THWARTING NUCLEAR TERRORISM

Many civilian research reactors contain highly enriched uranium that terrorists could use to build nuclear bombs

BY ALEXANDER GLASER AND FRANK N. VON HIPPEL

The atomic bomb that incinerated the Japanese city of Hiroshima at the close of World War II contained about 60 kilograms of chain-reacting uranium. When the American "Little Boy" device detonated over the doomed port, one part of the bomb's charge—a subcritical mass—was fired into the other by a relatively simple gunlike mechanism, causing the uranium 235 in the combined mass to go supercritical and explode with the force of 15 kilotons of TNT. The weapon that devastated Nagasaki a few days later used plutonium rather than uranium in its explosive charge and required much more complex technology to set it off.

Despite the production of more than 100,000 nuclear weapons by a few nations and some close calls during the succeeding 60 years, no similar nuclear destruction has occurred so far. Today, however, an additional fearful threat has arisen: that a subnational terrorist organization such as al Qaeda might acquire highly enriched uranium (HEU), build a crude gun-type detonating device and use the resulting nuclear weapon against a city. HEU is uranium in which uranium 235, the isotope capable of sustaining a nuclear chain reaction, has been concentrated to levels of 20 percent or more by weight.

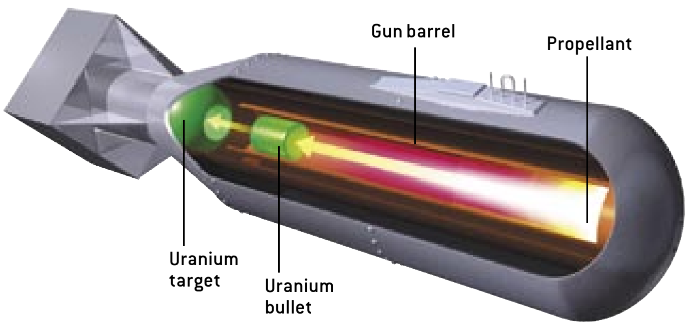
The engineering required to build a gun-type atomic bomb is so basic that the physicists who designed "Little Boy" did not perform a nuclear test of the design before deployment—they had no doubt that if the "gun" fired, the weapon would explode. Experts agree, therefore, that a well-funded terrorist group could produce a workable gun-type mechanism. Indeed, some have raised credible concerns that suicidal malefactors could penetrate an HEU storage facility, construct a so-called impro-

CERULEAN BLUE GLOW of Cherenkov radiation in the cooling water bath of a nuclear research reactor indicates that the system is fueled and operating. In many cases, the security measures that civilian facilities apply to protect highly enriched uranium fuel are lax, opening the possibility that the material could be stolen or otherwise acquired by terrorist groups.

ROGER RESSMEYER *Corbis*

BLUEPRINT FOR A BOMB

If terrorists obtained 60 kilograms of highly enriched uranium, they could make a nuclear explosive similar to the "Little Boy" atomic bomb that leveled Hiroshima in Japan at the end of World War II (*below*). Builders would shape a subcritical mass of the uranium into a "bullet" and place it just in front of a quantity of propellant at the far end of a closed cylinder. The remainder of the uranium (also a subcritical mass) would go at the other end of the "gun" barrel. Detonation of the propellant would send the bullet down the barrel, slamming it into the second uranium mass. The combined masses would then go supercritical and set off an explosive nuclear chain reaction.



vised nuclear device and detonate it before security guards could respond.

Although the production of HEU is beyond the means of nonstate actors, its procurement through theft or black market purchase is not: the globe is awash in around 1,800 tons of the material created during the cold war mostly by the U.S. and the Soviet Union. HEU today can be found at both civilian and military sites. We will, however, focus on that at civilian facilities in, or intended for use as, fuel for research nuclear reactors. We fret especially about civilian HEU because it is less securely guarded than military stores. (Uranium fuel for generating electricity at nuclear power plants is typically only slightly enriched—to 3 to 5 percent uranium 235 by weight.)

More than 50 tons of HEU are in civilian use, dispersed around the globe to support about 140 reactors employed to conduct scientific or industrial research or to produce radioactive isotopes for medical purposes. These sites are often located in urban areas and are minimally protected by security systems and guards. Especially worrisome is Russia's HEU-fueled reactor fleet, which constitutes about one third of the world's total and has associated with it more than half of all the civilian HEU that exists.

Improving security is essential [*see box on page* 62]. But in the long run, the most effective solution to the danger posed by nuclear terrorism is to eliminate wherever possible the use of HEU and remove accumulated stocks. The recovered HEU then should be diluted with uranium 238, the much more common uranium isotope that cannot sustain a chain reaction, to produce what specialists call low-enriched uranium (LEU)—material containing less than 20 percent uranium 235—which is not usable in weapons.

That the world has HEU at so many civilian sites stems mainly from the competitive efforts of the U.S. and the Soviet Union during the "Atoms for Peace" period of the 1950s and 1960s. As the two cold war superpowers constructed hundreds of research reactors for themselves, they simultaneously supplied such facilities to about 50 other nations to gain political favor and to establish their respective reactor technologies abroad. Later, in response to demands for longer-lived nuclear fuel, export restrictions were relaxed, which resulted in most research reactors being fueled with the bomb-grade HEU that the rivals were producing in huge quantities for nuclear weapons. This very highly concentrated material is approximately 90 percent uranium 235. As of the end of 2005, some 10 metric tons of exported bomb-grade HEU still resided in countries that do not possess nuclear weapons—enough to make 150 to 200 gun-type explosive devices.

Overview/*Securing Civilian Uranium 235*

- Terrorists who acquired less than 100 kilograms of highly enriched uranium (HEU) could build and detonate a rudimentary but effective atomic bomb relatively easily. HEU is also attractive for states that seek to develop nuclear weapons secretly, without having to test them.
- Unfortunately, large quantities of HEU are stored in nuclear research facilities worldwide—especially in Russia, often under minimal security.
- The U.S. and its allies have established programs to bolster security measures, convert reactors to use low-enriched uranium (which is useless for weapons) and retrieve HEU from research-reactor sites around the world. Dangerous gaps remain, however.
- High-level governmental attention plus a comparatively small additional monetary investment could go a long way toward solving the problem for good.

Convert Reactors

THE U.S. GOVERNMENT first began taking steps in the 1970s to prevent diversion to nuclear weapons of the research-reactor fuel it had exported during the previous two decades. Notably, in 1978 the Department of Energy launched the Reduced Enrichment for Research and Test Reactors (RERTR) program to convert American-designed reactors so that they could run on LEU-based fuel. By the end of 2005, the effort had retrofitted 41 units. Together these

SLIM FILMS

converted facilities had received shipments of approximately 250 kilograms of fresh bomb-grade HEU from the U.S. each year.

The replacement of the HEU fuel used in 42 additional reactors is now under way or planned. Unfortunately, it will not be possible to convert to LEU fuel about 10 high-powered research reactors until new LEU fuel types with the necessary performance can be developed. These high-powered reactors, which today burn about 400 kilograms of HEU fuel every year, typically feature compact cores designed to maximize the flow of neutrons for neutron-scattering experiments or materials tests requiring high irradiation levels. Current LEU-based fuel does not perform adequately within compact reactor cores that were originally designed for HEU.

To minimize the impact of the conversion on the high-power reactor designs, researchers in the RERTR program need to make LEU fuel with the same geometry and fuel life as the HEU fuel it is to replace. The job is a major engineering challenge, however. Because about four uranium 238 atoms accompany every uranium 235 atom in the LEU, fuel-element designers need to increase the amount of uranium in the LEU-based fuel elements by about five times without increasing their dimensions. After years of work, the small program to develop LEU fuel appears to be close to mastering fabrication techniques for a promising new generation of high-density fuels.

Retrieve Weaponizable Fuel

IN THE 1990S the U.S. began to cooperate with Russia on securing and eliminating HEU stocks. This effort was spurred by thefts of fresh, unburned HEU fuel in Russia and other countries of the former Soviet Union. The robberies were usually reported by the authorities only after the material was recovered. No one outside Russia—and perhaps no one inside—knows how much may have been stolen.

To limit the amount of civilian HEU in Russia accessible for unauthorized removal, the U.S. established in 1999 a Material Consolidation and Conversion Program to acquire and blend down initially about 17 tons of surplus Russian civilian HEU. By the end of 2005 about seven tons had been diluted to 20 percent uranium 235 levels.

Another effort focuses on "spent" HEU reactor fuel. Even though about half the uranium 235 has been consumed by the nuclear fission chain reaction inside reactor cores by the time the used fuel is removed, uranium 235 still makes up about 80 percent of the remaining uranium, the same concentration as the atomic charge in the Hiroshima bomb.

For several years after spent fuel is extracted from a reactor, it is "self-protecting" from theft—that is, it is so radioactive that it would surely kill within a matter of hours anyone who tried to handle it. Nuclear workers manipulate

What Nuclear Terrorists Would Need

To make nuclear weapons, terrorists would first have to buy or steal a supply of highly enriched uranium. In nature, uranium consists mainly of the uranium 238 isotope, which does not sustain a fission chain reaction when it absorbs a neutron, and a very low concentration (about 0.7 percent) of the chain-reacting isotope uranium 235. The two isotopes differ in weight by about 1 percent. Engineers can exploit this fact to separate them and concentrate, or enrich, the uranium 235. Terrorists cannot perform these operations themselves, however, because all known techniques are too difficult, time-consuming and costly.

In a mass of HEU that is just barely critical, on average one of the two to three neutrons released by the fission of a uranium 235 nucleus will go on to cause another nucleus to fission. Most of the rest of the neutrons escape through the surface of the mass, so no explosion results. To make a gun-type bomb feasible, builders need about two critical masses of highly enriched uranium so that one fission would on average cause more than one fission, thus generating an exponentially growing explosive chain reaction such as the one that released the energy of the Hiroshima bomb in a millionth of a second.

Less than one critical mass is sufficient to produce a Nagasaki-type implosion weapon. In that design the mass of plutonium was driven to supercriticality by compressing it with specially shaped external explosive charges. This implosion reduced the spaces between the nuclei through which the neutrons could escape from the mass without causing fissions.

EASY-TO-HANDLE DISKS, each containing a small amount of weapons-grade uranium, are used in one Russian critical facility in the tens of thousands. Many such disks would be required to produce an atomic bomb, but their pocketability makes guarding them against pilferage a security nightmare.

Weapons-grade uranium contains 90 percent or more of chain-reacting, or fissile, uranium 235, but experts have advised the International Atomic Energy Agency that all highly enriched uranium (HEU)—any uranium with a uranium 235 fraction above 20 percent—must be considered "direct-use material"—that is, usable in nuclear weapons. Below 20 percent, the critical mass becomes too large to fit in a reasonably sized device. For example, to produce a critical mass using 93-percent-enriched uranium surrounded by a five-centimeter-thick beryllium neutron reflector requires about 22 kilograms, whereas it takes about 400 kilograms using 20-percent-enriched uranium. *—A.G. and F.N.v.H.*

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such material only by remote means while protected by heavy shielding. The intensity of the radiation danger lessens with time, however. After about 25 years, it would take about five hours for an unshielded person working a meter from a typical five-kilogram research-reactor fuel element to collect a radiation dose that would be lethal to about half of exposed individuals. At this level, say experts advising the International Atomic Energy Agency (IAEA), the fuel can no longer be considered self-protecting.

Growing Urgency

TO COPE WITH the danger of spent HEU fuel around the world that is becoming less and less self-protecting, in 1996 the U.S. government invited foreign countries that had received American HEU fuel to ship back two common types of spent fuel. Six years later the U.S. joined with Russia and the IAEA in an effort to return fresh and spent HEU fuel to Russia. Progress has thus far been modest, though. Spent fuel that originally contained about one ton of American HEU has been repatriated so far—leaving about 10 tons still overseas. One tenth of a ton of fresh HEU fuel has been sent back to Russia, leaving an estimated two tons of HEU in fresh and spent fuel of Russian origin stored in other countries. The spent research-reactor fuel that has been shipped back to the U.S. is currently being stored at the DOE facilities in South Carolina and Idaho. Russia separates out the HEU in its spent fuel and then blends it down to make fresh low-enriched fuel for nuclear power plants.

After the events of September 11, 2001, some nongovernmental organizations and members of the U.S. Congress intensified their pressure on the DOE to step up its attempts to secure civilian HEU stocks worldwide. Former Los Alamos National Laboratory weapons designer Theodore B. Taylor had warned about the danger of nuclear terrorism as early as the 1970s, but the September 11 tragedy greatly enhanced the credibility of his call for action, and demands for a "global cleanout" of nonmilitary HEU grew. In response, the DOE established a Global Threat Reduction Initiative to expand and accelerate some of the programs described above. Current targets aim to repatriate all unirradiated and spent HEU fuel of Russian origin by the end of 2006 and 2010, respectively, and all spent HEU fuel of U.S. origin by 2019. The plan also envisions that all U.S. civilian research reactors will be converted to LEU fuel by 2014.

Some elements of the HEU clean-out effort thus grew more active, but even a funding increase of more than 25 percent in fiscal year 2005 over the previous year (to about $70 million) left the program diminutive compared with multibillion-dollar programs established to deploy a missile defense system and enhance homeland security capabilities. Perversely, the low cost of the crucial HEU elimination project may partly explain why it has had no high-level advocate in any presidential administration and only a few committed supporters in Congress. Officials such as the secretary of energy and the chairs of key congressional appropriations subcommittees spend most of their time battling over big-budget programs.

In Russia, the situation is even worse. The government there appears relatively unconcerned about the danger that terrorists could acquire nuclear-explosive material. It has yet to commit to converting its research reactors to LEU fuel. Unfortunately, President George W. Bush recently backed off from pressing Russia to act. At a February 2005 summit meeting, he and Russian leader Vladimir Putin agreed to limit U.S.-Russian cooperative HEU clean-out efforts to "third countries." Putin's administration has grown increasingly resistant to programs mandating visits by foreigners to Russian nuclear facilities, particularly if those initiatives do not bring large sums of money into Russia.

The HEU clean-out projects that are still active in Russia are therefore em-

THE AUTHORS

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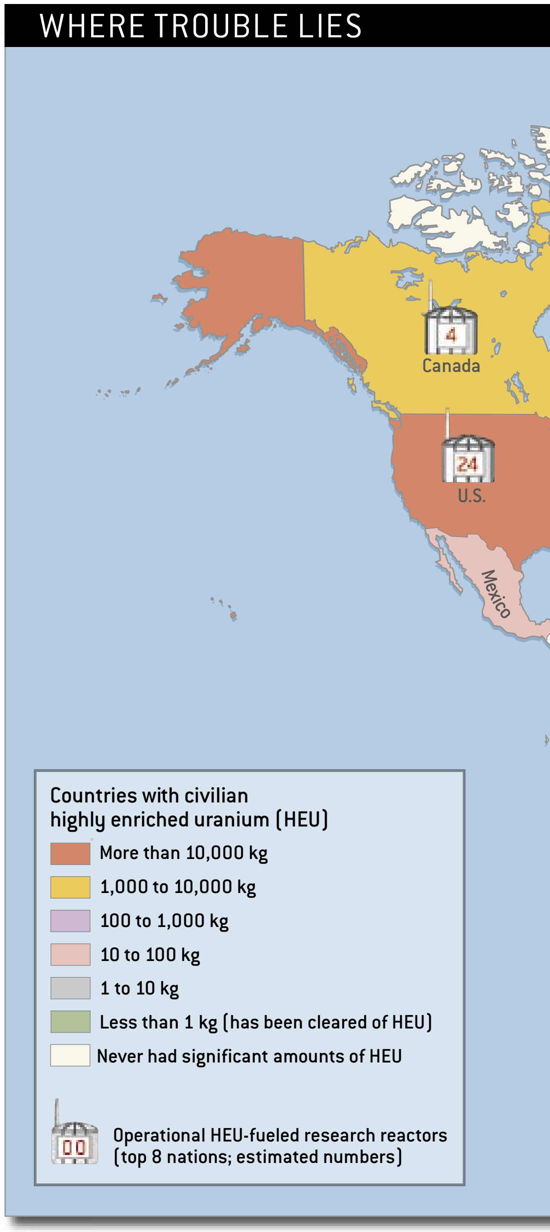

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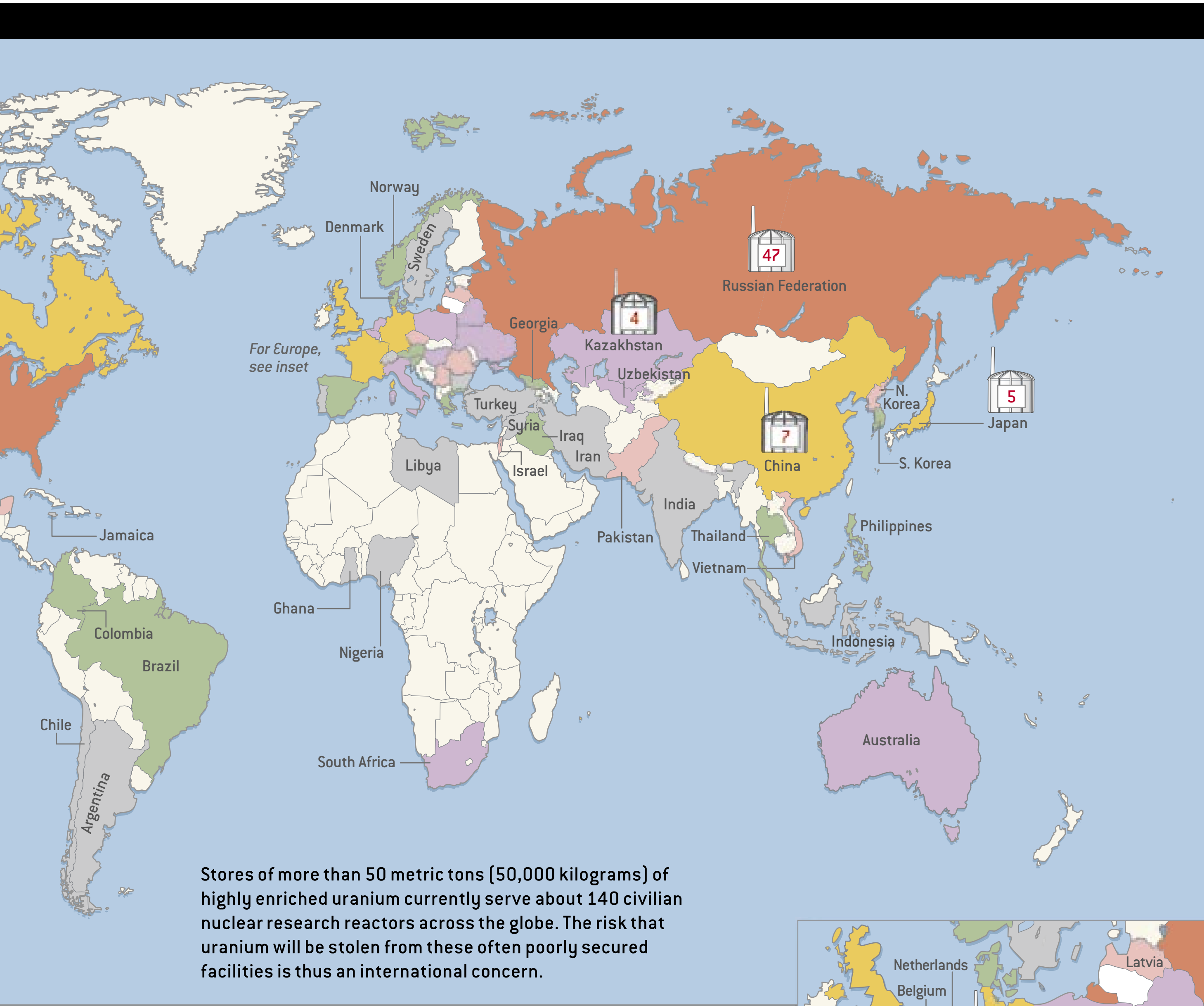

Stores of more than 50 metric tons (50,000 kilograms) of highly enriched uranium currently serve about 140 civilian nuclear research reactors across the globe. The risk that uranium will be stolen from these often poorly secured facilities is thus an international concern.

ploying a "bottom-up" approach. Their representatives negotiate on a local level directly with Russian nuclear institutes one by one, leaving the institutes to obtain permission from their government. Thankfully, a million-dollar effort that seems inconsequential to the Russian government can still be very welcome to a cash-strapped nuclear institute, so several of these projects are ongoing.

Neglected HEU Sources

CURRENT EFFORTS at HEU fuel conversion and recovery address primarily HEU-powered research reactors that require refueling. They largely ignore critical assemblies and pulsed reactors, two other classes of research reactors with cores that collectively contain huge quantities of the dangerous material.

A critical assembly is a physical mockup of a new reactor core that tests whether a core design will indeed sustain a fission chain reaction, or go critical, as the engineers intended. Because these assemblies are typically limited to generating only about 100 watts of heat, they do not require cooling systems, and engineers can construct them simply by stacking up fuel and other materials.

One of us (von Hippel) first encountered such an assembly in 1994, when, as a White House official, he toured the Kurchatov Institute, an atomic energy research center in Moscow, with American nuclear materials security and accounting experts. There, in an unguard-

Halting the Theft of Nuclear Materials

By Leslie G. Fishbone

While working to eliminate highly enriched uranium (HEU) stores to thwart the building of nuclear weapons by terrorist groups, countries need to better secure the civilian research reactors that use this fuel. One approach being carried out by a collaboration of U.S. and Russian experts on Russian sites exemplifies the kinds of steps that can be taken and the problems such programs encounter.

The need for enhanced security became clear in 1992, when an engineer at a nuclear facility near Moscow stole about 1.5 kilograms of highly enriched uranium (HEU) in many small bits over several months. He hoped to sell it for profit. Fortunately, the culprit was apprehended before the uranium could be transferred to a rogue state or terrorists. The theft could have been much worse, of course. Only about 25 kilograms of uranium is required to construct some types of nuclear-explosive devices, according to estimates by the International Atomic Energy Agency.

Far from being an anomaly, the pilfering incident reflected a much wider state of insecurity. The collapse of the Soviet Union in 1991 left its nuclear complex susceptible to threats from both insiders and outsiders. Scientists, engineers and guards went unpaid for months at a time, and the system's management structure deteriorated, leading to great concern about the potential for thefts of nuclear material. The leaders of Russia, the U.S. and other countries understood the risks that unprotected materials posed and established cooperative programs to mitigate those risks.

The Material Protection Control and Accounting (MPC&A) Program, established in 1993, is one such effort. As part of the program, the U.S. Department of Energy's national laboratories work with Russian Federation nuclear organizations. Sites undergoing upgrades include civilian research laboratories, nuclear reactor fuel-cycle plants, research and production facilities for military nuclear materials, and nuclear weapons storage complexes. U.S. personnel advise and facilitate the work of Russian experts, but Russians implement the upgrades, which may encompass construction of facilities, acquisition of equipment and modification of procedures. Americans and Russians also collaborate to improve nuclear materials regulations, standards, training and accounting practices.

In some instances, rapid partial fixes are implemented until more comprehensive changes can be instituted. For example, operators might initially replace a door with a reinforced entryway featuring a sophisticated lock. Later they could install a closed-circuit television system for surveillance and threat assessment. For materials control, managers might immediately introduce a rule that all work with nuclear material must involve two people operating in tandem. Afterward technicians could put in an automated access-control system that requires special identification cards, passwords and biometric verification. For materials accounting, a quick upgrade might include scheduling regular manual inventories of nuclear materials containers that are confirmed by tamper-indicating seals. A more comprehensive measure would be the introduction of computerized measurement stations that assay (via the gamma rays issuing from the containers) the enrichment levels of nuclear materials inside. The results would be automatically entered into a computerized database that would flag anomalies.

The dozen years of Russian-U.S. cooperation in this program have yielded considerable progress. Security upgrades have been completed at 41 of 51 identified nuclear materials sites in Russia and other countries of the former Soviet Union, including weapons complexes, civilian facilities (the focus of the main article), and naval fuel storage depots. Of the 10 that remain, upgrade operations continue at eight. There is no agreement to work at the other two locations, which are highly sensitive Russian facilities. Meanwhile upgrade efforts under the MPC&A program are ongoing at warhead storage and strategic rocket sites in the former Soviet Union.

Long-term sustainability is the main challenge for the future. During the next few years, U.S. support for the program is expected to shrink, leaving the Russians to shoulder the burden alone. Although the Russian government conducts its own independent MPC&A work, equipment and procedures at many sites would soon decline if the cooperative program were to end. Maintaining the MPC&A Program is crucial to our security. Quite simply, the consequences of a significant failure to safeguard HEU could be catastrophic.

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ed building, they were shown 70 kilograms of almost pure weapons-grade uranium disks stored in what looked like a high school locker. The uranium 235 was intended for a critical mockup of a space reactor. That visit led to the first U.S.-financed upgrade of the security of a Russian nuclear facility. More recently, the Kurchatov Institute and the DOE have begun discussions on a joint project that would "defuel" many of the institute's HEU-powered critical facilities.

Another such site is a critical facility at Russia's Institute of Physics and Power Engineering (IPPE) in Obninsk. This critical facility may possess the largest HEU inventory of any research-reactor site in the world: 8.7 tons, mostly in tens of thousands of thin aluminum- and stainless-steel-clad disks about two inches in diameter [*see box on page 59*]. Operators pile the disks in columns that are interleaved with other disks containing depleted uranium to simulate various average fuel-enrichment levels. Because these items emit only low levels of radiation, technicians can stack them by hand. Ensuring that no one walks out with any disks constitutes a security nightmare. We recently conducted an analysis that appears to have convinced the facility director that the laboratory does not need its weapons-grade uranium. Officials at the DOE are interested in establishing a joint project to dispose of this material.

The other underappreciated users of HEU fuel—pulsed reactors—typically

SECURITY MEASURES at many nuclear research reactor sites in the former Soviet Union do not do enough to protect highly enriched uranium from theft. American and Russian personnel are collaborating to beef up those crucial safeguards. Inspectors have found that the fencing, gates and other forms of perimeter security at some sensitive locations were often inadequate and even in an advanced state of disrepair (*top*). Since such facilities underwent security upgrades, barrier systems such as this "clear zone" around a building have presented much tougher obstacles to intruders (*bottom*).

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operate at very high power levels for periods of milliseconds or less. Weapons laboratories generally employ pulsed reactors to evaluate the responses of materials and instruments to intense but short bursts of neutrons, such as those generated by nuclear explosions. These systems pose a similar security problem to critical assemblies because their fuel, too, is only slightly radioactive. A pulsed reactor at the All-Russian Scientific Research Institute of Experimental Physics, Russia's first nuclear weapons design laboratory, located about 400 kilometers east of Moscow, contains 0.8 ton of HEU—enough for 15 Hiroshima bombs. After hearing a talk by one of us (von Hippel) about the dangers of HEU, researchers at the institute proposed to study the feasibility of converting the reactor to LEU.

Although more than 70 HEU-fueled critical assemblies and pulsed reactors exist worldwide—over half in Russia—only a few are needed for research today. Most were built in the 1960s and 1970s and are now technically obsolete. Much of their mission can be accomplished with desktop-computer simulations that calculate the progress of neutron chain reactions occurring in detailed three-dimensional reactor models. Engineers can usually confirm the validity of these mathematical simulations by checking them against the archived results of past criticality experiments. A few multipurpose HEU-fueled critical facilities may still be required to fill in gaps in previous trials, however. Engineers could convert to low-enriched fuel the few pulsed reactors that may still be needed.

More generally, one IAEA specialist has estimated that more than 85 percent of the world's aging research-reactor fleet could be decommissioned. He observed that the services they provide could be better satisfied by a small number of regional neutron sources using the latest technology. To be attractive to the researchers who use reactors, a decommissioning program could invest simultaneously in strengthening the capabilities of the remaining research-reactor centers. European nations and Japan could join with the U.S. in such an endeavor. In fact, the closings could provide a source of funding for the institutes owning reactors with large inventories of lightly irradiated HEU: these stores would bring in about $20 million per ton of HEU after it was blended down to the safe LEU used to fuel nuclear power plants.

Toward a Solution

THE EFFORT TO CONVERT HEU-fueled reactors has already dragged on for more than a quarter of a century. That the use of HEU continues has little to do with technical reasons. This failure has resulted largely from a dearth of sufficient high-level governmental support. Resistance on the part of reactor operators fearing relicensing or shutdown has also caused holdups.

Despite current concerns over nuclear terrorism, most segments of the HEU clean-out program are still proceeding much too slowly. Governments need to increase funding to accelerate the conversion of reactors for which substitute LEU fuel is available and to ensure that practical replacement fuel elements are developed with which to convert the remaining ones. Further, the program must be broadened to include all HEU-fueled critical assemblies, pulsed reactors and a few other civilian users of HEU fuel, such as Russia's nuclear-powered icebreakers.

If the U.S. and its allies were to take seriously the challenge of preventing nuclear terrorism, civilian HEU could be eliminated from the world in five to eight years. Continued delay in completing this task only extends the window of opportunity for would-be nuclear terrorists. SA

MORE TO EXPLORE

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