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Decreasing HEU Stocks and Use at the Institute of Physics and Power Engineering

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One legacy of the Soviet nuclear program is great quantities of high enriched uranium (HEU) that were used in different research programs. The Institute of Physics and Power Engineering (IPPE), founded in 1946, was (and still is) actively involved in nuclear energy development and application, including fast breeder, naval propulsion and space power reactors. IPPE built a special experimental complex containing critical assemblies and research reactors. During 50 years of research activities, a great quantity of HEU fuel was accumulated. Some of the HEU is still used in critical assemblies, notably BFS (Fast Physical Stand) and a considerable amount of material remains in storage. Some HEU has been shipped off for blend-down and some could be used to fabricate new fuel with reduced enrichment levels. This article describes the issues related to reducing the use of HEU in IPPE research facilities—especially for the BFS critical assemblies.

INTRODUCTION

The first research reactors (United States in 1942 and the Soviet Union in 1946) were critical assemblies designed to demonstrate a chain reaction in a natural uranium and graphite reactor. After enriched uranium became available, researchers designed compact and powerful reactors to provide neutrons for research. During that period all reactor research was conducted by and benefited military nuclear programs. The scientists and engineers who designed the new military reactors did not consider the potential and ramifications for proliferation when HEU-fueled reactors were supplied to non-weapon states.

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The Institute of Physics and Power Engineering (IPPE), one of the first U.S.S.R. nuclear research centers, was established to:

- Study the behavior of materials under irradiation to determine their suitability for use in reactors;
- Mock up different types of nuclear power installations for civil power, naval propulsion, transportable nuclear power plants and space power;
- Test nuclear fuel elements; and
- Carry out thermo-hydraulic research for cooling systems using liquid metals (Hg, Na, Na-K, Pb-Bi, etc.) as well as water.

Considerable quantities of HEU—thousands of kilograms—in different physical and chemical forms were used in this research and placed in storage after the research programs were finished. Today, IPPE is facing the challenge of utilizing or disposing of this legacy material.

HISTORY OF IPPE'S REACTORS AND CRITICAL ASSEMBLIES

As in the United States, from the beginning, the idea of using nuclear energy as a source of power was considered by scientists involved in the Soviet nuclear weapons program. After the first successful nuclear bomb test in 1949, the leaders of the Soviet nuclear program proposed a nuclear power program to the Soviet leadership. The first Soviet nuclear power plant, commissioned at IPPE in 1954, was a graphite moderated water cooled reactor that used uranium enriched to 5% of uranium-235.

Fast neutron reactors were pursued early in the Soviet program because of the potential for plutonium fueled fast breeder reactors (FBRs) to provide fuel for nuclear power generation. In 1950, at the suggestion of IPPE scientific leader, A.I. Leypunsky, the decision was made to establish the technological base for future FBRs at the IPPE. The research reactors BR-1, BR-2 and BR-5/10 were constructed in quick succession. BR-1 and BR-2 operated only briefly (between 1 and 2 years) using HEU fuel, but BR-5/10 operated for more than 40 years. Its research program included testing uranium and plutonium-based nitride, carbide, metal, and oxide fuels. After irradiation, fuel elements from BR-5/10 were examined in hot cells to determine the effects of irradiation. Used fuel and wastes from this research were collected in IPPE storage.

In the mid-1950s, a decision was made to expand IPPE experimental capability for research on FBRs and other types of reactors.[1] Some of these critical assemblies and research reactors are still in operation or were shut down only recently:

- **BR-1**, the first Soviet fast-neutron reactor (1955), was fueled with weapon-grade plutonium and became a unique calibrated neutron source. It is being decommissioned.
- **BFS-1 and BFS-2** (literary translated: big physical stand) are critical facilities used to model possible FBR cores using disks made from HEU and plutonium interleaved with disks of natural and depleted uranium (see Figure 1).
- **KOBRA** was a critical assembly fueled with HEU from the BFS used for measuring fundamental reactor physics constants (reactivity effects of small samples of different materials, for example). It has been shut down and is in the process of being decommisioned.[2]
- **MATR,** an LEU-fueled critical assembly, is still used to study different neutron-moderation regimes in water-moderated, water-cooled VVER reactors.
- **BARS–6**, a pulsed reactor fueled with 90% enriched HEU, is used for fundamental research and experiments on nuclear-powered lasers.

Other Critical Assemblies

About 30 different types of critical assemblies were installed and operated during more than 50 years of IPPE research. Some were fueled with LEU and some with HEU with enrichments ranging from 21% to 90%. With the exception of those listed above, all of them have been shut down and their fuel transferred to central storage or to irradiated nuclear material storage. Their buildings are either under decommissioning or have been repurposed.

Nuclear Propulsion Reactors

In the early 1950s, the Soviet Union—like the United States—began to develop nuclear reactors for submarine propulsion. In the Soviet Union, two HEU-fueled critical assemblies, 27/VM and 27/VT, were operated for more than 60 years to train submarine reactor operators. They are now shut down and awaiting a final decision on decommissioning. Their irradiated fuel is in IPPE storage.

Transportable Nuclear Power Plant

At the end of the 1950s, IPPE worked on developing an HEU-fueled transportable nuclear power plant, known as Project TES-3. A pilot plant was tested between1960 and the early 1970s. Decommissioning was completed in 1978 and the spent fuel was placed in IPPE storage.

Figure 1: The BFS-2 critical facility. The machine above the critical assembly is used for placing and removing fuel assemblies and tubes.

Space Reactors

In the mid-1950s, scientists in IPPE and other Soviet nuclear institutes worked on space nuclear reactor. The reactors developed in IPPE were constructed, tested in a special facility in IPPE, and sent into space. This program was shut down after the breakup of the Soviet Union in 1991 but some of these reactors, with slightly irradiated nuclear fuel, are still kept in IPPE storage.

SECURITY OF IPPE NUCLEAR MATERIALS

Since 1995, significant improvements have been made in the security of IPPE nuclear materials through the U.S.-Russian Material Protection Control and

Accounting (MPC&A) program. The MPC&A program began in 1994, when a group of experts from the U.S. Department of Energy and the U.S. national nuclear laboratories visited IPPE for the first time. As of early 2013, the collaboration is still continuing.

Initiatives taken under The MPC&A program include consolidating nuclear materials from decommissioned and shut down facilities in a central storage facility which contains more than 90% of the Institute's nuclear materials within a highly-secure "Nuclear Island" at IPPE. The island also contains the BFS critical facilities and central storage for fresh nuclear materials, i.e. unirradiated fuel.

A number of critical assemblies and other facilities are located outside the nuclear island, some containing significant quantities of fissile materials, e.g. the BARS-6 pulsed reactor, the RMTC training center where students do non-destructive assay of materials, and a building where nuclear materials are processed. Their security and safety also has been strengthened and improved—either under the U.S.-Russian program or using IPPE's own resources. The improvements include eliminating unnecessary windows and doors, reinforcing doors, access control systems and portal monitors, video surveillance systems, etc.

All irradiated nuclear material is stored in a separate facility which also was upgraded. All old doors were replaced with new reinforced doors. Locks were replaced with modern ones and detection and access control systems were installed. Nevertheless, safeguarding this legacy material is dangerous and costly.

DISPOSING OF THE IRRADIATED NUCLEAR MATERIALS

The quantity (approximately 11.5 tons of uranium), volume, physical characteristics, and chemical form of the irradiated fuel accumulated at IPPE varies in size from centimeters to meters; contains pins, pellets, and alloys: is in the form of metal, oxide, carbide, nitride, metal ceramic, etc.; has differing irradiation levels; and cooling times and amounts of available documentation vary. About 10% is HEU; the remainder is LEU with 5–10% enrichment.

Before these accumulated materials can be disposed, a number of preparatory steps must be undertaken:

1. Processing resources (human, financial, hardware, etc.) must be acquired.
2. All available information must be collected and analyzed to pinpoint exact locations, geometry, characterization, irradiation level and cooling times, etc.
3. The material must be inspected to verify these data.

4. Technology must be acquired or developed to load the items from their storage locations into transportation containers that are standard or specially designed for specific cases.
5. A special location for loading this material must be determined, taking into account that some items are radioactive and may be damaged. In IPPE, a decommissioned building is currently being used.

Administrative arrangements must be made to transport the materials to the Mayak RT-1 facility in Ozersk for storage and reprocessing.[3]

Under a U.S. DOE-Rosatom agreement a special program was initiated in 2009 to assist Russia with collecting and eliminating irradiated HEU from research reactors and critical assemblies. IPPE was chosen as a site for a pilot project.[4] This work is done as part of the Russian Federal program on nuclear and radiation safety. The first shipment has already been transferred to Mayak for reprocessing and recycling to LEU. The program is expected to be completed in 5–10 years. However, there is some uncertainty about the future of the U.S. DOE-Rosatom agreement—and the entire MPC&A Program. If the program is terminated, the recycling and reprocessing program could be delayed.

THE BFS FACILITIES

Experiments related to the design of FBRs began in the late 1940s.[5] The main goal of these experiments was to determine FBR neutronics. The first research reactors were the BR-1 (1955) and the BR-2 (1956).

About the same time, design, equipment production, and construction of the BFS critical assembly began.

BFS-1 was commissioned in June 1961. Its first core was a model of the Pulsed Fast Reactor (PER or IBR) to be built at the Joint Nuclear Research Center in Dubna. It was followed by the models of the BOR reactors that were later constructed at the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad and the BN-350 fast power reactor that was later built at Shevchenko–Aktau in Kazakhstan.

In the mid-1960s, it became clear that a critical facility with larger capacity was required. BFS-1 can accommodate cores with diameters up to 2 meters and heights up to 2.2 m (total volume 6 m^3) and has enough nuclear and non-nuclear materials to simulate an FBR with total power up to 1000 MWth (megawatt thermal). It was not big enough, however, to serve as a model of more powerful commercial FBRs. The decision, therefore, was made to build a new critical facility, BFS-2, which could be used to simulate FBRs with capacities of 2500–3000 MWth.

BFS-2, which was commissioned in 1971, can accommodate core diameters up to 5 m and core heights up to 3.2 m with total volume up to 60 m^3 with two additional volumes for simulation of shields.

BFS has been used to simulate the cores of the BOR, BN-350, and BN-600, BN-800, CEFR (China Experimental Fast Reactor) and the proposed KALIMER South Korean fast reactor.

BFS-1 is used to simulate small and medium reactors with different types of coolant, as well as for special models used for verifying calculation methods and refining nuclear cross section data (benchmark experiments).

BFS-2 is used to simulate full-scale models of commercial FBR cores, such as the BN-800 (under construction) and the proposed BN-1200.

BFS-1 and BFS-2 are equipped with open-top vertical tubes with diameters of 50 mm that can be loaded with steel-clad disks with diameters of 47 mm containing different nuclear materials (depleted, natural, or highly enriched uranium and plutonium) and other reactor materials (sodium, steel, aluminum, etc.) to simulate fast-neutron reactor cores. The facilities are used to measure FBR nuclear safety parameters such as:

- Criticality
- Reactivity effects of samples of nuclear materials, Doppler-coefficients[6] and control and safety rod effectiveness
- Neutron flux and power distributions
- Kinetics
- Effects on reactivity of sodium coolant voids
- Neutron spectrum and breeding parameters
- Shielding effectiveness; and
- Other parameters by request of the designers

BFS operates with two shifts of 6 hours each working day. When not in operation, BFS is shut down with added security measures.

In a future research program, BFS-2 will be used to simulate the BN-800 with different core loadings, the BN-1200 and FBRs with lead and lead-bismuth coolants. There also are plans to use the BFS facilities for international cooperative research program. It therefore appears that the facility will be fully occupied for at least the next 10–15 years.

Taking into account the pulsed electron accelerator (MI-30) that can drive the BFS-1 (and formerly the critical assembly KOBRA) with a precision oscillator device created in cooperation with the Institute for Nuclear Research (Rossendorf, Dresden, GDR),[7] a unique experimental complex was created for study across a wide spectrum of nuclear reactor physics.

The IPPE critical facility complex (including BFS-1, BFS-2 and KOBRA) has a common store of nuclear material that is not in use and temporary storage facilities close to each critical facility for loading and unloading nuclear materials during experiments.

NUCLEAR MATERIALS USED FOR SIMULATIONS OF DIFFERENT BFS CORES

The sizes of the FBR cores simulated at the BFS facility require significant quantities of nuclear materials.[8] The facility allows the study of converter cores that produce plutonium with uranium fuel as well as breeder cores with mixed uranium-plutonium fuel. As of 2013, the researchers have approximately 0.9 tons of plutonium in metal form; approximately 8.7 tons of 90% and 36% enriched HEU in metal and dioxide form, more than 250 tons of depleted uranium dioxide, 20 tons of depleted uranium in metal form and about 10 tons of thorium in metal form.[9] The disks are all 47 mm in diameter but the thicknesses of the nuclear materials ranges between 0.5 mm to 150 mm for uranium and 0.5 to 10 mm for plutonium. In addition, there is a full-size BN-600 core subassembly containing uranium dioxide enriched to 21%, a MOX fuel subassembly containing 17% plutonium mixed with depleted uranium, and a subassembly with depleted uranium in metal form.[10] Lastly, there are 250 disks containing a total of 10 kg of neptunium dioxide.

POSSIBLITIES FOR DECREASING THE ENRICHMENT OF THE BFS HEU DISKS

Starting in the mid-1960s, the authors participated in research at the BFS. In the 1950s and 1960s, the problem of proliferation of nuclear weapons and potential spread of weapon-usable nuclear materials was discussed at the intergovernmental level but it was not a design consideration for the Soviet fast reactor program. India's test of a "peaceful nuclear explosive" in 1974 also was not widely discussed in the Soviet Union mass media or among Soviet nuclear scientists and engineers. Nor was the possibility of loss or unauthorized use of potentially weapon-usable nuclear materials. Guards and governmental security controls on people working with nuclear materials were considered sufficient protection against theft. After the breakup of the Soviet Union it became clear that this level of protection is insufficient. At the MPC&A program initiated by Russia and the United States as part of a broader effort to assist Russia with dealing with the legacy of the Cold War, discussions began on strengthening the security of IPPE's nuclear materials to prevent unauthorized access to these materials.

The terrorist events on 11 September 2001 in the United States generated extreme anxiety about the potential for nuclear terrorism. Scientific and technical analyses by the international community of specialists have shown that terrorists have the capacity for designing a primitive (improvised) nuclear explosive device—especially with highly enriched uranium. The primary obstacle is acquiring sufficient suitable nuclear material. The nuclear engineers and scientists at IPPE understand that some of the nuclear materials in IPPE are adaptable for this purpose. In the post September 11 environment, IPPE faced two options:

1. Remove all weapon-usable materials from the Institute and shut down most of its research programs; or
2. Improve and strengthen the security system to protect against inside and outside threats using the MPC&A as the main programmatic and funding source.

In 1992, as part of the U.S.-Russian MPC&A program, the U.S. partners were informed of the types and quantities of nuclear materials used in IPPE—particularly in the BFS. General data were published about proceedings of several conferences which aroused interest in the expert community of nuclear material management because some of the materials used at BFS were what the IAEA categorizes as "direct use materials." [11]

At various times during this work, the question of the possible conversion of Russian research reactors (including critical assemblies) to low enriched fuel was discussed. Operators of research reactors and scientists using those reactors as instruments were not ready to give a definitive answer about the possibility of conversion.[12] The questions raised include the following:

- Is it possible to preserve the performance of research reactors while substituting LEU for HEU fuel?
- What is the best type of LEU fuel?
- How long will it take to replace one type of fuel for the other?
- What are the costs of the substitution?
- Since LEU as well as HEU is subject to MPC&A in Russia, do we reduce (or increase) MPC&A management problems with the substitution?

The idea of converting the BFS facilities to LEU fuel prompts additional questions.[13]

There are two types of disks that are candidates for replacement:

1. Metal and dioxide HEU with 90% enrichment; and
2. Metal and dioxide HEU with 36% enrichment.

The 90% HEU metal is the most attractive for weapons because it has the smallest critical mass. The 90% HEU dioxide is also quite attractive because it can be converted to metal relatively quickly. The 36% enriched uranium is not as attractive because of its larger critical mass.

Physicists conducting research at BFS and BFS facility managers have slightly different opinions as to what enrichment is required for the BFS to be able to simulate future FBR cores. Taking into account the projected research program, the following approach to the reduction of the enrichment of the uranium used at BFS can be formulated:

- For experiments planned for BFS-1 (small modular reactors, benchmark experiments) it is necessary to keep 0.5 to 1.5 tons of HEU with at least 36% enrichment in dioxide form.
- On the basis of calculations, the optimal enrichment for full-scale simulations of future commercial FBR cores should be about 20% ± 2%, which could be above the 20% enrichment level that is accepted as a boundary between LEU from HEU. The managers of programs working on conversion of HEU-fueled reactors have been reluctant to compromise on enrichments above 20%, however, for fear of eroding an internationally recognized boundary.

At the same time, the BFS manager would like to minimize the amount of HEU and plutonium metal in the facility, as they are considered Category 1 materials for the purposes of physical protection and accounting. Reducing the amount of these materials would allow a reduction in the frequency of conducting a physical inventory and decrease the worker radiation health and safety risks. Uranium with enrichment below 20% is a material with less stringent health and safety requirements and lower human health risks.[14]

Based on the projected future research program it also appears that replacement of metal HEU with oxide LEU would be better for both modeling and decreasing the attractiveness of the materials. At the same time, the size of the batches of reduced-enrichment material, replacement schedule, the technical specifications of replacement disks, and a number other details need to be finalized.

Figure 2 is an example simulation of enrichments around 20% with weapon-grade uranium mixed with depleted uranium and with 22% uranium. Fine adjustments down from 22% could be carried out by adding thin disks of depleted uranium (DU). If the thickness of the fuel in the 22% enriched disks were 10 mm, for example, a 0.5 mm disk of DU would reduce the average enrichment by 1%—or one disk for every two 22% enriched disks would reduce the average enrichment by 0.5%. The total amount of uranium in the stack could remain constant by adding thin sodium disks.

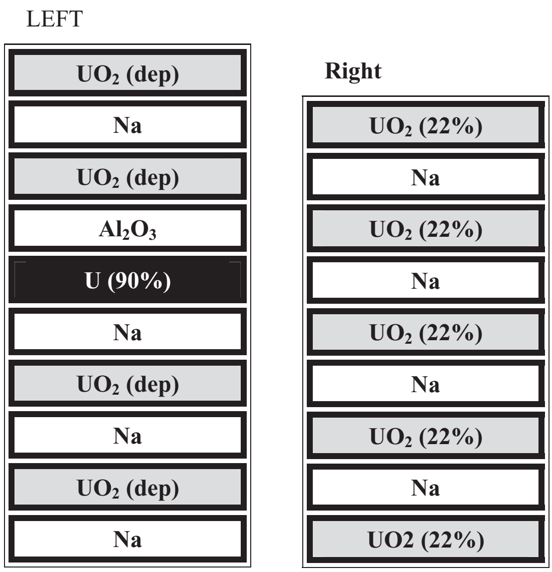

Figure 2: An example of a simulation of approximately 18% HEU fuel with a mix of current 90% HEU disks and disks of depleted uranium (left) and 22% HEU (right).

Advantages and Disadvantages of HEU with Reduced Enrichment

Decreasing the HEU enrichment in BFS disks has advantages and disadvantages. Advantages include:

- Reduction of heterogeneity effects from interleaving disks of 90% enriched uranium and depleted uranium to achieve an average of about 20% enrichment;
- Increasing nuclear safety by increasing negative Doppler-effect temperature feedback on reactivity from temperature broadening of uranium-238 resonance neutron absorption; and
- Decreasing the health and safety risks for workers during the mandatory monthly physical inventory of Category 1 and 2 materials.

At the same time, there are costs associated with reductions of HEU:

- A four-fold increase in the amount of nuclear material in the BFS storage facilities, to as much enriched uranium as uranium-235, caused by the change from 90% to 22% HEU and the need to increase the size of storage facilities; and
- Direct financial and labor costs associated with replacing HEU with LEU.

CONCLUSION

There is no question that the risks from use of HEU in the civil nuclear sector must be reduced to the greatest extent possible. To deal with these risks, IPPE is pursuing consolidation and down-blending of HEU as well as improvement of MPC&A measures with modern technology, improved security and the security culture, and increased international cooperation. Although at this point no firm decision about elimination of HEU has been made and IPPE plans to continue using its HEU research facilities, the institute began implementing a program that aims to decommission some of its research facilities and remove spent HEU fuel from the institute.

NOTES AND REFERENCES

1. "Nuclear Facilities and Stands", *Institute of Physics and Power Engineering*, http://www.ippe.ru/ibasa/ust.php (in Russian).

2. V.I. Golubev et al., "Experiments for K_{inf} measurement for U-235 and Different Construction Materials," Preprint IPPE, FEI-2692, Obninsk; "Results for Calculated and Experimental Multiplying Parameters of U-Th Compositions with Different Content of Moderator at the COBRA Critical Assembly," Preprint FEI-2938, Obninsk 2004; and S.M. Bednyakov, "Testing Reactor Functionals in Fast Critical piles," *Atomnaya Energiya*, 69, 1 (1990): 3.

3. Mayak RT-1 facility in Ozersk is an industrial complex and one of the largest nuclear facilities in the Russian Federation. As part of the Russian nuclear weapon program, Mayak was formerly known as Chelyabinsk-40 and later as Chelyabinsk-65.

4. See "Ten years of RRRFR Programme," http://www.sosnycompany.com/10-rrrfr_en.html; and "Spent Fuel Preparation and Removal from Institute of Physics and Power Engineering," http://sosnycompany.com/ippe-article-en.html. This activity is separate from the U.S. DOE's Material Consolidation and Conversion program (MCC). Under the MCC program, only fresh HEU is collected and down-blended at the PO Luch facility in Podolsk, Moscow region. Some fresh HEU from IPPE has been eliminated through the MCC program.

5. S. Belov, V. Dulin, A. Zvonarev, and I. Matveenko, "Proceedings of "IPPE – 50 years," *Obninsk*, 1997.

6. The BFS assemblies have no external heating system and the allowable internal power level is very low (a few hundred watts) but without ventilation their temperatures can be increased enough so that the reactivity effect of the Doppler broadening of the uranium-238 neutron absorption resonances is measurable.

7. V.I. Golubev et al. , *op. cit.*; and S.M. Bednyakov, *op. cit*.

8. "Proceedings of International conferences on MPC&A," Obninsk, Russia, 1997, 2000, 2005, 2009.

9. I. P. Matveyenko et al., "Physical Inventory of Nuclear Materials in BFS Facility," Proceedings of 3rd MPC&A Conference, Obninsk, Russia, 2000.

10. For a more precise study of the physical parameters of reactor cores, a few BFS tubes were replaced with one assembly (a hexagonal tube filled with 127 fuel pins). BN-600 and BN-800 have similar fuel assembly geometries.

11. "Proceedings of the International Conferences on MPC&A," Obninsk, Russia, 1997, 2000, 2005, and 2009; V.V. Kuzin, G.M. Pshakin et al., "MPC&A System in IPPE," Proceedings of the 37th Annual International Nuclear Materials Management (INMM) Meeting, Naples, FL, August 1996; and S. Belov, et al., *op. cit*.

12. A.S. Diakov, "Conversion of Research Reactors in Russia," *Moscow Center for Arms Control Studies*, 21 June 2012 <www.armscontrol.ru/pubs/conversion-of-research-reactors-in-russia.pdf>.

13. See for example, Proceeding of International Symposium "Science and Society History of the Soviet Atomic Project," Dubna, Russia, 1 (1996): 80–93, and discussions at the U.S./Russian Academies of Sciences workshops on Progress, challenges and opportunities for converting U.S. and Russian research reactors from highly enriched to low enriched uranium fuel, Washington, 29–30, November 2010 and Moscow, 8–11 June 2011.

14. Categorization of nuclear materials is similar in Russia (OPUK) and the U.S. DOE, Order 5603. More than a certain quantity of HEU, plutonium, uranium-233 is in Category 1. Natural and depleted uranium are in Category 4.