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Excerpt from "Summary of Near-Term Options for Russian Plutonium-Production Reactors

Editor's Note:

Battelle Pacific Northwest Laboratories has done a detailed study of conversion options for the Russian production reactors. ("Summary of Near-Term Options for Russian Plutonium Production Reactors," by D.F. Newman, C.J. Gesh, E.F. Love and S.L. Harms, PNL-9982, July 1994) Excerpts from that study follow.

INTRODUCTION

The Russian Federation desires to stop producing weapons-grade plutonium. During the last several years, ten graphite-moderated, water-cooled, production reactors have been shut down. However, complete cessation of weapons-grade plutonium production is impeded by the fact that the last three operating Russian plutonium-production reactors supply electrical energy and district heat as well as produce plutonium. These reactors are major suppliers of heat in the Tomsk and Krasnoyarsk regions of Siberia.

Reactor Design and Operations

The three operating Russian plutonium-production reactors are located in the Tomsk and Krasnoyarsk regions of Siberia (see figure 1). These reactors were designed and constructed in the 1960s. The design and operations were conducted in a closed environment necessitated by the security requirements of the nuclear weapons program. No U.S. citizen has ever visited these plants. Information available to the U.S. indicates that these reactors have a very unique design; the only comparable plants are located at the U.S. Hanford site.

Figure 2 shows a simple block diagram of the reactors developed from the available design information. The reactor fuel is located in the process tubes, the active core region being in the center of the graphite region. Figure 3 shows a schematic of the reactor heat and electricity delivery systems for the Tomsk station. They illustrate how the reactor coolant loop interfaces with the

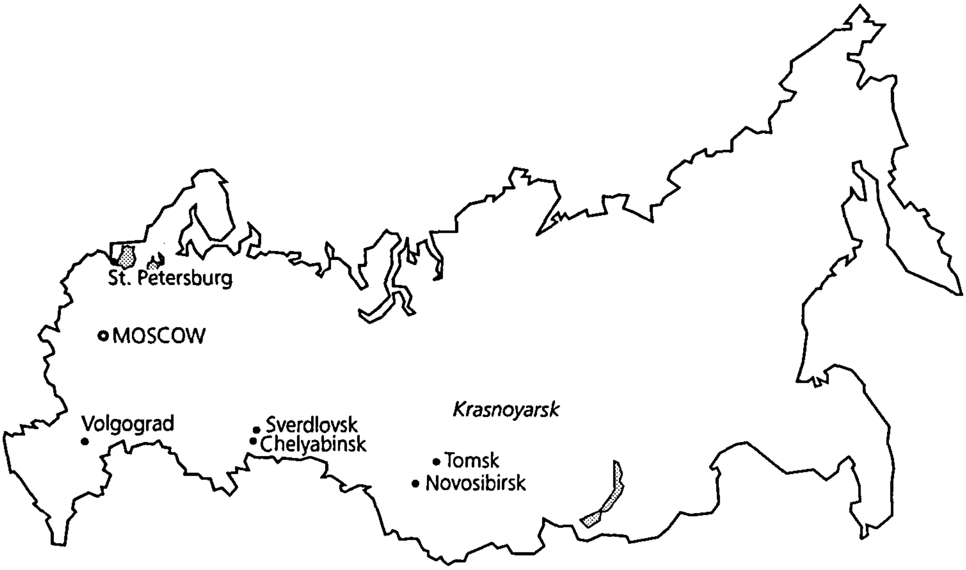

Figure 1: Map of Russia.

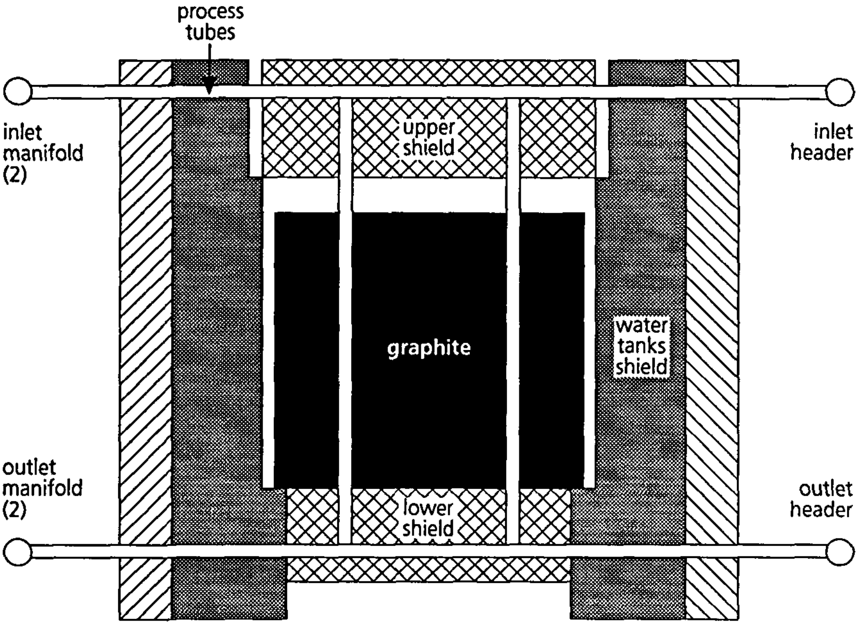

Figure 2: Russian production reactor diagram.

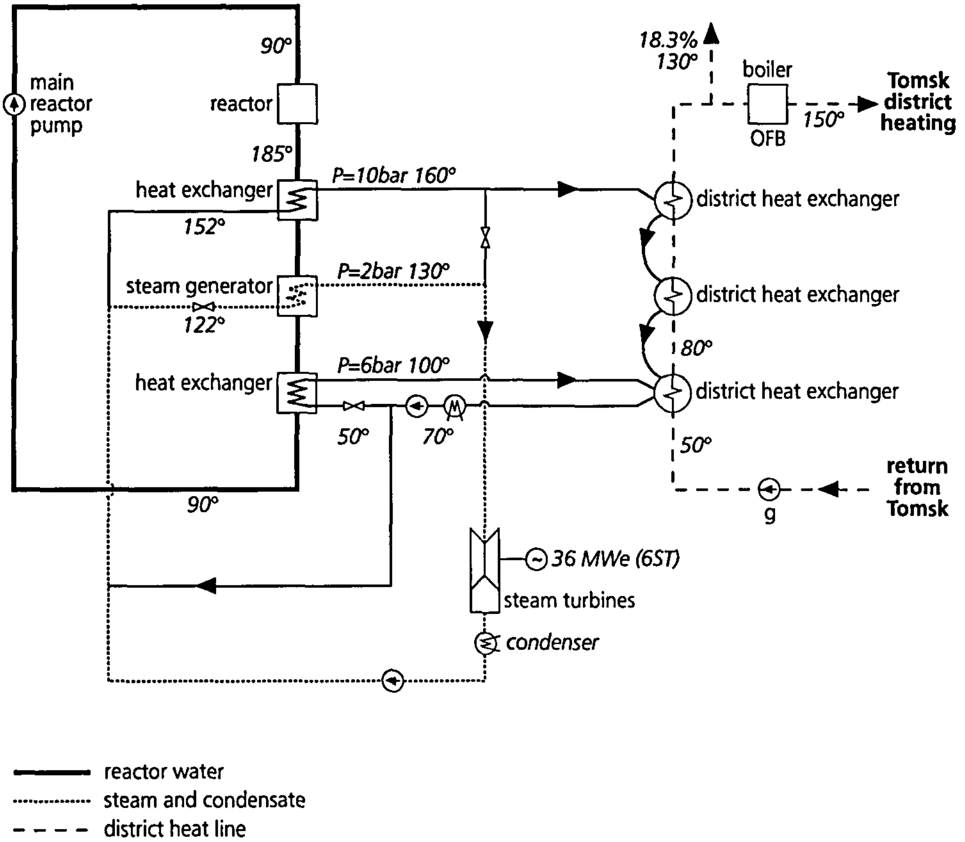

Figure 3: Tomsk production reactor schematic.

distribution of district heat to local regions.

As a result of the closed environment in which the Russian production plants exist, there has been essentially no opportunity for the designers or operators of these plants to benefit from the considerable nuclear infrastructure that exists today for other plants. The development and use of analytic tools, the performance and analysis of experiments, and the construction and operation of the reactors was largely done in isolation.

A similar condition existed in the U.S. at the Hanford site for many years. Scientists and engineers at the Hanford site designed, constructed and operated eight single-pass graphite-moderated, water-cooled reactors for plutonium production, in a highly isolated technical environment. The ninth plant, N-reactor, was a dual-purpose plant that produced weapons-grade plutonium and steam for generating electricity. The N-reactor was also different in that some external safety reviews were conducted during its design, and extensive design and operational safety reviews and upgrades were performed during the operating life of the plant. Considerable effort was expended in order to apply modern safety criteria to a one-of-a-kind plant. When the U.S. requirements for weapons-grade plutonium diminished, the plant was operated in the power-only mode (with higher fuel burn-up) for a period of about 10 years.

NEAR-TERM OPTIONS

Current Situation

Russian technical experts provided sufficient information to PNL staff regarding the production reactors' configuration, fuel and control rod composition, reactor core loading, and operating parameters to initiate investigation of alternative fuel cycle comparisons. The Russian production reactors are currently fueled primarily with natural uranium metal fuel. Fuel channels and control channels are vertically oriented in graphite blocks on a 200-millimeter square pitch. The reactor core contains about 300 tonnes of natural uranium, and half of it is discharged after every 30 effective-full-power-days (EFPD) of operation. Approximately 1,200 tonnes of spent fuel is discharged annually from each reactor. In the central region of the core, a control rod is located in each 4 × 4 array of channels. This control rod system has a total reactivity worth of about eight percent, at operating conditions. Reactivity of the natural uranium fuel changes less than three percent during irradiation. The principal safety issue regarding this fuel is that the reactivity increase with fresh fuel due to voiding the water coolant in fuel channels is about 0.5 percent (about 70 percent of the delayed neutron fraction). The positive reactivity void defect increases during irradiation as indicated by the coolant temperature coefficient of reactivity. Reactivity transients due to coolant voiding must be controlled by 25 fast-acting rods (worth about one percent of reactivity), which can be inserted in two seconds. Even though the natural uranium metal fuel has sufficient excess reactivity to achieve a 360 EFPD burn-up rate (comparable to N-reactor fuel), it would not be technically feasible to operate Russian production reactors with such large positive reactivity effects due to coolant voiding at those fuel exposures. About half a metric ton of weapons-grade plutonium is being discharged annually from each operating reactor. This fuel is being reprocessed within a year or two after discharge because of the concern about potential degradation of the aluminum cladding on the natural uranium metal fuel and consequences of exposed uranium dissolution during wet storage. Dry storage of such a large quantity of spent fuel would be too costly. As a result, the separation, recovery, and stockpiling of an additional 1.5 tonnes of weapons-grade plutonium continues each year with the current natural uranium fuel cycle.

Fuel Cycle Alternatives

Potential fuel cycle alternatives were evaluated using the following criteria:

- convert plutonium-production reactors from military to civilian use,
- meet needs for district heat and electricity
- eliminate discharge of weapons-grade plutonium in spent fuel,
- eliminate positive coolant void reactivity,
- reduce quantity of spent fuel discharged,
- reduce quantity of plutonium discharged,
- eliminate need for reprocessing spent fuel and recovery of plutonium,
- provide options for long-term spent fuel storage,
- use current technology and have minimum impact on facilities,
- meet near-term implementation requirements.

Four fuel types were evaluated as shown in table 1.

Each of these fuels met the screening criteria. However, the medium-enriched uranium cermet fuel can be fabricated at the existing Russian fuel plant that produces the cermet fuel for the spiked fuel columns in these production reactors. Additionally, this alternative does not involve weapons-usable material in fresh fuel and contains only low concentrations of highly burned plutonium (> 30% Pu-240/Pu) in the spent fuel. As a result, the medium-enriched cermet fuel was chosen as the preferred fuel option.

Editor's Note:

The PNL Report assesses the preferred fuel option in detail. This analysis is not excerpted here. Appendix C of the Report, which is included below, briefly analyzes the other options, including that of long-term dry storage.

Table 1: Four fuel types containing natural erbium burnable absorber.

Feed material	Fresh fuel composition	Cladding material	Spent fuel quantity/reactor
low-enriched uranium	1.2% enriched uranium metal 0.5 wt% erbium (burnable absorber)	zircaloy-2 (coextruded with fuel)	2/3 core/year
medium-enriched uranium (< 20% U-235)	33 wt% U_3O_8 (19.9% U/U_{total}) 6 wt% Er_2O_3 (burnable absorber) 61 wt% aluminum (cermet)	aluminum (coextruded with fuel)	1/4 core/year
highly enriched uranium (> 20% U-235)	7 wt% U (93% U-235/U_{total}) 6.9 wt% erbium (burnable absorber) 86 wt% aluminum (alloy)	aluminum (coextruded with fuel)	1/3 core/year
weapons-grade plutonium	20 wt% Pu (6% Pu-240/Pu_{total}) 38 wt% erbium (burnable absorber) 42 wt% aluminum (alloy)	aluminum (coextruded with fuel)	1/3 core/year

CONCLUSIONS

Although the U.S. and Russia have a formal agreement on shutdown of the Russian plutonium-production reactors, it is not expected to be implemented until after the turn of the century. Minatom will continue to operate these reactors to provide electricity and district heat in the meantime.

The earliest opportunity for stopping production of weapons-grade plutonium is to change the fuel cycle within the next two to three years. Such a fuel cycle change provides the opportunity to enhance the inherent safety characteristics of these reactors by adding erbium to the fuel, which can eliminate the undesirable positive coolant-void-reactivity effect.

The most proliferation-resistant fuel cycle that could be implemented quickly and reliably contains 33 wt% uranium oxide (19.9 percent U-235/U) and 6 wt% erbium oxide in aluminum, as a cermet, coextruded with aluminum cladding. This fuel cycle would be economical, minimize fuel fabrication and spent fuel storage requirements, enhance reactor operational safety, and discharge minimal quantities of reactor-grade plutonium containing more than 30 percent Pu-240. The spent fuel would be suitable for long-term storage in existing pools.

U.S. assistance to Russia would likely be required for any near-term change in the fuel cycle for the Russian production reactors. Implementation of a proliferation-resistant fuel type containing erbium would require U.S. technical support for changes in fuel fabrication, materials behavior, reactivity and burn-up analytical methods, and safety analysis.

APPENDIX: ADDITIONAL OPTIONS FOR RUSSIAN PRODUCTION REACTOR OPERATION IN A CIVILIAN POWER MODE

The main body of this report discusses the preferred fuel option for operating the Russian production reactors in a civilian power mode. This preferred option was determined through the comparison of proliferation resistance, relative safety parameters, and costs. Several additional options have been investigated. This appendix serves to document the results of the options analyzed in addition to the one preferred.

FUEL CYCLE OPTIONS

Four additional fuel cycle options were analyzed in support of this report as summarized in table A-1. The options are:

- long-term dry storage,
- conversion to a zircaloy-clad LEU metal fuel cycle,
- conversion to a zircaloy-clad non-fertile HEU fuel cycle,
- conversion to a zircaloy-clad non-fertile weapons-grade Pu fuel cycle.

GENERAL INFORMATION

As a result of continuing operations, about 1,000 tonnes of spent fuel is discharged from each of the production reactors annually. The reactors will continue operation and produce plutonium with the aluminum-clad uranium-metal fuel currently being irradiated if viable civilian fuel cycles are not implemented.

The storability of aluminum-clad spent uranium metal fuel in water is very sensitive to water quality. Experience (e.g., Argentina, Hungary, Italy) with aluminum-clad spent nuclear fuel has shown acceptable storage in deionized water for up to 24 years. The evidence of integrity is primarily based on measurement of radionuclides released to the pool. Pitting corrosion in deionized water was projected to penetrate aluminum cladding after approximately 30 years of pool storage (International Atomic Energy Agency, 1992). Al-clad fuel has failed in impure water in 10 to 15 years.

The spent fuel pools at Russian production reactors are not lined with stainless steel nor is the water deionized. Spent fuel is stored in these pools for no more than two to three years because of the concern for Al-clad failure. The consequences of cladding failure during wet storage are release of radioactive species to the pool and eventual degradation of the cladding and exposed fuel.

Table A.1: Fuel option comparisons.

	Natural U	**LEU**	**HEU**	**Plutonium**	**Cermet**
Fuel development cost (*million dollars*)	—	20	30	50	30
In-reactor residence time (*EFPD*)	60	360	750	750	1,000
Net fabrication cost reduction factor	—	3	6	2	8
Uranium feed material cost reduction factor	—	2.5	2	—	1.5
Current storage pool capacity	3 years	18 years	lifetime	lifetime	lifetime
Front-end proliferation considerations	low	low	high	high	low
Back-end proliferation considerations	high	moderate	moderate	moderate	low
Other costs	—	update spent fuel cooling	update spent fuel cooling	update spent fuel cooling	update spent fuel cooling

Radioactive particulates can eventually be released into the pool.

Some of the fuel cycle options analyzed consider the use of zircaloy-clad fuel instead of aluminum-clad. Zircaloy-clad fuel has shown no perceptible degradation in deionized water for periods up to approximately 30 years. Zircaloy-clad fuel has not shown a sensitivity to the purity of the pool water.

The U.S. Nuclear Regulatory Commission has issued rules permitting wet storage of zircaloy-clad spent fuel for up to 100 years. It is expected that zircaloy-clad fuel for Russian production reactors could be maintained in wet storage for a similar period of time without difficulty.

To implement any of the alternative fuel cycle options (except dry storage) for the production reactors would be expected to require a three to five year development program (specific lengths for specific options are listed below) to optimize fuel design, verify fuel models and codes, conduct in-reactor tests, demonstrations, and post-irradiation examinations, and to verify fuel performance and safety requirements. The development program would result in regulatory approval for full-scale implementation of fabrication and utilization of the fuel option in Russian production reactors. The cost of fabricating the uranium fuel options is not expected to be more than a factor of two higher than that for natural uranium metal fuel. However, the amount of fuel fabricated in all cases is reduced in comparison to natural uranium fuel, so net fuel fabrication cost reductions result.

DRY STORAGE OPTION

The spent fuel from the Russian production reactors could be stored instead of being reprocessed to recover the plutonium. Wet storage of spent fuel in pools would be used for the first two to three years after discharge to reduce the decay heat rate to less than 300 watts per metric tonne. The spent fuel would be transferred into large metal dry storage casks such as the GNS CASTOR-5 and inerted for long-term monitored storage.

Spent Fuel Pool Storage Limitations

Based on three years of pool storage, about 3,000 tonnes of spent fuel would be stored underwater at each Russian production reactor. This is consistent with current practice and does not impose any new limitations.

Dry Storage Requirements

Instead of reprocessing three-year cooled spent fuel from pool storage, dry storage casks would be used to store spent fuel in an inert atmosphere.

Inerted dry storage has been licensed in the U.S. and other countries for commercial spent fuel and used for storage of aluminum-clad test reactor fuel in Japan.

Large metal dry storage casks, such as CASTOR-5, being used in the U.S. and Europe would be used for long-term monitored storage of spent fuel. Each of these casks has a mass of about 100 tonnes empty with an overall size of about eight feet in diameter and 16 feet in height.

Since the aluminum-clad uranium-metal fuel has about twice the density of commercial LWR fuel, about 20 tonnes of production reactor spent fuel could be loaded into each cask. The loaded weight of the cask (120 tonnes) would be a practical limit considering typical crane capacity available at reactor sites. The heat dissipation rate from the cask (< 6,000 watts) would keep the metal fuel from rapidly oxidizing if the inert atmosphere in the cask were lost.

The cost of these dry storage casks (in large quantities) is about $1 million apiece. The expected cost for obtaining dry storage casks at each reactor would be about $50 million per year. About three acres of land per year would be added to the space occupied by dry storage casks at each reactor.

Dry Storage Option Costs

In addition to the $50 million per reactor-year for obtaining dry storage casks, a reinforced concrete pad about half a meter thick would be required for the dry storage array ($2 million per reactor-year). Monitoring costs are expected to be about $10 million per reactor-year. Thus, the total cost for the dry storage of spent fuel at each reactor is expected to be about $65 million per year.

ZIRCALOY-CLAD LEU METAL OPTION

The production reactors could continue operation with a zircaloy-clad fuel containing about 0.5 wt% erbium with 1.2 wt% U-235 enriched uranium metal. This fuel could be fabricated by a hot co-extrusion process similar to that used for N-reactor. The spent fuel would be maintained in wet storage and would not be reprocessed for up to 100 years.

Fuel Exposure Limitations

Fuel containing 1.2 wt% U-235 in uranium metal with zircaloy clad has been irradiated in N-reactor to exposures up to 4,400 megawatt-days per tonne. To enhance the negative coolant temperature coefficient and void coefficient during irradiation, 0.5 wt% erbium would be alloyed with the 1.2 percent enriched uranium metal fuel. The erbium also acts as a burnable absorber which minimizes the reactivity change of the fuel during burn-up. Allowing for an axial power peaking factor of 1.2, the channel-average discharge exposure of fuel would be about 3,600 megawatt-days per tonne, six times the current natural uranium metal fuel exposure. As a result, only about 160 tonnes of spent fuel would be discharged from each production reactor annually. The spent fuel would contain about 0.7 wt% of fuel-grade plutonium (>17% Pu-240).

Spent Fuel Pool Storage Limitations

The decay heat of LEU/erbium metal fuel elements would be about a factor of five higher than that of natural uranium-metal spent fuel. Therefore, the spent fuel pool cooling equipment would need to be upgraded to accommodate the higher decay heat loads associated with the more highly burned fuel.

Spent Fuel Storage Requirements

Since the zircaloy-clad LEU/erbium metal fuel would be burned for 360 EFPD, whereas the natural uranium-metal fuel is currently being burned for only 60 EFPD, the quantity of spent fuel generated annually would be reduced by a factor of six. Wet storage pools designed to hold three years worth of natural uranium-metal fuel discharges could accommodate 18 annual discharges of the more highly burned zircaloy-clad LEU/erbium metal fuel.

LEU Metal Fuel Option Costs

To implement the LEU metal fuel burning option in Russian production reactors is expected to require a $20 million development program over the next two years.

The amount of LEU metal fuel fabricated is reduced by a factor of six in comparison to natural uranium fuel, so the net fuel fabrication cost is reduced by about a factor of three.

The cost of LEU which could otherwise be sold commercially for use in LWRs is estimated to be about $6.20 per gram of U-235. This corresponds to about $75,000 per tonne of 1.2 percent enriched uranium metal. The LEU feed requirements for each production reactor operating on LEU fuel would be about 160 tonnes per year. The LEU feed costs amount to about $12 million per year for each reactor. This amounts to only 40 percent of the annual cost for natural uranium feed material (1,000 tonnes per year) per reactor for the current fuel cycle.

HEU Disposition Rate

Since the LEU/erbium metal fuel would reside in the Russian production reactors for 18 months, two-thirds of the core would be discharged annually from each reactor. The total quantity of LEU metal fuel that would have to be fabricated and loaded into all three of the production reactors annually to sustain their operation could contain 5.1 tonnes of HEU blended with 475 tonnes of depleted uranium.

ZIRCALOY-CLAD NON-FERTILE HEU OPTION

The production reactors could continue operation with a non-fertile fuel containing highly enriched uranium (HEU) and erbium in an aluminum matrix clad with zircaloy. This fuel would not produce significant quantities of plutonium, and most of it would be non-fissile Pu-238. The spent fuel would be maintained in wet storage, and would not be reprocessed for up to 100 years.

Fuel Exposure Limitations

Fuel containing 7 wt% HEU and 6.9 wt% erbium in an aluminum matrix can sustain a three-year in-reactor residence time (750 EFPD). The reactivity change with burn-up is about 12 percent over the fuel lifetime. After equilibrium xenon has built up, the reactivity increases for the first 480 EFPD, reaches a maximum value of $K_\infty = 1.12$, and then decreases. More than 60 percent of the uranium is annihilated during the fuel lifetime. The discharged uranium contains less than 60 percent U-235, and more than 27 percent U-236.

Safety-Related Parameters

Non-fertile HEU/Er/Al fuel, with the same clad dimensions (18 millimeter radius) as the natural uranium-metal fuel currently being used, has a Doppler coefficient that changes linearly from $-9 \cdot 10^{-6}$/K at end-of-life. These values are somewhat less negative than those for natural uranium ($-1.1 \cdot 10^{-5}$/K).

The coolant temperature coefficient also becomes less negative with burn-up, changing from $-1.2 \cdot 10^{-4}$/K at beginning of life.to $-5 \cdot 10^{-5}$/K at end of life. These values are much more negative than the value for natural uranium metal ($-6 \cdot 10^{-6}$/K) at beginning of life.

The reactivity change with burn-up will require about four percent more control rod worth than for the natural uranium-metal fuel. A comparison of the 7 wt% HEU/Er non-fertile fuel burn-up reactivity change with that of natural uranium during the first year of irradiation shows similarities. The burn-out of erbium slightly overcompensates for the reactivity loss due to U-235 burnout in the non-fertile HEU/Er fuel.

Spent Fuel Pool Storage Limitations

The decay heat of the non-fertile HEU fuel elements would be about a factor of 10 higher than that of the natural uranium-metal spent fuel. Therefore, the spent fuel pool cooling equipment would need to be upgraded to accommodate the higher decay heat loads associated with more highly burned fuel.

Spent Fuel Storage Requirements

Since the non-fertile HEU/Er/Al fuel would be burned for 750 EFPD, whereas the natural uranium-metal fuel is currently being used for only 60 EFPD, the quantity of spent fuel generated annually would be reduced by more than a factor of 12. Wet storage pools designed to hold three years worth of natural uranium-metal fuel discharges could accommodate the reactor lifetime discharges of non-fertile HEU fuel.

Non-Fertile HEU Fuel Option Costs

Implementing the HEU burning option in Russian production reactors is expected to require a $30 million development program over the next three years.

The amount of fuel fabricated is reduced by a factor of 12 in comparison to natural uranium fuel, so the net fuel fabrication cost is reduced by about a factor of six.

The cost for HEU which could otherwise be blended with depleted uranium and sold commercially for use in LWRs is estimated to be about $18 per gram of U-235. This corresponds to about $17 million per tonne of HEU. The HEU feed requirements for each production reactor operating on non-fertile fuel would be about 0.9 tonnes per year. The HEU feed costs amount to about $15 million per year for each reactor. This amounts to only half the annual cost for natural uranium feed material (1,000 tonnes per year) per reactor for the current fuel cycle.

HEU Disposition Rate

Since the non-fertile HEU/Er/Al fuel would reside in the Russian production reactors for three years, one-third of the core would be discharged annually from each reactor. The total quantitate of non-fertile fuel that would have to be fabricated and loaded into all three of the production reactors annually to sustain their operation would contain 2.6 tonnes of HEU. About one tonne of reactor-grade uranium would be discharged annually in spent fuel.

ZIRCALOY-CLAD NON-FERTILE WEAPONS-GRADE PLUTONIUM OPTION

The Russian production reactors could be reloaded with a non-fertile fuel containing weapons-grade plutonium and erbium in an aluminum matrix clad in zircaloy. The spent fuel would be maintained in wet storage, and would not be reprocessed to recover the remaining reactor-grade plutonium for up to 100 years.

Fuel Exposure Limitations

Fuel containing 20 wt% weapons-grade plutonium and 38 wt% erbium in aluminum can sustain a three-year in-reactor residence time (750 EFPD). The reactivity loss with burn-up is only seven percent in 750 EFPD for this fuel. Plutonium in the spent fuel contains about 80 percent of the initial amount of plutonium loaded, but the Pu-240 content is increased to more than 17 percent (about the same as that in VVER spent fuel).

Safety-Related Parameters

Non-fertile fuel, with the same clad dimensions (18 millimeter radius) as the uranium-metal fuel currently being used, has a Doppler coefficient that remains fairly constant at a value of $-1.2 \cdot 10^{-5}$/K. The water coolant temperature coefficient changes linearly from $-1.6 \cdot 10^{-5}$/K at beginning of life to $-1.0 \cdot 10^{-5}$/K at end of life. The fractional destruction of both Pu-239 and Er-167 are closely matched as the fuel is burned. Burnout of about one-fourth of these isotopes essentially compensates for their reactivity effects over the fuel lifetime. Lower initial concentrations of plutonium and erbium result in less closely matched destruction rates and shorter lifetimes before the coolant temperature coefficient becomes positive.

Spent Fuel Pool Storage Limitations

The decay heat of non-fertile fuel elements would be about a factor of 10 higher than that of natural uranium-metal spent fuel. Therefore, the spent fuel pool cooling equipment would need to be upgraded to accommodate the higher decay loads associated with longer burned fuel.

Spent Fuel Storage Requirements

Since the non-fertile Pu/Er/Al fuel would be burned for 750 EFPD, whereas the natural uranium-metal fuel is currently being used for only 60 EFPD, the quantity of spent fuel generated annually would be reduced by more than a factor of 12. Wet storage pools designed to hold three years worth of natural uranium-metal fuel discharges could accommodate the reactor lifetime discharges of non-fertile fuel.

Non-Fertile Weapons-Grade Plutonium Option Costs

Implementation of the plutonium burning option in Russian production reactors is expected to require a $50 million development program over the next five years.

The cost of fabricating plutonium-bearing fuels for LWRs has been four to five times higher than for uranium fuels because the processes must be conducted in glove boxes to contain the potential spread of contamination. Since the quantity of plutonium-bearing fuel required is a factor of 12 lower than that for natural uranium-metal fuel, the net annual fuel fabrication cost should be less than half that currently being incurred.

Plutonium Disposition Rate

Since the non-fertile Pu/Er/Al fuel would reside in the Russian production reactors for three years, one-third of the core would be discharged annually from each reactor. The total quantity of non-fertile fuel that would have to be fabricated and loaded into all three of the production reactors annually to sustain their operation would contain eight tonnes of weapons-grade plutonium. About six tonnes of reactor-grade plutonium would be discharged annually in spent fuel.