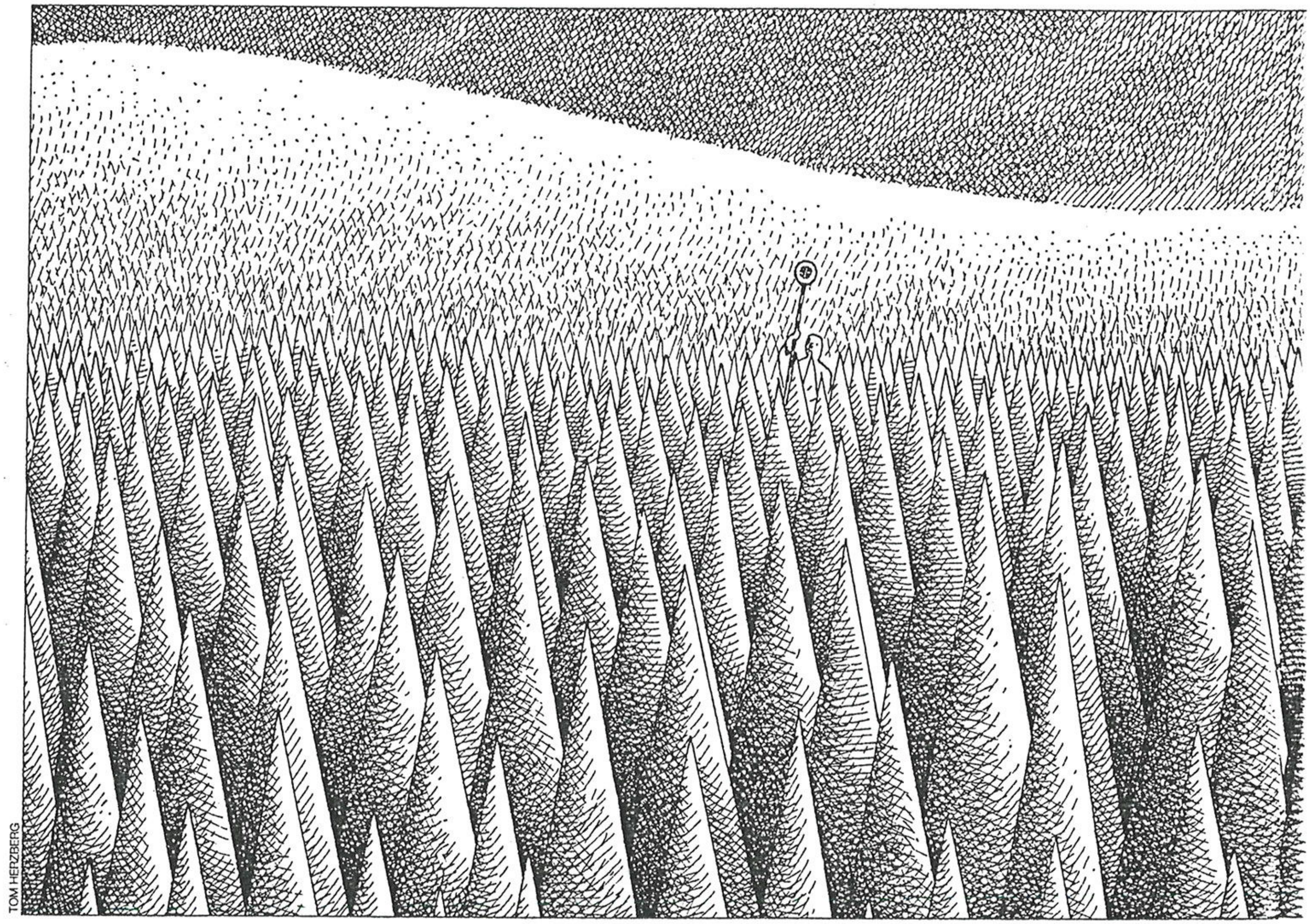
PLUTONIUM: TRUE SEPARATION ANXIETY

By FRANS BERKHOUT, ANATOLI DIAKOV, HAROLD FEIVESON, MARVIN MILLER, and FRANK VON HIPPEL

The first priority is keeping plutonium out of the hands of would-be bomb-makers. This presents some difficult technical—and political—problems.



Oscar Wilde observed that "In this world, there are only two tragedies. The first is not getting what one wants, and the other is getting it."

The world should collectively cheer the prospective dismantlement over the next decade or so of as many as 45,000 nuclear warheads in the arsenals of the United States and the Commonwealth of Independent States (CIS). But dismantlement also presents a staggering headache. What will become of the 100–200 tons of plutonium and 500–1,000 tons of highly enriched uranium (HEU) that will be recovered from these weapons?

For now, the United States reserves the option of refabricating this fissile material into new weapons. Because of that, there is no official U.S. interest in drafting an agreement on the bilateral verification of weapons dismantlement, or fissile materials storage. Nor has there been a response from either the United States or Russia to offers by Hans Blix, director general of the International Atomic Energy Agency (IAEA), to bring surplus weapons material under international safeguards. Thus, control over weapons materials remains with the national military establishments.

In the post–Cold War world, there simply is no weapons use for most of the fissile material that will become available as dismantlement proceeds. But if reductions in the nuclear arsenals are to be permanent, it is essential that the United States and Russia (which is also responsible for disposing of the warheads withdrawn from the other former Soviet republics) take steps to assure each other, and the rest of the world, that the fissile material recovered from excess warheads will not be reused in future weapons. Indeed, the question of what to do with the fissile materials from dismantled weapons has become one of the most urgent problems in arms control.

The disposal of HEU presents no intractable problems. It can be "denatured"—reduced to low-enriched uranium—and then burned in civilian power reactors.

But weapons plutonium presents a more difficult set of technical, economic, and political problems. Plutonium cannot be isotopically denatured

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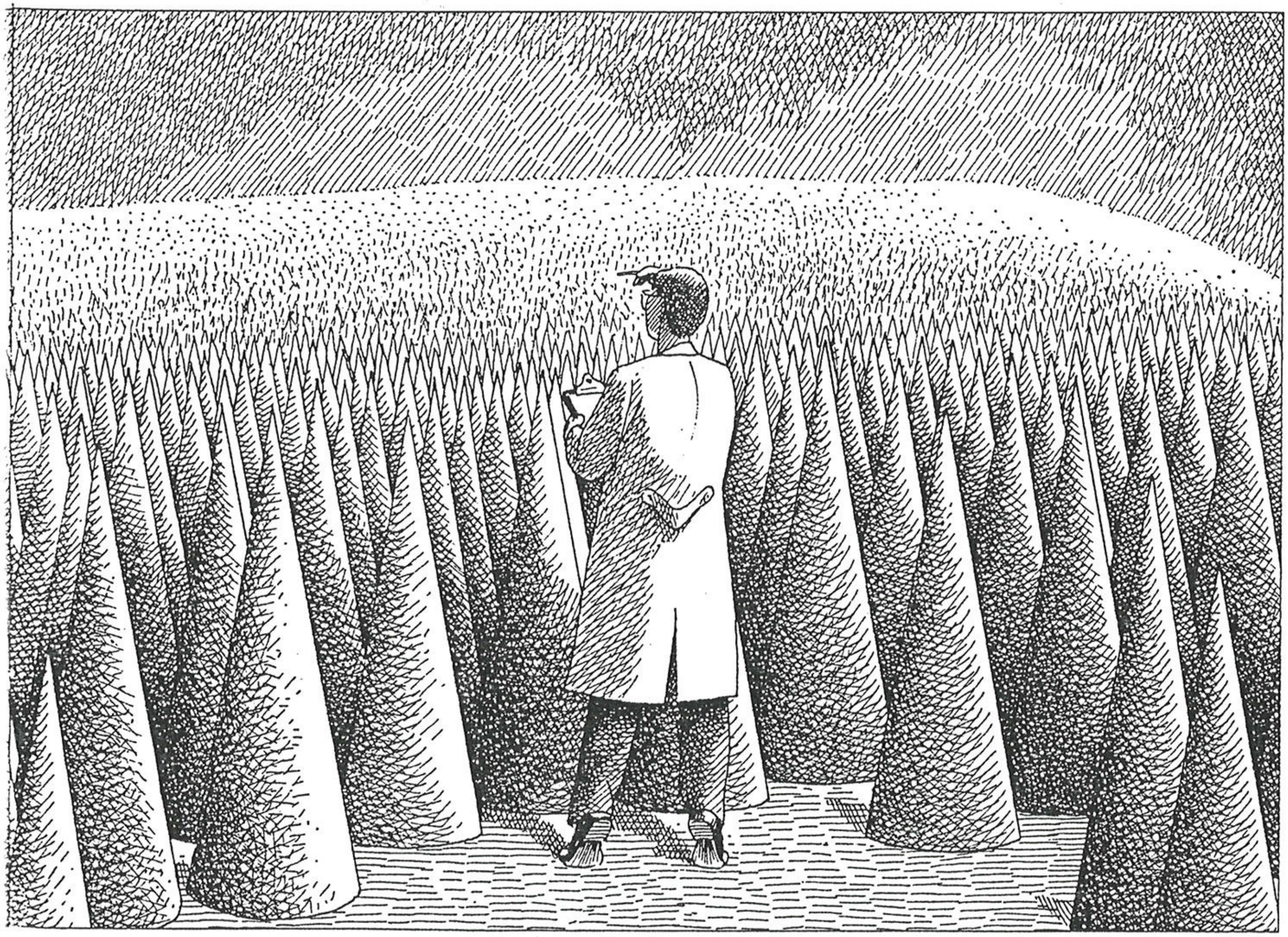


like highly enriched uranium. Consequently, proposals to fabricate CIS weapons plutonium into power-reactor fuel raise the same difficult security issues that have plagued all proposals to use plutonium in reactor fuel. "Plutonium-economy" advocates in Western Europe and in Japan are eager to use the problem of disposition of weapons plutonium as a way to legitimize the use of plutonium in fuel. However, poor economics and a worldwide shortage of capacity to fabricate plutonium-uranium fuel, added to the controversies over the dangers of diversion by terrorists, are causing utilities in those countries to reconsider their commitments to the reprocessing of spent fuel and to the recycling of the recovered plutonium.

The real-world risks and cost of fueling civilian reactors with fuel containing plutonium far outweigh the possible advantages. The first priority is not to figure out ways to make weapons-plutonium work in the civilian power cycle. Rather, the first priority must be to keep plutonium—weapons-grade and reactor-grade—out of the hands of would-be bomb-makers.

Warhead dismantlement

Given that the former Soviet Union and the United States began 1991 with about 35,000 and 20,000 warheads respectively, and are in the process of reducing to about 3,000 strategic and 2,000 tactical warheads each, they will have to dismantle a combined total of about 45,000 warheads over the next decade.

Assuming an average of three kilograms of plutonium and 15 kilograms of HEU per warhead, about 45 metric tons of plutonium and 225 metric tons of HEU will eventually be released from U.S. warheads, and about 90 metric tons of plutonium and 450 metric tons of HEU from CIS warheads. (All tons referred to are metric.) In addition, based on estimates of past production, each country probably already has tens of tons of weapons-grade plutonium and hundreds of tons of HEU in stored weapons components, metal, and scrap.

At present, the rate at which warheads are being dismantled appears to be roughly the same in both Russia and the United States—about 2,000 to 2,500 warheads per year. Dismantling is taking place at facilities previously used for warhead assembly. The United States has only one such facility, at Pantex near Amarillo, Texas.

Russian officials say that Commonwealth warheads are being dismantled at four sites in Russia: Nizhnaya Tura and Zlatoust in the Urals, and at Penza and Arzamas, south of Gorky. The potential dismantlement rate at the four Russian facilities could be as high as 6,000 warheads a year. (This larger Russian assembly/ dismantlement capacity reflects both the larger size of the Soviet nuclear-warhead arsenal in the 1980s and the shorter life of Soviet warheads.)

> Safeguarded stored plutonium might be safe from terrorists—but available to the governments that own it.

The United States plans to use existing facilities for the storage of warhead components and fissile materials. Currently, most of the plutonium-containing "pits" are being stored at Pantex in "igloos"—bunkers used in the past principally for the temporary storage of nuclear warheads. The thermonuclear components, which contain most of the HEU, will be shipped to the Y-12 facility at Oak Ridge for further disassembly, after which the HEU may be processed into standard metal "buttons" and stored. Because of its very high density, even a 10-kilogram (22-pound) mass of uranium metal is compact. It could fit into a cylinder 2.5 centimeters high and 16 centimeters in diameter—about twice the size of a hockey puck.

While the U.S. administration currently seems content to adapt already-existing storage facilities to the new demands, Russia has requested U.S. assistance for the construction of a massive central storage facility to hold all of the plutonium and HEU recovered from its warheads. According to officials of the Russian Ministry of Atomic Energy, the ultimate capacity of this facility would be 100,000 containers, each holding 4–5 kilograms of plutonium or 10 kilograms of HEU. The U.S. government appears to be basically sympathetic but, at the time of this writing, discussions were continuing on certain aspects of the design—especially the size, since there is no obvious reason for long-term storage of most of the HEU.

Highly enriched uranium

Russian nuclear officials say that ultimately most of the HEU extracted from surplus CIS nuclear warheads will be diluted to low-enriched levels and used as nuclear fuel. Recently, the Russian Ministry of Atomic Energy (Minatom) agreed to sell Allied-Signal Corporation approximately 500 tons of HEU over a period of 20 years for conversion to low-enriched fuel for commercial reactors. Although it is not yet clear who will dilute the enriched uranium to reactor level, the U.S. government approved the purchase in late August. Allied-Signal will buy no less than 10 tons annually for the first five years and no less than 30 tons annually for the next 15 years. Approximately 10 tons of Russian weapon-grade HEU per year should support 20 1,000-megawatt reactors, the equivalent of 20 percent of U.S. nuclear capacity.

Diluted, low-enriched uranium fuel cannot sustain the fast-neutron chain reactions required to generate a nuclear explosion. However, it does sustain the slow-neutron chain reactions that drive nuclear power-reactors. It can only be converted back into weapons-grade uranium using the same isotopic-enrichment techniques that are used to produce HEU from natural uranium—although only about half as much enrichment work is required per kilogram of HEU produced. Conversion to low-enriched uranium would therefore reduce the size of the high-security storage required for weapons-usable HEU.

Some of the weapons-grade HEU would be retained undiluted because naval propulsion reactors and a few research and isotope-production reactors are fueled with HEU. However, Russia needs only about 1.5 tons of HEU for these purposes each year and the United States only about three tons. A stockpile of 100 tons of HEU—about 10 percent of the amount produced by the Soviet Union and the United States for weapons—could fuel these reactors for two decades. If 600 tons of surplus weapons-grade HEU were diluted for reactor fuel, it could fuel the world's 300 gigawatts of light-water reactor capacity for about three years. (A gigawatt is 1,000 megawatts; 1,000 megawatts is the typical electrical generating capacity for a modern power reactor. "Light" or ordinary water reactors make up more than 80 percent of the world's nuclear capacity.)

Plutonium

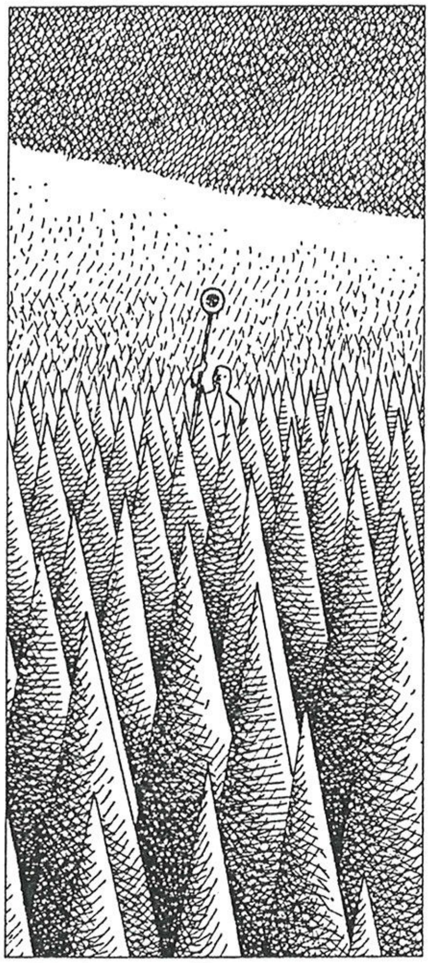
Since there is no practical way to isotopically "denature" weapons plutonium, it must be stored in a high-security facility, such as the one proposed by Russia, that features a large guard force—the plutonium equivalent of Fort Knox. The costs of storing civilian plutonium are typically estimated in the West to be about one dollar per gram per year, which would amount to about $100 million per year for 100 tons.

While safeguarded storage could make the plutonium relatively safe against theft by terrorist groups, it would remain available to the government that owned it—a fact that explains why there is considerable international interest in converting weapons plutonium into a form less easily reused in weapons.

Weapons plutonium has about the same fuel value as HEU per kilogram, but nuclear warheads, on average, contain only about one fifth as much plutonium, which means that weapons plutonium represents a much smaller potential energy resource. The approximately 200 tons of plutonium that have been produced for U.S. and CIS weapons would fuel the world's light-water reactors for less than a year if plutonium fuel completely replaced low-enriched uranium fuel.

Proponents of nuclear power sometimes argue that military plutonium should be stored to provide startup fuel for fast-neutron plutonium-breeder reactors when they eventually become commercially feasible. However, that argument makes little sense. Plans to commercialize these uranium-efficient but expensive reactors have been postponed indefinitely. They are not even close to being cost-effective.

Interest in breeder reactors is not likely to revive unless world nuclear capacity greatly increases—to, say, 1,000 gigawatts. However, to start up 1,000 gigawatts of breeder capacity would require some 6,000 tons of plutonium (or an equivalent amount of enriched uranium). A few hundred tons of already-separated plutonium would not make a significant difference. The wisest course: convert surplus weapons plutonium into a form that is less susceptible to weapons use.



Less accessible plutonium

There are two principal near-term options for converting plutonium into more proliferation-resistant forms: fabrication into mixed-oxide (MOX) fuel for nuclear reactors, and incorporation into glassified high-level waste.

Both options would make the plutonium relatively inaccessible for weapons use by imbedding it in a matrix roughly equivalent to spent power-reactor fuel, in which the plutonium is mixed, at a concentration of roughly one percent, with highly radioactive fission products. This is a useful comparison because most of the world's plutonium—more than 70 percent—is currently held in spent power-reactor fuel that is not likely to be reprocessed.

Other possible measures designed to get rid of the plutonium entirely have been proposed. These include rocketing the plutonium into the sun; the complete fissioning (sometimes called "transmutation") of plutonium with fast-neutron reactors or accelerators; and using nuclear explosions in manmade caverns deep underground to mix weapons plutonium into a glass produced out of the surrounding rock melted by the heat of the explosion. However, it is unlikely that such costly and difficult processes would be undertaken, except as part of an international program to completely rid the world of plutonium. The latter goal would require separating out, under effective safeguards, all of the plutonium that has been accumulating in the world's unreprocessed spent fuel. That would amount to over 1,000 tons by the year 2000.

Plutonium as fuel

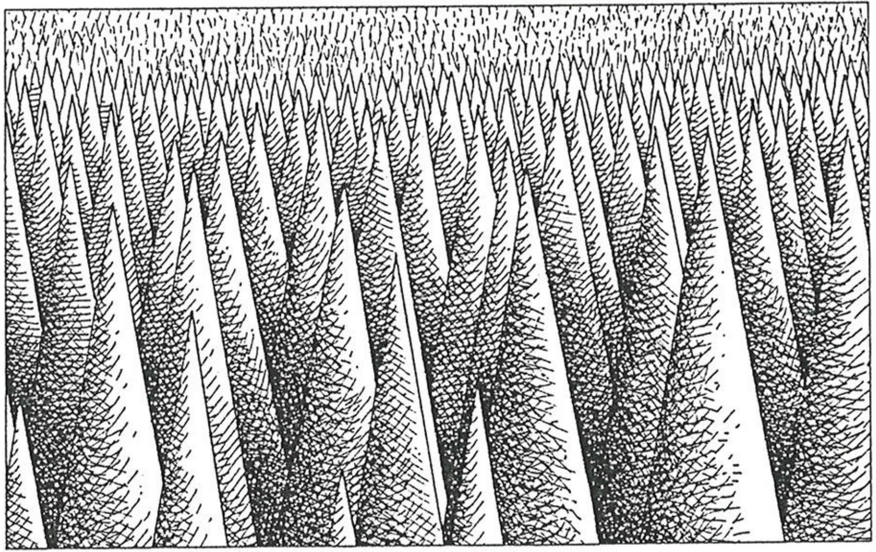
The plutonium disposal method preferred by the nascent commercial plutonium industry in Western Europe and Japan is to use it to make plutonium-uranium "mixed oxide"—MOX—fuel for light-water reactors.

Utilities in the United States rejected commercial plutonium recycling a decade ago on economic grounds, and they would be very reluctant now to use MOX fuel, with all of the attendant licensing, safeguards, and political problems.

In Russia, however, some parts of the Ministry of Atomic Energy (Minatom) seem interested in MOX fuel. Siemens AG, a German company, has proposed building in Russia a duplicate of the MOX-fuel fabrication plant that it has completed (but has been unable to license) in Hanau, Germany. The Russian plant could produce up to 120 tons of MOX a year, which would consume about five tons of weapons plutonium per year.

Siemens estimates that the facility could be constructed in three years at a cost of about half a billion dollars.

According to Siemens's estimates, the cost of producing MOX fuel at its plant, when operating at full capacity, would be roughly the same as producing low-enriched uranium fuel at today's uranium and separative-work prices—about $1,000 per kilogram. Although these estimates appear optimistic compared to the current West European prices for MOX fabrication of $1,300–1,600 per kilogram, even a cost penalty of, say, $1,000 per kilogram of MOX fuel might be an acceptable price for making the plutonium less accessible and useful to potential bomb-makers. At such a cost penalty, the extra cost of burning 50 tons of plutonium would be a modest $1.2 billion spread over a decade.



Just how interested Minatom is in a "turnkey" MOX plant is unclear. Early this year, some Minatom officials tried to get a group of visiting U.S. senators interested in funding the completion of a partially built MOX-fuel fabrication plant near the Mayak reprocessing plant in the Urals near Chelyabinsk. This plant was initially designed to produce fuel for fast-neutron plutonium-breeder reactors, but construction was suspended in 1987 when the future of the Soviet fast-reactor program fell into doubt.

Minatom also has made it clear that it would give first priority to using—in any MOX-fuel fabrication plant—its stockpile of about 30 tons of separated power-reactor plutonium. This stockpile is continuing to grow at a rate of 2.5 tons a year because of the continued reprocessing of Commonwealth and East European power-reactor fuel at the Mayak reprocessing plant. Giving priority to the use of this plutonium would delay fuel use of the weapons-plutonium indefinitely after MOX fabrication began.

Even though MOX and low-enriched uranium have similar fuel values, they are not completely interchangeable. Because their nuclear properties differ somewhat, the margin of control of the chain reaction in an unmodified light-water reactor would be significantly reduced if more than about one-third of the fuel assemblies in the reactor core were made of MOX fuel.

At this level—one-third loadings of the core—it would require all of Russia's operating (five) and partially-built (four) 1-gigawatt light-water reactors to absorb one-half the output of the proposed Siemens plant. (Other classes of Russian reactors have safety problems so severe that they are expected to be shut down over the next ten years.) Over a decade, some 25 tons of weapons plutonium—or about one quarter of the weapons plutonium that would become available—could be irradiated in reactors, at least in theory. (We say "in theory" because, as noted before, the first priority is likely to be the fabrication of already separated power-reactor plutonium into MOX fuel.)

It is important to be clear that feeding MOX fuel into light-water reactors does not dispose of all the plutonium. Although much of the plutonium would be fissioned, some would be converted to higher plutonium isotopes, and some of the U-238 in the fuel would be converted to plutonium as a result of neutron capture. Therefore, the MOX fuel, which would contain about 4 percent weapon-grade plutonium when fed into the reactor, would still contain about 2.5 percent when discharged.

Nevertheless, spent MOX fuel would be much less useful to potential bomb-makers than fresh MOX fuel because of the admixture of fission products, and because the isotopic composition of the plutonium would have been shifted toward the heavier isotopes.

However, using MOX fuels in Russia would burden that country with the major problem of assuring that no plutonium was diverted during fabrication and transport at a time of great political instability and uncertainty.

If MOX is not the right road to take in Russia, could Commonwealth (or U.S.) weapons-plutonium be sent to West Europe and Japan, where the recycling of civilian plutonium in light-water reactors is already being undertaken?

Probably not. Even if the security problems could be dealt with, these countries are already awash in civilian plutonium separated from spent power-reactor fuel. As of the end of 1990, almost 50 tons of surplus civilian plutonium were in storage in Western Europe—principally at reprocessing plants in Britain and France. With large additional reprocessing capacity now coming on line in these countries, an additional 170 tons of plutonium are programmed to be separated from spent fuel from West European and Japanese reactors by the end of the century. This is more than twice the amount of plutonium that can be absorbed in MOX fuel during this period and would result in a tripling of the stockpile of stored civilian plutonium to about 150 tons by the year 2000.

Furthermore, interest in the use of plutonium as fuel is rapidly waning among both European and Japanese utilities. Their plutonium recovery programs were originally launched to provide startup fuel for the fast reactors that they expected to be building in large numbers beginning in the 1990s. As interest in breeders receded, they believed for a time that it might be economic to recover and recycle plutonium in light-water reactors to reduce their consumption of uranium.

However, the cost of reprocessing has risen while the cost of uranium has fallen, and the economics of recovering plutonium from spent fuel for recycling have become absurd. Reprocessing costs about $1,000 per kilogram of spent fuel. It requires the reprocessing of about six kilograms of spent fuel to recover enough plutonium to make one kilogram of MOX fuel. Adding a minimum $1,000 per kilogram for MOX-fabrication costs brings the full cost of MOX containing civilian plutonium to $7,000 per kilogram. The equivalent amount of low-enriched uranium fuel costs about $1,000.

Today, MOX fuel programs are motivated primarily by the need to get rid of existing stockpiles of separated civilian plutonium, and the additional plutonium scheduled to be separated during the next decade under partially prepaid reprocessing contracts. Given the limited MOX fuel-fabrication capacity and the restricted number of power reactors licensed to use MOX fuel, it will probably take at least 20 years to work off the backlog of separated civilian plutonium. Even then, given the tremendous political, safeguards, and licensing problems associated with the use of plutonium in fuel, West European and Japanese utilities would probably be reluctant to volunteer to use MOX fuel made with CIS or U.S. weapons plutonium.

Indeed, the safeguards problems associated with recycling separated "reactor-grade" (but weapons-usable) plutonium in Western Europe and Japan are daunting enough without adding huge quantities of weapon-grade plutonium. Recycling 20 tons of civilian plutonium annually into MOX, as currently planned by the end of the decade in Western Europe and Japan, would call for fuel containing plutonium to be shipped to about 50 nuclear-power reactors in five countries. This would impose an enormous new burden on safeguards agencies, and it would clearly increase the risk of diversion or theft. A group that stole a half-ton MOX fuel assembly could chemically separate out about 25 kilograms of plutonium within a few days—enough to make two or three crude Nagasaki-type bombs.

If MOX use was largely segregated from ordinary commercial nuclear activities, some of the diversion risks could be significantly reduced. One possible approach would be to redesign the control systems of a few light-water reactors so they could accept 100 percent MOX cores. If, in addition, the MOX fuel was irradiated in the reactor only long enough to convert the contained plutonium to reactor grade (about two years), then 1.5 tons of plutonium could be converted into spent fuel each year. This would allow safeguards and security systems to be focused on many fewer reactors. Almost 50 tons of Russian weapons plutonium could be processed over a 10-year period in three reactors at a single site (Balakovo), rather than at nine reactors at three sites.

Mixing plutonium with high-level waste glass would make plutonium recovery impossible.

Light-water reactors are not the only vehicles for using MOX fuel. Fast breeder reactors without uranium blankets around the cores operating on a once-through MOX fuel cycle could process more plutonium into spent fuel per reactor than could light-water reactors.

For example, a 1-gigawatt reactor of this type would have a throughput of about 2.4 tons of plutonium per year, of which about one quarter would be fissioned. However, less than 1.5 gigawatt of breeder reactor capacity is operating worldwide following the effectively permanent closure of the large French-Italian "Superphénix" reactor in July—and additional shutdowns are planned.

The Japanese Science and Technology Agency has suggested building a fast breeder reactor without blankets—a plutonium "burner" in Russia. However, the Japanese government has made clear that it will not go forward with this proposal unless it is cofunded by Western Europe and the United States. This is unlikely, since the idea is regarded, even by many in Japan, as make-work for Japanese breeder-reactor designers after the completion of Japan's 280-megawatt Monju "demonstration" breeder reactor in 1993. There seems to be no good reason to build a new fast-neutron reactor at great cost to "burn" plutonium when existing light-water reactors can do the same job much sooner. It also appears unlikely that Russia will complete its proposed 800-megawatt breeder reactor without external assistance.

High-level waste

Burning weapons plutonium in reactors—whether light-water reactors or fast-neutron "burners"—is feasible, but fraught with safety and security risks. An obvious alternative to feeding plutonium into reactors is simply to mix plutonium back into the liquid high-level waste that was generated when the plutonium was originally separated at the reprocessing plant. Much of this waste is now scheduled to be vitrified (glassified) prior to geological disposal. Six vitrification plants are now in operation—none in the United States. Seven more are planned, including two by the U.S. Energy Department. Although there is some confusion in the literature, it appears that at least one percent plutonium (by weight) could be dissolved in the borosilicate glass being used by the United States.

Plutonium could be mixed into the high-level waste glass as it is produced. The fission products contained in the glass would make plutonium recovery impossible without remote chemical reprocessing techniques similar to those used to recover plutonium from spent fuel. Indeed, the glass would probably be somewhat more difficult to dissolve (an early step in the recovery process) than the spent fuel.

The United States has a huge amount of liquid high-level waste stored in tanks at the military reprocessing facilities at Savannah River, South Carolina, and Hanford, Washington. Billion-dollar glassification facilities are being built at both sites. The plant at Savannah River is under construction. When it will actually go into operation is currently in question because of the need to "pretreat" the waste. If and when it does operate, however, it could produce 400 tons of glassified high level waste a year operating at 50 percent capacity. At a one percent plutonium loading, four tons of weapons plutonium could be absorbed a year—about the same as could be processed by 17 light-water reactors with one-third MOX-fuel loadings.

Since the glass will be made in any case, the cost of plutonium disposal would be the extra cost associated with converting the metal plutonium into oxide form, transporting it to the vitrification facility, arranging for its incorporation into the glass, and establishing a safeguards system to monitor the process. About 5,000 tons of glass are planned to be produced at Savannah River and 25,000 tons at Hanford—enough to incorporate all surplus U.S. weapons plutonium at a concentration of less than 0.3 percent. This is approximately the concentration of plutonium and other transuranic elements in the waste glass being produced at the large commercial reprocessing plants at Sellafield, Britain, and La Hague, France. A Pacific Northwest Laboratory group has estimated the total cost of adding 50 tons of weapons plutonium to the waste glass at a concentration of 0.3 percent at about $50 million.

Russia has stored high level waste at only one of its three military reprocessing sites—that near Chelyabinsk. (At the other two sites, near Tomsk and Krasnoyarsk, the wastes have been routinely disposed of by injection into a deep aquifer.) At the Chelyabinsk site, about one quarter of the high-level waste has been discharged into an open pond, and some of the remainder has already been glassified. However, about as much high-level waste remains in tanks (measured in terms of its radioactivity) as is at the Savannah River site. Most of the high-level waste at Chelyabinsk has come from civilian power-reactor fuel, which has been reprocessed there since 1978.

The concentration of high-level waste in the glass being produced at Chelyabinsk is, however, about double that planned at Savannah River, which means that less glass—about 3,000 tons—would be produced from the waste currently in the tanks. At a one-percent plutonium concentration, this amount of glass would accommodate only 30 tons of plutonium. If higher concentrations of plutonium are not possible, and no additional glass is produced, vitrification may be only a partial solution to the Russian plutonium problem.

Surplus civilian plutonium could also be disposed of in glassified high-level waste in Britain and France. However, at this time such a proposal would almost surely be rejected by reprocessors, because it would represent a dramatic demonstration that separating civilian plutonium was a mistake. The same problem will probably also arise in Russia within Minatom, where some officials are interested in the possibility of earning hard currency by reprocessing foreign fuel, as is being done in Britain and France.

A dangerous distraction

The most critical near-term task is to ensure that all HEU and plutonium recovered from dismantled weapons is stored in monitored, secure facilities under bilateral or international safeguards. Conversion of highly enriched uranium to low-enriched uranium as quickly as possible after the HEU is recovered from weapons would also minimize both security concerns and storage costs.

By the end of the century, it should be possible to begin to imbed separated plutonium into more proliferation-resistant forms. The United States, which is unlikely to turn to plutonium recycling, should look seriously at incorporating weapons plutonium into glassified high-level waste. Although more research and development is needed to optimize this approach, vitrification looks technologically and economically feasible.

For Russia, the preferred approach—or the best mix of approaches—is less clear. However, the Russian nuclear establishment's first priority should be to shut down the country's most dangerous nuclear power plants and improve the safety of those that remain. Given that, it would be a dangerous distraction for Russia to rush into the widespread use of MOX fuel, as some nuclear industry and government officials in Western Europe and Japan are urging.

Whichever option is taken, the waste forms (either spent MOX fuel or glassified wastes) will ultimately have to be disposed of. Spent MOX fuel is little different from ordinary spent fuel when it comes to final disposal. With about one percent added plutonium, the fractions of plutonium and fission products in glassified wastes would be similar to those of conventional spent fuel.

Therefore, although the problems associated with plutonium migration from geological repositories have not been fully resolved, disposal of these waste forms does not appear to raise environmental issues greatly different from the problems presented by the disposal of conventional spent fuel.

By irradiating plutonium in MOX fuel in dedicated reactors or adding it to high-level waste, we would be adding only modestly to our already very large spent-fuel disposal problem. In exchange, we would gain a great reduction in the security threat posed by huge quantities of separated plutonium. ■