# Safety Issues Associated with Plutonium Involvement in the Nuclear Fuel Cycle

# NATO Science Series

*A Series presenting the results of activities sponsored by the NATO Science Committee. The Series is published by IOS Press and Kluwer Academic Publishers, in conjunction with the NATO Scientific Affairs Division.*

*General Sub-Series*

| | |
|---|---|
| **A. Life Sciences** | IOS Press |
| **B. Physics** | Kluwer Academic Publishers |
| **C. Mathematical and Physical Sciences** | Kluwer Academic Publishers |
| **D. Behavioural and Social Sciences** | Kluwer Academic Publishers |
| **E. Applied Sciences** | Kluwer Academic Publishers |
| **F. Computer and Systems Sciences** | IOS Press |

*Partnership Sub-Series*

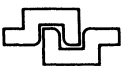
| | |
|---|---|
| **1. Disarmament Technologies** | Kluwer Academic Publishers |
| **2. Environmental Security** | Kluwer Academic Publishers |
| **3. High Technology** | Kluwer Academic Publishers |
| **4. Science and Technology Policy** | IOS Press |
| **5. Computer Networking** | IOS Press |

*The Partnership Sub-Series incorporates activities undertaken in collaboration with NATO's Partners in the Euro-Atlantic Partnership Council – countries of the CIS and Central and Eastern Europe – in Priority Areas of concern to those countries.*

**NATO-PCO-DATA BASE**

The NATO Science Series continues the series of books published formerly in the NATO ASI Series. An electronic index to the NATO ASI Series provides full bibliographical references (with keywords and/or abstracts) to more than 50000 contributions from international scientists published in all sections of the NATO ASI Series.
Access to the NATO-PCO-DATA BASE is possible via CD-ROM "NATO-PCO-DATA BASE" with user-friendly retrieval software in English, French and German (© WTV GmbH and DATAWARE Technologies Inc. 1989).

The CD-ROM of the NATO ASI Series can be ordered from: PCO, Overijse, Belgium.



**Series 1: Disarmament Technologies – Vol. 23**

# Safety Issues Associated with Plutonium Involvement in the Nuclear Fuel Cycle

edited by

Theodore A. Parish
Texas A&M University,
College Station, Texas, U.S.A.

Vyacheslav V. Khromov
Moscow Engineering Physics Institute,
Moscow, Russian Federation

and

Igor Carron
Texas A&M University,
College Station, Texas, U.S.A.

Springer Science+Business Media, B.V.

Proceedings of the NATO Advanced Research Workshop on
Safety Issues Associated with Plutonium Involvement in the Nuclear Fuel Cycle
Moscow, Russia
2–6 September 1997

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 978-0-7923-5593-9 ISBN 978-94-011-4591-6 (eBook)
DOI 10.1007/978-94-011-4591-6

---

*Printed on acid-free paper*

---

## CONTENTS

## PLUTONIUM USAGE IN EXISTING/NEAR-TERM REACTORS

## FOREWORD

The "VOLGA" conferences, hosted in odd-numbered years by the Department of Theoretical and Experimental Reactor Physics of the Moscow Engineering Physics Institute (MEPhI), are some of the most prestigious technical meetings held in Russia. Traditionally, these conferences present the opportunity for reactor physicists from around the world to gather at MEPhI's holiday camp on the banks of the Volga river (near Tver) to exchange ideas and explore innovative concepts related to nuclear power development. In 1997, NATO became involved in the "VOLGA" meetings for the first time by co-sponsoring "VOLGA97" as an advanced research workshop. This workshop broke with tradition a bit in that the venue was moved from MEPhI's holiday camp to a location nearer Moscow.

The workshop program was effectively organized in order to cover a broad range of topics relating to the theme of the meeting. Generally, the papers concerned safety-related questions associated with utilizing both weapons-grade and reactor-grade plutonium in the nuclear fuel cycle, including facility requirements, licensing issues, proliferation risks, and a variety of advanced concepts for alternative fuel cycles. The program contained a total of ninety-nine papers presented in five days of sessions.

The first plenary session featured four interesting papers which established the international tone of the workshop. The first paper was presented by Bruce Bevard and Alexander Chebeskov of ORNL and IPPE Obninsk, respectively, on the joint US/Russia projects for the disposition of weapons-grade plutonium. Vladimir Kagramanian of the IAEA gave a global perspective on energy needs and the future role of nuclear energy in the context of sustainable development. Alexander Dmitriev of Gosatomnadzor (the Russian Nuclear Safety and Licensing Authority) provided a regulatory-based overview of the options for plutonium disposition in Russia. Finally, David Boyle of Texas A&M University described the activities of the Amarillo National Resource Center for Plutonium in temporary storage, plutonium disposition and public outreach.

In the subsequent sessions, attention was generally given to the role of plutonium and the minor actinides in various types of reactors and in the nuclear fuel cycle. On a practical level, papers from the United Kingdom and France dealt with currently operating facilities for MOX fuel fabrication, including process modifications and safety constraints which would arise in constructing a MOX fabrication plant for weapons-grade plutonium. In contrast, papers from Germany and Russia offered innovative ideas on "denaturing" weapons-grade plutonium with reactor-grade plutonium, requirements for long-term applications of nuclear energy, and the use of new fuel forms to increase proliferation resistance. A feature of the program which was appreciated by the participants was the lively question and answer periods following each paper, and the free expression of divergent viewpoints. These discussions often carried over to the breaks and the social functions as well.

Over 100 participants took part in the workshop. Personnel representing virtually all of the major Russian research institutes and organizations active in nuclear fuel cycle activities, as well as, universities and nuclear power plants attended the workshop. Some of the Russian organizations included the Institute of Physics and Power Engineering-Obninsk, the Kurchatov Institute, the Bochvar Institute of Inorganic Materials, the

Russian Academy of Natural Sciences and the nuclear weapons laboratories at Arzamas-16 and Chelyabinsk-70. Specialists from several nuclear power plants including Kalinin, Kursk and Smolensk also attended the workshop. The foreign delegation consisted of representatives from international agencies, national laboratories, industry, and academia. Each of the foreign participants presented papers and were key contributors to the workshop. This delegation consisted of Peter Chan, Atomic Energy of Canada, Ltd., John Magill of the EURATOM Transuranium Institute, Cyril de Turenne of Cogema, Erich Merz of the Juelich Research Center and the University of Aachen, Dieter von Ehrenstein and Roland Reimers of the University of Bremen, Vladimir Kagramanian of the IAEA, Lynn Farrington and Peter Broome of BNFL, Bruce Bevard of Oak Ridge National Laboratory and David Boyle, Ted Parish and Lee Peddicord of Texas A&M University.

The workshop was held at the Center for Education and Information Techniques of the Russian Employment Service (TSEZAN). TSEZAN is a wholly contained facility with guest rooms, cantine, meeting rooms, an auditorium and a lobby/social center. It is located on a wooded campus in the town of Ivanteevka, 35 kilometers northeast of Moscow. The meeting auditorium was equiped with public address and earphone systems which allowed for all of the papers presented in Russian to be simultaneously translated into English. The papers presented in English were interpreted into Russian sequentially.

The breadth and quality of the technical presentations, and the spirit of good will, friendship and collaboration which characterized the workshop, contributed immeasurably to the meeting's success. The key role of NATO was noted in both the opening and closing sessions.

*Theodore A. Parish, Texas A&M University*
*Vyacheslav V. Khromov, Moscow Engineering Physics Institute*
*Igor Carron, Texas A&M University*

## ACKNOWLEDGMENTS

The organization of the workshop was the dual responsibility of the Moscow Engineering Physics Institute (MEPhI) and Texas A&M University (TAMU). MEPhI took care of most of the arrangements for organizing the meeting while TAMU primarily handled selecting the international delegation and editing the proceedings.

At MEPhI, a number of people were key to making the workshop a success. Professor Khromov served as the workshop Co-Director and provided top level guidance in the organization of the meeting. Due to his illness, a number of other people stepped forward to assume important roles. Professor Vladimir Naumov is acknowledged for compiling and editing the Russian language version of the meeting transactions. Special commendation also goes to Dr. Edward Kryuchkov, Dr. Vladimir Savander, Dr. Anatoli Chmelev, Mr. Pavel Tsvetkov, Mr. Vyacheslav Okunev, Mr. Yuri Mitjaev and Mr. Igor Zonov for their contributions in conducting the conference. Dr. Alexander Chebeskov of IPPE Obninsk is thanked for providing key assistance through his service on the steering committee. Professor Boris Onykii who had recently been elected as the new Rector of MEPhI is thanked for presenting the conference opening address. Of particular note was the quality of the interpreters, Ms. Ludmila Belatis and Mr. Sergei Yelovsky, who both possessed excellent familiarity with scientific terminology. Finally, the faculty, staff and students of the Department of Theoretical and Experimental Reactor Physics at MEPhI are thanked for all their efforts in tending to the requests/needs of the international delegation, and for generally making the workshop a success.

The support of the Nuclear Engineering Department at Texas A&M University made possible by its head, Dr. John W. Poston, Sr., is greatfully acknowleged. A number of individuals from the Nuclear Engineering Department were crucial to the workshop's success and deserve special mention here. The responsibilities for the workshop were primarily handled by Professor Parish, the workshop Co-Director, Dr. Igor Carron, and Ms. Gia Alexander. Professor Parish supervised the NATO grant and served as the chief editor of the proceedings. Dr. Igor Carron was instrumental in assuring the success of the workshop by taking care of many administrative details concerning travel reimbursement and financial reports. Dr. Carron also edited papers. Mr Bradley Rearden, a TAMU student, is acknowledged for the help he gave to Dr. Carron. Finally, Ms. Gia Alexander deserves special mention for her efforts which contributed to the success of the workshop. Her experience in editing earlier NATO proceedings was priceless in terms of advising authors, collecting the permission to publish forms and formatting the papers. Ms. Alexander was assisted by two TAMU students, Mr. Giby Joseph and Mr. Max Oyola.

Special thanks go to the MEPhI organizers, in particular, Dr. Edward Kryuchkov, Dr. Vladimir Savander and Mr. Pavel Tsvetkov, for hosting a number of social activities to provide the workshop participants with entertainment after the technical sessions. On Wednesday evening, there was a barbecue along with the singing of Russian folk songs. On Thursday afternoon, a trip was made by everyone to the Trinity Monastery in nearby Sergiev Posad. On Friday evening, there was a lively and festive banquet. And on Saturday afternoon, there was a visit to the recently reconstructed Christ the Savior Cathedral and a tour of Moscow at the height of its 850th birthday celebration.

This NATO advanced research workshop brought together Russian and western specialists to discuss questions associated with the safe elimination of both weapons-grade and reactor-grade plutonium in reactors. This workshop was the fourth in a series of workshops centered on plutonium disposition sponsored by the Scientific Affairs Division of NATO. Mrs. Nancy T. Schulte, Program Director of the Disarmament Technologies Division at NATO, gave invaluable and timely assistance.

The contributions of each participant in the meeting whether or not their papers are included in these proceedings is also thankfully acknowledged.

*Theodore A. Parish, Texas A&M University*
*Vyacheslav V. Khromov, Moscow Engineering Physics Institute*
*Igor Carron, Texas A&M University*

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

A. CHEBESKOV
A. KALASHNIKOV
*State Scientific Center—Institute* of *Physics and Power Engineering*
*I Bondarenko Sq.*
*Obninsk, Kaluga Region*
*249020 Russian Federation*

B. BEVARD
D. MOSES
*Oak Ridge. National Laboratory*
*PO Box 2009*
*Oak Ridge, Tennessee 3783*
*United States*

A. PAVLOVICHEV
*State Scientific Center—Kurchatov institute*
*I Kurchatov Sq.*
*123182 Moscow*
*Russian Federation*

**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 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, and the existing BN-600 fast-neutron reactor at the Beloyarsk



*T. A. Parish et al. (eds.),*
*Safety Issues Associated with Plutonium Involvement in the Nuclear Fuel Cycle,* 1–13.

Nuclear Power Plant in Russia. The use of Canadian CANDU reactors is also an option. 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 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 1,300 Kg or 1.3 metric tons (MT) of surplus weapons plutonium to spent fuel each year. The steps needed to convert the 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 the 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, US 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's 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 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 fuel production from weapons-grade plutonium 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 fuel usually employed, 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, up to 100% of the core, 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 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-640s 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 are allowed to 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 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 diagnostic 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 of the $^{10}B$ isotope in the absorber rods. 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 the negative reactivity worth of the rods near 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-640s) should be able to handle full MOX cores safely because they will employ twice the number of control rods used in most existing VVER-l000s. The following passive safety systems are also planned to be installed in the new VVER-640 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 on-site containers; and
3. Develop fresh MOX fuel containers and transportation equipment.

Spent MOX fuel subassemblies submersed 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, or the rack needs to be made of structural steel containing boron or other elements with high neutron-absorbing properties. The spent MOX fuel container and the methods for transporting and storing 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.

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. This is 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-l000s 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 normally fueled with enriched uranium oxide. To date, 24 MOX fuel subassemblies have been irradiated in the 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, BOA-60, and BN-350 fast-neutron reactors.

The steps needed to convert BN-600 to a full MOX, plutonium-burner core are as follows: (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 subassembly 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 the BN-600 must safely and reliably be extended to at least 2020. The BN-600 power plant 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 BN-600 power plant judges the limits to extended life to be tied to the financial situation in Russia. not to any technical or safety-related restrictions.

The first step in reconfiguring the BN-600 to become 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. These contain ~120 kg of plutonium with about 95% $^{239}$Pu. However, the blanket is also needed to attenuate the neutrons leaking from the core into the in-vessel spent fuel storage area 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, there is sufficient space in the BN-600 water-cooled ex-vessel spent fuel storage pool for about 3 years, then alternative storage for the irradiated blanket subassemblies will have to be found, 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 one 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 the BN-600 around the base of the refueling elevator outside the radial blanket, but the conceptual design would use different locations adjacent to the core. The candidate material is 12% chromium, 1% molybdenum ferric 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 at 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 to not pose 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 probabilities 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 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.

### 3.1.1 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. However, 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 already 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