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Energy AND Security

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The Use of Weapons Plutonium as Reactor Fuel

BY ARJUN MAKHIJANI AND ANITA SETH

At the end of the Cold War, the United States and Russia face an unprecedented and unexpected problem: surpluses of plutonium and highly-enriched uranium (HEU), the two key materials used to make nuclear weapons. In principle, the uranium poses the lesser problem of the two, because it can be blended down into the low-enriched uranium fuel that is widely used in nuclear reactors. In 1993, the United States and Russia signed a deal according to which the United States agreed to purchase, over a period of 20 years, 500 metric tons of Russian HEU that is being blended down into reactor fuel in Russia. Although implementation of this agreement was initially slow, it is now going forward at the agreed rate.

More difficult is the issue of converting the surplus plutonium into forms not usable for making nuclear weapons. The United States has declared about 50 metric tons (out of a total stock of about 100 metric tons) to be surplus,[1] while Russia has not yet made any formal declaration of surplus. Total Russian plutonium in the military sector is thought to be about 130 metric tons, perhaps more.

There is disagreement between the United States and Russia about the best way to handle surplus weapons plutonium. The Russian Ministry of Atomic Energy (Minatom) regards plutonium as a valuable energy resource, but the prevailing US view (notwithstanding some disagreements that continue) is that it is a security and economic liability. Despite

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▲ *Glove boxes are used to process plutonium because inhalation, even in tiny quantities, poses severe risks.*

EDITORIAL

Will Disposition be the Road to a Plutonium Renaissance?

Disposition of surplus weapons plutonium in the United States and Russia is an urgent non-proliferation goal. However, the current course of favoring conversion of surplus plutonium into MOX fuel raises serious proliferation and safety concerns. The use of MOX fuel for disposition would establish the infrastructure of facilities and financial interests for a long-term plutonium economy and hence pose additional proliferation risks.

It was hoped that if the United States agreed to MOX use, Russia would agree not to reprocess MOX spent fuel or to use facilities built for disposition of surplus weapons plutonium for commercial purposes. These hopes have not been realized. Instead, in the name of disposition, the US seems not only to be relinquishing its decades-old policy of not using plutonium in commercial reactors, but aiding and abetting Russian plans to build a plutonium economy.

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EDITORIAL

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The Joint US/Russian Plutonium Disposition Study, which was signed by the Science Advisors to Presidents Clinton and Yeltsin (see main article), demonstrates this US acquiescence: "To facilitate the objective of disposition as rapidly as practical, if the reactor option is pursued, the resulting material should not be reprocessed and recycled at least until current excess stockpiles of separated plutonium are eliminated. Once that is complete, final decisions can be taken as to whether the intensely radioactive plutonium-bearing materials resulting from the reactor option should go directly to geologic disposal, as the U.S. prefers; or should eventually be reprocessed to recover separated plutonium, the current preference for Russia."[1] Later, the report is even more explicit: ". . .Russia will ultimately recycle any plutonium left in the [MOX spent] fuel." And, "the U.S. objective of plutonium disposition" appears to be satisfied if MOX spent fuel "is stored for several decades before reprocessing."[2]

It is not very relevant whether MOX spent fuel is reprocessed now or in a few decades. So long as the infrastructure for MOX fuel production and reprocessing is created and maintained, there will be plenty of other spent fuel to reprocess and plenty of surplus plutonium to occupy MOX fuel fabrication plants in the meantime. Furthermore, if Russia reprocesses MOX spent fuel, then the idea that MOX fuel use would lock up surplus plutonium in a highly radioactive matrix so that it cannot again be used in weapons will have been defeated. While the Russian government may not want to use reactor-grade plutonium in weapons, some non-nuclear governments or terrorist organizations may be willing to pay a high price for this weapons-usable material. Further, the use of weapons-grade plutonium in fast breeder reactors may not degrade its isotopic composition significantly. In fact, breeder reactors, when operated with uranium blankets, can be used to upgrade reactor-grade plutonium into weapons-grade. The main limitation will likely continue to be money for the reactors and reprocessing plants.

The joint report also notes that "there is some uncertainty as to whether the cost of decommissioning of [MOX] facilities built primarily for electricity production [in Russia] should be assigned to the plutonium disposition mission since these facilities are likely to be used by a civilian plutonium program once the plutonium disposition campaign is complete."[3] A MOX fabrication facility, if used for commercial purposes after military plutonium disposition is completed, would provide a crucial link that is currently missing in Russia's plans for a plutonium economy.

Thus, the net result of the plutonium disposition program will have been for the United States to subsidize the very thing that it should be against: an infrastructure for a plutonium economy in Russia. Interestingly, and perhaps not coincidentally, a similar infrastructure would be created in the United States since a MOX plant would be built and since the U.S. appears increasingly reluctant to shut down its decades-old military reprocessing plants at the Savannah River Site in South Carolina.

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Energy & Security

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Health Effects of Plutonium

Plutonium-239 is a very hazardous carcinogen which can also be used to make nuclear weapons. This combination of properties makes it one of the most dangerous substances. Plutonium-239, while present in only trace quantities in nature, has been made in large quantities in both military and commercial programs in the last 50 years.

Other more radioactive carcinogens do exist, like radium-226, but unlike plutonium-239 cannot be used to make nuclear weapons, or are not available in quantity. Highly enriched uranium (HEU) can also be used to make nuclear weapons, but it is roughly one thousand times less radioactive than plutonium-239. The danger is aggravated by the fact that plutonium-239 is relatively difficult to detect once it is outside of secure, well-instrumented facilities, or once it has been incorporated into the body. This is because its gamma ray emissions, which provide the easiest method of detection of radionuclides, are relatively weak.

The main carcinogenic property of plutonium-239 arises from the energetic alpha radiation it emits. Alpha particles, being heavy, transfer their energy to other atoms and molecules within fewer collisions than the far lighter electrons which are the primary means of radiation damage for both gamma and beta radiation.[1] Alpha particles travel only a short distance within living tissue, repeatedly bombarding the cells and tissue nearby. This results in far more biological damage for the same amount of energy deposited in living tissue.

The relative effectiveness of various kinds of radiation in causing biological damage is known as "relative biological effectiveness" (RBE). This varies according to the type of radiation, its energy, and the organ of the body being irradiated. A simple factor, called quality factor, is used to indicate the relative danger of alpha, beta, gamma and neutron radiation for regulatory purposes. The International Commission on Radiation Protection currently recommends the use of a quality factor of 20 for alpha radiation relative to gamma radiation.[2]

Once in the body, plutonium-239 is preferentially deposited in soft tissues, notably the liver, on bone surfaces, in bone marrow and other non-calcified areas of the bone, and areas of the bone that do not contain cartilage. Deposition in bone marrow can have an especially harmful effect on the blood formation which takes place there. By contrast, radium-226, another alpha emitter, is chemically akin to calcium and so becomes deposited in the calcified areas of bones.

When it is outside the body, plutonium-239 is less dangerous than gamma-radiation sources. Since alpha particles transfer their energy within a short distance, plutonium-239 near the body deposits essentially all of its energy in the outer dead layer of the skin, where it does not cause biological damage.

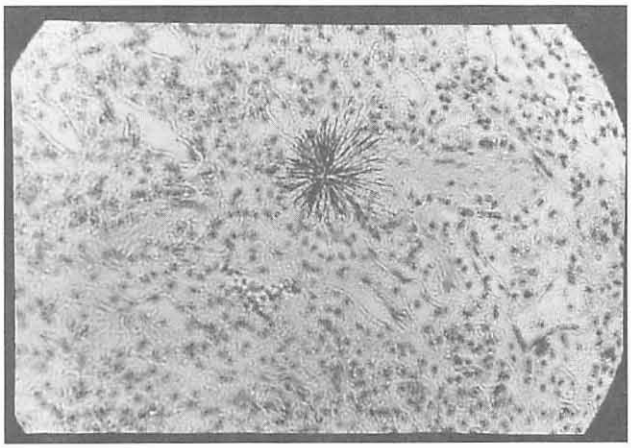

PHOTO BY ROBERT DEL TREDICI

▲ *The black star shows the tracks made by alpha radiation emitted by a particle of plutonium in the lung tissue of an ape (magnified).*

The gamma rays emitted due to plutonium-239 decay penetrate into the body, but as these are relatively few and weak, a considerable quantity of plutonium-239 would be necessary to yield substantial doses from gamma radiation. Thus, plutonium-239 can be transported with minimal shielding, with no danger of immediate serious radiological effects. The greatest health danger from plutonium-239 is from inhalation, especially when it is in the common form of insoluble plutonium-239 oxide. Another danger is absorption of plutonium into the blood stream through cuts and abrasions. The risk from absorption into the body via ingestion is generally much lower than that from inhalation, because plutonium is not easily absorbed by the intestinal walls, and so most of it will be excreted.

The kind of damage that plutonium-239 inflicts and the likelihood with which it produces that damage depend on the mode of incorporation of plutonium into the body, the chemical form of the plutonium and the particle size. The usual modes of incorporation for members of the public are inhalation or ingestion. Plutonium may be ingested by accidental ingestion of plutonium-containing soil, or through eating and drinking contaminated food and water. Incorporation via cuts is a hazard mainly for workers and (in former times) for personnel participating in the atmospheric nuclear testing program.

In general, plutonium in the form of large particles produces a smaller amount of biological damage, and therefore poses a smaller risk of disease, than the same amount of plutonium divided up into smaller particles.

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HEALTH EFFECTS

FROM PAGE 3

When large particles are inhaled, they tend to be trapped in the nasal hair; this prevents their passage into the lungs. Smaller particles get into the bronchial tubes and into the lungs, where they can become lodged, irradiating the surrounding tissue.

Other plutonium isotopes that emit alpha radiation, like plutonium-238, have similar health effects as plutonium-239, when considered per unit of radioactivity. But the radioactivity per unit weight varies according to the isotope. For instance, plutonium-238 is about 270 times more radioactive than plutonium-239 per unit of weight.

Experimental data

The health effects of plutonium have been studied primarily by experiments done on laboratory animals. Some analyses have also been done on workers and non-worker populations exposed to plutonium contamination. Measurements of burdens of plutonium using lung counters or whole-body counters, together with follow-up of exposed individuals, have provided information which is complementary to experimental data and analysis. Experiments injecting human beings with plutonium were also done in the United States. Between 1945 and 1947, 18 people were injected with plutonium in experiments used to get data on plutonium metabolism. They were done without informed consent and have been the object of considerable criticism since information about them became widely known in 1993.

Experiments on beagles have shown that a very small amount of plutonium in insoluble form will produce lung cancer with near-one-hundred-percent probability. When this data is extrapolated to humans, the figure for lethal lung burden of plutonium comes out to about 27 micrograms. Such an extrapolation from animals, of course, has some uncertainties. However, it is safe to assume that several tens of micrograms of plutonium-239 in the lung would greatly increase the risk of lung cancer. Larger quantities of plutonium will produce health problems in the short-term as well.

The precise quantitative effects of considerably lower quantities of plutonium are as yet not well known. This is due to several factors such as:

- the difficulty of measuring plutonium in the body;
- uncertainties regarding excretion rates and functions due to the large variation in such rates from one human being to the next (so that the same body burden of plutonium would produce considerably different doses);
- complicating factors such as smoking;
- uncertainties in the data (as, for instance, about the time of ingestion or inhalation);
- differing and largely unknown exposure to other sources of carcinogens (both radioactive and non-radioactive) over the long periods over which studies are conducted;
- failure to study and follow-up on the health of workers who worked with plutonium in the nuclear weapons industry to the extent possible.

One of the few attempts to analyze the effects of microgram quantities of plutonium on exposed human subjects was a long-term study of 26 "white male subjects" from the Manhattan Project exposed to plutonium at Los Alamos in 1944 and 1945, where the first nuclear weapons were made. These subjects have been followed for a long period of time, with the health status of the subjects periodically published. Recent results were published in a study in 1991.[3]

The amounts of plutonium deposited in the bodies of the subjects were estimated to range from "a low of 110 Bq (3 nCi) . . . up to 6960 Bq (188 nCi),"[4] corresponding to a weight range of 0.043 micrograms to 3 micrograms. However, weaknesses in the study resulted in considerable uncertainties about the amount and solubility of plutonium actually incorporated at the time of exposure.[5]

Of the seven deaths by 1990, one was due to a bone cancer (bone sarcoma).[6] Bone cancer is rare in humans. The chances of it normally being observed in a group of 26 men over a 40-year timeframe is on the order one in 100. Thus, its existence in a plutonium-exposed man (who received a plutonium dose below that of current radiation protection guidelines) is significant.[7]

There are data for plutonium exposure in other countries, notably in Russia. These are still in the process of being evaluated. Collaborative US-Russian studies are now beginning under the Joint Coordinating Committee on Radiation Effects Research (JCCRER) to assess the health effects of the Mayak plant to both workers and neighbors of the facility.

—ARJUN MAKHIJANI

1 Gamma rays consist of high energy photons, which are "packets" or quanta of electromagnetic energy.

2 The energy deposited in a medium (per unit of mass) is measured in units of grays or rads (1 gray = 100 rads), while the biological damage is measured in sieverts or rems (1 sievert = 100 rems).

3 G.L. Voelz and J.N.P. Lawrence, "A 42-year medical follow-up of Manhattan Project plutonium workers." *Health Physics*, Vol. 37, 1991, pp. 445–485.

4 *Ibid*, p. 186.

5 These aspects of the study are discussed in some detail in Gofman 1981, pp. 510–520 (based on the status of the Manhattan Project workers study as published in Voelz 1979). J. W. Gofman, *Radiation and Human Health* (San Francisco: Sierra Club Books, 1991), p. 516.

6 Three of these deaths were due to lung cancer. It is difficult to assess the significance of this large percentage, since all three were smokers.

7 Voelz, p. 189.

MOX Fuel Use in France and Belgium

BY JEAN-PIERRE MORICHAUD

The first European industrial-scale tests of MOX took place in 1963 at the BR3 reactor in Mol, Belgium and in 1974 at the Chooz A reactor (now shut down) located on the French border with Belgium. These tests were the result of early French-Belgian MOX development. Belgonucléaire and COGEMA began producing MOX fuel jointly at two small plants in Dessel, Belgium (which started operation in 1973), and Cadarache, France (which started operation in 1970). The capacities of these plants are 35 metric tons and 15 metric tons of MOX fuel per year respectively. Also as a part of the joint French-Belgian work, four Belgian pressurized water reactors (PWRs) at Tihange and Doël and the 28 first French 900 MW PWRs, which began operation between 1980 and 1984, were designed to use MOX fuel. They have four unused vessel head guide tubes in which supplementary control rods deemed necessary for MOX use can be placed. Curiously, the twenty-two 1300 MW reactors that were built later in France are not adaptable to MOX use. This is probably because after an initial wave of MOX development for LWRs, emphasis for plutonium fuels shifted fast neutron reactors (or "breeder" reactors), and MOX use in light water reactors was relegated to second place.

MOX use in LWRs is the last chance for proponents of plutonium fuel.

It was not until 1984, after it became clear that initial hopes for breeder reactor programs would not be achieved, that Belgonucléaire and COGEMA were able to regroup to commercialize MOX in LWRs. As a result of these new efforts, MOX was loaded into a French reactor for the first time in 1987, at Saint-Laurent-les-Eaux (in the Loire region). Out of the 52 fuel assemblies replaced each year (one-third of the entire core), 16 are MOX. Since then, nine other reactors have also been loaded with up to 30% MOX, the maximum loading accepted by French nuclear safety officials for MOX, containing no more than 5.3% plutonium. In Belgium, as a result of parliamentary debates in December 1993, two reactors can be loaded with only up to 20% MOX core, but with a 7.7% plutonium content. This second wave of MOX development for LWRs also resulted in a new fabrication facility in Marcoule, France, called Melox, with a capacity of 115 metric tons. A license was granted for construction of the plant in 1990, and it began operation in 1995. By the end of 1996, it had reportedly delivered 96 MOX assemblies to the French utility, EDF.

Only 16 of the 28 French 900 MW reactors were licensed to receive MOX at the time of their construction. Public debates are currently being conducted which would allow MOX use in four additional reactors in Chinon, on the Loire river. This step runs counter to the government decision to have experts conduct an "environmental and economic assessment of MOX use" by June 1997. The Forum Plutonium has also demanded that results of the public survey in Chinon be reported in autumn 1997.

The security, safety, and economics of MOX fuel use have long been questioned by many experts in France. In November 1990, when the decision was made to build the Melox plant, Jean-Paul Schapira, a well-known nuclear physicist questioned the value of MOX use in the journal *La Recherche*.[1] Recently, in the *Gazette Nucléaire*, Monique Sené of the GSIEN (Association of Scientists for Nuclear Energy Information), shows that the objections raised by J.P. Schapira have been borne out by the MOX fuel assemblies that have been used by EDF.[2]

Schapira and Sené identify a number of safety problems posed by MOX compared to traditional uranium fuel which it replaces: more delicate fabrication of fuel rods to protect against contamination, greater risk of loss of control during reactor operation despite the presence of extra control rods, release of fission gases, corrosion of fuel rods during reactor operation. Given the signs of aging which are now appearing in the French 900 MW reactors, these complications are all the more problematic.

The security problems associated with MOX use are linked to the transport of nuclear materials that can be used to make nuclear weapons or other weapons that could disperse radioactive material. In France, plutonium and MOX fuel are transported by road under police escort, during the day only, along routes which are kept secret.[3] Since plutonium is produced at La Hague (in the northwest Contentin region), and the MOX fabrication facilities are in Belgium and in southeast France, MOX fabrication requires a significant number of plutonium shipments. In addition, the transport of MOX along routes scattered throughout France and Europe, creates the potential for a radiological pollution of the ecosystem that could last for millenia.[4] In addition, MOX is intimately related to the policy of reprocessing spent fuel, which is probably the most environmentally dangerous activity of the nuclear industry. Recent studies near La Hague and Sellafield have shown numerous health and

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Status and Perspectives for MOX Fuel Production in Russia

BY ANATOLI DIAKOV

Work on using plutonium as a fuel for nuclear reactors was begun in Russia as early as the 1950s, although systematic research did not begin until the early 1970s. In this research, preference was given to the use of plutonium in fast neutron reactors.

The first experimental MOX fuel assemblies for research fast neutron reactors BR-5 (BR-10) and BOR-60 were made in the 1970s. Experimental MOX fuel assemblies have also been tested in prototype fast reactors BN-350 and BN-600, which generally use highly-enriched uranium fuel. Table 1 presents data on the quantities of MOX fuel fabricated and loaded into Russian experimental and industrial reactors. In all, more than 2000 fuel rods have been made and tested in BN-350 and BN-600 reactors with 9–11 percent fissile material being burned up.

Research on the use of plutonium in light-water reactors began only recently as a part of the plutonium disposition program and as a result of the lack of state financial support for fast reactor programs. No experiments have been carried out yet in industrial VVER-1000 reactors, although research is being conducted on the use of MOX in VVER-1000 reactors and aimed mainly at the use of MOX fuel in the new VVER-640 (or NP-500) reactors. A special testing facility has been established in order to generate experimental data and establish a design program for the use of MOX fuel. Research on fuel rod arrangement in uranium-plutonium fuel assemblies for VVER reactors is also proposed at this facility. A program to use MOX-only fuel assemblies in an existing reactor is being developed as well.

Existing MOX Fuel Fabrication Facilities

Two pilot plants for MOX fuel fabrication exist in Russia: the Paket and Granat plants, both located at Mayak (Chelyabinsk-65). These two plants are designed to work with weapons-grade plutonium, and are designed to produce MOX fuel for fast reactors. Their capacity is not large—the maximum throughput of plutonium at the Granat plant is 50 kg per year (or one metric ton of MOX fuel) with a limited single loading of 300 g of plutonium. The capacity of the Paket plant is 100 kg of plutonium per year, or 30–36 fuel assemblies, which corresponds to one metric ton of MOX fuel with 20% plutonium content.

The Paket plant was started up in 1980. At this facility, uranium and plutonium oxide powders, which have been produced separately, are mechanically mixed together. Next, a binding agent is added to the mixture, and everything is again mixed, granulated, and pressed into fuel pellets. Then the pellets are dried and sintered. After that, fuel pellets are tested, cladding is prepared, the pellets are placed into columns, the columns are placed into the cladding, and the rods are welded and tested. After decontamination, the rods are taken to the Elektrostal plant, where fuel assemblies are produced. Russian specialists believe that the Paket plant can also be used to fabricate experimental fuel rods from weapons plutonium for research thermal neutron reactors.

The Granat facility, which began operating at the beginning of 1988, is devoted to fabrication of granulated MOX fuel for fast reactors, with plutonium from reprocessed fast reactor spent fuel or from weapons plutonium, with a plutonium concentration of

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TABLE 1. HISTORY OF MOX FABRICATION IN RUSSIA

Manufacturing process	Manufacturing pilot	Reactor	No. of assemblies (mass of Pu)
Comilling (pellets)	Dimitrovgrad (1970)	BOR-60 (1973)	(a few tens of kg)
Pyrometallurgy	Dimitrovgrad (1970)	BOR-60 (1975)	(a few tens of kg)
Coprecipitation carbonate (pellets)	PO Mayak (1980) Dimitrovgrad (1970)	BOR-60 (1980)	(10 kg)
Plasma chemestry (pellets)	Moscow (1980)	BOR-60 (1981)	2 fuel pins (about 1 kg)
Comilling (pellets)	PO Mayak (1980)	/BN-350 (1980)	10 fuel assemblies (about 80 kg)
Ammonia coprecipitation (pellets)	PO Mayak (1980)	BN-350 (1992)	1 fuel assembly (about 10 kg)
Ammonia coprecipitation (pellets)	PO Mayak (1980)	BN-600 (1992)	8 fuel assemblies (about 80 kg)
Comilling (pellets)	PO MAYAK (1980)	BN-600 (1990)	12 fuel assemblies (about 100 kg)

MOX IN RUSSIA

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up to 25%. The Granat facility has currently stopped operating for safety reasons.

This facility consists of 14 glove boxes. The MOX fuel fabrication technology at Granat is based on co-precipitation of uranium and plutonium from nitric acid solutions. The resulting granules are very dry and generate almost no dust when handled. These granules are then taken to the Paket plant for fabrication into pellets and rods.

Construction began in 1984 on the "Complex 300" plant, which is designed to prepare fuel rods for fast reactors. The capacity of the plant is 30 metric tons of MOX per year. Work on the plant was stopped in 1989 because of delays in the construction of BN-800 reactors. The plant contains a line of chambers designed to accomodate a production line to manufacture fuel rods from MOX granulate. A complete set of production equipment exists, but has not been installed. The MOX fuel fabrication technology at Complex 300 is the same as that used at that used at the Paket plant. However, because Complex 300 (unlike Paket) is also designed to work with reactor-grade plutonium, it is equipped with shielded boxes and manipulators.

As a result of the halt in construction, the condition of the building and assembly equipment has deteriorated. On the whole, Russian experts are skeptical about continuing construction on this plant, since the technical solutions proposed in its design are much less sophisticated than those in design concepts for similar MOX fuel fabrication facilities in the West.

It is unlikely that the Complex 300 plant could be used for fabrication of MOX fuel for thermal reactors using military plutonium, since it is designed to make fuel pellets for fast reactors which have a number of differences from pellets for thermal reactors. In addition, the assembly equipment is not designed to handle military plutonium.

At the present time, Russia is working closely with Germany and France in order to develop a pilot MOX fuel production plant which would take advantage of Western experience and technology. Two designs are under consideration. The first is the "Tomox 1300" facility, specified in the joint French-Russian AIDA-MOX program to convert 1300 kg of weapons plutonium into MOX fuel annually. The total capacity of the facility would be 30 metric tons of MOX fuel per year. A joint German-Russain study proposes a pilot plant with capacity of one metric ton of weapons-grade plutonium per year, which corresponds to 10 metric tons of fuel for LWRs with a maximum plutonium content of 15%. These preliminary studies have been completed, and currently all three sides are carrying out negotiations on the location and financing for the plant. The estimated cost is about $130 million. Further study is needed to determine whether or not this pilot plant could also be used for fabrication of MOX fuel for fast neutron reactors with up to 45% plutonium content.

Anatoli Diakov is a professor of physics at the Moscow Institute of Physics and Technology. In 1990 he established jointly with Professor Frank von Hippel the Center for Arms Control, Energy and Environmental Studies at the Moscow Institute of Physics and Technology. Dr. Diakov's current activities include work on the Russian policy for weapon grade plutonium disposition, transparency and irreversibility of nuclear arms reduction.

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environmental problems resulting from reprocessing.

At the same time that plutonium is accumulating at La Hague (36 metric tons at the end of 1995), the price of natural uranium is decreasing, and uranium produced from reprocessing is also accumulating. By June 1, 1995, 7500 metric tons of uranium had been recovered at La Hague from reprocessing of spent fuel, enough to fabricate 15,000 fuel assemblies. Given these large amounts of uranium available at low prices, MOX fuel cannot compete economically with uranium fuel. MOX fuel fabrication is considerably more expensive than uranium fuel, even if the plutonium is considered to be free. If reprocessing costs are also taken into account, it becomes clear that MOX fuel is not economically viable.

MOX producers are faced also by a number of technical constraints for the fabrication and storage of MOX, which cannot but increase their cost.

- the presence of strong alpha-emitters and of americium-241, a highly radioactive gamma-emitter;
- limited storage period of 2 to 3 years for plutonium extracted for the production of MOX before its use (see p. 8);
- a greater enrichment of fuel necessary in order to increase the time fuel rods can remain in a reactor, which is avidly sought by EDF: 4.2 percent for uranium fuel, but 8 percent for MOX. The MOX currently authorized in France contains only 5.3 percent plutonium. It produces 30,000 megawett days per metric ton of heavy metal while uranium fuel produces 47,000. Therefore, EDF has requested authorization (so far unsuccessfully) to increase the plutonium content in MOX to 7 percent.

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How Plutonium Changes with Time

A typical plutonium sample is not pure plutonium-239, but consists of a mixture of isotopes. There are 15 isotopes of plutonium, with mass numbers ranging from 232 to 246. They are all radioactive—that is, their nuclei decay and in the process new elements are formed. All of the decay products of plutonium isotopes are also radioactive. Hence, each plutonium isotope forms a decay chain. A simplified decay chain of plutonium-239 is shown in Table 3.

The isotopes commonly found in plutonium made in nuclear reactors range from plutonium-238 to plutonium-242. The amount of isotopes other than plutonium-239 produced in military or commercial reactors depends on the nature of the fuel used, the design of the reactor and to length of irradiation time.

Table 1 shows the two most common variants of plutonium isotope mixtures. The first is weapons-grade plutonium (often abbreviated WPu), which contains 93 percent or more plutonium-239. The other is a typical composition of reactor-grade plutonium (often abbreviated RPu), as produced in nuclear power reactors of the light water design. Note that reactor-grade plutonium from light water reactors usually contains more than 20 percent plutonium-240 and more than 10 percent plutonium-241. Plutonium produced in other reactors, such as graphite-moderated reactors (some of which are in operation in Britain, Russia, and elsewhere) or heavy water reactors used in Canada and elsewhere, has a composition in between that shown for weapons grade and reactor grade plutonium in the table. Table 1 also gives the half-life and specific activity of the most common plutonium isotopes. The half-life refers to the amount of time it takes for one-half of the atoms in a given sample to disintegrate. The specific activity (which is inversely related to half-life), indicates the radioactivity of a certain weight of material.

Both weapons grade and reactor grade plutonium contain some plutonium-241. Plutonium-241 decays into americium-241 by emitting a beta particle. Since americium-241 has a far longer half-life (432 years) than plutonium-241 (14.4 years), it builds up as plutonium-241 decays. The gamma radiation from americium-241 decay, which is far stronger than that from plutonium-239, also builds up with the age of the plutonium sample. Therefore, the more plutonium-241 there is and the older the sample, the greater the gamma radiation from the build-up of americium-241.

Since reactor-grade plutonium contains substantial amounts of plutonium-241, the older the sample, the greater the radiation dose to workers handling it. When

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"Science for the Critical Masses" will be a regular feature in *Energy & Security*. It will provide readers with some technical background to the policy questions discussed in each issue, as well as the chance to test your understanding of these technical points. Notice that there are several missing values in Table 2. Fill them in based on the information provided in the accompanying article. The answers will appear in the next issue.

TABLE 1

Plutonium isotope	Half-life, years	Specific activity, curies per gram	Amount in weapons grade plutonium, percent	Amount in reactor grade plutonium, percent[1]
plutonium-238	87.74	17.3	—	1.3
plutonium-239	24,110	0.063	93.0	56.6
plutonium-240	6,537	0.23	6.5	23.2
plutonium-241	14.4	104	0.5	13.9
plutonium-242	379,000	.004	—	4.9

1 Typical for pressurized water reactors, the most common type of reactor in operation.

TABLE 2

Isotope	Initial composition	after 2 years	after 5 years	after 14.4 years	after 28.8 years
plutonium-241	1	0.91	?	0.5	?
americium-241	0	0.09	?	0.5	?

HOW PU CHANGES

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countries use plutonium separated from light water reactor spent fuel to make mixed oxide fuel (MOX fuel), older plutonium samples result in greater radiation doses to MOX plant workers. Older MOX plants are designed to handle reactor grade plutonium that is less than about two years old after reprocessing (which removes americium isotopes present in the spent fuel). Newer MOX plants can handle reactor-grade plutonium that is about three years old. Thus, countries like Japan and Russia that are not using reactor grade plutonium but have been separating it and stockpiling it for many years have wasted a great deal of money because the older plutonium will probably have to be reprocessed again to remove the americium-241. Therefore, it would be financially prudent, even for MOX proponents, to stop reprocessing until reasonably close to the time when the plutonium is actually fabricated into fuel.

Table 2 shows how americium-241 would build up in a 200 gram sample of reactor grade plutonium containing 1 gram of plutonium-241 at the time of reprocessing. It contains a blank column for the reader to fill in as an exercise to sharpen your technical skills. Note that the half-life of plutonium-241 is 14.4 years and that for every half-life, one-half of the plutonium-241 decays into americium-241. We are neglecting the decay of americium-241 for simplicity and since 28.8 years is a short time compared to its half life of 432 years.

1 Typical for pressurized water reactors, the most common type of reactor in operation.

TABLE 3
MAIN BRANCHES OF THE PLUTONIUM-239 DECAY SERIES

Plutonium-239
(half-life: 24,110 years)

⇩ *alpha decay*

Uranium-235
(half-life: 704,000,000 years)

⇩ *alpha decay*

Thorium-231
(half-life: 25.2 hours)

⇩ *beta decay*

Protactinium-231
(half-life: 32,700 years)

⇩ *alpha decay*

Actinium-227
(half-life: 21.8 years)

⇩ *beta decay*

Thorium-227
(half-life: 18.72 days)

⇩ *alpha decay*

Radium-223
(half-life: 11.43 days)

⇩ *alpha decay*

Radon-219
(half-life: 3.96 seconds)

⇩ *alpha decay*

Polonium-215
(half-life: 1.78 milliseconds)

⇩ *alpha decay*

Lead-211
(half-life: 36.1 minutes)

⇩ *beta decay*

Bismuth-211
(half-life: 2.15 minutes)

⇩ *alpha decay*

Thallium-207
(half-life: 4.77 minutes)

⇩ *beta decay*

Lead-207
(half-life: stable)

Half-life values from *CRC Handbook of Chemistry and Physics*, 1988.

MOX IN FRANCE AND BELGIUM

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- tests of reprocessing MOX fuel have produced a form of plutonium that is less fissile (and therefore produces less energy) with a higher level of transuranic elements (and thus a higher level of radioactivity) than reprocessed uranium fuel. In August 1996, EDF announced that it wanted to store spent MOX fuel. Thus, so far there is no policy regarding what to do with MOX spent fuel.

In sum, MOX, regarded by some as a way to reduce plutonium stocks, is not without its problems. Since the failure of "breeder" reactors, it remains the last chance for plutonium proponents in their competition with uranium proponents within COGEMA. However, if the mediocre economic balance-sheet for MOX were added to the plutonium industry's already disastrous environmental balance-sheet, plutonium could become a waste in France. There is, therefore, some hope that future generations will have less plutonium to manage than what is currently envisioned in COGEMA's reprocessing contracts.

Jean-Pierre Morichaud, a retired physical-chemistry engineer, began his career at the Saclay research center in 1957. He was the president of a coalition opposed to the Melox plant from 1992 to 1994. He is currently the coordinator of the Forum Plutonium, a coalition of organizations in France, Belgium, and Switzerland.

1 J. P. Schapira, "Une nouvelle stratégie pour le plutonium," *La recherche*, No. 226, November 1990.

2 M. Sené, "Dossier MOX," *La Gazette Nucléaire*, No. 155/156, January 1997.

3 M. Pavageau, J. Hazeman, M. Schneider, *Les transports de l'industrie du plutonium en France*, WISE-Paris, 1995.

4 *Plutonium: Deadly Gold of the Nuclear Age*, IPPNW/IEER, 1992, French edition in Médecine et Guerre Nucléaire, Vol. 8, No. 3, 1993.

their conceptual differences, the United States and Russia have been working together since 1994 on methods for disposition of this surplus weapons plutonium. The *Joint United States/Russian Plutonium Disposition Study*, prepared by teams of scientists and officials from both countries and published in September 1996, is one result of this joint work.

The joint study outlines a number of options, and reflects agreements as well as disagreements between the governments of the two countries. Both governments agree that it is very important to put surplus military plutonium into non-weapons-usable forms in a timely manner. In the report, the US and Russia present four options jointly, while Russia presented two options in addition on its own. The four jointly presented options are:

1. use as MOX in light water or heavy water reactors
2. use as MOX in fast reactors
3. immobilization in glass or ceramics
4. direct geologic disposal of plutonium

The two options presented by the Russian side alone are: (i) high-temperature gas reactors, and (ii) accelerator-based systems.

The first two reactor options involve using plutonium in reactor fuel. The plutonium would be converted into an oxide chemical form, mixed with uranium oxide, and fabricated into ceramic fuel pellets (called MOX fuel for short). The isotope of uranium used in MOX fuel is uranium-238, which is not fissile. MOX fuel would be put into fuel rods and loaded into reactors as a complete or partial substitute for the uranium fuel currently used, which is enriched in the fissile isotope, uranium-235. Of the options considered, MOX fuel (in LWRs and fast reactors) and immobilization (the mixing of plutonium with glass or ceramics), are the two technologies under serious consideration for implementation in the near-term.

The study concludes that the most mature of the technologies considered are those involving "reactor options involving known and demonstrated reactors and MOX fabrication technologies." Immobilization technologies are deemed the next most mature. This judgment is based primarily on the European experience of using MOX in LWRs, and Russian experience in the development of MOX fuel for fast reactors. However, a number of differences between civilian plutonium (used in Europe) and military plutonium make this judgment less certain. Further, the decades of European experience in vitrification (the most developed method of immobilization) of high level radioactive waste appears not to have been factored into the overall judgment of relative technological maturity.

Recognizing the differences that exist between the two governments, the report states that "the United States and Russia need not use the same plutonium disposition technology. Indeed, given the very different economic circumstances, nuclear infrastructures, and fuel cycle policies in the two countries, it is likely that the best approaches will be different in the two countries."[2] Furthermore, each country may use more than one option.

MOX Fabrication[3]

MOX has not been fabricated from weapons-grade plutonium on an industrial scale. Current industrial MOX facilities use plutonium dioxide derived from facilities that reprocess spent power reactor fuel (called reactor-grade plutonium). There are some important differences (see p. 8). Commercial reprocessing plants currently use aqueous technology (that is, acids and other liquid solvents) to separate plutonium and uranium in spent fuel from fission products and from each other. The final product is a plutonium dioxide powder that can be directly used in MOX fuel production. In contrast, most military plutonium is in the form of "pits" which consist of plutonium metal with small quantities of other materials. Further, in the United States and Russia (and probably in other nuclear weapons states as well) weapons plutonium is alloyed with up to one percent gallium. Gallium complicates the MOX fuel fabrication process and therefore it must be almost completely removed from weapons grade plutonium prior to fuel fabrication. Hence, weapons plutonium metal must both be purified and converted into oxide form (not necessarily in that order) before it can be used. Thus, MOX fuel fabrication from weapons-grade plutonium involves steps and processes that are not needed for reprocessed plutonium from power reactor fuel.[4]

The current processes for making weapons plutonium into suitable feed for a MOX fuel fabrication plant use aqueous technology similar to reprocessing, which involves huge liquid waste discharges (for more information on reprocessing, see *E&S* #2). Dry processes that could be used to make plutonium oxide and remove gallium have not yet been developed beyond the laboratory scale. They will take four to five years more to reach the industrial scale needed for plutonium disposition using MOX. The U.S. has declared its intent to use the dry ARIES process to remove gallium from plutonium pits, while Russia is primarily considering aqueous and molten salt technologies (it is cooperating in this work with France).

In the United States, MOX fuel was used in tests in LWRs during the 1960s and 1970s. MOX has been made in the U.S. only in small-scale glove-box facilities.

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REACTOR FUEL

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If the U.S. decides to pursue a MOX option, it would have to construct a new fuel fabrication plant or complete the partially-finished Fuel Materials Examination Facility at the Hanford site in Washington state, built in the 1970s to produce fast breeder reactor fuel.

Russia has a long history of development of MOX fuel for breeder reactors, but Minatom had apparently not considered using MOX in LWRs until the U.S. plutonium disposition program created greater incentives to look at this option. If the fast reactor option were pursued, MOX fuel fabrication would take place at Mayak (near Chelyabinsk), where the partially-built Complex 300 facility is located. If the water reactor option is pursued, plutonium conversion and MOX fuel fabrication facilities would be built at the RT-2 plant in Zheleznogorsk (Krasnoyarsk-26). (For more on Russian MOX fuel fabrication, see p. 6.)

All reactor options will likely take much longer than some vitrification options for putting surplus plutonium into non-weapons-usable-form.

The joint study cites a number of safety precautions necessary in the fabrication of MOX fuel relative to uranium fuel. MOX fuel emits higher gamma radiation and much higher neutron radiation than uranium fuel. Therefore, a separate fresh fuel storage facility designed for MOX only fuel containers for on-site use, and transport equipment for fresh fuel may be necessary. Dust resulting from MOX fabrication is also a concern for worker safety because of the dangers of inhaling plutonium (see health effects article, p. 3).

Reactor Options under Consideration

The time it would take to convert plutonium into non-weapons-usable irradiated fuel in reactors depends on a number of factors:

- the number, size, and type of reactors used
- the average reactor power output
- the percentage of plutonium in the MOX fuel
- the percentage of the reactor core that is loaded with MOX fuel

It should be noted that all of the reactor options are widely expected to take considerably longer than some vitrification options for meeting the goal of putting surplus plutonium into a non-weapons-usable form. In addition, the initial timeframe estimates for reactor options are likely underestimates. The options involving reactor construction are likely to take the longest.

Russia is considering using MOX fuel (a mixture of the oxides of plutonium and uranium) in both fast reactors (also known as fast breeder reactors) and light water reactors (LWRs) for disposition, while the United States declared in December 1996 that it would pursue a "dual-track" strategy of studying the use of MOX in light water reactors as well as immobilization options that do not involve the use of plutonium as a fuel at all.[5] Although the U.S. contributed to the section of the joint report which discusses MOX use in fast reactors, it will not pursue this option. The following sections look at the main options for using LWRs and at Russian possible plans to use MOX in fast reactors.

Existing Thermal Reactors

The U.S. has a large number of operating reactors which could potentially be loaded with MOX. The Department of Energy has obtained expression of interest at one time or another from 18 utilities offering 38 reactors for burning plutonium as MOX. Not all are currently interested, but the situation is fluid. A formal process for utilities to develop proposals and for the Nuclear Regulatory Commission (NRC) to license them to use MOX (if it believes the license applications to be appropriate) is underway.

Russia's options for plutonium disposition using existing thermal reactors are more limited. For safety reasons, the graphite-moderated RBMK reactors and small light water VVER-440 reactors have been excluded from consideration. Only the larger LWR design, the VVER-1000, could be loaded with MOX, and only with a one-third MOX core (in other words, two-thirds of fuel rods in the reactor would be conventional uranium fuel, and the remaining one-third would be MOX). However, a 1995 report by the United States National Academy of Sciences (NAS) notes that even VVER-1000s "do not currently meet international safety standards,"[6] and therefore must be upgraded prior to MOX use.

A further complication is that Russia's seven operating VVER-1000 reactors would not be able to consume 50 metric tons of surplus plutonium within the timeline of 20 to 40 years set by the joint panels. In order to pursue a water reactor option, three partially-built VVER-1000 reactors in Kalinin and Rostov would need to be completed. Another proposal has been to load eleven VVER-1000 reactors in Ukraine with MOX fuel in addition to the Russian reactors. Other possible measures to shorten the time needed for disposition such as extending the reactors' operating lives beyond the currently foreseen 30 years, loading more than a one-third MOX core, increasing the plutonium content of the MOX (beyond the 3.9% current envisioned) would pose additional safety risks that have not been adequately addressed.

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Even with a one-third MOX core, modifications will probably be necessary before VVER-1000s can be loaded with plutonium fuel. The joint report mentions several possible measures, most of which are connected with maintaining reactor control (see below for further discussion of safety issues). The timeline given in the joint report assumes the first VVER-1000 reactor would accept MOX in 2001, and disposition (using 10 reactors with one-third MOX cores and a plutonium content in the MOX of 3.9%) would be completed in 2028.

"Evolutionary Reactors"

Both the U.S. and Russia are considering plans to use newer reactor designs that would be able to take a 100% MOX core because appropriate provisions have been made for additional control. In the U.S. three existing System-80 reactors of the Arizona Public Services Company located at Palo Verde could be used. Russia is also considering construction of up to five VVER-640 (NP-500) reactors (with instrumentation and control systems provided by Siemens). However, even if 100 percent MOX cores were allowed in these reactors, the percentage of plutonium in the MOX would likely be relatively low, so that a larger amount of MOX fuel would have to be fabricated. Hence the advantages from the point of view of speed of disposition of such an approach may be relatively small. The joint report says that "it is believed" that the VVER-640s would be able to take a full MOX core, with 3.7%.[7]

CANDU Reactors

A third option considered by both the U.S. and Russia is the Canadian heavy water reactors (called "CANDU" reactors, which use natural uranium as fuel and heavy water as a moderator and coolant). Unlike LWRs, which are shut down periodically for refueling, these reactors are continually fueled.

CANDU reactors would use 100 percent MOX cores. According to the Atomic Energy of Canada Limited (AECL), CANDU reactors can use 100 percent MOX cores containing from 0.5 to 3 percent plutonium without physical modification,[8] but new licensing would be required because no CANDU reactors are currently licensed to use MOX fuel. CANDU reactors could accommodate 100 percent MOX cores because they have adequate space for any additional control blades (similar to control rods) that may be needed.

CANDU reactors appear to have a number of significant advantages in the use of MOX fuel in terms of controllability. The power production per unit of fuel would be higher with MOX fuel than with natural uranium fuel. With higher power production, the volume of high-level radioactive waste produced by these reactors would be smaller than that now produced by CANDU reactors.

Yet CANDU reactors also possess many disadvantages, such as the need for international transport of MOX fuel, which can be chemically separated into uranium and weapons-usable plutonium in a relatively straightforward manner. Because CANDUs use small fuel bundles and have the potential for on-line removal of fuel bundles (because they are continuously refueled), greater security against theft and diversion of plutonium is necessary. Use of CANDU reactors may also require production of a greater volume of MOX fuel than use of LWRs, since the fuel would contain between 1.5 percent and 2.7 percent plutonium,[9] rather than the 2.5 to 6.8 percent range possible in light water reactors (depending on the specific reactor).[10]

Fast Neutron Reactors

The U.S. discontinued its fast reactor program (also called "breeder" reactors) due to their high cost and concerns over proliferation. However Minatom, because it views plutonium as an energy treasure, has continued extensive research into breeder reactors. Currently, Minatom is operating one fast neutron reactor, the BN-600 at Beloyarsk, loaded with highly-enriched uranium fuel. Four additional fast neutron reactors have been planned, three at Mayak and one at Beloyarsk. Construction was started on two of these (one at each site) in the 1980s, but was halted in the early 1990s because of lack of funds and local environmental opposition. Minatom has recently declared its intention to resume construction and the projects are now undergoing licensing review, but funding is still very uncertain.

Disposition of plutonium can be accomplished in a fast neutron reactor by removing the breeding blankets around the radius of the reactor core, thus turning the reactor from a plutonium producer, to a net burner (note that this does not mean that all of the plutonium is consumed, just that there may be somewhat less in the spent fuel than in fresh fuel). Of course, one problem with breeder reactors from a proliferation standpoint is that the uranium blanket can be inserted and used to make more plutonium, including weapons-grade and super-grade plutonium.

Minatom proposes to build one BN-800 at Mayak for plutonium disposition. BN-800 reactors are designed to take 100% MOX cores, and joint report states that a BN-800 reactor could use 1.6 metric tons of plutonium per year, thus completing disposition of 50 metric tons of plutonium in 30 years. BN-800s are designed to take MOX with reactor-grade plutonium, but, based on calculations that are two decades old, the

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report states that use of weapons-grade plutonium would not significantly change reactor performance. A more recent and independent evaluation would appear to be needed in view of the seriousness of the issue.

Minatom also plans to complete construction of a second BN-800 at Beloyarsk which could be fueled with MOX containing the approximately 30 metric tons of commercial plutonium which have already been separated at the RT-1 plant at Mayak. This second reactor could serve as a backup for plutonium disposition as well. The timeline given in the report foresees construction on the first BN-800 to be completed by 2005, contingent on adequate financing, which has not yet been arranged.

The joint report states that the existing BN-600 could be used as a demonstration reactor for MOX use as early as the year 2000, assuming early funding for conversion and fuel fabrication facilities. However, the BN-600 is only able to handle a partial MOX core, and the report states that additional research would need to be conducted on the safety of using MOX fuel in this reactor with no radial breeding blanket. This reactor could consume about 0.5 metric tons per year, or about 5 metric tons before the end of its operating life in 2010.

Disposition in breeder reactors poses a number of additional safety and proliferation risks. MOX fuel for fast reactors has a significantly higher plutonium content than fuel for LWRs. Because of the higher plutonium content of the fuel, there would be additional plutonium in the spent fuel as well: approximately 20% according to the report. Although Minatom declares the safety and environmental record of the BN-600 to be "excellent," the report also notes that about 30 sodium leaks have occurred in its first 14 years of operation. In addition, the international experience with fast breeder reactors has not been very positive. Safety and technical operating problems or accidents have resulted in the temporary or permanent shut downs of this type of reactor in the United States, Japan, and France.

Light Water Reactor Safety and Licensing Issues Related to MOX

The vast majority of LWRs were not designed to use plutonium as a fuel. While both plutonium-239 and uranium-235 are fissile materials that generate similar amounts of energy per unit weight, there are a number of differences between them as reactor fuels that affect reactor safety. The basic set of concerns relates to control of the reactor. The chain reaction in a reactor must be maintained with a great deal of precision. This control is achieved using control rods usually made of boron and (in pressurized water reactors) by adding boron to the water. Control rods allow for increases and decreases in the levels of reactor power and for orderly reactor shut-down. They prevent runaway nuclear reactions that would result in catastrophic accidents.

It should be noted that while all commercial LWRs have some amount of plutonium in them which is made during the course of reactor operation from uranium-238 in the fuel, the total amount of plutonium is about one percent or less when low enriched uranium fuel is used. When MOX fuel is used, the total amount of plutonium would at all times be considerably higher. It is this difference that creates most reactor control issues.[11]

Changing the fuel can affect the ability of the control rods to provide the needed amount of reactor control and modifications to the reactor may be required before the new fuel can be used. Therefore, changing the fuel in any significant way also requires re-licensing of the reactor.

Several differences between the use of MOX fuel and uranium fuel affect safety:

- The rate of fission of plutonium tends to increase with temperature. This can adversely affect reactor control and require compensating measures. This problem is greater with MOX made with weapons-grade plutonium than that made with reactor-grade plutonium.
- Reactor control depends on the small fraction of neutrons (called delayed neutrons) emitted seconds to minutes after fission of uranium or plutonium. Uranium-235 fission yields about 0.65 percent delayed neutrons, but plutonium yields only about 0.2 percent delayed neutrons. This means that provisions must be made for increased control if plutonium fuel is used, if present control levels and speeds are deemed inadequate.
- Neutrons in reactors using plutonium fuel have a higher average energy than those in reactors using uranium fuel. This increases radiation damage to reactor parts.
- Plutonium captures neutrons with a higher probability than uranium. As a result, a greater amount of neutron absorbers are required to control the reactor.
- The higher proportion of plutonium in the fuel would increase the release of plutonium and other transuranic elements to the environment in case of a severe accident.
- Irradiated MOX fuel is thermally hotter than uranium fuel because larger quantities of transuranic elements are produced during reactor operation when MOX fuel is used.

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Overall, the issues related to reactor control, both during normal operation and emergencies, are the most crucial. Most independent authorities have suggested that only about one third of the fuel in an LWR can be MOX, unless the reactor is specifically designed to use MOX fuel. However, there are some operational problems associated with using partial-MOX cores since MOX fuel is interspersed with uranium fuel. Their differing characteristics regarding control, radiation and thermal energy mean that there are non-uniform conditions in the reactor that can render operation and control more complicated. Some reactor operators claim they can use 100 percent MOX cores without needing to make physical changes to the reactor or control rods. The safety implications of such claims need to be independently verified.

In the U.S. the licensing procedure will be public and likely contentious. In Russia, the role of Gosatomnadzor is still not clear. Will it have sufficient resources?

The details of licensing procedure in the United States are well known. It is an elaborate, public and expensive process that will almost certainly be contentious, as the joint report acknowledges. However, the role of Gosatomnadzor, the Russian nuclear regulatory agency, is not yet clear; nor is the issue of whether it will have sufficient resources to assure a thorough licensing process. The joint report acknowledges that Gosatomnadzor has not yet begun considering MOX licensing issues, and public participation in the licensing process is also a question mark. The report gives no details about the Russian licensing process but says only that "all facilities are assumed to be licensed by appropriate national authorities."

MOX Spent Fuel

Plutonium is both used up and produced when MOX fuel is used in reactors. MOX spent fuel contains more plutonium than conventional spent fuel (that is, spent fuel resulting from loading an LWR with low enriched uranium fuel). Conventional spent fuel from LWRs typically contains about one percent plutonium when it is withdrawn from the reactor. The amount of residual plutonium in MOX spent fuel would depend on the initial plutonium loading (percent of plutonium in the fuel), the burn-up of the fuel, and the configuration in which the fuel is used.

For light water reactors using MOX fuel, the NAS calculates that residual plutonium in the spent fuel would range from 1.6 percent (for a 33% MOX core with 4% plutonium loading) to 4.9 percent (for a 100% MOX core with 6.8% plutonium loading). Ranges of 2.5 percent to 6.8 percent plutonium loading have been suggested. In the case of a CANDU reactor using a 100% MOX core, the percentage of plutonium in MOX spent fuel would be between 0.8 and 1.4 percent for MOX fuel containing 1.2 percent and 2.1 percent plutonium, respectively.[12]

Repository disposal of MOX spent fuel is complicated not only by the higher plutonium content in MOX, but by the larger quantities of transuranic elements in the spent fuel as well. This results in MOX spent fuel being thermally hotter than conventional spent fuel. The presence of greater amounts of transuranic radionuclides like americium-241 also cause persistent higher spent fuel temperatures, and cause the decay of thermal power level to be slower. MOX spent fuel use may therefore require that a host of issues be revisited, such as design of transportation and disposal canisters, and design of on-site spent fuel storage casks. For instance, the higher temperatures may cause storage problems at reactors that have limited storage room in their spent fuel pools. The higher temperature may also result in a need for more repository space, unless a repository is designed to take hotter fuel and withstand higher temperatures. Greater repository space would result in proportionally higher repository disposal costs. In addition, if the amount of residual gallium in MOX spent fuel is too high, it may result in deterioration of the spent fuel cladding, create new issues in evaluating the suitability of a repository, and pose greater risk of groundwater contamination. There are some uncertainties as to the concentration of gallium that might adversely affect spent fuel integrity.

The differences between spent MOX fuel and spent uranium fuel pose many complication for reprocessing as well.

Non-Proliferation Concerns

While much of the official discussion about MOX is that it would "burn" the plutonium, in reality plutonium is both consumed ("burned") and produced in nuclear reactors, as noted above.[13] The main function of plutonium disposition options is not to get rid of all the plutonium. Rather it is to:

- mix plutonium with other materials, usually very radioactive fission products, so that it would be very difficult to re-extract for use in weapons; and
- prevent diversion of plutonium by putting it into highly radioactive storage forms that would be lethal to anyone wanting to steal it.

The joint report judges each plutonium disposition option on non-proliferation criteria, according to its

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timeliness, resistance to theft or diversion, and resistance to retrieval, extraction, or reuse. It was agreed that in order to meet the timeliness goal, the options should provide for disposition of 50 metric tons of plutonium within 20–40 years. The commonly-used yardstick to measure the resistance to theft and diversion of the final form of plutonium after disposition is the so-called "spent fuel standard." This criterion was identified by the NAS in their 1994 report, and means that the plutonium should be as inaccessible to theft, diversion, and re-extraction as plutonium in stored commercial low-enriched spent fuel.

However, there is a major flaw in this standard when judging the long-term security of plutonium. The "spent fuel standard" inherently assumes that the plutonium will remain in spent fuel (or whatever form it has been placed into)—that is, that it be slated for geologic disposal. However, the joint report states that Russian policy does not allow for final burial of plutonium-bearing materials" (which would include spent fuel), but rather the reextraction of plutonium through reprocessing. Minatom has stated very clearly on numerous occasions that it intends to reprocess spent MOX fuel, rendering the "spent fuel standard" effectively meaningless over the long-term. The U.S. appears ready to allow Minatom to reprocess spent MOX fuel from the plutonium disposition program. The joint report notes that ". . . Russia will ultimately recycle any plutonium left in the [MOX] fuel. The U.S. objective of plutonium disposition is satisfied when the isotopics of the weapons-grade plutonium have been altered by irradiation, the fuel attains a significant radiation barrier, and the fuel is stored for stored for several decades before reprocessing."

Financial Issues

Even though plutonium will be used to generate electricity in nuclear reactors, the use of MOX fuel will involve net costs. This is because it is more expensive to fabricate MOX fuel even when the plutonium is free than it is to purchase low-enriched uranium fuel, taking all costs, including raw material costs, into account (for further discussion of costs see *E&S* #1). Using NAS estimates, MOX fuel costs for 50 metric tons of plutonium will be about $2 billion. If the plutonium content of the MOX is 5 percent, the excess costs for disposition of 50 metric tons of plutonium would be about $500 million for MOX fuel fabrication alone, compared to uranium fuel costs. The actual U.S. costs are likely to be far higher because utilities want subsidies to carry out the disposition mission and because many other uncertainties and delays are likely to raise costs.

Overall cost estimates in the U.S. and Russia differ because of differences in the structure of reactor ownership and operation, and because of differing spent fuel policies. In addition to the fuel costs themselves, there would be licensing costs for reactors, transportation and safeguard costs, and reactor construction and modification costs (if required). In general, Russian cost estimates are less certain because of the rapidly-changing economic situation. Because of the policy to reprocess spent fuel, Russian cost estimates include only 50-year storage costs rather than those of final disposal.

1 Almost 12 metric tons of this is non-weapons-grade plutonium produced in military plants.

2 *Joint United States/Russian Plutonium Disposition Study*, September 1996, p. ExSum 2.

3 Unless otherwise mentioned, technical aspects of the use of MOX fuel in reactors are from: Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, National Academy Press, Washington, DC, 1995.

4 Fabrication of lead test assemblies in Europe has been considered in order to allow MOX to be tested in reactors before new fabrication facilities are built, but seems increasingly unlikely.

5 Unless otherwise mentioned, the facts regarding DOE's options are from: *Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement: Summary*, Office of Fissile Materials Disposition, U.S. Department of Energy, December 1996. Information on Russia's options is taken from the *Joint United States/Russian Plutonium Disposition Study*, September 1996. Unfortunately, the report is available only in English. The summary was published in Russian in mid-1997.

6 NAS 1995, p. 137.

7 Joint Report, p. WR-27–WR-29.

8 By comparison, MOX fuel in an LWR core would range from one third to 100% of the core with a plutonium content of 2.5 to 6.8 percent.

9 See NAS 1995, pp. 146–151, for a discussion of advantages and disadvantages of the use of CANDU reactors relative to U.S. LWRs. The 1.5 to 2.7 percent range of MOX has been suggested by the reactor manufacturer.

10 NAS 1995, pp. 121–122.

11 For more information on reactor control, see Science for Democratic Action, Vol. 5, No. 4, February 1997.

12 NAS 1995, p. 252, Table 6-1.

13 Plutonium is formed in commercial reactors from the transmutation of uranium-238 under bombardment by neutrons.

EDITORIAL

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In return, the U.S. would gain a few decades before Russian MOX spent fuel is reprocessed and, one hopes, the full cooperation of Russia on materials accounting. But so far, unlike the United States, Russia has made no declarations of surplus materials, and even more important, no declarations of total military and commercial weapons-usable materials production.

Even the modest goals of the current US MOX disposition program are unlikely to be realized in a timely way. Plutonium disposition using MOX will take at least three decades in Russia and probably about that in the United States. In the meantime, much plutonium will be stored in weapons-usable form. It may take far longer because many people in the United States and Russia oppose the use of MOX fuel, given its potential role in the establishment of a plutonium economy. Intense controversy has been manifest in the media and at the grassroots since the United States declared last December that it would include the MOX option in its disposition plans. In Russia, there has been consistent public opposition (outside the nuclear cities) to the construction of plutonium-processing facilities since 1989. That opposition continues today. Construction of both the BN-800 fast breeder reactor and the RT-2 reprocessing plant were stopped in the late 1980s and early 1990s due to local objections, and a lack of money.

There is considerable grassroots opposition in both the U.S. and Russia to the use of MOX fuel in reactors.

Russia does need a great deal of financial help in securing its weapon-usable materials and putting surplus plutonium into non-weapons form, far more than the United States is now providing. And the United States stands to derive immense security benefits from Russia's actions by providing greater aid. But potential US aid in the creation of a plutonium infrastructure in Russia would be counterproductive for the very same reasons that such expenditures should be avoided in the United States itself.

The US and Russian governments should decide now to vitrify their plutonium and store the resulting glass logs, since Russia does not want to dispose plutonium-bearing materials as waste. One of the gains of the negotiations so far has been that Russia has agreed at least to consider the immobilization option. Vitrification followed by secure storage would be a safer, faster, and cheaper way to address the urgent short-term security goal of putting surplus plutonium into non-weapons-usable form and to gain the time needed to arrive at sound agreements on long-term plutonium security issues.

—ARJUN MAKHIJANI

1 Joint United States/Russian Plutonium Disposition Study, September 1996, p. ExSum-2.

2 *Ibid*, p. WR-35–37.

3 *Ibid*.

IEER is pleased to welcome Robert Brooks to our staff, as assistant coordinator of the global outreach project. In the past year, Robert has worked for the Greenpeace Toxics Campaign (Environmental Justice), and on environmental projects along the United States/Mexico border in West Texas. He is also a jazz musician.

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