By Alexander Glaser
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Global Cleanout:
Reducing the Threat of HEU-Fueled Nuclear Terrorism

The greatest opportunity for would-be nuclear terrorists or countries seeking a quick bomb or two are poorly secured sites that contain significant quantities of highly enriched uranium, (HEU)—uranium containing a high percentage of the chain-reacting isotope uranium 235. HEU is the material of choice for terrorists or for states that seek to proliferate clandestinely without testing their weapons.

Unlike plutonium, HEU can be worked without special protections. It can also produce a full-yield explosion in a simple gun-type design in which one subcritical mass of HEU is fired into another. The bomb that destroyed Hiroshima, built with about 60 kilograms of 80 percent enriched HEU, used this design. Today, there is little disagreement that a terrorist group could design a workable gun-type device. It is therefore critical to make current stocks of HEU as inaccessible as possible.

The most effective approach in the long term to the risk of diversion or theft of HEU is to eliminate it from as many locations as possible and blend down excess HEU to low-enriched uranium (LEU). In contrast to HEU, LEU contains less than 20 percent U-235.[1] It is considered non-weapons-useable primarily because the amount of uranium needed to set off a sustained nuclear chain reaction—about one critical mass—is so large (see figure 1).

The United States and Russia have already slimmed down their stockpiles of weapons HEU somewhat. At the end of the Cold War, the Soviet Union and the United States together had about 2,000 metric tons of HEU, enough for about 35,000 gun-type or more than 100,000 implosion-type bombs. Other countries had an estimated 60 tons. Most of this material was in weapons. Due to the downsizing of their nuclear stockpiles, Russia and the United States declared, respectively, 500 and 174 metric tons of HEU as excess.[2] Most is being blended down to LEU for use as power-reactor fuel.[3]

Outside of its use in weapons, HEU also is used as a fuel for naval and research reactors and for the production of certain medical isotopes. Recently, Secretary of Energy Samuel Bodman announced that an additional 200 tons of excess U.S. weapons uranium will be reserved for future use as naval reactor fuel (160 tons) and space-reactor and research-reactor fuel (20 tons) and blended down to LEU for use as research and power reactor fuel (20 tons).[4]

The size of the reserve for the nuclear Navy indicates that the naval-reactor fuel cycle will be a major challenge to the goal of reducing global stockpiles of HEU. This issue has been explored elsewhere.[5] We therefore focus here primarily on uses of HEU in land-based civilian reactors.

Although the current global HEU stockpile for land-based reactors (50-100 metric tons)[6] is much less than the quantities of HEU in nuclear weapons and reserved for naval reactor fuel, it is still enough for at least 1,000 gun-type devices. The Department of Energy's National Nuclear Security Administration (NNSA) estimated in 2004 that there were 128 research reactors and

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associated facilities worldwide with at least 20 kilograms of HEU.[7] Many of these facilities are in urban locations with only modest security, presenting potential targets to would-be nuclear terrorists. A large fraction are in Russia, which has yet to give adequate priority to cleaning out facilities containing HEU that is no longer needed. At several sites, there is enough HEU to make more than 10 gun-type weapons.

Decommission Excess Reactors

Whereas power reactors are fueled with uranium that is less than 5 percent enriched, HEU is still widely used to fuel civilian research reactors. During the 1950s and 1960s, as part of their competing Atoms for Peace programs, the United States and the Soviet Union built hundreds of research reactors domestically and for export to more than 40 other countries. In response to demands for longer-lived fuel and maximum reactor performance, exports restrictions were relaxed, which resulted in most of these reactors being fueled with weapons-grade HEU enriched to more than 90 percent.

Figure 2 shows the countries that have or have had HEU-fueled reactors. Fortunately, according to our research, 13 of these countries no longer have HEU because of international efforts to convert research reactors to LEU and to return their irradiated HEU-containing fuel to its country of origin.

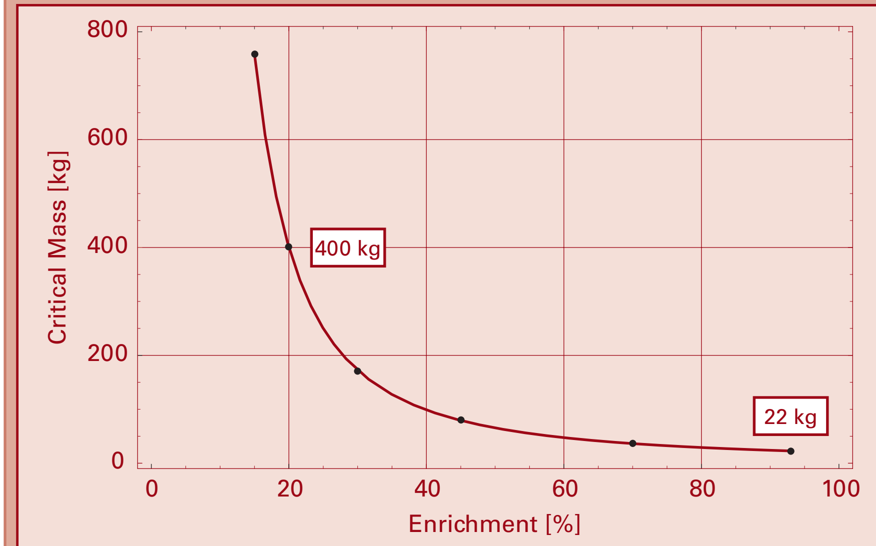
Most of the world's aging HEU-fueled research reactors are no longer needed. Two International Atomic Energy Agency (IAEA) research-reactor experts put it this way at the 2003 international Reduced Enrichment for Research and Test Reactors (RERTR) conference: "Only reactors with special attributes (such as a high neutron flux, a cold [neutron] source, in-core loops to simulate power reactor conditions) or with commercial customers (such as radioisotope production or silicon doping) are adequately utilized."[8]

Eliminating excess reactors would reduce the total number of research reactors worldwide from hundreds to tens. In some cases, research reactors could be replaced by accelerator-driven neutron sources. A few years ago, the United States decided to build such a neutron source at the Oak Ridge National Laboratory. The laboratory had first proposed building a powerful new research reactor but ran into opposition because it was to be fueled with HEU.

Just shutting down an HEU-fueled reactor, however, is not sufficient. To eliminate the danger of diversion or theft, the HEU fuel must be removed, i.e., the reactor must be "decommissioned." In 2000 the IAEA's International Nuclear Safety Advisory Group urged consideration of proper decommissioning of 258 shutdown research reactors worldwide. In a follow-up analysis, one reason cited for these reactors not being decommissioned was "the hope that the reactor will be returned to operation."[9]

To make a decommissioning program attractive in Russia and elsewhere, it might be necessary for concerned countries to invest in strengthening the surviving research-reactor centers. Such assistance should be conditioned, however, on the management being willing to allow research groups from decommissioned facilities to become "users groups" on a nondiscriminatory basis. Such arrangements are standard in the United States and western Europe but are still foreign to Russia, where a group does not have an opportunity to do experiments if it does not have its own reactor.

Figure 1 **Critical mass of a uranium sphere surrounded by a 5-cm beryllium "neutron reflector" as a function of uranium-235 enrichment.**



Reactor Conversion and Fuel Takebacks

So far, the United States has shied away from promoting the decommissioning of reactors. Instead, it has focused on converting facilities to less-risky fuels. Both the Soviet Union and the United States launched efforts in the late 1970s to convert HEU-fueled research reactors to lower-enriched fuel. By 1991 the Soviet Union had converted most of the foreign research reactors that it supplied from 80 percent to 36 percent enriched fuel. The collapse of the Soviet Union halted the program, however, and also created a new group of independent countries with HEU-fueled reactors. The Energy Department estimates that Soviet-designed research reactors inside and outside Russia today use a total of about 350 kilograms of HEU fuel per year.[10]

In 1993 the United States began to work in Russia to revive the Russian program with the objective of converting all Soviet-designed research reactors to LEU. The first such conversion, in the Czech Republic, was completed in October 2005.[11]

The United States began its own efforts to convert HEU-fueled reactors to LEU in 1978. The original purpose of the U.S. RERTR program was to convert to LEU foreign reactors to which the United States was supplying HEU fuel. In 1986 the U.S. Nuclear Regulatory Commission required that the nongovernmental research reactors that it licenses in the United States (mostly located at universities) also convert to LEU if such fuel is available and if the Energy Department makes available the funding for the conversion. By the end of 2005, the program had converted or partially converted 31 foreign and 11 domestic reactors. These research reactors had previously required together annually about 250 kilograms of fresh HEU.

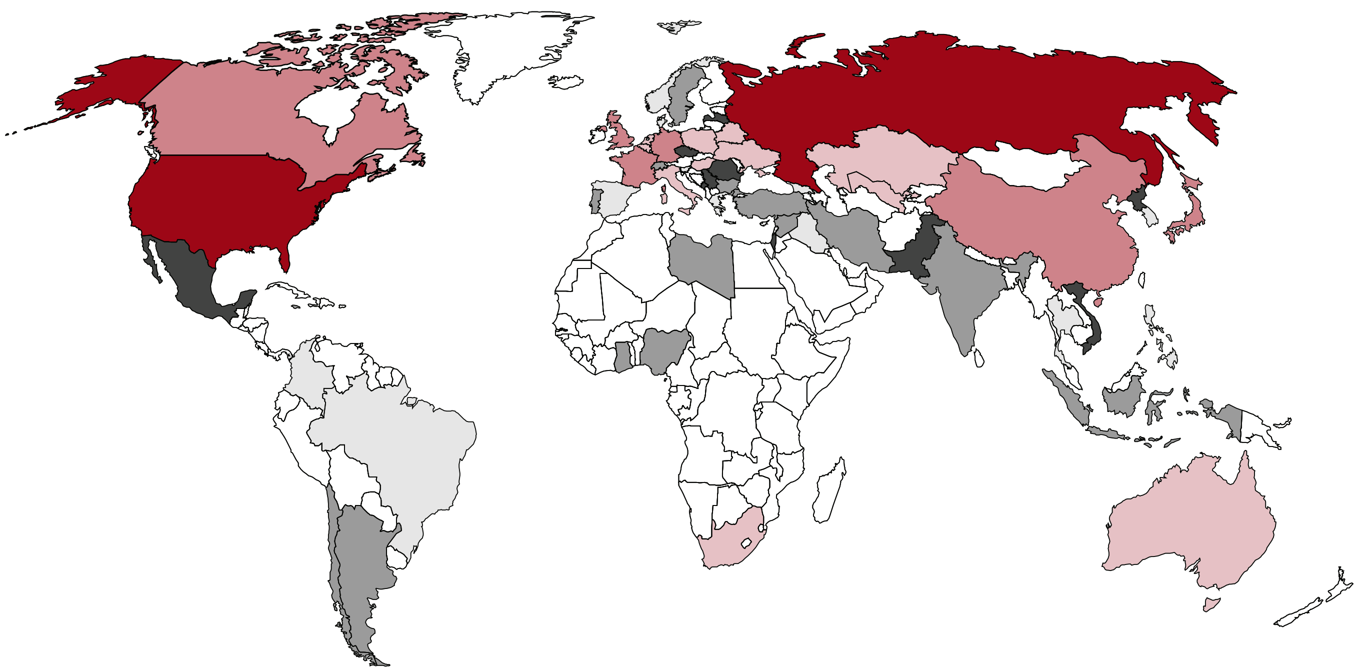
The bulk of the task, however, remains to be done. The Energy Department's list still contains 120 operating HEU-fueled reactors, and this list is incomplete. The Energy Department also estimates that the world's remaining HEU-fueled research reactors consume about 1,000 kilograms of HEU per year. About 500 kilograms of this HEU is for Western-designed reactors, mostly supplied by the United States, and the remainder provided by Russia and China. The RERTR program estimates that 41 of these reactors can be converted using existing LEU fuels.[12] However, of the Western-designed reactors, 10 that consume the bulk of the HEU cannot be converted until advanced LEU fuels are developed.[13]

These 10 research reactors have compact, high-powered cores designed to maximize neutron intensity for testing reactor fuels and materials to high irradiation levels and for neutron-scattering measurements used to probe the arrangements of atoms in complex materials.

Because a high concentration of U-235 is needed for compact cores, HEU is an ideal fuel. To achieve a similar density of U-235 in an LEU-based fuel has been the primary challenge for the conversion program.

The approach of the RERTR program has been to develop 20 percent-enriched LEU fuels that make up for the lower level of enrichment by increasing the relative concentration of uranium vis-à-vis other elements in the nuclear fuel. In 20 percent-enriched LEU, unlike HEU, each gram of U-235 is diluted with 4 grams of uranium 238. So, the uranium density in the LEU fuel must be about five times higher than in the HEU fuel. Fortunately, the densities of the HEU fuels that have to be replaced are mostly quite low, between 3 percent and 9 percent of the density of solid uranium. The most advanced LEU fuel commercialized thus far has a uranium density of 25 percent of solid uranium. A higher uranium density fuel, which was to be commercialized this year, has not fared well. Because of its unexpected poor irradiation performance, the availability of fuels with the densities required to convert the research reactors into those with compact, high-powered cores has slipped to approximately the year 2010. The most promising fuel currently under development—solid uranium alloyed with molybdenum—has a uranium density of 84 percent of that of solid uranium and could be used to convert all remaining high-powered research reactors.[14]

Figure 2 Global Distribution of Civilian HEU Reactor Fuel



Quantity of Civilian HEU*	Countries
More than 10,000 kg	Russia, United States
1,000 - 10,000 kg	Canada, China, France, Germany, Japan, United Kingdom
100-1,000 kg	Australia, Belarus, Belgium, Hungary, Italy, Kazakhstan, Netherlands, Poland, South Africa, Ukraine, Uzbekistan
10-100 kg	Czech Republic, Israel, Latvia, Mexico, North Korea, Pakistan, Romania, Serbia, Vietnam
1-10 kg	Argentina, Bulgaria, Chile, Ghana, India, Indonesia, Iran, Jamaica, Libya, Nigeria, Portugal, Syria, Sweden, Switzerland, Turkey
Cleared of HEU (less than 1 kg)	Austria, Brazil, Columbia, Denmark, Georgia, Greece, Iraq, Norway, Philippines, Slovenia, South Korea, Spain, Thailand

SOURCE: "Civil HEU Watch: Tracking Inventories of Civil Highly Enriched Uranium" by David Albright and Kimberly Kramer, with some updates by the authors of this article. Quantities have been translated to weapons-grade (90 percent-enriched) equivalents. We do not include the spent fuel of Kazakhstan's BN-350 shutdown breeder reactor, as this fuel was only enriched to 20-25 percent when fresh.

Table 1 Budgets for National Nuclear Security Administration programs aimed at eliminating civilian HEU-fuel use ($ millions).[1]

Program	FY 2004	FY 2005 (pre-GTRI)	FY 2006
Global Threat Reduction Initiative			
Reduced enrichment research and test reactor	6.63	18.81	24.7
U.S. foreign research reactor fuel return	6.12	4.50	8.7
Russian research reactor fuel return	9.69	15.2	14.7
GTRI Subtotal	22.44	38.51	48.1
Materials consolidation and conversion	32.00	30.00	28.00

1. William Hoehn, Russian-American Nuclear Security Advisory Council, private communication with author, November 2005.

Spent Fuel

The residual uranium in spent HEU fuel is also still potentially usable for weapons. It typically contains about half of its original U-235. HEU that was originally weapons grade is of special concern because it is still near weapons grade.[15] For some years after discharge from the reactor, the spent fuel is considered "self-protecting" by the IAEA because the radioactive fission products it contains emit highly dangerous gamma rays as they decay.[16] As this radiation field dies down with time, however, the spent fuel becomes a greater proliferation concern. Typically, research-reactor fuel elements are no longer self-protecting 25 years after discharge.

In 1996, therefore, the United States invited foreign countries that had received U.S. HEU fuel to ship back two common types of spent HEU fuel and began to work in 2002 with Russia similarly to retrieve Soviet/Russian-origin HEU fuel from outside Russia. As of the end of 2005, however, only about a ton of the U.S.-origin fuel had been returned to the United States.[17] Progress in returning Russian HEU is at an even earlier stage. About 122 kilograms of HEU in un-irradiated fuel had been shipped back to Russia, but as of November 2005, fuel originally containing approximately 2,000 kilograms of HEU that had been shipped from Russia to 17 countries remained abroad.[18]

The United States in 1999 also established a Materials Consolidation and Conversion (MCC) program to acquire excess Russian civilian HEU and blend it down to 20 percent-enriched LEU. This low-profile program has made steady progress. As of the end of 2005, about 7 tons of an estimated 17 tons of excess Russian civilian HEU had been blended down, but as yet, not a single site has been completely cleaned out.[19]

Overall, therefore, although programs to reduce the number of locations where HEU can be found are in place, they have achieved only a small fraction of their objectives, despite the additional impetus given by the 2001 terrorist attacks on the United States.

Post-September 11 Developments

In 2004 the Energy Department responded to congressional concern about how slowly the HEU cleanout programs were moving by combining its reactor-conversion and spent HEU fuel takeback efforts into a Global Threat Reduction Initiative (GTRI) program. Then-Secretary of Energy Spencer Abraham committed that the GTRI would help Russia repatriate all Russian-origin fresh HEU fuel by the end of 2005—which has since slipped to 2006—all Russian-origin spent HEU fuel by 2010, and all U.S.-origin HEU spent fuel by 2014. Abraham also pledged to convert all U.S. civilian research reactors to LEU by 2013—now 2014—and to convert all other research reactors "throughout the world." All told, Abraham promised that the United States would spend about $450 million on this effort.[20] That comes to about $45 million per year over 10 years, which is about the current level of effort (see Table 1).

These are laudable goals. Unfortunately, Russia, which accounts for about one-third of the world's HEU-fueled reactors and more than half of the world's civilian HEU, has yet to make a commitment to convert or decommission any of its own HEU-fueled research reactors. President George W. Bush took pressure off of Russia to do so at a February 2005 summit with Russian President Vladimir Putin.

Ending HEU Use in Medical-Isotope Production

Some medical-isotope production reactors use highly enriched uranium (HEU) as a "target" for neutron bombardment to produce the fission product molybdenum-99. The decay product of this isotope, Technicium-99, is used annually in tens of millions of medical procedures.[1] There is currently no domestic producer of this material and the Department of Energy estimates that a total of 85 kilograms of weapon-grade HEU are used for this purpose annually in reactors in Belgium, Canada, France, the Netherlands, and South Africa.[2]

Argonne National Laboratory has developed a means of substituting low-enriched uranium (LEU) for the more dangerous HEU in this process. Two smaller producers have converted to LEU and another is in the process of doing so. But the largest producers do not want to incur the cost of conversion. Two of them, Nordion of Canada and Mallinckrodt, which produces in Europe, backed a successful lobbying effort to include a provision in this year's Energy Policy Act. This provision suspends the application of a 1992 law that conditions exports of U.S. HEU to foreign users on their willingness to convert to LEU as soon as LEU fuel or targets become available.

ENDNOTES

1. Six-hour half-life technicium-99m emits a 0.14 MeV decay gamma ray used for medical imaging.

2. Office of Nonproliferation, National Nuclear Security Administration, "RERTR Program Project Execution Plan," February 16, 2004.

The two leaders agreed to limit to "third countries" U.S.-Russian cooperative efforts to deal with the danger from HEU-fueled reactors.[21] Russian government officials have reportedly used this agreement as a reason for suspending further discussions with the United States on the conversion of Russia's own HEU-fueled reactors. Fortunately, as discussed below, Russia's nuclear institutes still appear open to cooperation in this area.

Toward a Comprehensive Program

Current efforts also largely exclude reactor types that make up about half of the world's HEU-fueled reactors: critical assemblies and pulsed reactors. Worldwide, there are at least 38 HEU-fueled critical assemblies and 19 HEU-fueled pulsed reactors. Most are among the 59 HEU-fueled research reactors listed in the 2004 RERTR Program Execution Plan as "research reactors using HEU fuels that are not part of the RERTR Program."[22] These reactors do not consume fuel, but their cores often contain huge quantities of HEU.

Critical assemblies are used to determine the physics properties of proposed reactor-core designs. Most pulsed reactors were designed to determine the effects of neutron bursts from nearby nuclear explosions on nuclear warheads and other objects. The fuel of both types of reactors is only slightly radioactive—orders of magnitude less than required for self-protection.[23]

Once again, most of these reactors could be decommissioned. Most critical assemblies are obsolete because their mission can be accomplished today by inexpensive and highly accurate computer simulations. Indeed, Russia has more than 60 percent of the world's HEU-fueled critical assemblies because it has decommissioned so few. An effective program needs to be mounted to help it do so. In 2002 the Moscow-based Kurchatov Institute of Atomic Energy, which has 12 HEU-fueled critical assemblies, requested U.S. assistance to decommission most of them. The Energy Department's MCC program has recently begun discussions with Kurchatov about this proposal.

Likewise, most pulsed reactors are no longer needed because the effects of their neutron bursts can be simulated with computers. In 2004 Abraham cited this as a reason to shut down one of the Sandia National Laboratory's two HEU-fueled pulsed reactors: "[A]fter operations of three years or perhaps less, the Sandia Pulsed Reactor will no longer be needed, since computer simulations will be able to assume its mission.… When its mission is complete, this reactor's fuel will be removed from Sandia National Laboratories, New Mexico, allowing us to reduce security costs at Sandia and further consolidate our nuclear materials."[24]

For those facilities that will be kept, steps should be taken to convert them to LEU or at least to reduce significantly the enrichment of their fuel. An indication that this is possible is provided by two Russian facilities with huge HEU inventories:

- One critical facility at the Institute of Physics and Power Engineering in Obninsk contains 8.7 tons of HEU, as well as 0.8 tons of plutonium, mostly in the form of tens of thousands of disks less than 2 inches in diameter. Some of the HEU is at a 36 percent-enrichment level, while some is weapons grade (90 percent). It appears that the safer 36 percent-enriched uranium should be sufficient for mocking up large breeder reactor cores, which is the main mission of the facility.[25]

- A pulsed reactor at the Institute of Experimental Physics in Sarov (Russia's counterpart to the Los Alamos National Laboratory) contains 833 kilograms of weapons-grade uranium, enough for 15 Hiroshima bombs. The GTRI program recently committed to fund a proposal from the institute to do a feasibility study on converting this reactor to LEU. The MCC program could potentially help fund the conversion.[26]

Other HEU-Fueled Reactors

There are also other types of civilian HEU-fueled reactors that should be addressed. For example, Russia has a fleet of seven civilian nuclear-powered icebreakers whose 11 reactors currently annually require HEU fuel containing about 225 kilograms of U-235.[27] The Moscow-based Bochvar Institute, which develops Russia's nuclear fuels, began in the late 1990s to develop LEU fuel suitable for a floating nuclear power plant whose reactor design is derivative from one used to power Russia's nuclear icebreakers. The privately funded Nuclear Threat Initiative is negotiating with the Bochvar Institute to build on this work and develop LEU fuel that could be used to convert the nuclear icebreakers.

Russia also has dedicated HEU-fueled isotope-production reactors. Two high-powered isotope-production reactors at the Mayak Chemical Combine in the Urals are reportedly fueled with weapons-grade uranium. During the Cold War, they consumed an estimated 800 kilograms of HEU per year, mostly for the production of tritium for weapons.[28] Today, given Russia's smaller number of operational nuclear warheads, the primary use of these reactors is probably to produce radionuclides for medical and other civilian purposes. They might therefore be appropriate targets for a cooperative conversion effort.

Conclusion and Recommendations

The recently launched GTRI hopes to achieve complete elimination of HEU-fuel shipments to research reactors outside Russia by 2014. Few of the critical assemblies and pulsed reactors that collectively contain huge quantities of barely irradiated HEU have been targeted yet, however, and Russia has not yet agreed to convert or decommission its own HEU-fueled reactors.

What is needed is a broader international effort to decommission HEU-fueled

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research reactors that are no longer needed, accelerate the conversion of operating research reactors for which replacement LEU fuel is available, and assure that fuels are developed as soon as possible to convert the remaining HEU-fueled research reactors that are still needed.

The key countries whose cooperation is required are those that have built and exported or that operate large, high-powered, HEU-fueled research reactors, large critical assemblies, or pulsed reactors. China, France, Germany, Japan, Russia, the United Kingdom, and the United States account for more than 90 percent of the global civilian HEU inventories and demand. Their joint engagement in an accelerated conversion and cleanout effort would likely bring along the other countries that receive or have received fuel from the major HEU suppliers.

The reluctance of Russia's government to give this effort high priority domestically at the same time that the leading Russian nuclear institutes have been asking for U.S. funding for projects to convert or decommission their HEU-fueled reactors illustrates the importance of working directly with the institutes as well as on a government-to-government level. This bottom-up approach, in which U.S. programs engage the Russian institutes directly and the institutes help get their government's approval, has been key to virtually all successful U.S.-Russian cooperative nuclear security initiatives.

More serious engagement by high-level U.S. officials is also required. The recent acceptance by the White House of a limitation to U.S.-Russian cooperative efforts on HEU cleanout to "third countries" illustrates the types of misstep that can occur when high-level officials are not adequately informed.

Finally, consideration needs to be given to ways to make it more attractive to decommission or shut down little-used HEU-fueled reactors. In particular, consideration should be given to facilitating the concentration of research-reactor or accelerator neutron services in regional centers of excellence open to all appropriate scientists.

If the international community takes its responsibility to prevent nuclear terrorism and to support nonproliferation efforts seriously, a global cleanout of civilian HEU could be achieved within the next five to eight years. **ACT**

ENDNOTES

1. See A. Glaser, "About the Enrichment Limit for Research Reactor Conversion: Why 20%?" International Meeting on Reduced Enrichment for Research and Test Reactors (hereinafter referred to as RERTR conference), Boston, November 2005.

2. See David Albright et al., *Plutonium and Highly Enriched Uranium 1996* (Oxford: Oxford University Press, 1997).

3. See Laura Holgate, "Accelerating the Blend-Down of Russian Highly Enriched Uranium," Nuclear Threat Initiative, June 2005.

4. See Wade Boese, "U.S. Trims Nuclear Material Stockpile," *Arms Control Today*, December 2005, p. 29.

5. Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *Nonproliferation Review*, Spring 2001, p. 86.

6. David Albright and Kimberly Kramer, "Civil HEU Watch: Tracking Inventories of Civil Highly Enriched Uranium," Institute for Science and International Security, August 2005. The estimate of 165-184 tons includes 123 metric tons of excess U.S. weapons HEU and 10 tons of BN-350 spent fuel in Kazakhstan not included in our estimate. Also, we believe that their range of 15-30 tons for civilian HEU in Russia may be low.

7. U.S. Government Accountability Office, "Nuclear Nonproliferation: DOE Needs to Take Action to Further Reduce the Use of Weapons-Usable Uranium in Civilian Research Reactors," GAO-04-807, July 2004, p. 28.

8. Pablo Adelfang and Iain Ritchie, "Overview of the Status of Research Reactors Worldwide," RERTR conference, Chicago, October 2003.

9. International Atomic Energy Agency (IAEA), "Safety of Research Reactors," Topical Issues Paper No. 4, p. 10.

10. Office of Nonproliferation, National Nuclear Security Administration (NNSA), "RERTR Program Project Execution Plan," February 16, 2004.

11. NNSA, "NNSA Completes Czech Research Reactor Conversion," November 4, 2005.

12. Andrew Bieniawski, Statement, RERTR conference, Boston, November 2005.

13. NNSA, "RERTR Program Project Execution Plan."

14. Pure uranium metal is not suitable as a reactor fuel because it swells seriously under irradiation at only a fraction of the desired fuel life.

15. The enrichment of a high-burn-up fuel that was originally 93 percent would still be above 75 percent. The critical mass of the 75 percent HEU would be only about 30 percent higher than that of the original material.

16. The IAEA considers a spent fuel element self-protecting if the dose rate one meter away exceeds one Sievert (100 rems) per hour. Five Sieverts over a period of less than two weeks is a median lethal dose for an adult. See IAEA, "The Physical Protection of Nuclear Material and Nuclear Facilities," INFCIRC/225/Rev. 4, June 1999.

17. Michael Dunsmuir, interview with author, September 2005. About 13.7 tons (80 percent) of the 17.5 tons of HEU reported as still abroad in 1993 was in the European Union (EU), within which much of the material was traded between facilities and some reprocessed. U.S. officials believe that 2 tons of 35 percent-enriched HEU exported to the EU was blended down there to LEU. See Albright, *Plutonium and Highly Enriched Uranium 1996*, pp. 245-253.

18. Andrew Bieniawski, Presentation, RERTR conference, Boston, November 2005.

19. Tom Wander, interview with author, November 2005.

20. IAEA, "Remarks Prepared for Energy Secretary Spencer Abraham," Vienna, May 2004.

21. Office of the Press Secretary, The White House, "U.S.-Russia Joint Fact Sheet: Bratislava Initiatives," February 2005.

22. Table B8 of the RERTR Program Project Execution Plan includes 21 reactors identified as critical assemblies and 10 identified as "fast burst," "prompt burst," or pulsed.

23. In the case of critical assemblies, this is because they release fission heat at an extremely low rate, typically only about 100 watts instead of millions. Pulsed reactor fuel accumulates only trace quantities of fission products for a different reason: they operate at high powers but mostly in infrequent pulses for less than one-thousandth of a second.

24. "Remarks Prepared for Energy Secretary Spencer Abraham for the Security Police Officer Training Competition," May 7, 2004.

25. The core of Russian's BN-600, which is HEU fueled, has a peak enrichment of 26 percent. See O. M. Saraev, "Operating Experience With the Beloyarsk Fast Reactor BN600 NPP," Technical Committee Meeting on Unusual Occurrences During LMFR Operation, IAEA, Vienna, November 1998, p. 103. Thirty-six percent-enriched fuel therefore should be more than sufficient. See also Frank von Hippel, "Future Needs for HEU-Fueled Critical Assemblies," RERTR conference, Boston, November 2005.

26. The MCC program pays the Elektrostal Fuel Fabrication Facility and the Dimitrovgrad Scientific Research Institute of Atomic Reactors to acquire and blend civilian HEU down to 20 percent LEU and dispose of the LEU. Part of the payment is passed on to the organization that is releasing the excess HEU. This incentive payment could be used to defray much of the cost of the core conversion, and some of the blended-down material could be used to fuel the converted core.

27. Oleg Bukharin, interview with author, September 2005.

28. "Lyudmila" and "Ruslan" are reportedly light-water reactors, each with a 1000 thermal-megawatt capacity. Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security*, Vol. 6 (1996), p. 59.