cycle.

In the West some proponents of the use of plutonium fuels mask the true cost of MOX fuel by arguing that reprocessing is a necessary step in waste management. They then attribute the reprocessing cost to the LEU fuel cycle cost and treat the plutonium as a free good. But this is not true since spent fuel can be disposed of as a waste and in the United Stated it is Government policy to do so. Moreover, in any case, as seen by comparing the results in Table 5, MOX is uneconomically even if the plutonium is treated as a free good, i.e., even if you ignore the cost of reprocessing and the uranium credit in Table 5.

Some may argue that a comparative analysis of LEU and MOX fuel for VVER-1000 reactors is irrelevant because Minatom plans to use MOX in liquid metal fast reactors (BN type) and not in VVERs. Because of the higher fuel fabrication costs the fuel for BN reactors will be more expensive than the VVER-1000 LEU fuel even if the plutonium is treated as a free good. More importantly, the fuel cost of a nuclear plant represents only about 15 percent of the total cost of the electricity it produces. About 75 percent of the electricity cost os associated with the cost od constructing the plant. BN-600 turned out to be 1.5 to 1.7 times as expensive to construct as a 1000 MWe VVER.[22] Although one-third larger than BN-600, the BN-800 did not benefit from economies of scale. The new breeder was estimated in 1990 to cost 900 rubles/kw compared to 600-650 rubles/kw for the improved-safety VVER.[23] These estimates no doubt understate the true cost difference between BN and VVER reactors. In any case fast breeders turned out to uneconomical in Russia as they have proven in the West.

Since the cost of construction of a BN type reactor is more than 50 percent greater than the constructing a VVER-1000, even if the BN fuel were free, the electricity generated by a BN reactor would be substantially greater than the cost of electricity generated by a VVER-1000.

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[22] Ibid., p. 15. BN-600 cost 550 rubles per installed kw compared to 333 rubles/kw for the 1000 Mw_e VVER; *Nucleonics Week*, July 26, 1990, p. 14.

[23] *Nucleonics Week*, July 26, 1990, p. 14.

Table 4. Composition of MOX fuel using reactor-grade plutonium.
Recovered from 4.4% enriched VVER-1000 spent fuel after 35 MW_td/tHM burnup.

	Total (kg)	**Fissile (kg)**
Pu (75.27% fPu)	0.0559	0.0421
U (0.2% U-235)	0.9441	0.0019
Total	**1.000**	**0.0440**

(a) Using uranium from enrichment tails.

	Total (kg)	**Fissile (kg)**
Pu (75.27% fPu)	0.0391	0.0294
U (1.52% U-235)	0.9609	0.0146
Total	**1.000**	**0.0440**

(a) Using uranium recovered by reprocessing VVER-1000 fuel.

Table 5. VVER-1000 Fresh MOX Fuel Cost ($/kg)

	Requirements (per kgHM fuel)	Unit Cost	Cost ($/kgHM)
Reprocessing	4-5 kg/HM spent fuel	$900/kgHM	3600-4500
Fabrication	1 kgHM	$1250-1800/kgHM	1250-1800
Uranium Credit			
U_3O_8	11-14 kg	$16-20/kg	(176-280)
Conversion	11-14 kg	$6-9/kg	(66-126)
SWU	4.4-5.5 kg SWU	$75-100/kg SWU	(330-410)
Total			**$4000-5700**