FISSILE MATERIAL SECURITY IN THE POST-COLD-WAR WORLD

The breakup of the Soviet Union has led to welcome progress in nuclear disarmament but also to a worrisome vulnerability of the vast nuclear stockpiles accumulated there. The US has been working with Russia to tighten controls on fissile material that could be used in nuclear weapons.

Frank von Hippel

During the cold war, the US and the Soviet Union each produced enough fissile material to make tens of thousands of nuclear weapons—between 100 and 200 metric tons of plutonium and about 1000 tonnes of highly enriched uranium (uranium enriched to more than 20% in U-235). This weapons-usable fissile material seemed invulnerable to theft until the collapse of the Soviet Union in 1991. Since then, subkilogram quantities of plutonium and multikilogram quantities of highly-enriched uranium have been intercepted in Russia, the Czech Republic and Germany—apparently stolen from Russian nuclear facilities and intended for sale. The old Soviet security system for fissile material, which focused on the surveillance and control of those in contact with such material, has been largely swept away. Gone too is the economic security of nuclear workers, who may now be tempted or threatened by predatory criminal groups. The situation poses a grave risk to global security, because the biggest obstacle facing non-nuclear-weapons states or even terrorist groups interested in acquiring nuclear weapons is lack of access to the bomb material.

During the last four years, the US along with Western Europe and Japan, has begun to help Moscow strengthen the security of its nuclear warheads and nuclear materials. Congress began four years ago with the Nunn–Lugar program. In the last year and a half the Clinton Administration has developed a relatively comprehensive set of additional initiatives. (I was involved in these initiatives while working last year in the White House Office of Science and Technology Policy; I discuss my experiences in OSTP in the Opinion piece on page 51.) Most of the initiatives are in an early stage of implementation, however, and political support for them is at risk in the wake of the Russian army's brutal suppression of the uprising in Chechnya and the Ministry of Atomic Energy's (MinAtom) nuclear-energy contract with Iran.

In addition to the nuclear weapons materials one must worry about the security of weapons-usable materials at many points in the fuel cycles of various types of reactors in the former Soviet Union. Figure 1 shows the locations of many sites where weapons-usable material has been produced or stored. As shown in figure 2, highly enriched uranium was produced not only for warheads but also to fuel reactors for plutonium and tritium production, naval propulsion, research and space uses. And over 30 tonnes of "reactor grade" but weapons-usable plutonium has been separated from spent fuel and stockpiled in Russia for future recycling in fuel for power reactors.

The package of initiatives undertaken to address the vulnerabilities of both weapons materials and weapons-usable civilian materials in the former Soviet Union includes efforts to:

▷ strengthen the security of the existing materials
▷ stop further production
▷ dispose of the excess
▷ increase the "transparency" of warhead and fissile material management.

Securing existing stockpiles

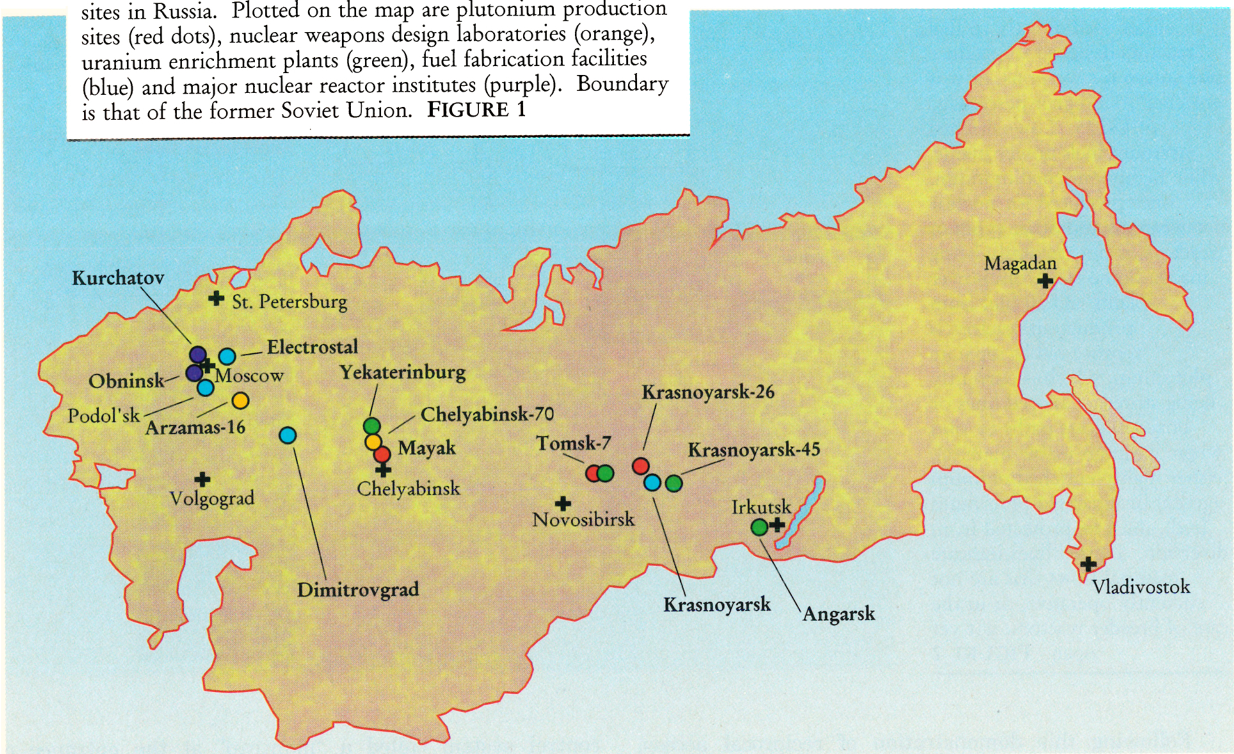
Amounts of easily portable weapons-usable fissile material ranging from significant to huge are held under varying levels of security in the facilities of approximately 100 organizations in the former Soviet Union—mostly in Russia. Consider two examples:

▷ At the Mayak spent-nuclear-fuel reprocessing combine, located in the Urals north of Chelyabinsk, plutonium has been recovered from the spent fuel of first-generation Soviet light-water power reactors (of the VVER-440 type) since 1978. One very ordinary building, built 40 years ago for storage of chemicals, today contains about 30 tonnes of plutonium in over 10 000 thermos-bottle sized containers. Security against penetration by outsiders appears relatively good, but little thought appears to have been given until recently to the possibility that insiders might carry material out of the storage building. Although the facility personnel are committed to their responsibilities to safeguard the plutonium, and the closed city has been somewhat protected from Mafia-type activities, a deputy director of Mayak was mysteriously murdered last October.

▷ Building 116 at the Kurchatov Institute of Atomic Energy in Moscow contains about 70 kilograms of weapons-grade uranium (uranium enriched to more than 90% in U-235) formed

FRANK VON HIPPEL, *a theoretical elementary-particle physicist by training, is a professor of public and international affairs at Princeton University. From September 1993 through December 1994 he served as assistant director for national security in the White House Office of Science and Technology Policy.*

MAJOR FISSILE MATERIALS PROCESSING and nuclear R&D sites in Russia. Plotted on the map are plutonium production sites (red dots), nuclear weapons design laboratories (orange), uranium enrichment plants (green), fuel fabrication facilities (blue) and major nuclear reactor institutes (purple). Boundary is that of the former Soviet Union. **FIGURE 1**



into flat annuli the size of large washers; these are stacked in tubes and used for zero-power criticality tests of a compact reactor designed for use in space. Yet the wall around the institute is falling down, and until recently there was no fence around building 116 and no sensors within it that could detect unauthorized entry or removal of the material. Also until recently, the only basis for an inventory of the quantity of weapons-usable fissile material at the institute was boxes of old paper receipts in a dusty room.

The former Soviet Union never developed an adequate *materials control* system because it had a pervasive central system regulating the movements of its citizens and monitoring suspicious activities. With that *people control* system now largely swept away (fortunately), the Russian government needs to compensate by introducing the systems of material protection, control and accounting that have been developed in the West.

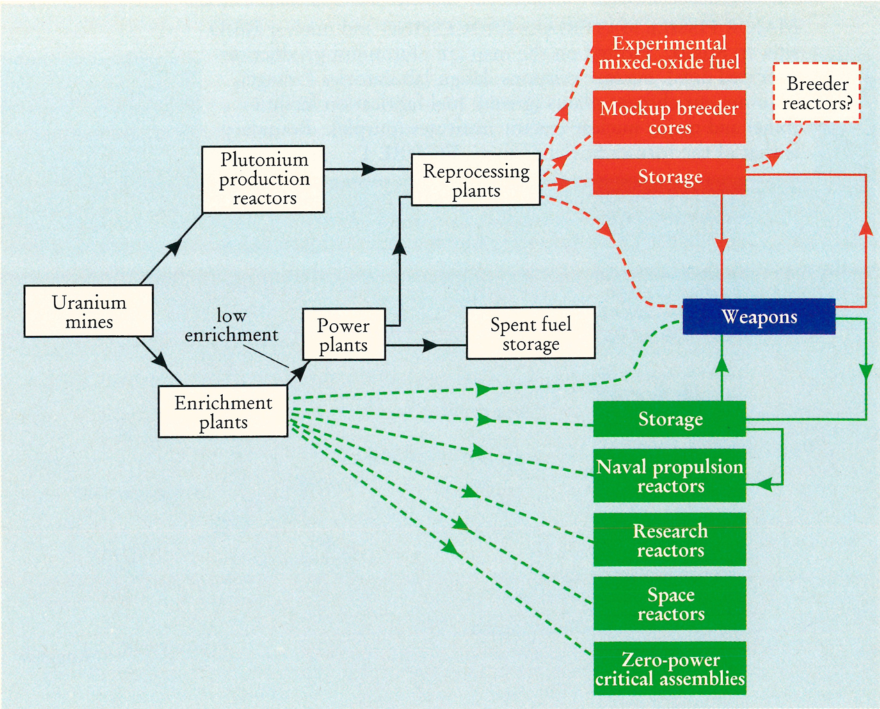
The US government has undertaken two types of initiatives to help do this: a "top down" government-to-government program and a "bottom up" lab-to-lab approach started by the Department of Energy.

Government-to-government program. This program was started within the Department of Defense with funding from the Nunn–Lugar program (named after Senators Sam Nunn and Richard Lugar). Congress launched the Nunn–Lugar program in October 1991 to assist the former Soviet Union in "the transportation, storage, safeguarding, and destruction of nuclear and other weapons [and] the prevention of weapons proliferation."

The Nunn–Lugar program has had some important successes in helping eliminate surplus missiles and missile silos in the former Soviet Union. However, it has had little direct impact in strengthening the security of Russian nuclear warheads and materials, because of two DOD policies that undercut its effectiveness: First, DOD insisted on audit and inspection rights at the sites where US assistance was being used. Russian hard-liners were thus able to protray the Nunn–Lugar program as a US effort to buy unilateral access to Russian secret facilities. Second, DOD insisted on using US, rather than Russian, goods and services, as encouraged by the bill authorizing the Nunn–Lugar program. This policy drastically diminished the motivation of the economically stressed nuclear sites to cooperate with the program; Russians cynically note that the money that a US contractor or consultant spends for a night in a Moscow hotel could support a Russian scientist for a month.

Because of Russian concerns about the intrusiveness of the Nunn–Lugar program, it took two years to reach an agreement on a demonstration safeguards system, and then only at a plant for fabricating low-enriched uranium fuel in Electrostal, 50 km east of Moscow. Even Electrostal's fabrication line for highly enriched uranium fuel was exempted from this model safeguards system because it was considered too "sensitive."

To defuse concerns about the potential intrusiveness of US assistance, the Clinton Administration decided in the spring of 1994 to offer Russia reciprocal access to US facilities. In July a Russian delegation inspected the physical security arrangements at a plutonium storage facility at DOE's Hanford site in the state of Washington. And in October 1994 a US team was allowed to visit the Mayak plutonium storage facility. Afterward DOE shipped demonstration equipment to Mayak to strengthen protection against insider diversion threats, including portal detectors sensitive to the neutron radiation from plutonium, two-person access controls requiring personal identification numbers, personnel identification equipment (hand-geometry and retinal scanners) and video cameras with motion-detection alarms to monitor the inside of the storage facility.



NUCLEAR FUEL CYCLES in Russia. Natural uranium is either used directly to fuel reactors designed to produce plutonium for weapons, or it is enriched to a higher percentage of U-235. Low-enriched uranium fuels power plants, while highly enriched uranium, once produced for nuclear weapons and other types of reactors, is not currently being made. Some fuel from power plants and all fuel from production reactors is reprocessed to separate plutonium, which is currently being stored. Colored lines or boxes indicate paths or sites where weapons-usable material, either highly enriched uranium (green) or separated plutonium (red), must be protected from diversion. Dotted lines indicate material flows that are not currently operative, or in the case of breeder reactors, not yet open. **FIGURE 2**

Following this demonstration of reciprocal access, MinAtom agreed to permit expansion of the government-to-government program into a number of other facilities handling large quantities of civilian but weapons-usable plutonium and uranium, including the fabrication lines for civilian highly enriched uranium fuel at Electrostal and Podolsk; the Obninsk Institute of Physics and Power Engineering, which designs plutonium breeder reactors; and the Nuclear Research Reactor Institute in Dimitrovgrad, which develops plutonium-containing fuels. In exchange the US government committed an additional $20 million to the program. This spring, however, after being admonished by Congress to drop its nonmilitary activities, DOD transferred to DOE responsibility for funding the government-to-government program.

Lab-to-lab Program. Last spring DOE also authorized materials security experts at its national laboratories to approach their Russian counterparts directly to propose joint work on materials security. This "lab-to-lab" program has taken off more quickly than the government-to-government approach, not surprisingly, because it empowers US and Russian technical experts to negotiate directly with each other and for the first time includes US payments for Russian time and equipment. The funding for the lab-to-lab program is ramping up quickly to a proposed level of $40 million in 1996. The rule of thumb has been to spend approximately equal amounts on US salaries, Russian salaries and equipment (Russian and US). For the same money the program can employ about 20 times as many Russians as Americans.

The lead labs on the Russian side initially have been the Kurchatov Institute, which has been independent of MinAtom since 1992, and MinAtom's counterpart to Los Alamos National Laboratory, the Institute of Experimental Physics in the closed city of Arzamas-16 (now Kremlev). Last December, Kurchatov became the first Russian site to demonstrate, in building 116, a comprehensive upgrade of physical security arrangements and materials control and accounting procedures Figure 3 shows an access control system called a "mantrap" at the entrance of building 116.

Arzamas-16 and Los Alamos had begun to collaborate a few years ago on experiments creating ultrahigh magnetic fields and even before the start of the lab-to-lab program had discussed the possibility of expanding their cooperation into the area of fissile materials control and accounting, in which both have relevant technical expertise.

Although MinAtom had insisted on a step-by-step approach to the government-to-government program, when the US proposed such a cautious approach in a draft workplan, Arzamas-16 responded last November with a much bolder plan, which includes in its first 18 months the installation of modern materials-security systems in some of the major Russian nuclear-materials processing and weapons-dismantlement facilities.

Both the government-to-government and lab-to-lab programs have focused principally on facilities under the control of MinAtom. But a large fraction of Russian fissile materials are in nuclear warheads and naval nuclear reactors controlled by the Russian Ministry of Defense. Additional facilities dealing with submarine nuclear reactors are operated by the Russian navy and the Committee of the Defense Industry, and research reactors are run by institutes such as Kurchatov that are not affiliated with either MinAtom or the Ministry of Defense. DOE is now attempting to launch new cooperative initiatives to address these facilities.

Stopping further production

Given the huge surplus of highly enriched uranium and separated plutonium, it would make sense to have a moratorium on further production. In fact, the rate of production of fissile materials *for weapons* is already low, and there is hope that it can be halted completely. In September 1993 the UN passed a consensus resolution supporting negotiations for a global ban on production of fissile materials for weapons. Negotiations are expected to begin in Geneva this month.

Russia has shut down most of its 13 military plutonium production reactors but continues to operate 3 because they produce by-product heat and electricity for the populations of the neighboring cities. Unlike the fuel of most civilian power reactors, the aluminum-clad uranium-metal fuel used in these reactors cannot be stored for long periods in water. It must therefore be reprocessed, with the separated plutonium adding to the existing surplus.

In December 1993 Vice President Gore broached with Russian Prime Minister Chernomyrdin the possibility of a joint Russian–US effort to shut down these reactors, and the following June the two countries signed an agreement under which Russia agreed to shut the reactors down by the year 2000 and to put under bilateral safeguards the plutonium recovered from the reactor fuel in the interim. In exchange the US offered to help provide alternative sources of heat and electricity. However, progress has been slow. The US government hopes that the alternative energy sources can be financed by Western investors or international banks, and MinAtom insists that the replacement energy sources be nuclear. The two sides have held joint workshops to consider the possibility that the plutonium production reactors could be shifted to a fuel that does not require reprocessing and hence would not add to the stores of separated plutonium. However, the reactors, which are graphite-moderated like those at Chernobyl—but of an earlier, less safe design—should be shut down for safety reasons as soon as possible in any case.

In addition to the plutonium from production reactors, MinAtom is continuing to reprocess spent light-water reactor fuel at Mayak, separating out reactor-grade but weapons-usable plutonium at a rate of 1–2 tonnes per year. (See the box on page 31 for a discussion about the usability of reactor-grade plutonium.) Given the huge stockpile of already separated civilian and excess weapons plutonium that must be dealt with, it would be safer to leave the unseparated civil plutonium securely stored in spent reactor fuel.

However, MinAtom's principal concern is to ensure the economic future of the cities it built. The ministry is therefore seeking prepaid foreign reprocessing contracts to finance the completion of a very large civilian reprocessing plant at Krasnoyarsk-26 to sustain employment there when the military reprocessing plant shuts down. Helping Russia's plutonium cities find new missions that don't involve the separation of plutonium should be a high priority for the outside world.

Disposing of the excess

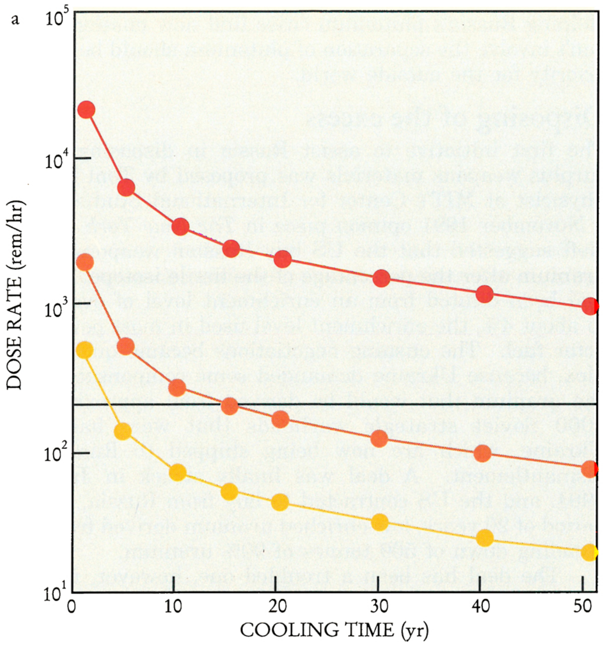
The first initiative to assist Russia in disposing of its surplus weapons materials was proposed by Tom Neff, a physicist at MIT's Center for International Studies. In a November 1991 opinion piece in *The New York Times*, Neff suggested that the US buy Russian weapons-grade uranium after the percentage of the fissile isotope, U-235, had been diluted from an enrichment level of over 90% to about 4%, the enrichment level used in most power-reactor fuel. The ensuing negotiations became quite complex, because Ukraine demanded some compensation for the uranium that would be derived from approximately 2000 Soviet strategic warheads that were based in Ukraine, which are now being shipped to Russia for dismantlement. A deal was finally struck in January 1994, and the US contracted to buy from Russia, over a period of 20 years, low-enriched uranium derived from the blending down of 500 tonnes of 90% uranium.

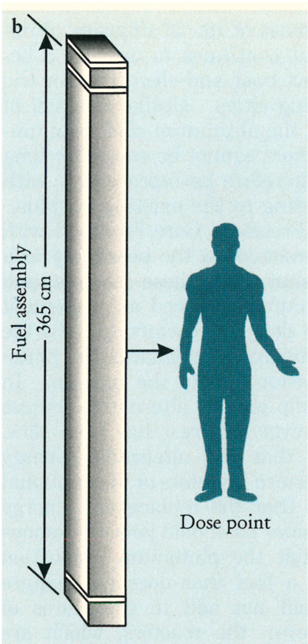
The deal has been a troubled one, however, in part because the management of the US Enrichment Corporation, the government-owned corporation that operates the US uranium enrichment plants and was given the exclusive rights to sell the Russian low-enriched uranium, does not like the price that the US government negotiated with MinAtom. The US has also had to design the deal around the restrictions resulting from a suit brought by the US uranium mining industry, which accused Russia of "dumping" uranium at low prices on the US market.

The disposal of plutonium is even more difficult. In the case of uranium, one can denature the fuel, that is, render it totally unusable for nuclear weapons, by mixing it with the common uranium isotope U-238, which does not chain react. One cannot do the same thing with plutonium, because no isotope is available in sufficient quantities to denature the plutonium. (See the box on page 31.) Furthermore, the plutonium is not attractive as a fuel for nuclear reactors, because just the cost of making plutonium into fuel would render it more expensive than the alternative fuel, low-enriched uranium.

In its 1994 report *Management and Disposition of*

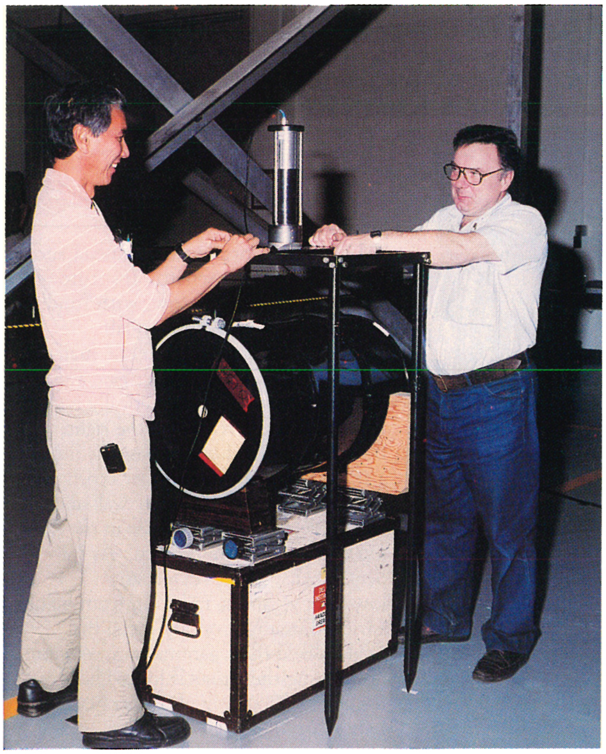
"MANTRAP" produced in Russia and installed at the Kurchatov Institute of Atomic Energy, Moscow, with funding from the US DOE's lab-to-lab cooperative program on fissile materials security. To open the outer gate a person must insert a magnetically coded ID card into the reader on the right. Before the individual can pass the inner gate, the personal ID number typed into the keypad on the left inner wall and the weight determined by a scale in the floor must agree with the ID card. As the person exits, sensors detect any low-energy gamma radiation from highly enriched uranium or any metal that might shield these gamma rays. Anyone not passing these tests is locked between the gates. (Courtesy of Sandia National Laboratory.) **FIGURE 3**





DETERRENTS TO THEFT OF SPENT FUEL. **a:** Dose rate from the spent fuel assembly of a pressurized-water nuclear reactor at distances of 1 meter (red), 5 meters (orange) and 10 meters (yellow) from the assembly, given as a function of time. The horizontal black line denotes the threshold for acquiring a lethal dose after a one-hour exposure. **b:** Height of a fuel assembly compared with the size of a person. (Adapted from W R. Lloyd, M. K. Sheaffer, W. G. Sutcliffe, preprint UCRL-ID-115199, Lawrence Livermore National Lab, 1994.) **FIGURE 4**

Excess Weapons Plutonium, the National Academy of Sciences recommended that the US and Russia move with all deliberate speed to make their excess weapons plutonium as inaccessible as the tenfold-greater quantities of plutonium that will have accumulated in unreprocessed spent power-reactor fuel by the year 2000. The intense gamma radiation field generated by the fission products in the spent fuel protects such plutonium against theft. So do the large size and mass of the spent fuel assembly containing plutonium. (See figure 4.) One spent fuel assembly contains about 5 kg plutonium: The same amount of plutonium is packed into just two of the thermos-bottle-sized containers of separated plutonium now stored at Mayak.



Building on previous analyses, the NAS report recommended as worthy of further investigation three options for the disposal of plutonium:

▷ subsidized use in the fuel of existing US light-water or Canadian heavy-water power reactors

▷ mixing with the concentrated fission-product waste from which US weapons plutonium was originally separated as that waste is converted into a low-leachability solid for deep-underground disposal

▷ emplacement in multikilometer deep boreholes.

The DOE is studying these options and soliciting public opinion on them; the agency hopes to have a recommendation in the fall of 1996.

In Russia, however, MinAtom's first choice is to save its excess separated plutonium to be used some time in the future as the startup fuel for a new generation of 800-megawatt (electric) plutonium breeder reactors—although the construction of the first three such reactors has been suspended since 1987 because of lack of funds. Too many sacrifices were involved in the production of the plutonium, MinAtom's leaders feel, to treat it as waste.

While awaiting a resolution to the problem of plutonium disposal, we must focus on assuring its secure interim storage. Fortunately DOD and MinAtom have finally begun to move forward on a collaborative project to build a secure storage facility near the Mayak combine for excess Russian weapons materials. The US has agreed to help build the facility, while Russia has pledged not to recycle the fissile material into new warheads and to let

RUSSIAN AND AMERICAN SCIENTISTS collaborate on an experiment designed by the Russians to determine the shape of a plutonium object in a cylindrical storage container. Ray Domingo (left) of Lawrence Livermore National Laboratory assists Vayacheslav Yanov of the Research Institute for Pulse Technology in Moscow in repositioning the Russian collimated gamma-ray detector (vertical tube) to a new location on the scanning jig. (Courtesy of Lawrence Livermore National Lab.) **FIGURE 5**

Can Reactor-Grade Plutonium be Used in Weapons?

There is an ongoing debate about the usability for nuclear weapons of the plutonium in spent fuel discharged by nuclear power plants. If this "reactor grade" plutonium were essentially unusable in weapons, as some argue, then one could separate it from the spent fuel without significantly aggravating the risk of nuclear weapons proliferation. Typically about one quarter of reactor grade plutonium is the isotope plutonium-240, compared with less than 6% in the "weapons grade" plutonium of reactors operated specifically to make material for bombs.

Advocates of plutonium recycling point out that Pu-240 is undesirable in a weapon because it generates through spontaneous fission about one million neutrons per second per kilogram. Thus the higher the percentage of Pu-240, the greater is the probability that a chain reaction will be initiated prematurely in an imploding mass of plutonium before it reaches supercriticality.[1] If the chain reaction begins as soon as the imploding mass reaches the critical density required to sustain a chain reaction, the explosive will produce its lowest, or "fizzle" yield.

Even if a nuclear weapon fizzled, however, it could wreak terrible damage. For example, in a declassified letter written on 23 July 1945 to advise the US Army on the optimal height of explosion for the Nagasaki bomb, Robert Oppenheimer stated that the fizzle yield would be "not much less than one thousand tons" of TNT. Although considerably below the realized yield of 20 000 tons, this fizzle yield would still have been 2000 times more powerful than the chemical explosives used in the terrorist bombing of the World Trade Center in 1993.

A second reason advanced by plutonium-recycle advocates for the unsuitability of reactor-grade plutonium for weapons purposes is that it contains up to 2% Pu-238, while weapons-grade plutonium contains only about 0.01%. Pu-238 has a relatively short halflife of 88 years and generates 560 watts of decay heat per kilogram. If the 6-kg plutonium core of the Nagasaki bomb had been made of reactor-grade plutonium containing 2% Pu-238, the decay of this and other isotopes would have generated about 85 watts of decay heat. Within the bomb's thick layer of high explosives, the core would have heated by about 250 °C, potentially destabilizing the explosives. This temperature rise, however, could be reduced by about two-thirds by a thermal bridge of aluminum with a cross section at the surface of the core of only about 3 cm^2.

The third argument made by plutonium-recycle advocates is based on the fact that the gamma and neutron doses from reactor-grade plutonium are higher than those from weapons plutonium by almost an order of magnitude. If the Nagasaki core had been made out of reactor-grade plutonium, the radiation dose 1 meter from the bare core would have been on the order of one rem per hour. This dose is a significant occupational hazard when compared with the maximum permissible dose for radiation workers of 5 rems per year. However, since the short-term lethal dose is at least a few hundred rem, it would not necessarily be a major deterrent to a determined terrorist group.

For these reasons, the International Atomic Energy Agency makes no distinction in its safeguards standards between different grades of plutonium—except for plutonium containing more than 80% Pu-238.

Reference

1. For a more detailed discussion of the pre-initiation issue see J. Carson Mark, Science & Global Security **4**, 111 (1993).

the US monitor its storage and disposition.

Verifying declared stockpiles

It would be easier for the US and Russia to collaborate on improving the security of fissile material if its management were more "transparent," that is, if each side declared its inventories of nuclear material and allowed the other to make spot checks of these declarations. Increased transparency would also make it possible to verify nuclear disarmament. To date, the verification of nuclear arms reductions has been limited to missiles, their launchers and bombers. It has not yet been extended to warheads and warhead components.

At their January 1994 summit Presidents Clinton and Yeltsin agreed to launch negotiations on "steps to ensure the transparency and irreversibility of the process of reduction of nuclear weapons." The initial focus has been on techniques that would be used to confirm, in reciprocal inspections, declarations of stocks of plutonium "pits" that each country had accumulated from dismantled warheads. In July 1994 a Russian delegation was invited to the shut-down pit-production facility at Rocky Flats, Colorado, to see the techniques the US proposed to use to verify from the outside that a container indeed contained a pit; in August a US team saw a similar demonstration at a counterpart facility in the closed city of Seversk (formerly Tomsk-7). Figure 5 shows a subsequent demonstration at Lawrence Livermore National Laboratory.

The two sides agreed on a procedure that involves measuring a small portion of the energy spectrum of the gamma rays from the containers to determine the isotopic makeup of the plutonium, then measuring the spontaneous neutron emission rate to deduce the pit's mass and finally using a collimated gamma counter to infer the rough size and shape. Because some of the data that would be revealed by such measurements is classified, actual implementation of the inspections awaits completion of an "Agreement of Cooperation" specifying how each country would protect the other's classified information.

Last September Clinton and Yeltsin also agreed to begin regular confidential bilateral exchanges of data on "aggregate stockpiles of nuclear warheads; on stockpiles of fissile materials and on their safety and security." Negotiations on such exchanges began this April. To assure the rest of the world that US and Russian nuclear warhead reductions are irreversible, the two presidents also agreed in January 1994 to consider putting under the safeguards of the International Atomic Energy Agency fissionable materials released in the process of nuclear disarmament. As of the end of 1994, the US had unilaterally placed under IAEA safeguards about 10 tonnes of highly enriched uranium and plutonium.

This March Clinton declared that an additional 200 tonnes of highly enriched uranium and plutonium would be withdrawn from weapons use, but much of the material is still in configurations whose shapes are classified and not yet ready to be submitted to international safeguards. Additional large quantities of excess weapons-grade uranium will probably be withheld from IAEA safeguards to assure its availability for future use in naval-reactor fuel.

Thus a rather comprehensive set of initiatives has been undertaken to secure the huge surpluses of weapons-usable fissile materials that are the legacies of the cold war and of the dream of an energy economy based on plutonium. The implementation of these critical initiatives has barely begun; to carry them through will require persistent high-level attention and adequate resources.

This article was written while the author was a visiting scientist at the Federation of American Scientists. ■