# THE COST OF RUSSIA'S CIVIL PLUTONIUM SEPARATION PROGRAM

by

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## I. Introduction

This report analyzes the direct costs to Russia of separating plutonium from civilian nuclear spent fuel and recycling the recovered plutonium as fuel in conventional or breeder power reactors. NRDC is primarily concerned with serious nuclear proliferation and environmental, health, and safety risks associated with spent fuel reprocessing. The Russian Ministry of Atomic Energy (Minatom), however, has consistently underplayed concerns about the safety of Russia's reprocessing program and its contribution to Russia's growing stockpiles of weapon-usable fissile materials, arguing instead that reprocessing has net economic and energy security value for Russia.

Our analysis shows that there are net economic disadvantages to reprocessing and plutonium recycling when compared to the use of fresh LEU (low-enriched uranium) fuel in Soviet-designed reactors. We conclude that, given the excessive economic cost of reprocessing and the proliferation risks associated with the separation of weapon-usable plutonium, civil spent fuel reprocessing should be halted indefinitely, until such time as all excess plutonium stockpiles are eliminated and the risks and costs of civil plutonium use have been dramatically reduced.

We will begin by providing a brief overview of the current status of Russia's reprocessing program, and Minatom's plans for its future expansion.

## II. Overview

### A. Russia's Nuclear Fuel Cycle and Soviet-designed Reactors

The fuel cycle of a nuclear reactor can be divided into three stages. The first stage, the so-called "front end," refers to the preparation of uranium for use in power reactors. Uranium is mined from typically low-grade deposits, requiring the extraction of natural uranium (0.7% $U^{235}$, 99.3% U-238) by a milling process that leaves a large, mildly-radioactive waste residue called mill "tailings." Further chemical refining produces a uranium compound called "yellowcake," which is then converted to uranium hexaflouride ($UF_6$), a gas at ordinary temperatures and pressures, and shipped to an isotope separation ("enrichment") plant, where a variety of techniques can be used to separate a "product" stream enriched in U-235 from a "tails" stream of "depleted" uranium. The slightly enriched uranium (typically 3-4.5 % U-235), still in the form of gaseous $UF_6$, then goes to a fuel fabrication plant, where it is converted to the form of solid pellets of uranium dioxide ($UO_2$) and inserted into tubes to form fuel rods. The rods are then assembled into bundles and shipped to the reactor site.

The second stage involves use of the fuel in the reactor, which for a typical fuel assembly normally last about three years. A portion of the U-235 atoms in the fuel undergo fission, releasing heat that is transferred via a coolant (usually pressurized water) to a "steam generator" that drives turbines which in turn generate electricity.

The third stage, the so-called "back-end" of the fuel cycle, refers to a variety of operations that may be performed on spent fuel, ranging from "wet storage" in pools at the reactor site; to "dry-cask" interim storage at, or away from, the reactor site; to "permanent disposal" in an underground waste repository; to possible "reprocessing" to extract the fissile plutonium for "recycling" into fresh "Mixed-Oxide" (MOX) fuel, in which plutonium takes the place of U-235.

There are two approaches that various countries have taken to managing the back-end of their civil nuclear fuel cycles. One of these, called the open or "one-through" cycle, involves storing spent nuclear fuel indefinitely, and ultimately disposing of it as a nuclear waste. The United States has, so far, taken this approach to handling its spent fuel. The second approach, called a closed cycle, requires that spent fuel be reprocessing to separate plutonium, unused uranium, and highly radioactive fission products into three streams. The plutonium and unused uranium can be reused as fresh fuel for nuclear reactors after suitable conversion and refabrication. The radioactive fission products then are disposed as nuclear waste after conversion and packaging. The United Kingdom, France, Japan, and Russia are currently reprocessing commercial spent nuclear fuel.

Minatom has pursued a closed-fuel-cycle policy for Russia's civil power reactors, and is now attempting to capitalize on the spent fuel storage crisis facing many Eastern European countries and former Soviet states today. The Soviet Union and its Eastern bloc allies relied almost entirely on Soviet-designed reactors for their nuclear energy.[1] Soviet-designed reactors now operate in ten countries throughout Eastern Europe and the former Soviet Union. There are presently 68 such reactors in operation and 23 reactors in various stages of construction.[2] With the exception of four small, older graphite-moderated water-cooled reactors and two liquid metal fast breeder reactors (LMFBRs), operating Soviet-designed power reactors fall into two main reactor types: 15 graphite-moderated water-cooled RBMK reactors, and 47 pressurized water-moderated and cooled VVER reactors (27 VVER-440's and 20 later-model VVER-1000 reactors).

Russia has not yet obtained financing for completion of all Minatom's desired reprocessing and fuel fabrication facilities. As outlined below, Russia is currently reprocessing spent fuel from VVER-440 reactors only.[3] Moreover, Russia still lacks a commercial-scale MOX fuel fabrication plant. Therefore, Russia currently stores its separated plutonium in canisters (each approximately 1930 cubic centimeters, holding no more than 3 kilograms (kg) $PuO_2$). These small, easily transportable containers leave Russia's stores of separated plutonium particularly vulnerable to nuclear theft, and only one to two such containers would be required to amass the minimum amount of plutonium needed for a nuclear explosive.

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[1] An exception is the Krsko plant in Slovenia, a Western model nuclear reactor built by Westinghouse.

[2] Energy Information Administration, *World Nuclear Outlook 1994* (Washington, DC: Department of Energy, December 1994), pp. 83-101. There are plans to complete two such reactors at Cienfuegos, Cuba. In addition, Minatom and the Iranian government signed a contract in January 1995 for the construction of a Soviet-designed power plant at Bushehr, Iran. Construction began at the end of 1995.

[3] RBMK spent fuel is not reprocessed, because the enrichment of the recovered uranium (0.72% U-235) and the concentration of plutonium (5 kg/tHM) is only 50-60% of that in VVER spent fuel. There is no evidence that Russia plans reprocess RBMK spent fuel in the future, which traditionally has been stored in on-site water-filled storage pools at the reactors.

### B. Russia's Civil Nuclear Fuel Reprocessing Program

Chemical separation (radiochemical, or reprocessing) plants are used to separate plutonium and uranium from the highly radioactive fission products contained in irradiated reactor fuel. The Soviet Union constructed chemical separation plants, which Russia still operates, at the three main sites where plutonium for weapons was produced and separated - Chelyabinsk-65, Tomsk-7 and Krasnoyarsk-26. Only one of these sites, Chelyabinsk-65, is used to reprocess spent fuel from civil power reactors.

***The RT-1 Plant.***[4] Spent fuel from VVER-440 civil power reactors is reprocessed at the RT-1 chemical separation plant, located at Chelyabinsk-65 (otherwise known as the Mayak Chemical Combine) in Ozersk in the Southern Ural Mountains. Since its conversion from military to civil operations in 1977, RT-1 has reprocessed naval fuel (from ice breakers and submarines), test reactor fuel, and fuel from VVER-440 reactors. Prior to the breakup of the Soviet Union, RT-1 also accepted VVER-440 spent fuel from civilian power reactors in Bulgaria, Finland, the former Czechoslovakia, the former German Democratic Republic, and Hungary.

The amount of spent fuel shipped to RT-1 has declined significantly since the collapse of the Soviet Union. As storage facilities in Eastern Europe and the former Soviet Union near capacity, however, these countries are again turning to Russia to manage their spent fuel. Bulgaria, Armenia, Hungary, and Ukraine all currently have reprocessing agreements with Russia.[5] Finland also has a reprocessing contract with Russia which will expire this year.[6]

RT-1 is said to have a capacity of 400 tones heavy metal (tHM) of spent fuel per year. Over its first ten years of operation, RT-1 received approximately 2380 tHM of civilian spent fuel, and reprocessed approximately 200 tHM of spent fuel annually. Currently, there are about 30 tonnes of separated plutonium stored in transport containers at RT-1.

***The Partially Constructed RT-2 Plant.***[7] Russia still lacks an operational chemical separation plant for VVER-1000 spent fuel. At Krasnoyarsk-26 (also called the Mining Chemical Combine) in Zheleznogorsk, construction of a second chemical separation plant for civil spent fuel, called RT-2, began between 1976 and 1978, but was never completed. RT-2 would have the capability to reprocess VVER-1000 spent fuel, which contains roughly one percent plutonium (10 kg of retrievable plutonium per tonne of spent fuel). Minatom also intends to use RT-2 to recover uranium, which could be refabricated into fresh VVER fuel assemblies.

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[4] Information in this section is from: Thomas B. Cochran, Robert S. Norris, and Oleg Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* (Boulder: Westview Press, 1995), unless otherwise specified.

[5] Thomas B. Cochran, Miriam B. Bowling, and Elizabeth Powers, "Difficult Legacy: Spent Fuel from Soviet Reactors," NRDC Nuclear Weapons Databook Series, 31 January 1996.

[6] Ibid.

[7] Information in this section is from: Thomas B. Cochran, Robert S. Norris, and Oleg Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* (Boulder: Westview Press, 1995), unless otherwise specified.

Following a reduction in funding for the project in 1985, the plant became increasingly controversial and faced considerable public opposition. In July 1989, *Komsomolskaya Pravda*, a major Russian newspaper, reported that more than 60,000 Krasnoyarsk residents signed a petition protesting RT-2, which resulted in construction being halted. In 1990, an order from Minatom further delayed construction for five years.

Despite President Boris Yeltsin's January 1995 decree (No. 72) which called for the completion of RT-2, it is clear that Russia cannot afford to complete the plant, and foreign investment in the project seems highly unlikely in the foreseeable future. Estimates of the cost of completing the plant range from $1.9 billion,[8] 3.5 trillion rubles[9] (early-1994 exchange rate: equivalent to $2.2 billion), and 2.08 trillion rubles[10] (1994 exchange rate: equivalent to $1.3 billion).

Most importantly, without contracts for foreign fuel reprocessing, there will simply not be enough available VVER-1000 fuel to justify completion of RT-2. Operating at full capacity, the RT-2 plant would possesses the capability to reprocess approximately 1,500 tonnes of spent fuel per year (producing 15 tonnes/yr of weapon-usable plutonium). The storage pool at the plant, which can hold up to 6,000 tHM of spent fuel, reportedly held approximately 1,200 tHM by the end of 1994.[11] Therefore, assuming an accumulation from past shipments of approximately 1,200 tHM, and a yearly production rate of Russian VVER-1000 reactors of approximately 100 tHM additional spent fuel for ten more years,[12] by 2005 (when Minatom hopes to bring RT-2 online), the plant would have only about 2,200 tHM of spent fuel to reprocess. Even operating at only 50% capacity, RT-2 could reprocess this amount of spent fuel within its first three years of operation.[13]

Minatom still holds hopes of obtaining reprocessing contracts from foreign countries - e.g., the Czech Republic, South Korea, and Taiwan - to make completion and operation of the plant economically feasible, but so far has been unsuccessful.[14] In late 1995, Switzerland and Germany,

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[8] Anatoli Diakov, E-Mail to Frank von Hippel, 8 April 1995.

[9] *Moscow INTERFAX* in English, 1624 GMT 31 October 1994 (Reproduced in FIBS-SOV-94-211, 1 November 1994, pp. 28-29).

[10] B.S. Zakharkin, *Khimicheskiye Osnovy Regeneratsii Otrabotavshego Topliva Transportnykh Reaktorov na Zavode RT-2*, January 17-18, 1995.

[11] Much of this spent fuel had accumulated prior to the collapse of the Soviet Union from Russia and Ukraine, whose VVER-1000 reactors produced approximately 130 tHM and 185 tHM of spent fuel per year respectively.

[12] There are five VVER-1000 plants in Russia, which each produce about 19.2 tHM/year (assuming a capacity factor of 70%).

[13] 2,200 tHM * 1/750 tHM/yr

[14] Anatoli Diakov, E-Mail to Frank von Hippel, 8 April 1995.

formerly the largest potential foreign clients of RT-2, announced that they would not sign reprocessing contracts with Russia.[15]

## III. Economic Analysis of Open and Closed Fuel Cycles for Soviet-Designed Reactors

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 costs 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 factors: 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 are 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 a VVER-440 reactor design, and that the results are also insensitive to the range of operating parameters for Soviet-designed reactors.

### A. Reference Case: The VVER-1000 Reactor

We have selected the VVER-1000 as a reference case, which is designed to operate with a thermal power output of 3000 Megawatt thermal (MWt) and a gross electrical power output of 1000 Megawatt electric (MWe), which implies that the efficiency for converting thermal to electrical energy is 33%. After the first couple of refuelings, VVER-1000 reactors are typically refueled with 4.4%-enriched uranium.

***Fresh Fuel Requirement.*** 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 ignoring slight processing losses, in order to produce one kilogram heavy metal (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 kilogram "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.

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[15] Sergey Fedorchenko, "Germany and Switzerland leave Krasnoyarsk-26 to stand idle," Segodnia (Russian newspaper), 29 November 1995.

***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, needed to calculate the economic value of reprocessing, is a function of the fuel burnup, which varies among operating reactors (typically ranging between 35 and 40 Megawatt day/kilogram heavy metal (MWd/kgHM) for VVER-1000 reactors). Within this burnup range, one tHM of spent fuel will contain:

| | 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)[16] | 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)[17] | 75.27 | 73.36 |

## B. Unit Costs of Fuel Cycle Components

The open and closed fuel cycles are depicted below. 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.[18]

[16] Since the Pu-240 concentration exceeds 19%, the plutonium is called *reactor-grade plutonium (RGPu).*

[17] Since only the odd numbered isotopes fission efficiently in thermal reactors such as the VVER, the Pu-239 and Pu-241 concentrations are added together to give the fissile plutonium (fPu) content of 73-75%. As the fissile content of the uranium and plutonium combined is slightly higher at 35 MWd/tHM than at 40 MWd/tHM, we will perform our economic calculations assuming the lower burnup of 35 MWd/tHM.

[18] For the conversion of fuel costs, when measured in $/kgHM, into electricity costs measured in cents/kilowatt-hour, multiply the fuel costs in $/kgHM by:

$$(100\ \text{cents}/\$)*(B\ \text{MWd/kgHM})^{-1}*(\in\ \text{MWe/MWt})^{-1}*(1\text{day}/24\text{hour})*(1\text{MW}/1000\text{kW})*F = (F/240B\in)(\text{cents/kWh})/(\$/\text{kgHM})$$

where B is fuel burnup measured in MWd/kgHM, $\in$ is the thermal conversion efficiency, and F is the average load factor. For a VVER-1000, as noted above, B is in the range of 30 to 40 MWd/kgHM, $\in = 1/3$, and F is meant to be about 0.75, but in 1994 averaged about 0.5 for 19 operating reactors.

| Open Cycle | Closed Cycle |
|---|---|
| Front End (Fresh Fuel Production) | Reprocessing |
| Yellowcake ($U_3O_8$) purchase | Plutonium and Uranium Storage |
| Conversion to $UF_6$ | MOX Fuel Fabrication |
| Uranium Enrichment | Low/Intermediate Waste Disposal |
| Conversion to $UO_2$ | High-level Waste Vitrification |
| LEU Fuel Fabrication | High-level Waste Storage |
| | High-level Waste Transportation |
| Back End (Spent Fuel Management) | High-level Waste Disposal |
| Spent Fuel Storage | |
| Spent Fuel Transportation | |
| Spent Fuel Disposal | |

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. What data there is, however, indicates that fuel cycle components cost proportionally less in Russia than in the West. Reducing all the costs by the same proportion, of course, would not change the overall conclusion of the economic analysis.[19]

***Yellowcake ($U_3O_8$) Unit Cost.*** There are several prices for $U_3O_8$ that are tracked by NUKEM, a uranium broker:[20]

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

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[19] The cost of uranium in Russia appears to be substantially less than in the West. NUKEM Market Reports quote unrestricted uranium spot market prices that are typically 75% of restricted uranium spot market prices, where unrestricted transactions imply purchases from republics of the Commonwealth of Independent States (CIS) - Kazakstan, Kyrgyzstan, Uzbekistan and Russia. Similarly, the average contract prices of natural uranium imported from the CIS has been 80-85% of the average price of U.S. domestically supplied uranium.

As noted previously, completion of RT-2 has been estimated by its Russian proponents as costing $1.3 to 2.2 billion, or 45-78% of the reported cost of the British reprocessing plant THORP. Western experts who have visited the RT-2 plant have expressed doubt that the existing RT-2 reprocessing building construction can be salvaged in light of its deterioration due to weathering. If the chemical separation plant must be abandoned this would substantially increase the cost. Moreover, RT-2 was designed without the more comprehensive physical protection and nuclear material control and accounting requirements of comparable U.S. facilities. Bringing RT-2 up to Western safeguard standards will require additional capital and operation costs.

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

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

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

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/kgHM) from domestic suppliers; and
\$10.53/lb $U_3O_8$ (\$27.40/kgHM) from imports

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

The OECD (1994) fuel cycle cost analysis assumes uranium reference price of \$50/kgHM (in 1990) increasing at 1.2% per year, and a sensitivity analysis range of \$40-90/kgHM.[21] 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/kgHM) 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/kgHM. The U.S. National Academy of Sciences (1994) assumed \$9±1/kgHM,[22] while the OECD (1994) assumed \$8/kgHM as its reference case and a sensitivity analysis range of \$6-11/kgHM.[23]. We will assume the same range, \$9±3/kgHM.

***Uranium 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.[24] The OECD (1994) reference case

[21] *The Economics of the Nuclear Fuel Cycle*, Nuclear Energy Agency, Organization for Economic Co-operation and Development (OECD), (Paris 1994), pp. 11 and 13.

[22] *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.

[23] OECD (1994), pp. 11 and 13.

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

estimate of the enrichment cost is \$110/kgSWU.[25] This is in agreement with the U.S. National Academy of Sciences' estimate of \$95 $\pm$ 15/kgSWU.[26] Due to current excess capacity and likely improvements in technology, the long-term trend in enrichment prices should be stable or downward in real terms, even in the face of rising demand. We will assume a price in the range of \$100 $\pm$ 25/kgSWU.

***Uranium Conversion ($UF_6$ to $UO_2$) Unit Cost.*** We will assume this cost to be in the range \$8 $\pm$ 2/kgHM. 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 $\pm$ 30/kgHM.[27] The OECD (1994) assumed for its reference case a much higher value, \$275/kgHM, and with a sensitivity range of \$200-350/kg.[28] As we believe the OECD reference estimate is unjustifiably high, we will assume fabrication prices in the range \$225 $\pm$ 25/kgHM.

***Fuel Reprocessing Unit Cost.*** Today in the West, estimates of the cost of spent fuel reprocessing (disregarding costs of long-term high-level waste storage, transportation, and burial) ranges from \$750/kgHM to \$1800/kgHM.[29] Cogema (France) and British Nuclear Fuel Limited (BNFL) reportedly charged their customers about \$1400/kgHM to \$1800/kgHM to subsidize construction of their respective plants at La Hague, France and Sellafield, England.[30]

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.[31] 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.[32] NUKEM claims two-thirds of the capital investment in THORP was met by advanced payments by utilities, and that 3300 tHM of the 7000 tHM second ten year campaign has been

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[25] OEDC (1994), p. 11.

[26] U.S. NAS (1994), p. 285.

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

[28] OEDC (1994), pp. 11 and 13.

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

[30] Ibid.

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

[32] Ibid., p. 19.

committed.[33] BNFL is said to be charging about $900/kg for contracts that would cover the second ten year operating period of its THORP plant at Sellafield.[34]

In Japan, the cost for reprocessing is currently $1600-$1700/kgHM (1995).[35] The official estimate of construction costs for the new Rokkasho reprocessing plant is in the range of $16-18 billion.[36] A 1982 study by Deguchi and Kikuchi[37] estimated a cost of $400/kgHM - a price significantly lower than the current price - for reprocessing over the next 50 years, and concluded that a closed fuel cycle would only become economical if the price of uranium increased 1-2%/yr for the next 40-50 years. Nagano and Yamaji[38] assumed a much higher price of $1300/kgHM in their 1989 study.

As in the RAND study by Chow and Solomon,[39] we assume the cost of reprocessing is $900/kgHM, where one-half of this represents capital costs and one-half represents operating costs. The $450/kgHM capital cost is based upon the reported cost of the THORP plant, $2.8 billion, with an average throughput of 700 t/year over a 25 year life.

***MOX Fuel Fabrication Unit Cost.*** 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.[40] The West European estimates appear to be reasonable for a new plant in the West.

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[33] NUKEM Market Report, September 1995, pp. 6-7.

[34] Ibid.

[35] Eugene Skolnikoff, Tatsujiro Suzuki, and Kenneth Oye, "International Responses to Japanese Plutonium Programs," The MIT Center for International Studies, August 1995, pp. 34.

[36] Shiro Sasaki, Executive Vice President, Japan Nuclear Fuel Limited, "Changes in the Construction Program of Rokkasho Reprocessing Plant," *Plutonium*, Spring 1996 No. 13 (Council for Nuclear Fuel Cycle), pp. 3-4.

[37] M. Deguchi and S. Kikuchi, "Kakunenryou Saikuru Wo Genmitsu-ni Hyoka Shite Miyo (Let's Examine in Detail the Economics of the Nuclear Fuel Cycle)," (in Japanese), Genshiryo Kogyo (Nuclear Engineering), Vol. 28, 9 November 1982, pp. 17-30, as cited in: Eugene Skolnikoff, Tatsujiro Suzuki, and Kenneth Oye, "International Responses to Japanese Plutonium Programs," The MIT Center for International Studies, August 1995, pp. 34.

[38] K. Nagano and K. Yamaji, "Nenryou Saikuru Saiteki-ka Moderu no Kozo To Saiteki-kai no Tokusei (Structure of Nuclear Fuel Cycle Optimization Model and its Characteristics)," (in Japanese), Denryoko Zeizai Kenkyu (Electric Power Economics Research), No. 26, 1989, pp. 73-83, as cited in: Eugene Skolnikoff, Tatsujiro Suzuki, and Kenneth Oye, "International Responses to Japanese Plutonium Programs," The MIT Center for International Studies, August 1995, pp. 34.

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

[40] Ibid., p. 32.

As one example, Siemens invested 1.2 billion DM to construct a 120 tHM/year MOX plant at Hanau, Germany.[41] The cost to purchase and operate the unfinished plant, unlikely to be completed now due to opposition by the Hesse SPD-Green government, 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
- 800 DM/kg MOX operating cost.[42]

Thus, had the Hanau plant been completed, the cost of MOX would have been about 2500 DM/kg-MOX [$1800/kg-MOX].[43] If the plant were purchased now at its scrap value and completed, the cost of MOX would be about 1700 DM/kg-MOX [$1200/kg-MOX].[44]

***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 (3000 MWt) power plant operating at 70% of the time (a 70% capacity factor) and at a burnup of 40 MWd/kgHM, this amounts to approximately $460/kgHM (see footnote 18), or $23 billion for storage of 50,000 tHM generated by 100 reactors operating 20 years each. Waste transportation and interim storage cost are a small fraction of the disposal cost and can essentially be ignored.

European estimates of the disposal costs generally are higher than those in the United States. A 1995 study titled "Economic Comparison of Various Spent Fuel Disposal Options," by Cologne University Institute of Energy Economics, provides the following summary of direct disposal cost estimates in DM (normalized to a spent fuel burnup of 40 MWd/kgHM):[45]

| | 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 |

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

[42] Ibid.

[43] ((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 amortization.

[44] ((300+200+500)*10^6 DM*0.11/(120*10^3 kg-MOX))+800 DM/kg-MOX= 1717 DM/kg-MOX.

[45] Ibid.

The last four projections of spent fuel disposal cost appear to be unrealistically high. These estimates are about three to five times higher than the projected cost of a repository in the United States.

*Reprocessing Waste Disposal Costs.* 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 high-level reprocessing waste and spent LEU fuel is less than a factor of two, and therefore the difference in the cost of storage will be no more than a factor of two. Assuming a spent fuel disposal cost in the range of $500-$1000/kgHM, the price of disposing of high-level waste from reprocessing would fall in the range of $250-$1000/kgHM.

Moreover, recent analyses indicate that when intermediate-level waste produced by reprocessing is added to the high-level waste, the volume of material requiring long-term disposal is up to ten times greater than spent fuel produced by LEU.

## C. Comparison of LEU and MOX Fuel Cycle Costs

*The Cost of LEU Fuel for the VVER-1000.* The first two columns of Table 1 give the fuel service requirements and unit costs of these services for LEU fresh fuel, and the last column gives the product of the two. The total cost of fresh VVER-1000 fuel based on Western prices is estimated to be in the range $1330±220.

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

| | Requirements (per kgHM fuel) | Unit Cost | Cost ($kgHM) |
|---|---|---|---|
| Yellowcake ($U_3O_8$) | 9.639 kg | $39±13/kg | 276±48 |
| Conversion ($U_3O_8$ to $UF_6$) | 8.219 kgHM | 9±3/kgHM | 74±25 |
| Enrichment | 7.460 kgSWU | 100±25/kgSWU | 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 |

*The Cost of MOX Fuel for the VVER-1000.* To estimate the cost of fabricating MOX for a VVER-1000, a good first approximation is to assume that the MOX must have the same fissile material concentration as fresh LEU fuel, or 4.4%. In Table 2(a) we have assumed that the MOX is made by blending recovered plutonium with depleted uranium tails from an enrichment plant. In Table 2(b) we have assumed that the uranium blend stock comes from uranium recovered by reprocessing VVER-1000 fuel. 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 2(a).

Plutonium requirements are lower in Table 2(b) compared to the requirements in Table 2(a) because the uranium blend has a higher enrichment. Table 2(b) illustrates that for every kilogram of MOX fuel, one must reprocess about four kilograms of VVER-1000 spent fuel in order to recover the necessary plutonium [4*0.00974 kg ≈ 0.0391 kg]. The ratio would be about five kilograms of spent fuel to one kilogram of MOX if we used a more careful calculation designed to match the neutronic behavior of the fuel at the end of the burnup period.

**Table 2. Composition of MOX Fuel Using Reactor-Grade Plutonium**
Recovered From 4.4% Enriched VVER-1000 Spent Fuel After 35 MWd/tHM Burnup

| | Total (kg) | Fissile (kg) |
|---|---|---|
| Pu (75.27% fPu) | 0.0559 | 0.0421 |
| U (0.2% U-235) | 0.9441 | 0.0019 |
| Total | 1.0000 | 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 | 1.0000 | 0.0440 |

**(b) Using Uranium Recovered by Reprocessing VVER-1000 Fuel**

***Conclusions of Economic Analysis.*** In Table 3 we summarize the cost of VVER-1000 MOX fuel in order to directly compare it with the cost of VVER-1000 fresh LEU fuel summarized in Table 1. We conclude that the cost of MOX fuel would be in the range of $4000-5700, or about three to four times as much as LEU fuel. In our calculations we have ignored fabrication and conversion losses, as these are only on the order of 1.5%.

We have included a credit in Table 3 for excess uranium separated in the closed fuel cycle - that is, uranium separated in reprocessing but not needed to blend with plutonium to make MOX.

**Table 3. VVER-1000 Fresh MOX Fuel Costs ($/kgHM)**

| | Requirements (per kgHM spent fuel) | Unit Cost | Cost (/kgHM) |
|---|---|---|---|
| Reprocessing | 4-5 kgHM 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 |

We have not included in our comparison any differences in costs associated with the back-end of the fuel cycle - including the management and disposition of fission product wastes and the storage of separated plutonium and uranium produced in reprocessing, and the storage and disposition of spent fuel from the once-through fuel cycle. As already noted in Section III B., however, the difference in the heat loading between high-level reprocessing waste and spent LEU fuel - the major determinant in the cost of long-term storage - is less than a factor of two (resulting in a high-level reprocessing waste storage cost of approximately $250-$1000/kgHM, assuming a spent fuel disposal cost of $500-$1000/kgHM). Moreover, secure storage of plutonium and uranium produced in reprocessing would be an additional cost to consider in the closed fuel cycle. Therefore, differences in the cost of waste management and plutonium and uranium storage would not alter the conclusion that reprocessing and plutonium recycling are uneconomical.

Some Western 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 approach is inaccurate, since spent fuel can be disposed of as a waste, and in the United States it is government policy to do so. Moreover, as seen by comparing the results in Table 3, MOX is uneconomical even if the plutonium is treated as a free good, i.e., even if one ignores the cost of reprocessing and the uranium credit in Table 3.

Other MOX proponents 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 reactors) and not in VVER's. Because of higher fuel fabrication costs for BN fuel than for conventional reactor fuel, this option would be even more uneconomical than the use of MOX in VVER's. Moreover, the BN reactor option has proven uneconomical for Russia for other reasons. The fuel cost of a nuclear plant represents only about 15% of the total cost of the electricity it produces; about 75% of the electricity cost is associated with the cost of plant construction. The BN-600 reactor turned out to be 1.5 to 1.7 times as expensive to construct as a VVER-1000.[46] The new breeder, BN-800, was estimated in 1990 to cost 900 rubles/kw compared to 600-650 rubles/kw for the VVER-1000.[47] While these estimates probably understate the true cost difference between BN and VVER reactors, they show that fast breeders are uneconomical in Russia, just as they have proven to be in the West.

## D. Historical Considerations

In the United States in the 1960s the prevailing view in the commercial nuclear industry was that the cost of civil spent fuel reprocessing would be relatively low, and that substantial cost savings could be realized recovering plutonium and uranium and recycling these materials in lieu of mining and enriching additional uranium. This view was shared by nuclear industry officials in other Western countries and no doubt in the Soviet Union as well.

In 1969, for example, the U.S. Atomic Energy Commission (USAEC) prepared a cost-benefit analysis of the U.S. breeder reactor program.[48] In this analysis the USAEC estimated that the cost of reprocessing civil light water reactor fuel - in Russia the equivalent would be VVER fuel - would be $37.30 per kilogram of heavy metal (kgHM) initially.[49] Projecting that the reprocessing industry would grow in size, the USAEC estimated that reprocessing costs as a consequence of economies of scale would drop to $19.70/kgHM by the year 2020.[50] Due to inflation, these projected costs in today's (1995) U.S. dollars would be about $150/kgHM initially and $80/kgHM by 2020. In 1969 the USAEC estimated that the electrical energy demand and growth in nuclear power use would be so great that without the introduction of breeder reactors low cost uranium resources would be depleted and uranium prices would climb from $8/lb to $50/lb $U_3O_8$ ($17.6/kg to $110/kg).[51] In today's U.S. dollars, these prices would be $32/lb and $200/lb ($70/kg and 440/kg), respectively.

As the price data summarized in this paper clearly shows, these early cost projections of the were completely wrong. The cost of spent fuel reprocessing has increased in the West sixfold or more since 1969, and the cost of uranium, after peaking in 1979, has decreased by a factor of three. Thus, the projected economic benefits of reprocessing and plutonium recycling never materialized.

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

[47] Ibid.

[48] U.S. Atomic Energy Commission, "Cost-Benefit Analysis of the U.S. Breeder Reactor Program," WASH 1126, April 1969.

[49] Ibid., . 68.

[50] Ibid.

[51] Ibid., p. 70.

## IV. Conclusion

Implementation of Minatom's plans for expansion of its civil spent fuel reprocessing program and for commercial MOX fuel production would not be cost effective for Russia. As our economic analysis shows, reprocessing and plutonium recycling would be at least three to four times more expensive than the use of fresh LEU fuel in Soviet-designed reactors.

Moreover, the completion and operation of the RT-2 chemical separation plant at Krasnoyarsk-26 will be economically infeasible without substantial contracts for spent fuel from outside Russia.

We conclude, therefore, that the excessive cost of reprocessing and the proliferation risks associated with the separation of weapon-usable plutonium make the closed fuel cycle a wholly impractical and potentially dangerous approach to meeting Russia's energy needs. Commercial reprocessing of spent fuel and construction of new reprocessing facilities should be halted until such time as all excess plutonium stockpiles have been eliminated and the risks and costs of civil plutonium use have been dramatically reduced.