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Securing Russia's HEU Stocks

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Production and use of HEU and plutonium are inherently dangerous due to the possibility of their diversion to terrorist groups or rogue nations. Of the two, HEU might be of greater concern. First, HEU is used in a wide range of applications and is therefore more readily available. Second, in many cases, HEU might be more vulnerable to diversion. Unirradiated HEU does not require containment and operating personnel often have a legitimate and prolonged direct access to the material. It is also less radioactive and therefore is harder to detect by conventional passive radiation-detection techniques that are employed at personnel and vehicle portals at nuclear facilities. Third, although the arsenals of the existing nuclear powers are built around plutonium, HEU is likely to be a material of choice for a less sophisticated bombmaker.[1] HEU processing is somewhat easier and it is a relatively minor health hazard. It also has a much lower rate of spontaneous fission, a fact that makes the weapon design job somewhat easier.[2]

HEU operations require stringent safeguards and security. The risk of diversion also could be reduced by minimizing (a) the number of locations where HEU is stored or processed, (b) HEU throughput at processing facilities, and (c) HEU transportation.

OVERVIEW OF HEU OPERATIONS IN RUSSIA

Between 1949 and 1988 the Soviet uranium enrichment complex produced an estimated 1,200–1,400 t of highly-enriched uranium.[3] This material has been used in various applications at many facilities in different locations (Figure 1, Table 1). Over half of the produced HEU was manufactured into nuclear weapons and is controlled by the Ministry of Defense. Large quantities of HEU are now being removed from the military inventories. These materials are recovered from retired weapons and are transferred to storage or converted to LEU for use in power reactors. Considerable amounts of HEU are also used to fuel naval propulsion and nuclear material production reactors as well as for research purposes.

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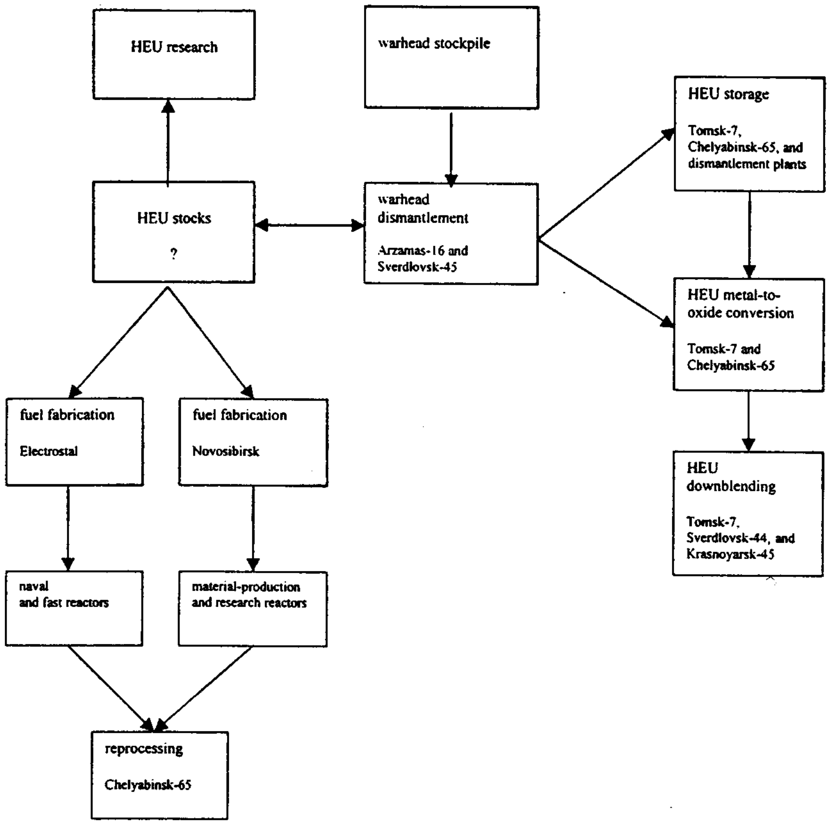

Figure 1: HEU operations in Russia.

Weapons Complex and Warhead Dismantlement

Dismantlement of nuclear weapons presently is the largest HEU operation in Russia. The Ministry of Atomic Energy (Minatom) has been dismantling nuclear warheads at a rate of 1,000–2,000 warheads per year since the late 1980s. Recovery of fissile materials takes place at the assembly plants in Arza-

Table 1: HEU operations outside of nuclear weapons production

Facility/Location	HEU attractiveness/ facility category	HEU activities
Weapons facilities		
Plant "Electrokhimpribor" (Sverdlovsk-45)	A/1	•HEU extraction from weapons •Storage of weapon components
Electromechanical Plant "Avangard" (Arzamas-16)	A/1	•HEU extraction from weapons •Storage of weapon components
Institute of Experimental Physics (Arzamas-16)	A/1	•Weapons R&D •HEU research reactors
Institute of Technical Physics (Chelyabinsk-70)	A/1	•Weapons R&D •HEU research reactors
Fuel cycle facilities		
Industrial Association "Mayak" (Chelyabinsk-65)	B/1	•Storage of HEU components •Metal-to-oxide HEU conversion •Reprocessing of HEU fuel •Operation of tritium reactors (HEU fuel storage/use)
Siberian Chemical Combine (Tomsk-7)	B/1	•Storage of HEU components •Metal-to-oxide HEU conversion •HEU downblending •Operation of plutonium reactors (HEU fuel storage/use)
Mining and Chemical Combine (Krasnoyarsk-26)	D/1	•Operation of a plutonium reactor (HEU fuel storage/use)
Ural Electrochemistry Combine (Sverdlovsk-44)	C/1	•HEU downblending
Electrochemistry Plant (Krasnoyarsk-45)	C/1	•HEU downblending
Machine-Building Plant (Electrostal)	C/1	•Fabrication of fuel for naval reactors
Chemical Concentrates Plant (Novosibirsk)	C/1	•Fabrication of fuel for material and research reactors

Table 1: (Continued)HEU operations outside of nuclear weapons production

Facility/Location	HEU attractiveness/ facility category	HEU activities
Research institutes and other facilities		
Inorganic Materials Institute, VNIINM (Moscow)	B?/1	•Fuel cycle research •Material research
Nuclear Reactors Institute, NIIAR (Dimitrovgrad)	C/1	•Fuel cycle technologies •HEU research reactors
Physics and Power Institute (Obninsk)	C/1	•HEU research reactors •HEU storage and processing
NPO Khlopin Radium Institute (St. Petersburg)	C/?	•Fuel cycle research
Kurchastov Institute (Moscow)	C/1	•Nuclear technologies •HEU research reactors
Production Association "Luch" (Podolsk)	C/1	•Fabrication of space reactor fuel •HEU research reactor
Tomsk Polytechnical Institute (Tomsk)	?	•HEU research reactor
Institute of Energy Technologies, Sverdlovsk branch (Zarechny)	?	•HEU research reactor
Karpov Institute of Physical Chemistry (Obninsk)	?	•HEU research reactor
Institute of Device-Building (Lytkarino)	?	•HEU research reactor
Moscow Institute of Physics and Engineering (Moscow)	?	•HEU research reactor
Moscow Institute of Theoretical and Experimental Physics	?	•HEU research reactor

Table 1: (Continued)HEU operations outside of nuclear weapons production

Facility/Location	HEU attractiveness/ facility category	HEU activities
Institute of Energy Technologies (Moscow)	?	• HEU research reactor
Institute of Nuclear Physics (St. Petersburg)	?	• HEU research reactor
Krylov Research Institute (St. Petersburg)	?	• HEU research reactor
Naval facilities	?	• Storage and use of HEU fuel
Atomflot icebreaker base (Murmansk)	?	• Storage and use of HEU fuel

mas-16 and Sverdlovsk-45, where "physics packages"—subassemblies containing fissile materials—are taken apart. HEU in the form of weapons components is packaged in containers and is placed in storage at the dismantlement sites, or shipped for storage or for downblending to Tomsk-7 and Chelyabinsk-65. Assuming the uranium content of 15–25 kg HEU per weapon, 15–50 t HEU, much of it of weapons quality, is recovered annually from retired warheads.[4] In 1997, Russia declared that 500 t of 90-percent enriched HEU will be withdrawn from military use.[5]

Much smaller HEU streams at the warhead production facilities are associated with warhead remanufacturing activities. Additional quantities of HEU are used by the weapons complex (primarily by its weapons R&D centers in Chelyabinsk-70 and Arzamas-16) for research purposes and as fuel for research and test reactors.

"Weapons to Fuel"

Connected with the arms reductions is a very large flow of weapon-grade HEU associated with the downblending of uranium from weapons to make fuel for power reactors. Under the 1993 U.S.-Russia agreement the United States is to buy LEU derived from at least 500 t HEU from weapons. The initial LEU deliveries to the United States took place in May 1995 and approximately 6 t HEU was downblended and delivered by the year-end. The scale of the operation has been increasing since and is expected to reach 30 t/y after 1998. Russia may also elect to blend down additional quantities of HEU to meet its own power reactor fuel requirements.

The HEU downblending is conducted at four sites. Thermal oxidation of HEU takes place at the chemical and metallurgical plants in Chelyabinsk-65 and Tomsk-7, the facilities that are also involved in manufacturing HEU and plutonium components of nuclear warheads. Each site has a capacity to process 15 t or more HEU per year.

The thermal oxidation process involves the following principal steps.[6] Warhead components are shredded into chips and shavings and the material is sampled and analyzed. HEU shavings are oxidized in special furnaces, and the oxide is milled and sieved to produce a uniform power. The powder is sampled, and, if the level of impurities is unacceptable, is recycled in a solvent-extraction process to remove impurities. (More than one solvent-extraction cycle is sometimes required.) Pure oxide is loaded in transportation containers (approximately 6 kg per container) and weighed. Transportation containers are placed in overpacks which are sealed and secured in a special railcar by a heavy containment device.

HEU oxide powder is shipped to Sverdlovsk-44 and Krasnoyarsk-45 for fluorination and downblending. Some material is also downblended in Tomsk-7.

At an enrichment site the HEU containers are weighed and material samples are checked for quality. HEU oxide is subsequently fluorinated in flame-type reactors and condensed in 6-liter technological vessels. Liquid UF6 is transferred to 12-liter vessels, weighted, and sampled to determine the concentration of U-235. HEU slugs, which are formed during fluorination, are sent for HEU recovery back to the oxidation facility.

The 12-liter vessels are transferred to the sublimation facility and gaseous HEU UF6 is fed to the T-pipe unit for mixing with 1.5-percent enriched UF6 to achieve a required level of enrichment (4.4- and 4.95-percent U-235 in Sverdlovsk-44 and Krasnoyarsk-45 respectively). The mixture is pumped to the desublimation unit. Finally, the LEU product is sampled, homogenized, and poured into 30B-type cylinders for shipments to the United States.

Nuclear Material Production

Both the plutonium and tritium production reactors in Russia utilize 90-percent enriched uranium. The plutonium production reactors are fueled with natural uranium that is spiked with HEU rods to flatten the radial and axial distribution of the neutron flux and power generation.[7] Each of the three plutonium production reactors still in operation (two in Tomsk-7 and one in Krasnoyarsk-26) contain approximately 80 kg 90-percent HEU fuel and consumes approximately 200 kg HEU per year.[8]

The production of tritium takes place in Chelyabinsk-65 in two light-water reactors. The tritium-production reactors have a driver-target configuration in which HEU fuel produces neutrons to irradiate lithium-6 targets. Assuming a reactor capacity of 1,000MW, a load factor of 60 percent, and fuel burn-up of 30 percent, the HEU fuel requirements may be estimated to be 1,5 t/y.[9] In reality, the HEU requirement might be significantly lower due to reactor outages for maintenance and lower load factors.[10]

HEU fuel for the material-production reactors is fabricated in Novosibirsk. The reactors use aluminum-clad cermet fuel in which uranium-oxide particles are dispersed in an aluminum matrix. Fuel is produced in a standard powder metallurgy process.[11] The process involves the following steps. First, commercial aluminum powder is blended with U3O8 powder (which is produced by pulverizing and sieving U3O8). Second, the mixture is placed in a mold and is compacted by an isostatic press. Third, fuel element cores are fitted with billet assemblies. And fourth, fuel elements are outgassed, lubricated, extruded, drawn, cut, and machined to required specifications.

At present, the production rate in Novosibirsk is approximately 2.1 t/y, down from 3.5 t/y at the time when the nuclear production program was at its peak. [12] It is likely that in the past the HEU feed was delivered to Novosibirsk from enrichment facilities. At present, the source of HEU is not known.[13] Reportedly, however, at least dome HEU feed material received by the plant is in the form of UF6.[14] Possibly, some HEU feed material is produced by recovering HEU from irradiated spike fuel of the plutonium production reactors and reenriching it at Tomsk-7.

In 1997, the United States and Russia signed an agreement to convert the cores of the three plutonium production reactors so as to end the production of weapon-grade plutonium. Under the current proposal, the reactors would be loaded with 90-percent enriched HEU fuel identical to the spike fuel. Combined, the three reactors would be irradiating 6 t HEU per year until they are shut down some time after the year 2010. The HEU option would thus increase the fuel-manufacturing rate in Novosibirsk to 7.5 t/y (including 1.5 t/y of HEU for the tritium reactors).

It is expected that this HEU would be derived from dismantled weapons. Some experts assume "transportation of HEU derived from weapons to the [Novosibirsk] fuel fabrication facility." Presumable, the operation would involve conversion of HEU metal from weapons to HEU oxide powder (or HEU hexafluoride) in Tomsk-7 and/or Chelyabinsk-65 and its delivery to Novosibirsk for fabrication into reactor fuel. (A report by experts from the Pacific Northwest Laboratory (PNL) suggests, however, a direct "transportation of HEU [metal] derived from weapons to the [Novosibirsk] fuel fabrication plant."[15]) It has not yet been decided on what would happen with irradiated HEU. It is, however, likely that it would be reprocessed some time in the future to recover residual uranium (containing approximately 80 percent U-235).

A leading alternative proposal is to convert the reactors to denser, 20-percent enriched fuel. Apparently, the technological scheme for this option has not been defined yet. One possibility would be to convert HEU metal from weapons to a solution, to dilute HEU solution with natural or depleted uranium to 20-percent enriched uranium, to precipitate uranium from solution, and to convert it to oxide. All these operations could be carried out in Chelyabinsk-65 and/or Tomsk-7. Oxide powder then would be shipped to Novosibirsk for fabrication into reactor fuel.

Naval Fuel Cycle

The Soviet Union has built and operated the world's largest fleets of nuclear-powered naval vessels and civilian icebreakers. Nuclear submarines and naval surface ships are assigned to the Northern and Pacific fleets. The icebreakers are operated by the Murmansk Shipping Company (MSC) out of the Atomflot base in Murmansk.[16]

With the exception of the liquid-metal reactor submarines of the Alpha-class (which currently are in retirement), all Russia's nuclear ships are powered by pressurized-water reactors (PWRs). Submarine PWRs use stainless-steel or zirconium-clad cermet fuel with medium-enriched uranium (19–45-percent U-235).[17] (The Alpha-class boats were designed to use uranium-beryllium fuel with 90-percent enriched uranium.) More powerful reactors of the Navy's cruisers, however, use higher-grade 55–90-percent enriched uranium.[18]

A significant fraction of the icebreaker fuel is believed to be weapon-grade uranium. According to the U.S./Russian MPC&A project paper, "The fuel is U-235 or 20 percent-90 percent enrichment with 600 percent average enrichment."[19] Most fuel is of the cermet type. An exception is approximately 20 cores of 90-percent enriched zirconium-clad uranium-zirconium alloy fuel produced for the Arctica-class icebreakers. The uranium-zirconium fuel, however, is not produced anymore and the existing stocks are likely to be exhausted before the year 2000.

Naval reactor fuel is fabricated in Electrostal (presumably, by extrusion) and is sent by rail to the Sevmorput shipyard at Murmansk and the Shkotovo site near Vladivostok in the Far East.[20] Fresh HEU fuel for icebreakers is delivered by rail to the Atomflot base and is stored prior to refueling on board of the "Imandra" service ship which is moored at the base.[21] Submarine fuel is delivered by the manufacturer to the storage facilities in the Northern and Pacific fleets where it is stored until needed.[22] The interim storage also takes place in land-based port facilities, on service ships, and at refueling facilities. After several years of storage irradiated fuel is transported to Chelyabinsk-65 for reprocessing.

In the past, the Navy and the icebreaker fleet each required five to ten fresh cores annually. In the recent years, the naval fuel requirement shave dropped to few reactor cores per year as the MSC and the Navy each presently conduct one to two refueling per year. Reportedly, the MSC, which procures on average two reactor cores of fresh fuel per year, has become the principal customer of the Electrostal naval fuel production line. Assuming that one core contains 200 kg HEU, the flow of weapon-grade uranium associated with the naval fuel cycle is 400 kg/y.[23]

HEU Use for Research Purposes

HEU is used extensively in research reactors and for material research. There are over 60 research and test reactors and critical facilities currently in operation in Russia.[24] Of these, 15 to 30 use HEU fuel.[25] For example, several tonnes of HEU are contained in large critical zero-power assembly models for fast-neutron reactors at the Institute of Physics nad Power Engineering in Obninsk.

Most research reactors use uranium-oxide cermet fuel manufactured by the Novosibirsk fuel plant.[26] (Reportedly, the research reactor fuel line is in the same building with plant's other HEU operations.) Some large reactor development centers, such as the Institute of Atomic Reactors in Dimitrovgrad, also manufacture HEU fuel.

A number of research institutes also handle HEU for material and nuclear fuel cycle research purposes. In most cases, the HEU quantities are relatively small: for example, the Khlopin Radium Institute in St. Petersburg has approximately 2 kg HEU.[27] Some facilities, however, have fairly large operations. For example, the inventories and throughputs at the "Luch" institute in Podolsk, which is involved in research on and small-scale fabrication of space reactor and experimental fuels, amount to approximately 100 kg HEU enriched to over 80 percent U-235.[28]

Reprocessing of HEU Fuel

Russia's standard fuel cycle practice has been to reprocess irradiated HEU fuel. The technology to reprocess spent HEU fuel was developed in the 1960s–70s in Chelyabinsk-65. The technology was designed to extract residual uranium as well as plutonium and neptunium. The HEU reprocessing line to process uranium-aluminum fuel of naval reactors became operational at the RT-1 radiochemical plant in 1976.[29] Subsequently, the plant has begun to reprocess irradiated HEU fuel from research, material-production, and fast-neutron reactors. (No reprocessing of HEU spike fuel from the Krasnoyarsk-26 and Tomsk-7 reactors has occurred in Chelyabinsk-65 since 1989–90.[30])

The HEU reprocessing technology is based on a modified PUREX process, in which fuel rods are cut and dissolved. (Irradiated fuel elements of the production reactors are sent directly to the dissolver unit.) Uranium, plutonium, and neptunium are separated from fission products by solvent extraction. Recovered HEU is purified in three solvent extraction cycles and is converted to uranium oxide (U3O8), RT-1's final product. Recovered HEU has been recycled to make fresh fuel for naval propulsion and fast reactors.[31] Reprocessed HEU has also been blended with uranium recovered from spent VVER-440 fuel (containing typically 1.3-percent U-235) to make LEU for RBMK and, later, VVER-1000 reactors.[32]

VULNERABILITY OF HEU OPERATIONS

Unirradiated HEU is vulnerable to a theft or diversion at all phases of its management cycle. The greatest risk during processing stems from an insider with a legitimate, hands-on access to the material.[33] In a low-security environment, a worker could simply stuff material in a pocket or a work-glove and walk out from the facility. A knowledgeable insider would minimize the risk of detection by removing uranium in small portions over a long period of time. For example, approximately 1.5 kg HEU was successfully diverted by a facility engineer from the "Luch" institute in Podolsk in a series of small (25–30 g) diversions over a period of several months. Such crimes of opportunity could be prevented by modern MC&A measures including material accounting and process monitoring, item control and accounting, visual surveillance, portal monitoring, and waste screening. Even an advanced safeguards system, however, could be defeated by a motivated and resourceful opponent.[34] The following factors increase the difficulty of safeguarding HEU:

- Large HEU throughputs proportionally increase the uncertainty of material measurements and accounting (unless the processing line is divided into small control units).

- Multiplicity of material streams, including large streams of scrap and waste, as well as multiplicity of HEU physical forms and chemical compositions complicate control and accounting procedures.
- Implementation of material control procedures is complicated by a large size of the workforce, as well as in large, older plants.[35]
- MC&A effectiveness could be compromised by material spills and industrial accidents.

HEU in storage is easier to control. The material is stored in the form of easy-to-count items (cans, fuel elements, etc.); the access to storage areas is typically limited; and control procedures, such as the two-man rules, are straightforward and are easy to implement. Personnel collusion, use of substitute objects and other sophisticated tactics could be employed by insiders to bypass such controls, however.

Another risk to an HEU facility is a penetration from outside. Such an attack could be conducted stealthily or by force and could rely on insider assistance. For example, at least on one occasion kilogram quantities of medium-enriched uranium fuel were stolen by outsiders from a naval storage facility in the Murmansk area in 1993.[36]

Outside threats are addressed by a physical protection system. Standard physical security measures for an HEU facility emphasize layered, defense-in-depth approach and incorporate the following elements: (a) integrated detection, assessment and communication capability, (b) engineered barriers (fences, locks, vaults), (c) entry control systems (badges, metal detectors), and (d) guard and response forces. Some of these are not feasible for transportation systems and HEU in transit is inherently more difficult to protect than a fixed site.

Physical protection requirements often drive up the overall cost of nuclear safeguards and security. Capital expenses associated with designing a physical protection system, installing engineering barriers, wiring sensors and surveillance cameras, and procuring security computers and other hardware could easily be in the $10–$15 million range for a medium-size site.[37] (The capital expenses are larger for a site with a longer perimeter that would increase the costs of fencing, CCTV cameras, intrusion detection sensors, and wiring.)

The level of safeguards and security depends on quantities and attractiveness of nuclear materials (Table 2). Category I facilities that contain significant quantities of attractive materials (which are easily convertible to metallic shapes), are of greatest concern.[38] The Russian nuclear complex has a very

Table 2: Attractiveness levels and safeguards categories from DOE order 5633.1.[39]

Type of material	Attractiveness level	Safeguards category (I = greatest concern) versus quantity of contained material (kg)							
		Pu or U-233				U-235			
		I	II	III	IV	I	II	III	IV
Weapons[a]	A	Any quantity is category I				Any quantity is category I			
Pure products[b]	B	>2	0.4–2	0.2–0.4	<0.2	>5	1–5	0.4–1	<0.4
High-grade materials[c]	C	>6	2–6	0.4–2	<0.4	>20	6–20	2–6	<2
Low-grade materials[d]	D	NA	>16	3–16	<3	NA	>50	8–50	<8
All other materials[e]	E	Any reportable quantity is category IV				Any reportable quantity is category IV			

a. Assembled weapons and test devices.
b. Pits, major components, buttons, ingots, recastable metal, and directly convertible materials.
c. Carbides, oxides, solutions >25g/L, nitrates, etc., fuel elements and assemblies, alloys and mixtures, UF4 or UF6 at 50 percent or more enrichment.
d. Solutions of 1–25 g/L, process residues requiring extensive processing, moderately irradiated material, Pu-238 (except in waste), UF4 or UF6 at 20–50 percent enrichment.
e. Highly irradiated forms, solutions <1 g/L, uranium in any form and quantity containing greater than 20 percent U-235. Level E materials are considered to be an unlikely theft or diversion target.

large number of Category I facilities (approximately twice as many as in the United States). Vulnerability of HEU can vary substantially among the sites and from one HEU program to another.

The bulk of most attractive materials (weapons, weapons components, and HEU metal) is handled at the facilities of the weapons production complex and is believed to be relatively secure. All such facilities are located in closed cities; HEU is largely handled or stored in the form of items (weapons components); and the security of classified fissile material operations at weapons facilities remains strict. HEU from weapons is most vulnerable during its transportation from the dismantlement sites to the long-term storage and downblending facilities. Most shipments are conducted by rail and the transportation routes often stretch for thousands of kilometers through sparsely populated areas.

The HEU-to-LEU operations take place in closed cities as well. They, however, are inherently more dangerous because of processing of bulk HEU. The HEU downblending also involves massive transportation of HEU between the dismantlement, oxide conversion, and downblending facilities.

Vulnerability of high-grade HEU materials might be even greater at the fuel fabrication plants in Electrostal and Novosibirsk. Both facilities are located in open cities, and, in addition to producing HEU fuel, they manufacture LEU fuel for commercial power reactors. The extrusion technologies, utilized to make HEU fuel at Electrostal and Novosibirsk, require very large scrap recovery and waste processing operations. According to PNL experts, "Significant quantities of reject fuel materials are produced at the ends of the extrusion fuel rods. Along with other fabrication wastes, the amount of fuel material that needs to be recycled in the fabrication process is about 30 percent"[40] Extensive processing of scrap and waste could be a complication from the MC&A standpoint. Additional problems might be associated with item control of thousands of relatively small fuel elements.[41]

HEU reactor fuel is a less attractive target due to the dilution of uranium oxide in aluminum.[42] (HEU oxide particles, however, could be easily concentrated by melting fuel.) Reactor fuel is at risk in transit and at reactor sites prior to loading in the reactor. (This is particularly true for research and naval reactors for the production reactors are located in the closed cities and are afforded better protection.) The risk could be somewhat reduced by shipping fuel to a reactor just-in-time for refueling. However, for some research reactors the procurement and shipment schedule is usually dictated by the availability of funding and/or fuel. Some research reactors also have large HEU fuel inventories leftover from Soviet times. Generally, research installations are considered more vulnerable because they often cannot afford elaborate security.

In the past several years, security of nuclear materials in Russia has been improved by Russia's internal effort as well as in cooperation with western countries, primarily the United States. The United States has been assisting Russia to improve its fissile material management infrastructure by providing containers to store and ship nuclear materials from weapons and by supporting the construction of a central storage facility in Chelyabinsk-65. The two countries have also been working together to upgrade safeguards and security of nuclear materials at individual nuclear facilities and in transit, and to establish a national-level nuclear safeguards infrastructure in Russia.

Nuclear safeguards and security in Russia, however, remain inadequate. Russia's internal effort has not been sufficient due to budge constraints. The effectiveness of international cooperation has been limited because many large HEU facilities are involved in sensitive operations. As of 1997, for example, cooperative safeguards work was just beginning at the HEU fuel fabrication lines at the Electrostal plant, and the HEU building at the Novosibirsk plant remained closed to foreigners. Most important problem, however, is the immense magnitude of the task due to the gigantic size of Russia's nuclear complex and material inventories, and the scale of necessary upgrades. In fact, the problem is unlikely to be eliminated unless a national economic recovery is achieved.

CONSOLIDATING HEU INVENTORIES AND ACTIVITIES

In view of the urgency of the security problem and the cost of upgrading nuclear safeguards in Russia the HEU operations should be reviewed with the objective of minimizing (a) the number of HEU locations, (b) HEU processing, and (c) HEU transportation.

Minimizing the number of HEU Locations

Ideally, HEU processing and storage should take place in a small number of well-protected sites, such as Minatom's closed cities, and in a smaller number of areas within these sites. Consolidation of HEU inventories and activities would be beneficial in several ways. It would reduce the risk of HEU diversion from poorly safeguarded sites, and, by eliminating the "weak links" in the national nuclear infrastructure, it would increase the effectiveness of investments made to improve security at the closely guarded locations. It also would save the Russian government hundreds of millions of dollars in avoided costs of upgrading and running nuclear safeguards and security across today's bloated complex.

Nuclear facilities will also have an incentive to curtail their HEU operations as Russia's nuclear industry moves towards greater economic independence and the regulatory oversight becomes more effective. Indeed, an HEU facility must have a dedicated security organization and very stringent and expensive security measures. In contrast, LEU plants (at least in the United States) are not required to go beyond standard industrial security. In addition to the extensive safeguards requirements, an HEU facility also must meet much higher requirements in the areas of nuclear criticality, and radiological, environmental, and industrial safety. To work with HEU, a facility must go through a long and laborious licensing process. Additional training of the workforce, special and difficult-to-maintain equipment, tight operational controls, and numerous administrative and engineering controls further drive up the cost of HEU operations.[43]

The U.S.-Russian Reduced Enrichment Research and Test Reactor (RERTR) program is a promising approach to reducing the number of HEU locations. The agreement between U.S. RERTR program (managed by the Argonne national laboratory) and a number of Russian institute to investigate the possibility of converting Russian-designed research reactor, and to design and manufacture 19.75 percent uranium fuel was signed in 1993.[44] The program will address the conversion issues for approximately a dozen reactors in Russia as well as Russian-designed reactors in Eastern Europe and former Soviet republics.

Because of the large experience of working with uranium oxide dispersed fuels, Russian experts elected to develop higher-density uranium oxide fuel.[45] However, a significant fraction of experimental fuel elements, which were loaded in the research reactors in the Kurchatov Institute in Moscow, Institute of Atomic Reactors in Dimitrovgrad, and Institute of Nuclear Physics in St. Petersburg, developed leaks. As of 1998, researchers were working to identify and correct the problem. If the problem persists, the proposal is to develop silicide fuels of the type, which have been extensively tested in the United States.

In the fall of 1997, the U.S. group also negotiated a contract with Russian institutes to assess feasibility of converting the existing Soviet-design reactors to LEU fuels. If the problem with denser fuel is resolved, first reactors, which probably will be the reactors in Poland, Hungary, and the Czech Republic, could be converted in 1999-2000. A transition to silicide fuels is likely to delay conversion by another two years.

The U.S. and Russian governments should direct the RETR program to investigate the possibility of converting HEU-fueled reactors of the icebreaker fleet. If successful, such a conversion could eventually eliminate storage and handling of weapon-grade HEU at MSC's Atomflot base and in the Murmansk area. Conversion of icebreaker reactors also could allow the Electrostal plant to phase out operations with weapon-grade uranium in this location.

Revision of the HEU operations also should focus on research institutes and other facilities using bulk HEU for research purposes. HEU inventories should be removed from those institutions that no longer conduct HEU research. In fact, this process is already underway but must be expanded and accelerated. Reportedly, the "Luch" institute in Podolsk has increased HEU scrap reprocessing, the fact that "reflects the need to consolidate HEU materials from various facilities to assure their physical security, as well as to facilitate their further reprocessing into low-enriched uranium for use in the fuel cycle."[47]

Increased security and cost savings could also be achieved by consolidating HEU in a small number of secure locations within sites. Many Russian facilities are already undertaking such steps. For example, at the research center in Obninsk there are presently approximately 35 category I material areas in 22 buildings (reactors, processing labs, hot cells, storage areas).[48] The plan is to create a "nuclear island" which would comprise three high-security areas including a new storage facility. This measure would reduce the number of material areas to 17 in 14 buildings, and approximately 70 percent of institute's nuclear materials would be inside the "nuclear island." Similarly, at the "Luch" institute in Podolsk, HEU has been moved from approximately 40 locations to the central storage facility.

Minimizing HEU Processing

Reductions in HEU processing would simplify material control and accounting procedures. HEU throughputs at the fuel fabrication facilities could be somewhat reduced as a result of the RERTR program. In Novosibirsk, however, these reductions would be more than offset by the proposed use of HEU to fuel the plutonium-production reactors. The HEU throughput at the Novosibirsk plant would increase three-fold. The facility would likely add an operation with higher-grade HEU metal (as opposed to less attractive uranium oxide and hexafluoride that are currently processed). In addition, an expanded use of HEU in the production reactors would likely create in a new HEU stream associated with reprocessing of irradiated HEU fuel.

Minimizing HEU Transportation

Reductions in a number of HEU shipments could be achieved primarily by establishing regional cooperation in the HEU-to-LEU processing cycle. In particular, the risk of transportation (which is roughly proportional to the amounts of transported HEU and to the time of transit) could be cut if all new HEU from the dismantlement plants were delivered for storage and oxidation to Chelyabinsk-65 (which is relatively close to the Sverdlovsk-45 dismantlement complex). Chelyabinsk-65 would send HEU oxide powder to Sverdlovsk-44 for downblending. In tern, Tomsk-7 could probably work for several years by digesting the HEU from weapons that had already been accumulated in Tomsk-7.[49] HEU oxide from Tomsk-7 would be sent for downblending to the enrichment plants in Tomsk-7 and Krasnoyarsk-45. Such cooperation would create two regional HEU-to-LEU cycles: one in the Urals and another in Siberia. The implementation of the RERTR program would also result in a reduced number of HEU shipments between the fuel fabrication facilities and reactor sites.

Again, the proposed use of HEU in the plutonium production reactors would considerably increase the volume of HEU transportation by additional shipments of HEU metal from the dismantlement plants to Novosibirsk and shipments of reactor fuel from Novosibirsk to Tomsk-7 and Krasnoyarsk-26. In contrast, if the LEU option is selected, HEU downblending to 20 percent U-235 could take place in Tomsk-7 (where HEU could be drawn from the existing inventories) and no HEU transportation would occur.

CONCLUSION

Russia has the world's largest stocks of HEU. Weapon-grade uranium is stored, processed and used in many locations across Russia. These operations present a considerable risk of HEU theft or diversion. Russia, in cooperation with Western governments, is working to improve nuclear safeguards and security. Many vulnerabilities, however, continue to exist. Consolidation and reduction in HEU operations must accompany MPC&A improvements. HEU consolidation would reduce the risk of diversion and also would cut the operation and maintenance cost of nuclear activities in Russia. In particular, it is important to weigh carefully relative technical and economic benefits associated with the conversion of the plutonium production reactors to HEU fuels against increased security costs and HEU vulnerabilities associated with this option.

NOTES AND REFERENCES

1. Plutonium has a somewhat larger cross-section for fission and emits more neutrons per fission by fast neutrons. Because of that it has a smaller critical mass therefore allowing for smaller, lighter, and more efficient fission primaries in thermonuclear weapons.

2. In particular, HEU can be used to make a gun-type explosive device, which could be somewhat easier to design and to manufacture. Plutonium is not suitable for manufacturing a gun-type device.

3. According to my earlier estimates, the total HEU production (90-percent HEU equivalent) was 1,435 t and the available inventory is 1,300 t. (Bukharin, O., "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science and Global Security*, Vol. 6, No. 1, 1996, pp. 59–77.) According to David Albright's calculation, the HEU inventory is 720–1,395 t. (Albright, D., F. Berkhout, and W. Walker, "Plutonium and Highly-Enriched Uranium 1996 World Inventories, Capabilities, and Politics," SIPRI, Oxford University Press, 1997, p. 113.)

4. In a nuclear weapon, HEU could be used in a fission primary (an all-uranium pit in an implosion- or gun-type device, or uranium-plutonium composite pit) and/or a thermonuclear secondary. The amounts of HEU and its levels of enrichment could vary significantly from one type of warheads to another. For example, the average enrich-

ment of the HEU stocks in the United States is 80 percent (Albright, D. et al., p. 84). Russian warheads reportedly use 36 to 98 percent enriched uranium. How much HEU is used per one warhead on average is not known. For a fission weapon or a primary, this amount could range from a few kg in a composite, uranium-plutonium pit to 50 or so kg in a gun-type device. (For example, the gun-type devices made in South Africa contained an estimated 55 kg HEU; Albright, D., "South Africa's Secret Nuclear Weapons," ISIS report, May 1994, p. 12.) The standard assumption is that modern thermonuclear warheads contain 15 to 25 kg HEU. Indeed, an estimated HEU inventory for weapons in the United States is 750 t 80-percent enriched uranium, corresponding to 670 t of 90-percent uranium (Albright, D. et al., p. 91). The U.S. stockpile peaked in 1967 peak at a level of 32,500 warheads. (Norris, R.S. and W.M. Arkin, "Estimated U.S. and Soviet/Russian Nuclear Stockpiles, 1945–94," *The Bulletin of the Atomic Scientists*, November/December 1994, pp. 58–59.) Assuming that all HEU available for the weapons program was fabricated into warhead components, warheads contained an average of approximately 20 kg HEU.

5. Minatom's Minister Mikhailov read the declaration by Boris Yeltsin to the IAEA's General Conference. The plan is to release 120 t HEU by 2000 in addition to 36 t already released. (*Uranium Institute News Briefing*, NB97.41–5, 97.41, p. 1, October 8–14, 1997.)

6. "Process Descriptions and Material Control and Accounting System," Annex 9 to the Protocol, *Record of the Second Transparency Review Committee Meeting*, Washington, DC, (August 4, 1995).

7. Uniformity of the neutron flux is required to assure plutonium's specifications with respect to the content of Pu-240 throughout the core.

8. Assuming that one reactor is 2,000 MWt and is operating at 80 percent of its capacity, it would produce annually 584,000 MWd energy. Reportedly, HEU fuel accounts for 10 percent of power generation (A. Diakov). Approximately 60 kg U-235 has to be fissioned to produce 58,400 MWd (1 MWd is produced by fissioning of 1.05 g U-235). Assuming a burnup rate of 30 percent this corresponds to the HEU requirements of approximately 200 kg/y.

9. Each 1,000-MW reactor produces 219,000 MWd/y by burning approximately 230 kg U-235. This corresponds to approximately 750 kg HEU/y.

10. For example, in 1995, the reactor "Ruslan" was shut down for an extensive maintenance and backfitting. (*Report on Gosatomnadzor Activities in 1995*, GAN, Moscow, 1996, p. 55.)

11. Newman, D.F., C.J. Gesh, E.F. Love, S.I. Harms, "Summary of Near-Term Options for Russian Plutonium Production Reactors," PNL-9982, PNL, (July 1994), p. 30.

12. The total capacity of the 13 plutonium reactors was 19,400 MW. The total HEU requirements for these reactors could be estimated at 2 t/y.

13. According to GAN officials, all the enrichment plants, with the exception of the Sverdlovsk-44 facility, are permitted to enrich uranium to less than 5 percent U-235. The Sverdlovsk-44 enrichment plant has a permission to enrich uranium to 30 percent U-235. (Communication with GAN officials, summer 1996, Moscow).

14. According to the plant official, "The starting material for this process [processing research reactor fissile materials in enrichments greater than 20 percent] is uranium hexafluoride." (Ustugov, A., G. Fuller, "Nuclear Fissile Material Control and Accounting System at the Fuel Elements and Assemblies Fabrication Plant, Novosibirsk Chemical Concentrates Plant, Novosibirsk, Russia," presented at the 38th INMM

Annual Conference, Phoenix, AZ, July 20–24, 1997.)

15. Also, according to the PNL report, "The HEU feed material to the fuel manufacturing plant at Novosibersk will be from dismantled weapons and contains about 90 percent U-235 when received. This HEU will be converted to U02 from at the first step in the process." ("Core Conversion Enrichment for Russian Production Reactors," Technical Issue Paper, PNL, February 1997, p. 7 and p. 19.)

16. MSC's nuclear fleet includes the now decommissioned icebreaker Lenin, five Arctica-class icebreakers powered by two 54-Mw reactors, two Taymyr-class icebreakers powered by one 32.5 MW reactor, and one Sevmorput'-class cargo vessel powered by one 29.42-Mw reactor.

17. Reactors of the first and second generations were fueled with uranium enriched up to 21 percent U-235. Reactors of the third generation have cores consisting of two to three enrichment zones with enrichment levels varying between 21 and 45 percent U-235. (Interview with Minatom officials, January 17–18, 1995, Washington, DC.) According to the U.S.-Russian MPC&A project paper, "The Russian Navy uses highly enriched uranium (20–90 percent) for nuclear-powered ships." (Croesmann, D. et al., "United States-Russian Cooperation on Protection, Control and Accounting for Naval Nuclear Materials," presented at the 38th INMM Annual Conference, Phoenix, AZ, July 20–24, 1997.)

18. The cruisers are powered by KN-3 type reactors. KN-3 reactors are fueled with 55–90 percent-enriched uranium. (*AtomInform*, No. 4, 1994.)

19. O'Brien, M. et al., "MPC&A Activities with Russian Icebreaker Fleet," presented at the 38th INMM Annual Conference, Phoenix, AZ, (July 20–24, 1997).

20. According to PNL experts, 20-percent enriched uranium fuel for naval reactors is also produced in Novosibirsk. (Newman, D., C. Gesh, E. Love, S. Harms, "Summary of Near Term Options for Russian Plutonium Production Reactors," PNL-9982 US-520, PNL, July 1994, p. 27.)

21. O'Brien, M. et al., "MPC&A Activities with Russian Icebreaker Fleet," presented at the 38th INMM Annual Conference, Phoenix, AZ, (July 20–24, 1997). According to the interview with MSC officials, fuel also might be delivered by a truck from a naval base in time for refueling. (Murmansk, June 1995.)

22. In the North, naval fuel is stored at the following locations: Sevmash submarine construction yard (Severodvinsk), Sevmorput shipyard 35 (Murmansk), Zapadnaya Litsa (Kola Peninsula), and Site 49 (Severomorsk, the primary storage site for the Northern fleet) 15 km northeast of Murmansk. In the Pacific, naval fuel is stored at the following locations: Shipyard 199 (Komsomolsk-na-Amure), Gornyak Shipyard (Petropavlovsk Kamchatsky), and Shkotovo-22 (Vladivostok).

23. For example, it was reported that icebreaker cores contain 151 kg of 90-percent enriched uranium. (*Nucleonics Week*, April 18, 1991, as quoted in Bradley, D., "Radioactive Waste Management in the Former USSR: Volume III," June 1992, PNL-8074, p. 6.13.) According to reactor designers, the reactor of the nuclear-powered ship Sevmorput' is fueled with 200 kg 90 percent enriched uranium. (Interview, St. Petersburg, September 1992.)

24. There are 43 research reactors, 52 subcritical and 18 critical assemblies under the supervision of Gosatomnadzor. Of them, 11 are under construction and 14 are being decommissioned (*GAN Report*, RD 03-02-93, 1993). The Ministry of Defense operates additional research and training reactors. A list of research reactors is provided in Cochran, T., S. Norris, O. Bukharin, "Marking the Russian Bomb: From Stalin to

Yeltsin," Westview Press, Boulder, Co, p. 198–201.

25. Communication with Armando Travelli (December 14, 1997).

26. A variety of experimental fuels are also manufactured in Electorstal.

27. "Foreign Travel Trip Report to Novosibirsk/St. Petersburg, Russia, May 12–23, 1996," (May 31, NIS-5-96-311, 1996), LANL.

28. "Nuclear MPC&A at the Luch Facility," *US/FSU Program for Nuclear Material Protection, Control and Accounting*, DOE Nuclear Material Security Task Force, (December 1996), pp. G-G 37–43.

29. Zakharkin, B., "Basics of Chemistry of Regeneration of Spent Nuclear Fuel of Propulsion Reactors at the RT-1 Plant," presented at the OTA workshop, (January 17–18, 1995).

30. In December 1993, a GAN official stated that, "[HEU] fuel has not been shipped to Chelyabinsk for 3–4 years." (Interview, Washington, December 17–21, 1993.) Reportedly, however, reprocessing of HEU spike fuel has recently begun in Tomsk-7.

31. Interview with Minatom official (June 1995, Moscow).

32. Zakharkin, B., "Basics of Chemistry of Regeneration of Spent Nuclear Fuel of Propulsion Reactors at the RT-1 Plant," presented at the OTA workshop, (January 17–18, 1995).

33. Particularly vulnerable are direct-use materials such as HEU metal and oxides because of their relative compactness and convenient physical form.

34. For a discussion regarding HEU diversion risks see Bukharin, O. and H. Hunt, "The U.S.-Russian HEU Agreement: Internal Safeguards to Prevent Diversion of HEU," *Science and Global Security*, Vol. 4, pp. 189–212.

35. For example, approximately 1,000 workers work at the HEU facility in Novosibirsk (Communication with Fran von Hippel, January 1997).

36. Bukharin, O., "Security of Fissile Materials in Russia," *Annual Review of Energy and Environment*, (1996), Vol. 21, pp. 467–496.

37. Communication with U.S. safeguards official (August 1996).

38. It is estimated that approximately 15–20 kg of HEUY might be enough to make a relatively simple, solid-pack implosion-type nuclear explosive device. A gun-type device might require as much as 50 kg HEU. It is estimated that for a single device up to 30 percent of fissile materials may end up in scrap and waste. The level of HEU attractiveness, that is, the extent of how easy and how fast diverted material could be fabricated into metallic shapes of an explosive device, is of particular importance. In order to be usable without further enrichment in a first-generation fission device of a reasonable weight and size, HEU probably has to contain more than 50 percent of the isotope U-235. A physical form and chemical composition of uranium are also important.

39. Wilkey, D.D. and D.W. Crawford, "Graded Safeguards: Determination of Attractiveness Levels for Special Nuclear Materials," Proceedings of the INMM Symposium, (1994), pp. 1,059–1,062.

40. "Core Conversion Enrichment for Russian Production Reactors," Technical Issue Paper, PNL, (February 1997), p. 7.

41. According to Bunn, M.: "The 200,000 fuel elements to be produced each year [if the

reactors are converted to HEU fuel] in this program are small and light—ideal targets for theft. To avoid simple 'insider' strategies—such as substituting dummy natural uranium fuel elements for real HEU elements—it may be necessary to put in place an MPC&A system that assays and barcodes every element, at considerable cost." (Letter to DOE's Leonard Spector, January 6, 1998).

42. The reactor fuel is "[HEU] cermet fuel contains 8.5 wt U02 (90 percent U-235/ U_{total}) dispersed in aluminum." (Newman, D., C. Gesh, E. Love, S. Harms, "Summary of Near Term Options for Russian Plutonium Production Reactors," PNL-9982 US-520, PNL, (July 1994), p. 27.) According to the DOE classification, solids containing between 0.1 and 10 weight percent of nuclear material are low-grade D-level materials.

43. For example, as a result of additional expense the cost of oxide-to-fluoride conversion for HEU is approximately a factor of 60 higher as compared to LEU. Brandon, N.E. and D.R. Hopson, "Elements of a Highly Enriched Uranium Infrastructure," Nuclear Energy Institute's International Uranium Fuel Seminar, (September 25–28, 1994), Beaver Creek, CO.

44. Reportedly, the Soviet Union initiated a program to reduce enrichment of research reactors in the late 1970s. Before this effort stopped in the late 1980s due to funding shortfalls, a number of reactors were converted from 90 to 36 percent enriched fuel. Hibbs, M., "US Will Help Russians to Develop LEU Fuel for Research Reactors," *Nuclear Fuel*, (December 6, 1993), pp. 7–8.

45. Communication with Armando Travelli (December 14, 1997).

46. *Report on Gosatomnadzor Activities in 1995*, GAN, Moscow, (1966), p. 49.

47. Mizin, P. et al., "Nuclear MPC&A at the Luch Facility," *US/FSU Program for Nuclear Material Protection, Control and Accounting*, DOE Nuclear Material Security Task Force, (December 1996), pp. G-G 37–43; and Mizin, P. et al., "Progress in MPC&A Upgrades at Luch," presented at the 38th INMMM Annual Conference, Phoenix, AZ, (July 20–24, 1997).

48. Poplavko, V., "Consolidation of Nuclear Materials in the RF State Science Center Institute of Physics and Power Engineering," *Proceeding of the Russian International Conference on Nuclear Material Protection, Control, and Accounting, Obninsk, March 9–14, 1997*, Obninsk, (1997), Vol. 2, pp. 483–486.

49. As of 1994, approximately 23,000 containers with HEU and plutonium were stored at Tomsk-7. The material was placed in storage before April 1992 and, because of the lack of storage capacity, no new material has been brought to Tomsk-7 since. (See Menshikov, V., *Yarderny Control*, No. 2, February 1995, p. 3.)