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THE U.S.–RUSSIAN JOINT STUDIES ON USING POWER REACTORS TO DISPOSITION SURPLUS WEAPONS PLUTONIUM AS SPENT FUEL*

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DISCLAIMER

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Abstract

In 1996, the United States and the Russian Federation completed an initial joint study of the candidate options for the disposition of surplus weapons plutonium in both countries. The options included long-term storage, immobilization of the plutonium in glass or ceramic for geologic disposal, and the conversion of weapons plutonium to spent fuel in power reactors. For the latter option, the United States is only considering the use of existing light-water reactors (LWRs) with no new reactor construction for plutonium disposition, or the use of Canadian deuterium-uranium (CANDU) heavy-water reactors. While Russia advocates building new reactors, the cost is high, and the continuing joint study of the Russian options is considering only the use of existing VVER-1000 LWRs in Russia and possibly Ukraine, the existing BN-600 fast-neutron reactor at the Beloyarsk Nuclear Power Plant in Russia, or the use of the Canadian CANDU reactors. Six of the seven existing VVER-1000 reactors in Russia and the eleven VVER-1000 reactors in Ukraine are all of recent vintage and can be converted to use partial MOX cores. These existing VVER-1000 reactors are capable of converting almost 300 kg of

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surplus weapons plutonium to spent fuel each year with minimum nuclear power plant modifications. Higher core loads may be achievable in future years. The BN-600 reactor, which currently uses enriched uranium fuel, is capable (with certain design modifications) of converting up to 1.3 metric tons (MT) of surplus weapons plutonium to spent fuel each year. The steps needed to convert BN-600 to a plutonium-burner core are (1) elimination of the depleted uranium breeding blankets and their replacement with a combination of a steel reflector and boronated shield, (2) initial conversion to a hybrid enriched uranium–plutonium-fueled core sufficient to preserve a zero value for the sodium void reactivity effect, and (3) ultimate conversion to the plutonium-burner core that requires several modifications to the fuel design and the reactor. The step involving the hybrid core allows an early and timely start that takes advantage of the limited capacity for fabricating uranium–plutonium mixed oxide (MOX) fuel early in the disposition program. Finally, the design lifetime of BN-600 must safely and reliably be extended by 10 years to at least 2020 so that a sufficient amount of plutonium (~20 MT) can be converted to spent fuel.

1. Introduction

Significant quantities of weapons-usable fissile materials [primarily plutonium and highly enriched uranium (HEU)] are becoming surplus to national defense needs in both the United States and Russia. These stocks of fissile materials pose significant dangers to national and international security. The dangers exist not only in the potential proliferation of nuclear weapons but also in the potential for environmental, safety, and health (ES&H) consequences if surplus fissile materials are not properly managed.

The first and second Strategic Arms Reductions Treaties (START I and START II) call for deep reductions in the strategic nuclear forces of both the United States and the former Soviet Union. In addition, in the aftermath of the Cold War, both the United States and Russia have initiated unilateral steps to increase the pace of strategic disarmament. Under START and subsequent unilateral initiatives, some 10,000 to 20,000 warheads in the United States (and a similar or greater number in the former Soviet Union) could possibly be declared "surplus" to national security needs. Thus, significant quantities of weapons-usable fissile materials have or will become surplus to national defense needs in both the United States and Russia.

On January 14, 1994, U.S. President Clinton and Russian President Yeltsin issued a statement on *Non-Proliferation of Weapons of Mass Destruction and The Means of Their Delivery*, in which the Presidents tasked their experts to jointly "study options for the long-term disposition of fissile materials, particularly of plutonium, taking into account the issues of nonproliferation, environmental protection, safety, and technical and economic factors."[1]

In 1996, the United States and the Russian Federation completed a joint study of the options for the disposition of surplus weapons plutonium in both countries [2]. The options included long-term storage, immobilization of the plutonium in glass or ceramic for geologic disposal, and the conversion of weapons plutonium to spent fuel in power

reactors. For the latter option, the United States is only considering the use of existing LWRs with no new reactor construction for plutonium disposition. The Russian government approach emphasizes use of plutonium as fuel for nuclear reactors because of its energy value. While Russia advocates building new reactors, the cost is high; an estimated $1.4 billion is needed to construct a BN-800 fast reactor. Therefore, the continuing joint study of the Russian options is considering only the use of the existing VVER-1000 LWRs in Russia and Ukraine, the use of Canadian deuterium–uranium (CANDU) heavy-water reactors in Canada, and the existing BN-600 fast neutron reactor at the Beloyarsk Nuclear Power Plant (BNPP) in Russia. This paper focuses on the use of the VVER-1000 and BN-600 reactors for disposition of surplus weapons plutonium in Russia.

2. The VVER Reactors

The isotopic composition of weapons-grade (or weapons-derived) mixed-oxide (MOX) fuel differs inherently from that of commercial reactor-grade MOX because weapons-grade plutonium has higher fissile content and lower ^{240}Pu content than reactor-grade plutonium. This difference is not expected to affect either the VVER-1000 fuel assembly configuration or the reactor performance of the MOX fuel. The reference conversion process for MOX power in the Russian Federation is expected to be aqueous conversion with purification such that the powder is chemically identical to that used commercially in reactor-grade MOX. Use of MOX fuel made from reactor-grade plutonium in LWRs is already under way in Europe on a substantial scale, with 34 reactors now licensed for MOX fuel use [3], and is planned to begin soon in Japan. Therefore, the technical feasibility of using MOX in LWRs is amply demonstrated. Although neither the United States nor Russia has any LWRs currently using such fuel, both have LWRs already in operation that may be suitable for using plutonium in the form of uranium–plutonium MOX fuel. The use of such reactors would allow weapons plutonium to be transformed into spent fuel in a timely fashion. This could begin within 5 years from a decision to undertake such a project and would extend over a period of 10 to 20 years thereafter. The fissile material in spent MOX fuel would be roughly as difficult to recover for use in nuclear weapons as the fissile material remaining in low-enriched uranium (LEU) spent fuel.

The use of MOX fuel changes the physics of the reactor core significantly compared to the uranium fuels usually used, and it is essential to ensure that nuclear safety is maintained if MOX fuel is to be used. Traditionally, most LWRs that have used MOX fuel have used it in only one-third of their fuel assemblies to limit the change in safety parameters compared to using uranium fuels. Using MOX in larger fractions of the fuel assembly, up to 100% of the assembly, is possible if adequate attention is paid to ensuring effective control of the reactor. Full MOX cores would have the advantage of greatly reducing the number of reactors needed to accomplish disposition of a given amount of plutonium in a certain period of time and therefore reducing the necessary transportation of fuel containing weapons-grade plutonium and the number of sites

handling such fuel. Belgium has demonstrated the use of a 70% MOX core in an experimental reactor; three operating U.S. reactors were specially designed for 100% MOX cores, although they have not been demonstrated or licensed in this mode; and a substantial number of other U.S. reactors are believed capable of full MOX core operation.

The United States has some past experience with LWR MOX dating from the 1950s, well before the 1976 U.S. decision not to pursue near-term plutonium separation and recycle. Computer codes for modeling the behavior of LWR reactor cores with MOX fuel are available and are being compared to existing Russian codes. Initial fuel development tests, in which MOX fuel rods containing weapons plutonium will be irradiated in test reactors simulating the conditions in a commercial VVER, are scheduled to begin in 1997–1998. Information gained in these tests will be used to help validate these computer codes.

Russia has no experience with the use of MOX in its LWRs because its plutonium fuel plans have been traditionally focused on fast-neutron reactors. The use of MOX in LWRs is now being studied however, and Russia may be able to make use of MOX experience in Europe. There are seven operational VVER-1000 reactors in Russia of which six are considered capable of supporting the plutonium disposition mission. Two more VVER-1000s are under active construction and are expected to be completed in the near future; they are estimated by Russia to be 80–90% complete. A third new VVER-1000 reactor, estimated to be 70% complete, has less current construction activity under way and is expected to be completed by 2003 if adequate financing is available. Two additional VVER-1000s and a number of the new VVER-640 designs are planned, but the availability of financing for these projects is uncertain. In addition to the VVER-1000 reactors in Russia, there are potentially 11 Russian-designed VVER-1000 reactors in Ukraine that may be available for the plutonium disposition program. These reactors were constructed from the 1980s through the mid-1990s and are believed to meet most Western safety standards. Thus, significant reactor modifications are not expected to be needed to convert from LEU fuel to partial MOX fuel.

In both the United States and Russia, the major factors determining when this option could begin are the need to provide the necessary fuel fabrication facilities and the need to acquire licenses and political approvals for both those facilities and the reactors that would use plutonium. To the extent possible, all alternatives would make use of existing infrastructure and capabilities at Russian nuclear sites. This approach would minimize cost and provide new missions for existing facilities, manpower, and intellectual resources rendered idle by the end of plutonium production for weapons.

Preliminary studies are under way on VVER-1000 reactors with one-third MOX cores to determine the extent of reactor modifications that may be necessary. Plutonium used as a fuel results in a more negative cooling water temperature reactivity coefficient and reduced boron efficiency. Control rod efficiency, boric acid concentration, and the rate of boric acid injection into the primary circuit under emergency conditions become the most important parameters to determine how many subassemblies will have MOX fuel. Modifications to the reactor safety systems could include increasing the diameter of the control rods, changing the material from which they are made, or adding more

Russia has pilot-scale MOX fabrication facilities at Mayak and Dmitrovgrad, which are capable after some redesign of producing small amounts of LWR MOX fuel for experimental purposes. Russia is currently collaborating with European partners on the conceptual design of an expanded pilot plant at Mayak with a capacity of 1.3 MT of plutonium per year, enough to provide partial MOX cores for four VVER-1000 reactors and for the BN-600 fast-neutron reactor. Several options for commercial-scale production of LWR MOX exist. Current Russian plans, subject to the availability of financing, call for construction of a MOX plant dedicated to producing LWR fuel beginning after the turn of the century, in conjunction with the planned RT-2 reprocessing plant at Krasnoyarsk-26. Alternatively, the partially completed "Complex-300" MOX plant at Mayak could be finished and one of the lines modified for production of LWR MOX, or a new facility could be built at that site. Further study of the costs, schedules, and nonproliferation and safety implications of each of these approaches is needed.

Assessing total program costs of the LWR option in Russia is very difficult because Russia's rapidly changing economic circumstances introduce substantial uncertainties into any long-term economic assessment. It is apparent that the small amount of NPP modifications and infrastructure changes necessary to use existing VVER-1000s would cost significantly less than building new NPPs. Current estimates reflect a cost for using these NPPs at a level similar to the cost of immobilizing the weapons-grade plutonium, but with the added advantage of realizing the electrical power potential of the plutonium. Russia is currently considering a substantial MOX program designed to manage the civilian plutonium arising from reprocessing. Financing of this program is uncertain. Therefore, the cost assigned to disposition of weapons plutonium by the MOX route should be the net additional cost of modifying the previously envisioned MOX program to handle both weapons plutonium and civilian plutonium. However, it is also important to identify the needed capital investments for any MOX program. This will facilitate planning for the necessary financing for disposition of either civilian or surplus weapons plutonium.

3. The BN-600 Reactor

Currently, BN-600 is fueled with enriched uranium and is a demonstration "breeder" reactor, although its current operations, which are directed at producing electrical energy, are not optimized to make it an efficient producer of fissile plutonium compared to the consumption of fissile uranium fuel. However, the ~100 blanket assemblies removed each year contain ~120 kg of plutonium with about 95% ^{239}Pu. The BN-600 reactor is capable, with certain design modifications, of being converted from a plutonium producer to a net burner of plutonium that can disposition up to 1.3 MT of weapons plutonium into highly radioactive spent fuel each year.

The BN-600 reactor is currently licensed by the Russian Federal Nuclear and Radiation Safety Authority (GOSATOMNADZOR or GAN) to operate with 18 fuel subassemblies containing MOX fuel elements in a core of 369 subassemblies that are

control rods. Preliminary designs allow for an increase in the number of control rods from 61 to 121 (the reactor design permits this upgrading) and introduction of new monitoring and diagnostics systems. To increase control rod efficiency in VVER-1000s, modifications could also include increasing the number of absorber rods in an assembly from 18 to 24 and increasing the boron enrichment in absorber rods with the ^{10}B isotope. It may be easiest to increase the absorber diameter. Preliminary investigation shows that it is possible to increase the absorber diameter from 7.0 to 7.6 mm with a simultaneous increase in the guide tube outer diameter from 12.6 to 13.1 mm. This improves the rod system efficiency by ~6% [2]. Another safety improvement option, not requiring reactor redesign, is to use a core reloading scheme with lower neutron leakage. In this scheme, part of the fuel assemblies with fresh fuel are loaded into the central part of the core. It is important to use fuel rods with gadolinium burnable poison. Along with flattening of the core power distribution, this loading scheme allows the neutron flux to rise in the fuel assemblies with control rods and hence to increase reactivity worth of the rods to the end of the reactor cycle, when it is most needed. Whether it is possible to increase the percentage of the core loaded with MOX fuel to 50, 75, or 100% without substantial and costly modifications to the reactor requires further study.

The planned new-design reactors (VVER-640) should be able to handle full MOX cores safely because they are designed with twice the number of control rods used in most existing VVER-1000s. The following passive safety systems are also planned to be installed in new reactors:

- core heat removal for use during reliable power supply failure (PCHRS);
- core flooding for accidents with blackout and primary circuit leaks;
- catching, confining, and cooling corium after reactor vessel melt-through;
- gas-vapor filtration for emergency discharge into the environment during an unanticipated pressure rise of more than 5 atm inside the containment; and
- double containment (steel and concrete).

Additionally, the following measures may be taken to reduce exposure for plant maintenance personnel when converting VVER-1000s to MOX fuel:

1. Construct separate storage for fresh MOX fuel at the nuclear power plant, designed for the MOX fuel for all reactors. This storage must have a MOX fuel subassembly inspection bay and facilities for loading the subassemblies into on-site containers.
2. Develop the on-site container.
3. Develop fresh MOX fuel containers and transportation equipment.

Spent MOX fuel subassemblies in water have a higher neutron multiplication factor than spent uranium fuel subassemblies. Therefore, it is necessary to increase the lattice pitch of the spent fuel storage pond rack design, or the rack needs to be made of structural steel containing boron or other absorbers with higher neutron-absorbing properties. The spent MOX fuel container and the methods of transporting and storing the spent MOX fuel are similar to those for spent uranium fuel. However, more long-term cooling of the spent MOX fuel assemblies is required at the nuclear power plant before the assemblies can be shipped to permanent storage facilities.

normally fueled with enriched uranium oxide. To date, 24 MOX fuel subassemblies have been irradiated in BN-600. Of these subassemblies, 6 contained vibro-packed MOX fuel fabricated at the Research Institute of Atomic Reactors (RIAR) in Dmitrovgrad, and the other 18 used pelletized MOX fuel fabricated at the PAKET pilot plant at Mayak, Chelyabinsk Region. The fuel in the BN-600 tests used plutonium oxide from reprocessed radial blanket subassemblies from BN-350 and BN-600 so that the plutonium isotopic composition is very close to that of weapons-derived plutonium. The irradiations in BN-600 supplement the extensive prior testing of plutonium oxide and MOX fuels at the BR-10, BOR-60, and BN-350 fast-neutron reactors.

The steps needed to convert BN-600 to a full MOX, plutonium-burner core are (1) elimination of the radial breeding blanket and its replacement with a combination of a steel reflector and boronated shield, (2) initial conversion to a hybrid core (based on a predominantly uranium-fueled core partly loaded with MOX fuel) sufficient to preserve a zero value for the sodium void reactivity effect (SVRE), and (3) ultimate conversion to the full MOX core. The hybrid core conversion requires a fuel fabrication facility capable of supplying MOX fuel using ~300 kg/year of surplus weapons-derived plutonium. The full MOX core requires modifications to the design of the fuel sub-assembly to obtain a negative SVRE value, reduction of the sodium pump head by modifying the main coolant pumps to accommodate the modified fuel subassemblies, and a MOX fuel fabrication capacity using ~1.3 MT/year of surplus weapons-derived plutonium and dedicated to BN-600.

The BN-600 reactor will reach the end of its initially planned design lifetime in 2010. To make a significant contribution to plutonium disposition (~20 MT), the lifetime of BN-600 must safely and reliably be extended to at least 2020. The BNPP has an aggressive in-service inspection program to monitor plant aging effects in structures and components. Life extension is judged to be feasible because the plant is in excellent condition and suppliers of replacement equipment exist. The BNPP judges the limits to extended life to be tied to the financial situation in Russia, not to any technical or safety-related restrictions.

A first step to reconfiguring BN-600 to be a plutonium burner is to eliminate the radial breeding blanket that surrounds the core and separates the core from the in-vessel spent fuel storage. The radial blanket consists of ~400 subassemblies fueled with steel-clad rods containing depleted uranium oxide pellets. About 100 of the subassemblies in the radial breeding blankets are removed each year, containing ~120 kg of plutonium with about 95% ^{239}Pu. However, the blanket is also needed to attenuate the neutron leakage from the core into the in-vessel spent fuel storage so that fission heating in the stored fuel is acceptably low. In recent years, the Russian RT-1 reprocessing plant at Chelyabinsk has ceased to accept the radial blanket subassemblies for reprocessing. Currently, BNPP has about 3 years to find alternative storage for the large number of irradiated blanket subassemblies gathering in the BN-600 water-cooled ex-vessel spent fuel storage pool, or the reactor may have to be shut down.

The optimum solution involves the elimination of the radial breeding blankets and the construction of a dry storage facility for previously irradiated blanket subassemblies. The current inventory in wet storage contains an estimated metric ton of weapons-

quality plutonium. The irradiated blanket subassemblies are substantially less radioactive than the irradiated fuel subassemblies. Axial breeding blankets are integral with the fuel rods in the fuel subassemblies that are highly radioactive after irradiation.

To eliminate the radial breeding blanket, several design changes are required for the core.

- Steel reflector subassemblies must be designed and fabricated to replace the radial breeding blanket subassemblies immediately surrounding the core. Similar subassemblies are used as gamma shielding in BN-600 around the base of the refueling elevator outside the radial blanket, but the conceptual design would use different materials in locations adjacent to the core. The candidate material is 12% chromium, 1% molybdenum ferritic stainless steel, which has a lifetime neutron fluence limit of 120 displacements per atom based on testing at Dmitrovgrad. Such subassemblies have also been used in the United States both at the Experimental Breeder Reactor II in Idaho and the Fast Flux Test Facility at Hanford, Washington.
- Shield subassemblies must be designed and fabricated to replace the radial breeding blanket subassemblies in the outer locations adjacent to the in-vessel spent fuel storage. Neutron leakage radially from the core to the spent fuel must be attenuated by the shield subassemblies in a manner comparable to the radial breeding blanket so that an acceptably low level of subcritical fission heating is maintained in the in-vessel-stored spent fuel. The conceptual design of the shield subassemblies is for steel-clad rods containing boron carbide pellets to moderate and capture neutrons leaking past the reflector subassemblies.
- The core must be enlarged slightly by adding ~20 fuel subassemblies to compensate for power generation lost by removing ~400 subassemblies from the radial breeding blanket. Compared to fuel subassemblies, radial blanket subassemblies have a different inlet orificing in the extension on the lower part of the subassembly to reduce flow. Adding 20 fuel subassemblies with higher flow and ~380 reflector/shield subassemblies with slightly reduced flows is calculated by the designers not to be a problem from the standpoint of the thermal-hydraulic margin of safety.

The elimination of the radial breeding blanket can proceed prior to or in parallel with the conversion to the hybrid partial MOX core. The important issues are to eliminate the production of ~120 kg of weapons-capable plutonium (as judged from its isotopic composition) each year in the blanket, to ensure that the margin of safety in the reactor is not compromised, and to secure in safe storage the ~1 MT of weapons-capable plutonium contained in irradiated radial breeding blanket subassemblies. The plan is to solve the problems of breeding blanket elimination and storage before 2001.

3.1. CONVERSION TO A HYBRID (PARTIAL MOX) CORE

The BN-600 core is licensed by GAN to contain up to 18 MOX subassemblies at any one time. The principal regulatory limit to adding additional MOX subassemblies without significantly changing the current fuel subassembly design is related to maintaining a nonpositive value for SVRE. Because of the reactivity transient that

occurred in the Chernobyl accident, the GAN regulations prohibit positive reactivity feedback due to voiding of the coolant. In the uranium cores of BN-600 even with a few MOX subassemblies, the SVRE value is strongly negative. As additional MOX subassemblies are added to the core, calculations show that the SVRE value becomes less negative and, at around 90 subassemblies or so (depending on the zoning arrangement), the SVRE value is close to zero. To meet the GAN requirements and to ensure that SVRE is at most zero or a negligibly small positive value, the designer must select a design that provides a sufficiently negative calculated value of SVRE to compensate for the uncertainties in calculations and experimental benchmarks. While applying the deterministic SVRE criteria in the design of the hybrid core, this effort will be supplemented by probabilistic safety analyses to demonstrate that the probability and consequences of total or partial core voiding are acceptably small for the hybrid core. The GAN licensing is expected to take about 3 years with simultaneous review of the safety case for elimination of the radial breeding blanket. The current planning is to initiate the BN-600 operations with a hybrid MOX core by 2002.

In addition to the design and safety studies on the behavior of the hybrid core during normal operations and accidents, which will be documented in the updated safety analysis report submitted to GAN, an adequate capacity for supplying reload MOX subassemblies must be developed and licensed. The initial hybrid core loading will require 70–90 MOX subassemblies, and core reloads will require 40–50 MOX subassemblies per year using ~300 kg of surplus weapons-derived plutonium annually. BN-600 has favorable irradiation experience with both vibro-packed and pelletized MOX subassemblies using reprocessed plutonium oxide from BN-350 and BN-600 radial breeding blankets and containing about 95% ^{239}Pu. Several options are being considered for interim MOX fabrication capacity to support the hybrid core.

- Upgraded PAKET pilot line at Mayak in Chelyabinsk Region: This option would upgrade and expand the Russian facilities used currently to make the four-subassembly batches of MOX fuel for BN-600. Currently, rod bundling of the four-subassembly batches takes place at Elektrostal near Moscow, but for 40–50 subassemblies per year, this capability would be replicated on a small scale either at the Mayak site or at RIAR where licensed plutonium-handling facilities exist. Collocating all fabrication facilities at Mayak would minimize transportation of fissile materials between sites and place the fabrication facilities on the same site as the dismantled weapon storage facility. At PAKET, conversion of weapons-derived metal into an oxide powder would be based on aqueous processing such as either an oxalate precipitation of plutonium oxide with subsequent mechanical mixing with uranium oxide powder or ammonia coprecipitation of MOX powder. Small-scale facilities for each process already exist at Mayak, and both types of pelletized fuel have been irradiated in BN-600 with excellent performance.
- Expanded vibro-packed capacity at RIAR in Dmitrovgrad: RIAR currently has facilities for recycling of civilian plutonium from the BOR-60 reactor fuel, but expanded facilities would be needed to provide the annual requirement for 40–50 subassemblies for the BN-600 hybrid core. RIAR uses pyroelectrochemical processing in a molten salt to produce the powder for vibro-packed fuel, which is

used in BOR-60 and has been tested in BN-600. This technology can be applied to the conversion of weapons-derived metal or oxide into MOX. The disadvantage to collocating all fabrication facilities at RIAR is that weapons-derived metal or oxide from Mayak would have to transported to RIAR. The production of oxide powder at Mayak would reduce the attractiveness of the material to theft or diversion during transport to RIAR from Mayak, but it also introduces an additional, unnecessary first step from the standpoint of fuel performance, requires additional accident analysis of potential contamination events in transit, and complicates material control and accountability.

- TOMOX–DEMOX: From 1993–1996, the French and Russians worked on a joint project on plutonium disposition designated AÏDA MOX Phase 1; AÏDA MOX Phase 2 is now starting. The products of this effort include the conceptual designs for a plutonium metal-to-oxide conversion pilot facility (TOMOX) and a MOX fuel fabrication pilot facility (DEMOX) with a capacity of 1.3 MT/year of plutonium metal. The vision for use of these facilities is to process 300 kg of surplus weapons plutonium into MOX fuel for BN-600 and 1000 kg for VVER-1000 fuel sub-assemblies. Thus, TOMOX–DEMOX would provide fuel for one fast reactor and about four water reactors. The full MOX option in BN-600 requires the dedication of a facility of equal capacity to TOMOX–DEMOX. The current reality of this proposal is that it has a split mission (BN-600 and VVER-1000), lacks consensus on location (Mayak or Krasnoyarsk), and lacks consensus on processes with France, the United States, and several Russian institutes advocating varying technologies especially for TOMOX. Without arriving soon at a consensus favorable to the BN-600 mission, it is likely that this approach may not be sufficiently timely to support early start of the hybrid core conversion; however, the upgraded PAKET option may also be subsumed by this proposal due to limits on Western financing of a pilot plant.

An additional concern raised by BNPP and the core designers with regard to using surplus weapons plutonium is the possible need for changes in the reactor fresh fuel handling and shielding systems to accommodate the higher gamma-ray source from ^{241}Am buildup in the weapons plutonium. Specialists from BNPP indicate that the measured radioactive exposure dose from experimental MOX subassemblies made from plutonium reprocessed from BN-350 and BN-600 radial blankets is higher than the exposure dose from conventional uranium subassemblies. BNPP stipulates that appropriate measures should be taken to protect workers during handling operations with MOX fuel subassemblies.

3.2. CONVERSION TO A FULL MOX CORE

Conversion of BN-600 to a full MOX plutonium-burner core requires design changes in the reactor system to ensure an acceptable nonpositive or negligibly small positive SVRE value. In addition, adequate fuel supply capacity is needed to provide a sufficient number of MOX subassemblies containing ~1.3 MT of surplus weapons-derived plutonium each year. The intent is to complete conversion to full MOX between the

years 2005 and 2007 so that ~20 MT or more of surplus weapons plutonium can be consumed and transmuted to spent fuel before 2020.

As discussed previously, replacing more than about 90 of the enriched uranium fuel subassemblies with MOX fuel subassemblies leads to a positive SVRE value when using the current subassembly design for BN-600. This problem was solved analytically, in conjunction with experiments in the BFS fast reactor critical facility, for the next-generation Russian fast reactor (BN-800) by modifying the design of the rod bundle within the subassembly can. This approach, which can be adapted to BN-600, is based on eliminating the upper axial breeding blanket in the fuel rods, introducing a sodium plenum immediately above the fuel rod bundle, and placing a cluster of boronated, short rods above the plenum within the subassembly can. In this case, the introduction of the sodium plenum requires reducing the core height by about 150 mm less than in the hybrid core. With this design, voiding that initiates in the hottest flow channels of the upper core rises to the upper plenum, displacing liquid sodium that serves as a neutron reflector and producing increased neutron leakage from the top of the core into the boronated shield. The loss of neutrons in such a scenario creates a negative SVRE value.

Because of the loss of fission heating due to shortening of the core height and removal of the upper axial breeding blanket, the radial size of the BN-600 full MOX core will also have to increase by about 35 subassemblies compared to the hybrid core to maintain the same power generation capacity for the plant and the same thermal performance margin of safety in the core. The additional removal of the lower axial breeding blanket may be desirable from the standpoint of further improving BN-600 operations as a net burner of plutonium, but it is not considered practical at this time and would require substantial further study.

An adequate supply of MOX fuel is needed to continue the BN-600 on full operations as a plutonium burner until its end of life. As indicated, the French-Russian TOMOX–DEMOX concept is for a pilot plant with the requisite capacity for BN-600 on full MOX, but it is currently envisioned to provide VVER-1000 fuel also. The capacity of the TOMOX–DEMOX pilot plant is not sufficient to supply the needs of BN-600 on full MOX and as many as 7 VVER-1000s in Russia (and possibly the 11 VVER-1000s in Ukraine) on partial MOX. However, at this time, it is not yet clear how many plutonium conversion facilities and MOX fabrication facilities will be constructed and at what capacity. This issue is currently being addressed separately in bilateral discussion between the Russians and France, Germany, and the United States, respectively. Thus, a major uncertainty for the BN-600 full MOX option is the timing of the fuel supply.

3.3. EXTENSION OF THE SAFE AND RELIABLE OPERATING LIFETIME FOR BN-600

As indicated previously, BN-600 has a predicted design lifetime of 30 years ending in 2010. The predictions are based on conservative estimates of materials and structural performance in nonreplaceable components and high-cost components. BNPP has an aggressive in-service inspection and maintenance program and has replaced steam generator evaporator modules, which performed as predicted. An intermediate loop heat

exchanger will be removed and inspected for evidence of age-related degradation phenomenon before 2000. The steam generator superheaters in the intermediate loop must also be inspected prior to the end of their conservatively predicted design life in 2010. Suppliers exist for all key components; financing replacement equipment procurement is the only issue for BNPP. The Experimental Design Bureau of Mechanical Engineering (OKBM) maintains an operational data base on thermal-hydraulics and structural-mechanical performance. OKBM has used measured neutron fluence data to validate its lifetime predictions for neutron-irradiated reactor components. The lifetime margins of irradiated structures vary from a factor of 1.6 for the rails of the in-vessel refueling elevator, which are replaceable, to a factor of 8 to 20 for the reactor vessel. The core barrel, which is not load bearing, is highly irradiated but not life limiting. The reactor coolant pump impellers have been redesigned for extended life. BNPP judges that the major impediment to life extension is the availability of financing in a timely manner to support the procurement of needed replacement equipment.

4. Conclusions

The use of existing VVER-1000 reactors and the BN-600 fast reactor for the disposition of surplus weapons-grade plutonium into spent nuclear fuel is a technically viable option. Compared to the construction of new reactors, the use of modified VVER-1000s and the BN-600 reactor with an extended lifetime offers a less expensive and more timely alternative by taking full advantage of existing facilities and equipment. Compared to the immobilization alternative, the existing reactor option has the significant advantage of using the enormous energy potential of plutonium. The technical and regulatory problems to be solved are tractable. The United States and the Russian Federation have currently embarked upon the planning and preliminary analyses needed to execute the work necessary to use these reactors in a timely and safe manner.

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