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Technical Aspects of the Use of Weapons Plutonium as a Reactor Fuel

by Arjun Makhijani[1]

The U.S. Department of Energy announced on January 14, 1997 that it will study a "dual-track" approach to put approximately 50 metric tons of plutonium rendered surplus by the end of the Cold War into forms not usable for making nuclear weapons.[2] One "track" would vitrify plutonium— that is, mix it with molten glass and other materials. The DOE proposes to use this for 8 to 17 metric tons of surplus weapons plutonium. The other track would convert plutonium into a fuel for nuclear reactors. This involves putting plutonium into an oxide chemical form, mixing it with uranium oxide, and fabricating it into ceramic fuel pellets (called MOX fuel for short). MOX fuel would be put into reactor
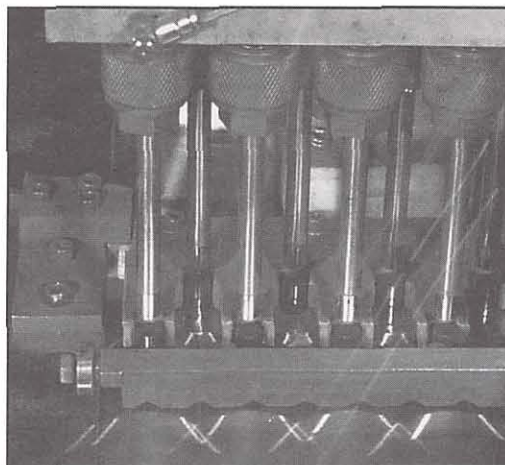

Fabrication of MOX fuel pellets

fuel rods and loaded into reactors as a complete or partial substitute for the uranium fuel currently used.

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.[3] MOX irradiated (or "spent") reactor fuel would still contain from 40 percent to over 70 percent of the original amount of plutonium after it is discharged from the reactor (see table in MOX spent fuel section).[4] This spent fuel contains highly radioactive materials resulting from fission and other nuclear reactions during reactor operation. The main function of both the vitrification and MOX options is not to get rid of all the plutonium. Neither method does that. Rather it is to:

- mix plutonium with other materials so that it would be very difficult to re-extract for use in weapons;

- prevent diversion of plutonium by putting it into highly radioactive storage forms that would be lethal to anyone wanting to steal it. This is automatically accomplished in the case of MOX spent fuel which is mixed with fission products. Plutonium can also be mixed with fission products during vitrification (see centerfold).

This article discusses technical issues related to the use of MOX fuel derived from weapons plutonium in nuclear power reactors.[5] Some economic issues are also discussed.

MOX Fabrication

MOX fuel has never been fabricated on an industrial scale from weapons-grade plutonium. Current industrial MOX facilities (see centerfold) use plutonium dioxide derived

EDITORIAL

Nix MOX

The Department of Energy recently decided to pursue two options for the disposal of surplus military plutonium—vitrification and conversion to mixed oxide fuel. The decision is based on two grounds: 1) The US should proceed in parallel with Russia, which will use its plutonium in this way anyway; and 2) We need a technical insurance policy in case insurmountable technical problems confront plutonium vitrification. Let us consider these two issues in turn.

The argument for pursuing the

MOX option in order to have symmetry with the Russians is not a sound one. Indeed, the timing for such a decision hardly could be worse. The danger of a black market in plutonium is especially acute today because of the enormous economic distress in Russia. This was epitomized by the suicide of the director of Chelyabinsk-70, one of Russia's leading nuclear labs, reportedly because lab personnel had not been paid their meager $50 salaries for months.

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from facilities that reprocess spent power reactor fuel (called reactor-grade plutonium). There are some important differences.

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 (see SDA Vol. 5 No. 1). The final product is a plutonium dioxide powder that can be directly used in MOX fuel production.[6] In contrast, most military plutonium is in the form of "pits" which consist of plutonium metal with small quantities of other materials. In the United States (and elsewhere) weapons plutonium is alloyed with up to one percent gallium. Since relatively pure plutonium dioxide powder is needed for MOX fuel fabrication, the weapons plutonium metal must both be purified and converted into oxide form (not necessarily in that order) before it can be used. It is particularly important to remove the gallium almost completely. Thus, MOX fuel fabrication from weapons-grade plutonium involves steps and processes that are not needed for reprocessed plutonium from power reactor fuel. (See Centerfold diagram and article on gallium.)

The current processes for making weapons plutonium into suitable feed for a MOX fuel fabrication plant use aqueous technology similar to reprocessing. That is, they involve dissolution of plutonium pits in acid

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CORRECTIONS

The label on the pie chart in "Dear Arjun" on p. 12 of SDA Vol. 5 No. 2 should read: UF6 — 95.2% —557,000 metric tons.

The "Scrubber efficiency %" under the second vertical bar in the chart on p. 6 of SDA Vol. 5 No. 3 should read "60," not "80."

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followed by purification of the plutonium and conversion into an oxide form. These aqueous processes produce large amounts of liquid radioactive wastes. For instance, one aqueous process would, for every 30 metric tons of weapons plutonium converted into plutonium dioxide, produce between 800,000 and 900,000 gallons of liquid wastes with specific radioactivity of 20 to 30 picocuries per liter.[7]

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.

MOX has been made in the US only in small-scale glove-box facilities. In order to use the MOX option, the United States 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 breeder reactor fuel. Besides Hanford, a MOX plant could be built at the Pantex Plant in Texas, the Idaho National Engineering Laboratory, or the Savannah River Site in South Carolina. Facilities in Europe may be used for initial MOX fuel loadings, but a US MOX facility would eventually be built.

MOX Utilization

Eighteen power reactors in Germany, France, and Belgium are using MOX fuel. France plans to expand the number of reactors using MOX from nine to 16 reactors by the year 2000. All of these are light water reactors (LWRs). These reactors use ordinary water for slowing down the neutrons needed to maintain the nuclear chain reaction and for cooling the reactor.

In the United States, MOX fuel was used in tests in LWRs during the 1960s and 1970s. But drawing on the

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European experience, dozens of LWRs could potentially be used for plutonium disposition (see below for discussion of safety issues). 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, and average reactor power output

■ the percentage of plutonium in the MOX fuel

■ the percentage of the reactor core that is loaded with MOX fuel

With one-third MOX cores, and 2.5 percent plutonium in the MOX, it would take 8 reactors (of 1,000 megawatts electrical each) about 30 years to complete disposition of 50 metric tons of plutonium. The number of years would be reduced proportionally to the increase in MOX core loading, the number of reactors used, and their power output. Thus, three reactors operating on a full MOX core with 6.8 percent plutonium could complete the disposition in about 10 years.

MOX fuel has not been used in Russian LWRs at all, but has been tested in other reactor designs, including the breeder (or fast neutron) reactor. In 1995, the US National Academy of Sciences (NAS) panel on reactor options for plutonium disposition determined that, for safety reasons, the VVER-440 reactors (smaller Russian light water reactors) and the carbon-moderated RBMK reactors (of the Chernobyl type) were unsuitable for MOX fuel use. Further, while the larger light water reactors, known as VVER-1000 reactors, could be considered for MOX use because their safety standards are higher than other Russian reactors, these reactors "do not currently meet international safety standards," according to the same NAS study.[8] However, the NAS notes that these reactors are being upgraded with

international assistance. There are seven reactors of this type in Russia and ten in Ukraine.

The Russian Ministry of Atomic Energy, Minatom, had not seriously considered the use of MOX in LWRs until the US plutonium disposition program created greater incentives to look at this option (see editorial). Minatom generally favors fast breeder reactors for the use of plutonium fuel. This preference arises from the fact that Russia considers plutonium an energy treasure and still has the long-term goal of creating a plutonium-fueled nuclear energy system using fast breeder reactors and reprocessing plants. Russia is also considering pursuing plutonium disposition using its one fast breeder reactor, BN-600, though that reactor now uses uranium fuel. Further breeder reactor construction in Russia is stalled due to lack of funds.

Canadian heavy water reactors (called "CANDU" reactors, which use natural uranium as fuel and heavy water as a moderator and coolant) are also being considered for disposition of US surplus military plutonium and also possibly for the Russian surplus. Unlike LWRs, which are shut down periodically for refueling, these reactors are continually fueled.

CANDU reactors would use 100 percent MOX cores. Atomic Energy of Canada Limited (AECL), which is the vendor of Canadian reactors, reported to the US NAS committee on plutonium disposition that it has extensive experience in testing the use of MOX fuel containing from 0.5 to 3 percent plutonium. According to the AECL, CANDU reactors can use 100 percent MOX cores without physical modification,[9] 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. 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,[10] rather than the 4 percent or more possible in light water reactors. Canada would use MOX made in the United States.

> *MOX spent fuel would still conatin from 40 percent to over 70 percent of the plutonium concentration in the fresh MOX fuel.*

Specific Plans for MOX in the United States

The MOX options that DOE is considering for disposition of surplus weapons plutonium are:

■ existing light water reactors (LWRs) in the United States

■ partially-completed LWRs which would be completed for the purpose of plutonium disposition

■ evolutionary LWRs (new reactors built by the DOE for the explicit purpose of plutonium disposition)

■ CANDU reactors

Eighteen US utilities have expressed interest in using MOX fuel. Some of them have also indicated an interest in making tritium for the nuclear weapons program. (See list in centerfold.)

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.

Changing the fuel can affect the ability of the control rods to provide the needed amount of reactor control. Hence, 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.

REACTOR CONTROL

Control of a nuclear reactor is accomplished through control of the rate of fission reactions in the reactor. Power output is directly proportional to the rate of fission reactions. When a reactor is critical, it has a sustained power output. When the reactor is supercritical, the power output is increasing, and when it is subcritical, power decreases until the reactor shuts down. **Reactivity** is a way of describing the criticality condition of the reactor. Positive reactivity means a supercritical reactor, zero reactivity means a critical reactor, and negative reactivity means a subcritical reactor.

The rate of fission in a reactor is controlled through the insertion and withdrawal of neutron-absorbing material, such as boron, in the form of control rods which are interspersed with the fuel rods. (In pressurized water reactors boron can also be added chemically to the water.) By lowering and raising the control rods, which absorb neutrons available for fission reactions, the rate of fission reactions, and hence the reactor's power output, can be controlled.

A particular property of fission makes it possible to achieve reactor control. While most neutrons emitted from the fission process are released immediately, (known as **prompt neutrons**), some are emitted seconds to minutes later.

These are known as **delayed neutrons**. In uranium-235 fission in a thermal reactor, the proportion of delayed neutrons is about 0.65 percent. In the case of plutonium-239 fission, the proportion is only 0.2 percent.

If the reactivity stays below the proportion of delayed neutrons, the reactor can be controlled. But if it increases above this proportion, control is lost and there will be a runaway nuclear chain reaction until the reactor is destroyed, as happened at Chernobyl. A smaller fraction of delayed neutrons can affect reactor control during emergencies, unless the reactor has appropriate control equipment.

Plutonium tends to absorb neutrons efficiently not only at the neutron energies for which light water reactors are designed, but also at a somewhat higher neutron energy. Heating of the fuel above normal operating temperatures tends to increase the rate of plutonium fission, which in turn increases the temperature. This phenomenon, called a **positive temperature coefficient of reactivity** (a positive feedback loop of reactivity and temperature) can cause problems for reactor control. The problem can be addressed by adding neutron absorbers, like erbium, with the ability to absorb neutrons at particular thermal energies.[11]

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 (see box on reactor control). 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

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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. (See box on reactor control.)

■ 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.

Overall, the issues related to reactor control, both during normal operations 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.

Some newer reactors, however, have been designed for the use of a 100 percent MOX core because during reactor design appropriate provisions were made for additional control. There are only three reactors of this type in the US: the three System-80 reactors of the Arizona Public Services Company located at Palo Verde. These reactors are under consideration for disposition of surplus US plutonium. However, even if 100 percent MOX cores were allowed, the percentage of plutonium in the MOX would likely be on the low side, 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.

MOX Spent Fuel

Using reactors to dispose of surplus weapons plutonium will not result in complete elimination of the plutonium. MOX spent fuel contains more plutonium and is thermally hotter than conventional spent fuel (that is, spent fuel resulting from loading an LWR with low enriched uranium fuel). Conventional spent fuel from light water reactors 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 percent MOX core with 4 percent plutonium loading) to 4.9 percent (for a 100 percent MOX core with 6.8 percent plutonium loading). Ranges of 2.5 percent to 6.8 percent plutonium loading have been suggested.[12] In the case of a CANDU reactor using a 100 percent 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.[13] (See table.)

Technical issues related to MOX spent fuel disposal

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

COMPARISON OF PLUTONIUM IN SPENT FUEL FOR VARIOUS REACTORS USING URANIUM AND MOX FUEL

type of fuel	type of reactor	% of fuel that is MOX	% Pu in fresh fuel	% Pu in spent fuel
Uranium	LWR	NA	NA	0.9
MOX	LWR	33	4	1.6
MOX	LWR	100	4	2.6
MOX	ELWR	100	6.8	4.9
MOX	CANDU	100	1.2	0.8
MOX	CANDU	100	2.1	1.4

Adapted from: NAS 1995 p. 252 table 6.1.

LWR: light water reactor
ELWR: evolutionary light water reactor
CANDU: Canadian deuterium-uranium reactor (which would use MOX fuel)
MOX: mixed [uranium-plutonium] oxide fuel

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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 (a possibility being considered for Yucca Mountain). 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 (see box on gallium in the Centerfold), 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.

> *If the amount of residual gallium in MOX spent fuel is too high, it may result in deterioration of the spent fuel cladding.*

Financial Issues[14]

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. The cost of LEU fuel estimated by the NAS is about $1,400 per kilo-gram. MOX fuel fabrication using a new MOX plant was estimated at about $1,900. (Estimates in 1992 dollars.) If the MOX fuel contains 5 percent plutonium, 50 metric tons of surplus weapons plutonium would yield 1,000 metric tons of MOX fuel. This would mean a fuel fabrication cost of about $1.9 billion in 1992 dollars, or over $2 billion in 1996 dollars.

The costs of MOX fuel fabrication may turn out to be higher than those estimated by the NAS. While an estimate of the costs of converting plutonium pits to oxide was included in the 1995 NAS report, there was no explicit treatment of the gallium problem. This was in part because DOE experts felt at the time that gallium might be left in the final MOX fuel. Subsequently, the severity of the problems created by gallium in the sintering process (the final step in MOX fuel fabrication) was discovered. Other potential problems that gallium could cause also came to light. Hence, it became necessary to separate the gallium from the plutonium, but these costs are not explicitly accounted for. In sum, the financial allowance for pit conversion to oxide made by the NAS may or may not be sufficient.

DOE policy appears to be that utilities would be sold MOX fuel at the cost of equivalent uranium fuel. Using the NAS cost estimates, this would make the net cost of making MOX about $500 million (for 50 metric tons of plutonium). DOE estimates of net MOX costs are generally lower.[15] In addition, there would be licensing costs for reactors, transportation and safeguard costs, and reactor modification costs (if such modifications are required).

It is difficult to estimate the total costs of plutonium disposition using MOX, but the DOE puts the estimate at about $2 billion for disposition in existing LWRs on the assumption that no subsidies to the utilities would be required.[16] However, the utilities want subsidies—that is, they want compensation well beyond out-of-pocket costs. For instance, Jack Bailey, Vice-president of the Palo Verde nuclear plants, which can use 100 percent MOX cores (and are therefore leading candidates for MOX fuel use), stated his company's requirements for added compensation quite bluntly and publicly in March 1996:

> We also stressed in our letters to DOE that any initiative should address potential benefits to ratepayers and shareholders . . . .
>
> The benefits must be substantial. If not, the entire proposition is a non-starter.
>
> What I mean specifically is that any agreement involving Palo Verde would require more than the incremental costs associated with using MOX fuel instead of uranium. That kind of payment would be insufficient.[17]

According to a survey by General Electric, other utilities have also expressed requirements for compensation far in excess of direct cost reimbursement. Specifically, since many nuclear reactors will rapidly become uneconomical as electricity is deregulated in the next few years, they would require subsidies in order to be kept in operation for the MOX disposition track.[18] For licensing and/or safety reasons, the newer reactors are generally more likely to be selected for MOX use. But the newer reactors are far more expensive than the older ones, which would mean the MOX option could involve huge subsidies. Licensing delays would add to these costs.

Finally, the overall costs of MOX spent fuel disposal may be higher than that of uranium spent fuel, possibly by as much as a factor of two.[19] The Final Programmatic Environmental Impact Statement says nothing about added MOX spent fuel disposal costs.

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At the nearby nuclear weapons industrial facility known as Chelyabinsk-65, more than 60,000 pounds of plutonium are stored in 12,000 stainless steel containers the size of thermos bottles. Two or three of them contain enough plutonium to make a nuclear bomb hundreds of times more powerful than the bomb that destroyed the federal building in Oklahoma City.

Moreover, Russia continues to separate more plutonium from used nuclear-reactor fuel in a chemical-processing facility. The RT-1 plant at Chelyabinsk-65 is separating one to two tons of weapons-usable plutonium every year. The Russian nuclear establishment proclaims plutonium to be a national energy treasure but is not yet using it as a reactor fuel. The one thing that Russia is missing to perpetuate its current plutonium policies is a plant to fabricate plutonium into a reactor fuel—that is, a MOX plant (see main article).

If Russia builds such a plant it could not only use it to make surplus weapons plutonium into fuel, it also could use it to make MOX fuel out of commercial plutonium. This would encourage Russia to continue operating its reprocessing plant to separate more plutonium, creating greater risks of diversion. Instead of encouraging Russia to stop the production and accumulation of weapons-usable plutonium, a US policy favoring MOX fuel would help to perpetuate it.

At an October 1996 international technical meeting of government officials in Paris, Russian officials refused to rule out the commercial use

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In fact, it assumes that there would be no added costs by stating that MOX spent fuel disposal costs are covered under the Nuclear Waste Policy Act, which did not anticipate higher costs associated with MOX spent fuel. However, as DOE's proposal now stands, any additional costs would be borne by the taxpayer.

Overall, the DOE estimates that using MOX fuel in existing reactors to dispose of 50 metric tons of weapons plutonium would cost about $2 billion, while vitrifying the plutonium would costs about $1.8 billion.[20] Given the many uncertainties surrounding plutonium disposition, this difference in cost estimates is not significant. However, as we have discussed above, DOE's estimates of MOX disposal costs will, in all likelihood, turn out to be severe underestimates. Therefore, the implication in DOE's analysis that MOX and vitrification disposition costs are comparable is likely to be wrong, and the MOX option will probably wind up being far more expensive.

[1] IEER would like to acknowledge the contributions of former Herbert Scoville Jr. Peace Fellow, Yurika Ayukawa, who helped provide some background information for this issue of SDA through her newsletter, "Yurika's E-Mail Pu-Update."

[2] 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. Copies are available upon written request from: Office of Fissile Materials Disposition, MD-4, Forrestal Building, U.S. Department of Energy, 1000 Independence Ave. SW, Washington DC, 20585.

[3] Plutonium is formed in commercial reactors from the transmutation of uranium-238 under bombardment by neutrons. Since plutonium separated from commercial reactor fuel can be fashioned into nuclear warheads, this material poses a proliferation risk, as does plutonium from the nuclear weapons program.

[4] Plutonium in fresh MOX fuel would be weapons-grade and contain about 6 percent of the non-fissile isotope, Pu-240. Plutonium in MOX spent fuel would be reactor-grade with over 20 percent Pu-240. However, reactor-grade plutonium, if separated from spent fuel, can also be used to make nuclear weapons. The change in isotopic composition of plutonium reduces the yield for a given amount of plutonium and makes the exact yield less predictable.

[5] 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.

[6] If separated reactor grade plutonium is stored too long (more than a few years) then a considerable portion of the plutonium-241 decays into americium-241, which is a strong gamma-emitting radionuclide. This makes MOX fuel fabrication more hazardous and hence the Am-241 must be removed by further processing prior to fuel fabrication.

[7] Calculated from data in materials from a talk by Carl A. Beard, "Issues Associated with Making Mixed-Oxide Fuel from Weapons Plutonium," Los Alamos National Laboratory, given at the Mixed Oxide Fuel meeting, Austin, Texas, August 29, 1996. The data show a waste generation of 500 to 600 liters per kilogram of plutonium treated, which would have to be diluted by a factor of two in order to decrease the radioactivity concentration to the 20 to 30 picocuries per liter needed to meet discharge limits. This would result in 1,000 to 1,200 liters of waste per kilogram of plutonium treated. Calculations are rounded to one significant figure. There are 3.78 liters in a gallon.

[8] NAS 1995, p. 137.

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

[10] 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.

[11] For more information on technical issues related to nuclear power in the United States, see Arjun. Makhijani and Scott Saleska, *The Nuclear Power Deception*, (Takoma Park, MD: Institute for Energy and Environmental Research, April, 1996.)

[12] NAS 1995, pp. 121–122.

[13] NAS 1995, p. 252, Table 6-1.

[14] For convenience of cost comparisons between vitrification and various reactor options, each option discussed in this section is evaluated for 50 metric tons of surplus weapons plutonium.

[15] US Department of Energy, 1996, *Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition*, DOE/MD-0003 Rev. 1, (Washington, DC: October 31, 1996), p. 4–5.

[16] Secretary of Energy Hazel O'Leary made an explicit commitment during the Record of Decision press conference on January 14, 1997 that there would be no compensation beyond actual added costs incurred by utilities. Press conference notes by Arjun Makhijani, January 14, 1997.

[17] Jack Bailey, remarks made at the 3rd International Policy Forum: "Deploying the Reactor/MOX Option for Plutonium Disposition Within the Current System of U.S. and Canadian Nuclear Reactors — Regulatory, Policy Impediments," Lansdowne, VA., March 21, 1996.

[18] Edwin S. Lyman, "Weapons Plutonium: Just Can It," *The Bulletin of the Atomic Scientists*, November/ December 1996. This article provides a description of the can-in-canister vitrification technology as well as an insightful analysis of the utility expectations of subsidies in light of financial issues related to impending electricity deregulation.

[19] NAS 1995, pp. 288–289. The NAS states that the costs could be the same as conventional spent fuel or higher by as much as a factor of two.

[20] DOE 1996, p. 4–10.

A CENTERFOLD FOR TECHNO-WEENIES

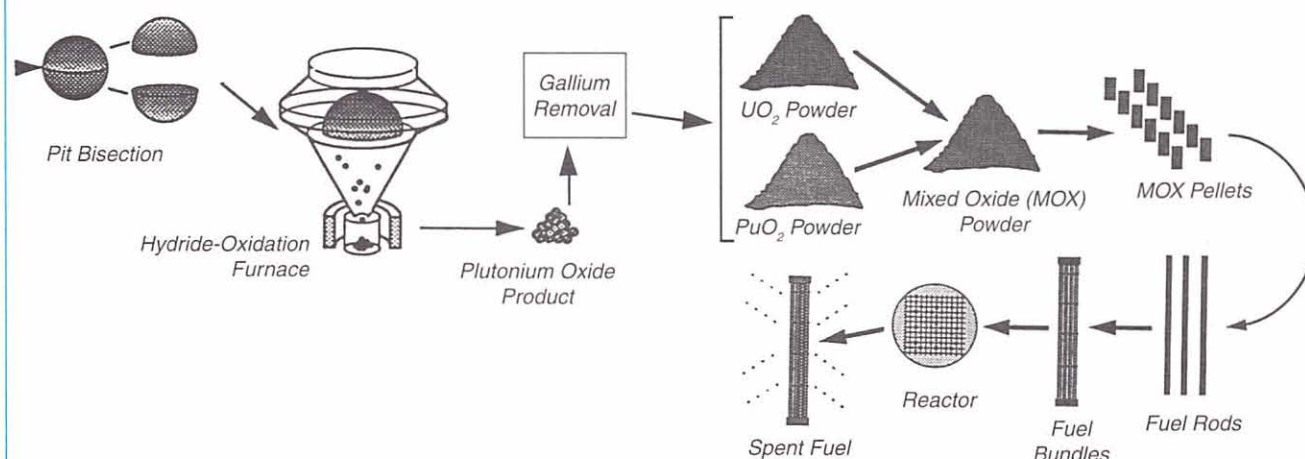# MOX Fuel Fabrication from Weapons Plutonium

The process for fabricating MOX fuel from weapons plutonium has different characteristics than the process that uses plutonium derived from a commercial reprocessing plant. Commercial PUREX (Plutonium-Uranium Extraction) reprocessing is generally arranged to yield plutonium in the form of an oxide as an end product (see SDA Vol. 5, No. 1). This plutonium dioxide powder can be mixed directly with uranium dioxide to make the mixed oxide that is fabricated into fuel pellets.

Plutonium pits from dismantled warheads consist primarily of plutonium metal, which must be converted to an oxide before it can be made into MOX fuel. Moreover, gallium, which is an alloying material added to plutonium, must be removed and the plutonium converted into an oxide form prior to MOX fuel fabrication (see box on gallium, p.11). Other constituents of plutonium pits, which are still classified, must also be removed. Plutonium dioxide suitable for MOX can be obtained from metal pits by currently-available aqueous processes. These involve dissolving

PLUTONIUM PIT CONVERSION AND MOX FUEL FABRICATION PROCESS

Pit Bisection

Hydride-Oxidation Furnace

Plutonium Oxide Product

Gallium Removal

UO_2 Powder

PuO_2 Powder

Mixed Oxide (MOX) Powder

MOX Pellets

Spent Fuel

Reactor

Fuel Bundles

Fuel Rods

Adapted from: US DOE

COMMERCIAL MOX FABRICATION FACILITIES CURRENTLY IN OPERATION

	Year operation began	Capacity (metric tons/yr.)	Operator
MOX fabrication facility, Cadarache, France	1963	15	Commissariat à l' Energie Atomique (CEA)
Dessel Plant, Dessel, Belgium	1973	35	Belgonucléaire
Melox Plant, Marcoule, France	1994	115	Cogéma
MOX fabrication plant, Sellafield, Britain	Start-up planned for 1997	120	British Nuclear Fuels, Limited (BNFL)

Adapted from: Yurika Ayukawa, "Fissile Material Disposition and Civil Use of Plutonium," *Yurika's E-Mail Pu Update*, Issue No. 2, October 3, 1996.

plutonium pits in acid, processing the liquids to separate various constituents, and finally, processing the separated plutonium to form plutonium dioxide powder, usable for MOX fabrication.

Aqueous processes, however, produce large quantities of liquid radioactive wastes. One process involving nitric and oxalic acids would, for instance, generate well over half a million of gallons of such wastes per 30 metric tons of plutonium converted into oxide form. Dry processes can greatly reduce waste streams, but they have yet to be demonstrated beyond the laboratory scale. (The box on gallium has more information on these processes.)

UTILITIES THAT HAVE EXPRESSED AN INTEREST IN USING MOX FUEL AND/OR PRODUCING TRITIUM

This list was released by the Department of Energy and includes utilities which responded to DOE's "Request for Expressions of Interest for Tritium Production," released December 15, 1995. Responses also include expressions of interest in plutonium disposition.

Utility	Reactor(s)
Arizona Public Service Company*	*Palo Verde Unit 1, 2, and 3*
Centerior Energy (OH)*	*Perry[1]*
Duke Power Co. (NC, SC) and Commonwealth Edison Co. (IL)	*McGuire Unit 1 and 2, Catawba Unit 1 and 2, Braidwood Unit 1 and 2, Byron Unit 1 and 2, LaSalle County Unit 1 and 2*
Entergy Operations Inc. (MS, LA)	*Grand Gulf Nuclear Station, River Bend Station*
Florida Power and Light Co.*[2]	*St. Lucie Unit 2*
Georgia Power Co.*	*Alvin W. Vogtle Unit 1 and 2*
IES Utilities Inc. (IA)	*Duane Arnold Energy Center*
Illinois Power Co.*	*Clinton Power Station*
Niagara Mohawk Power Co. (NY)*	*Nine Mile Point Unit 1 and 2[1]*
North Carolina Municipal Power Agency No. 1 and Piedmont Municipal Power Agency (SC)*	*Catawba Unit 2*
PECO Energy Co. (PA)	*Limerick Unit 1 and 2, Peach Bottom Unit 2 and 3*
Southern Nuclear Operating Co. (AL)	*Joseph M. Farley Unit 1 and 2*
Tennessee Valley Authority (AL)*	*Bellafonte Unit 1 and 2[3]*
Virginia Power*[4]	*North Anna Unit 1 and 2, Surry Unit 1 and 2*
Wisconsin Public Service Co.*	*Kewaunee*
Washington Public Power Supply System	*WNP-2*

Total: 18 reactor operators, 38 reactors.
(Reactor operators listed together have been counted separately.)

Note: The list does not include utilities which may have expressed interest since this list was compiled.

* Utilities also expressing interest in tritium production.

[1] Boiling water reactors. DOE target design precludes consideration for tritium production.

[2] The Florida Power and Light Co. is no longer under consideration for MOX fuel use. See Edwin S. Lyman, "Weapons Plutonium: Just Can It," *The Bulletin of the Atomic Scientists*, Vol. 52 No. 6, November/December 1996, p. 49.

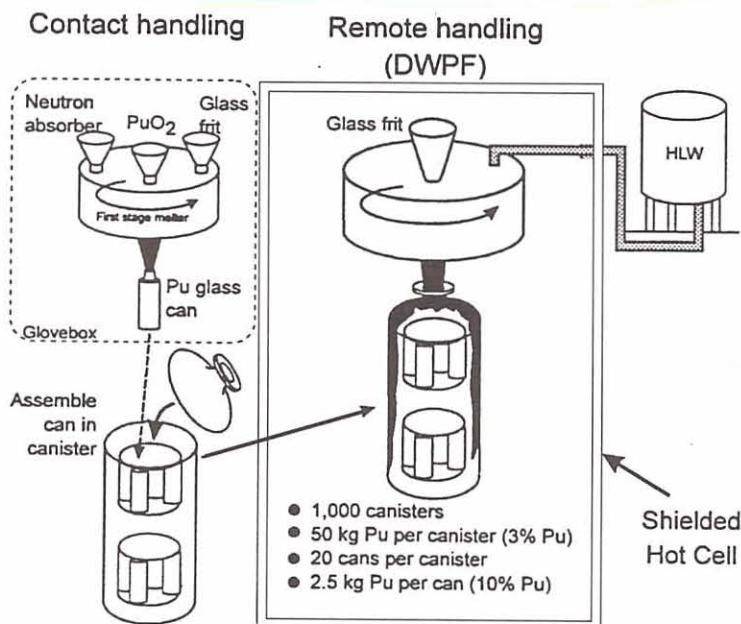[3] Partially complete reactors.

[4] Virginia Power has written to Greenpeace stating that it has withdrawn its interest in plutonium disposition and tritium production.

Source: US DOE

COMPARISON OF VITRIFICATION OPTIONS

Option	Advantages	Disadvantages
1. Vitrification of plutonium alone	Simplest and most rapid option	Least technical difficulty for plutonium re-extraction; low resistance to theft
2. Vitrification of plutonium with fission products	Highest initial proliferation-resistance both as regards difficulty of theft and of re-extraction	Likely to take the longest time; in a few centuries proliferation resistance declines to approximately that of vitrification of plutonium alone
3. Vitrification of plutonium with actinides or rare earths	Moderate to high technical proliferation resistance; can be done rapidly; durable proliferation resistance	Low resistance to theft; re-extraction less difficult than with Option 2
4. Option 3 with a gamma-emitting canister	High technical proliferation resistance; can be done rapidly; durable proliferation resistance; high resistance to theft	Re-extraction less difficult than with Option 2
5. Can-in-canister vitrification (see diagram)	Very high initial proliferation-resistance both as regards difficulty of theft and of re-extraction; can be done more rapidly than option 2	In a few centuries proliferation resistance declines to approximately that of vitrification of plutonium alone

CAN-IN-CANISTER VITRIFICATION

Contact handling

Neutron absorber　PuO$_2$　Glass frit

First stage melter

Glovebox

Pu glass can

Assemble can in canister

Remote handling (DWPF)

Glass frit

HLW

- 1,000 canisters
- 50 kg Pu per canister (3% Pu)
- 20 cans per canister
- 2.5 kg Pu per can (10% Pu)

Shielded Hot Cell

For additional information on Vitrification see IEER's book, *Fissile Materials in a Glass Darkly.* Ordering information on page 12.

Source: US DOE

Editorial, *from page 7*

of a MOX plant built for the purpose of converting plutonium into non-weapons usable form. Moreover, Russia's nuclear establishment is going along with the idea of using MOX fuel in its light water reactors mainly because the US has promoted that option. The Russian idea for MOX has been to use it in breeder reactors, and Minatom wants the MOX plant that might be built there to have the capability not only to fabricate light water reactor (LWR) MOX fuel, but also breeder reactor MOX fuel (which contains a higher proportion of plutonium).

So far, US-Russian post-Cold War relations on nuclear issues have involved the United States only in

Gallium in Weapons-Grade Plutonium and MOX Fuel Fabrication

by Dr. James W. Toevs,
*Project Leader for Nuclear
Materials Disposition*

Dr. Carl A. Beard, *Project
Leader for Nuclear Fuels
Research and Development*

Los Alamos National Laboratory

Gallium is used as an alloying element in the manufacture of plutonium pits in concentrations of up to 1 percent. (This information about gallium was declassified about one year ago.) Gallium at such concentrations presents various issues for MOX fuel fabrication and use. Therefore its concentration must be greatly reduced if the MOX option for plutonium disposition is pursued.

MOX fuel is essentially a ceramic material, prepared by sintering oxides of uranium and plutonium, which are initially both in the form of fine powders. At high concentrations, gallium affects the sintering behavior of the ceramic. Since plutonium pits do not all have the same concentration of gallium, the sintering process parameters would have to be adjusted as the gallium concentration changed (undesirable in an industrial-scale operation) unless the gallium was reduced to an acceptable level prior to fabrication.

In addition, there may be issues with using MOX fuel with excessive gallium concentration as a reactor fuel. While gallium would not interfere with the chain reaction (it is not a good neutron absorber), gallium metal chemically attacks zirconium. The tubes into which fuel is inserted are made of a zirconium alloy. The presence of excessive gallium in spent MOX fuel could therefore cause its deterioration and hence possibly cause waste management problems. There may also be other problems with the presence of large amounts of gallium, but it has not yet been established whether these are significant concerns. For instance, gallium may affect fission product migration in spent fuel.

Technologies for gallium removal and plutonium oxide production

The currently available fully developed technology for gallium removal and plutonium oxide production is an aqueous process which results in the generation of large quantities of liquid radioactive wastes. For this reason, it would be highly desirable to avoid using the aqueous process and in its stead use the dry processes being developed at the Los Alamos and Livermore National Laboratories.

Two approaches for converting plutonium pits into oxide are being investigated at Los Alamos and Lawrence Livermore National Laboratories. One is a process that converts plutonium metal into a hydride form, and then the hydride is oxidized. Another process would convert plutonium metal into a hydride, the hydride into a nitride (PuN), and thence to an oxide. After either process, gallium is also in oxide form, Ga_2O_3. (To remove plutonium and provide a metal product, the hydride is simply heated to drive off hydrogen, leaving a plutonium metal ingot.) These approaches are part of the "ARIES" process for pit disassembly and conversion.

In each case the gallium would be removed after plutonium oxide has been made. The gallium is driven out by reduction and conversion to a sub-oxide form (Ga_2O) in an atmosphere of argon with 6 percent hydrogen. The sub-oxide of gallium rapidly volatilizes from the plutonium-gallium mix at 1100°C. (Gallium volatilizes at lower temperatures, but at slower rates.) This process, which has been tested at the laboratory scale, gets gallium down from about 1 percent to ~200 parts per million. MOX fuel, which typically contains about 5 percent plutonium, would therefore have a gallium content of ~10 parts per million. Current thinking in the MOX fuel fabrication industry in Europe is that this level of gallium content is probably acceptable because it is comparable to or beneath the level of other contaminants, now present in MOX fuel used in European reactors, that also might interact with cladding.

The hydride process for converting plutonium to a metal ingot is now standard in plutonium processing at Los Alamos and Livermore. However, the conversion process to oxide and the gallium removal processes are not yet fully developed. The main problem with oxide conversion is managing the release of heat in converting the hydride to oxide, while maintaining the oxidation rate high enough to provide good production throughput. If the hydride becomes too hot, some hydride will be converted to plutonium metal, forming "clinkers." Similarly, in conversion of the nitride to oxide, overheating can cause formation of large, hard clumps of oxide. Engineering is underway to remove the excess heat efficiently, allowing shorter oxidation times and greater throughput.

Los Alamos and Oak Ridge National Laboratories are doing additional experiments with migration and diffusion of gallium in MOX to see if there is a need to remove gallium more completely. In that case, a backup process involving an aqueous technology (using nitric acid dissolution, ion exchange or solvent extraction to remove the gallium, and oxalate precipitation, for instance) would be used to process the plutonium dioxide that comes from the ARIES process.

No problems involving gallium that would affect plutonium vitrification have been identified. The matter is under study at Livermore National Laboratory, but no problems are anticipated at this time.

activities that increase nuclear safety. That would not be the case with MOX fuel use, which would raise new safety issues. Satisfactory resolution of those issues would be difficult, especially given the weak financial condition of many nuclear power plants, many of whose customers cannot pay their electricity bills. Moreover, Russia's agency for nuclear regulation, Gos-atomnadzor, is politically weak relative to Minatom and the Defense Ministry. This raises questions about the integrity with which licensing for MOX fuel use in Russian LWRs might be done. Given all these problems, an accident in a Russian LWR while it was using MOX fuel could cause

serious damage to US-Russian relations and to plutonium disposition in Russia, where timely progress is most crucial.

The other argument that the DOE uses for pursuing the MOX option is that of a technical insurance policy. While the idea of such insurance is a sound one, it does not require the US to pursue a MOX option. A similar result can be achieved without the negative proliferation consequences by pursuing ceramic immobilization of plutonium as a back-up to vitrification, and by building three or four vitrification pilot plants using different glass-making technologies.

Ceramic immobilization has a great deal in common with MOX technology, so the technological

insurance aspects are achieved by developing it. The uncertainties surrounding vitrification are, moreover, quite low, because there is already considerable global experience with vitrification of highly radioactive waste. Moreover, reactor safety issues and the vigorous public opposition to the use of MOX would not be obstacles for ceramic immobilization. When these problems are taken into account, it appears that the MOX option is a poor choice for an insurance policy.

A great deal of the impetus for pursuing the MOX option comes from concern in Russia about jobs in nuclear weapons plants, but this can and should be addressed in a manner compatible with non-proliferation objectives. A sound plutonium management and disposition program would first carefully account for and improve the storage of all plutonium, both military and commercial, at a level of effort far greater than the current bilateral program. Second, it would build several pilot vitrification plants and pursue ceramic immobilization research and development vigorously. Two of the pilot plants could be joint Russian-US facilities, one being built in the US and the other in Russia. Russia's greater experience with vitrification (they have had a plant for vitrifying radioactive waste in operation in since 1991) should be a great asset to this joint effort.

The United States should declare immobilization to be the sole approach it will use for all its surplus plutonium and encourage Russia and other countries to do the same. Practically all parties agree that plutonium is not an economical energy source today. But if the Russians insist that plutonium may be an economical energy resource in the future, an understanding might be that the plutonium could one day be re-extracted from the glass (after mutual US-Russian agreement that it had become economical) under international safeguards

SELECTED PUBLICATIONS

Prices include shipping and handling within the U.S. Contact IEER for international orders.

IEER Books

Nuclear Wastelands: A Global Guide to Nuclear Weapons Production and Its Health and Environmental Effects. MIT Press, 1995 • Hardbound, 666 pages • List price: $55 • SDA readers price: $40

Fissile Materials in a Glass Darkly (*Also available in Russian*)
IEER Press, 1995 (Currently out of print. Photocopies $5)

High-Level Dollars, Low-Level Sense Apex Press, 1992
(Currently out of print. Photocopies $5)

IEER Reports and Factsheets

The Nuclear Power Deception	$15
Risky Relapse into Reprocessing	$10
Tritium	$ 3
Fissile Material Basics	Free
Fissile Material Health and Environmental Dangers	Free
Physical, Nuclear and Chemical Properties of Plutonium	Free
IEER Yellow Pages (basic technical reference guide)	Free

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Remember! Many of our factsheets, newsletters, and reports are available on our webpage: http://www.ieer.org/

It Pays to Increase Your Jargon Power
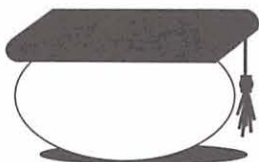
by Dr. Egghead

1. Ceramic immobilization

a. What Medusa practiced on her victims before she mastered turning them into stone.

b. What a sculptor has achieved after creating something too big to be moved.

c. The practice of using Velcro to attach expensive pieces of pottery to display stands so viewers will not knock them off.

d. The process of mixing plutonium in a ceramic medium to prevent its re-use in weapons. The process can also be applied to other radioactove materials.

2. Sinter

a. In word processing: to position text on a page so that it is equidistant from the left and right margins.

b. A type of block used in construction of bookshelves in college dorms.

c. To bond into a cohesive mass by exposing to extremely high temperatures. In the case of MOX fuel fabrication, sintering refers to the binding of uranium and plutonium oxides which are in the form of fine powders.

3. CANDU

a. Denoting proficiency in accomplishing tasks, as in "He's a real CANDU kinda guy."

b. A Hindu of Canadian descent.

c. Personalized license plate for couples named Carmen and Ulysses.

d. Abbreviation for Canadian Deuterium-Uranium reactor, which is a reactor that uses deuterium oxide (D_2O), or "heavy water" as a moderator and coolant.

4. Delayed neutrons

a. Neutrons that missed their bus in the morning.

b. Short for "de layed-back neutrons," abundant in California hot tubs.

c. Neutrons resulting from an atomic fission which are released from some short-lived fission products after fission occurs. This causes a delay between the fission and the emission of the neutron. In a typical light water reactor, delayed neutrons make up about two-thirds of one percent of the neutrons released during fissioning. Delayed neutrons are key to the control of a nuclear reactor.

Gallium discovers the gall bladder.

5. Gallium

a. One of the Knights of the Round Table, known for his ability to bring people together.

b. Name of the ancient Roman physician that discovered the gall bladder.

c. Chemical found only in brazen individuals, which gave rise to expressions such as, "Well Ebinezer certainly has a lot of gall!"

d. A metal, atomic number 31, discovered by Paul Émile Lecoq de Boisbaudran in 1875 and named for the Latin word for France (Gallia). It is used as an alloying material in the manufacture of plutonium pits in nuclear warheads.

Answers: 1) d; 2) c; 3) d; 4) c; 5) d.

NUCLEAR NEWS

■ Citizens Against Nuclear Trash (CANT), a group opposing a proposed uranium enrichment plant in Louisiana, has won the first round of its battle. The administrative judicial panel of the Nuclear Regulatory Commission (NRC) reviewing the case found that the NRC's Environmental Impact Statement was inadequate and that the applicant, a subsidiary created by large corporations, had not shown adequate financial qualifications for building the plant.

IEER provided technical assistance to CANT.

"Dear Arjun"

Dear Arjun:

What is vitrification, and does it work?

— Vittorio Vitalin,
Vadalia, VT

The term "vitrification" comes from the Latin *vita*, meaning "life," and the Old English *ryfe*, meaning "widespread" or "common." In ancient translations of Genesis, God instructs Adam and Eve to "Be fruitful and vitrify," and this populating of the earth was known as "vitrification." Modern translations dropped the term, however, after powerful lobby groups from Florida insisted that God told Adam and Eve to "Be fruitful and citrify." Distressed at the commercialism of the translation, biblical scholars changed the term to "multiply," and in so doing, warmed the hearts of mathematicians everywhere.

In the nuclear arena, vitrification refers to the process of mixing radioactive waste, mixed waste, or materials such as plutonium with molten glass and forming them into glass marbles, blocks, logs, or frit (fragments). The first pilot vitrification plant was built in Marcoule, France in 1967 to vitrify highly radioactive waste. Since that time, vitrification on a commercial scale has been successfully carried out in Russia, the United States, France, and several other countries.

Vitrification plants are typically designed to process high level waste, but plutonium can be vitrified as well. Vitrification is being considered as one option for putting surplus weapons plutonium in a non-weapons usable form (the option IEER recommends—see editorial). In this

"Be friutful and vitrify."

process, plutonium, in concentrations in the range of a fraction of one percent to several percent, would be mixed with a large quantity of molten glass and poured into metal containers to form glass logs, which can then be stored. Plutonium vitrification has only been tested on a very small scale, but large quantities of materials far more radioactive than plutonium (namely, high-level wastes from reprocessing) have been vitrified. Plutonium vitrification could be done in a number of ways, depending on the desired result and on the nature and form of the plutonium being vitrified. (See table in Centerfold for discussion of options.)

Since it is possible to re-extract plutonium from glass, provisions need to be made to prevent theft. One vitrification method is to mix the plutonium with highly radioactive fission products such as cesium-137. This would deliver a lethal radiation dose to anyone trying to steal the plutonium and would make re-extraction more difficult and costly.

Another method is to put the plutonium-laden glass log in a highly radioactive container that would be resistant to theft. Re-extraction could be further inhibited by mixing the plutonium with actinides—elements that are chemically similar to

plutonium. Actinides such as thorium-232 are difficult to separate chemically from plutonium, as are non-radioactive "rare earths" that have properties similar to actinides. An advantage of this option is that the vitrification plant would not have to handle high gamma-emitting materials, allowing vitrification to begin and be completed sooner.

Surplus weapons plutonium is currently in several forms: plutonium pits removed from warheads, and scrap and residues such as ash, sludge, and contaminated materials. In principle, each of these forms can be vitrified, but further research is needed to determine which vitrification technologies are most appropriate, and to develop them to handle the various forms of plutonium safely. Oak Ridge National Laboratory has experimented with direct vitrification which could be used for scrap and residues, but this technology has not yet been demonstrated at the pilot plant level.

Currently in the United States, high level waste is being vitrified at the Defense Waste Processing Facility at the Savannah River Site in South Carolina, and at the West Valley Demonstration Project in West Valley, New York. Simulation experiments are also being done to study "can-in-canister" vitrification, where high concentrations of plutonium in small glass logs would be placed inside high-level waste glass logs for storage or disposition.

The US could draw on the expertise of other countries with more experience in vitrification technology. France has three decades of

❋ ATOMIC   PUZZLER ❋

Welcome back, Puzzler fans! Our trusty sleuthing dog Gamma has a new puzzler for you. Today he's investigating a reactor using MOX fuel. So why not help him out and send us your answers? Remember, Dr. Egghead loves to hear from you. (Even if you don't want the $10 prize, send in your answer anyway with a note saying so.) Here's the puzzler:

Consider the following:

MOX fuel contains 4% plutonium and 96% uranium-238. (For simplicity we will assume that the plutonium consists of only fissile isotopes.) While plutonium is being fissioned, some of the uranium-238 is being converted into plutonium, some of which is in turn fissioned. So, destruction and build-up of plutonium are going on at the same time.

Gamma has determined that a certain reactor is fully loaded with such MOX fuel. (That is, it has a 100% MOX core.) Suppose that three-fourths of the original plutonium is converted to fission products, but 2.1% of the U-238 is also converted to plutonium.
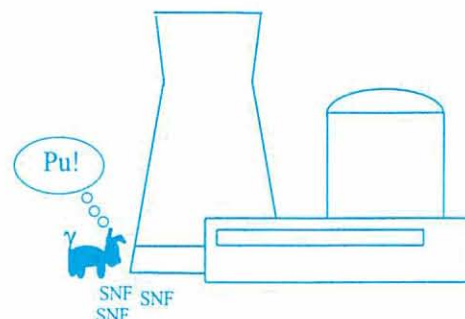
1. How much plutonium would be in the spent fuel if none of the new plutonium made from U-238 were fissioned? (Round to the nearest whole percentage point.)

2. How much plutonium would be left in the spent fuel if half of the new plutonium made from U-238 is fissioned also? (Round to the nearest whole percentage point.)

3. Gamma estimated that in Case 1 above, the spent fuel would have 3% fission products. Is he right? What percent of fission products exists in the spent fuel in Case 2? (For Case 2 round to the nearest whole percentage point.)

Send us your answers via fax (301-270-3029), e-mail (ieer@ieer.org), or regular mail (IEER 6935 Laurel Ave., Takoma Park, MD 20912) by **March 31, 1997!** IEER will award 25 prizes of $10 each to people who send in a solution to the puzzle, right or wrong. There is one $25 prize for a correct entry, to be drawn at random if more than one correct answer is submitted.

We received some very creative answers to our last puzzler, in which Gamma helped you calculate uranium releases from a DOE plant. Here's a sample:

> Pour Gamma a big bowl of organic kibble! He's barking up the right tree 'cause the plant operators have caused their releases to soar through the woof. We figure the stack is puffing out 4.3 kg per day. Shut down the plant and give Gamma a rays.
> —Rajiv Smith-Mahabir, Cynthia Mahabir & Gar Smith
> Berkeley, CA

Our $25 prize winners of that puzzler were:
    Laura Thoms of Durham, NC and
    John Dossett of Washington DC (winner of prize for advanced question)
Congratulations Laura and John!!
(If you would like to receive an answer sheet from this puzzler, contact IEER.)

Dear Arjun, *from page 14*

experience with high level waste vitrification, and Russia has operated a high-level waste vitrification plant at Chelyabinsk-65 for five years. In addition, Russia is constructing a new vitrification plant, which is nearly complete.

Plutonium vitrification is different from high-level waste vitrification in some important aspects. Problems specific to plutonium vitrification include accidental criticality risks both during processing and after vitrification, and the difficulty of achieving uniformity of the plutonium in glass. In order to sort out existing technical problems and fully address plutonium safety issues, the US should build several pilot plants to compare and study vitrification technologies. Two of these plants could be pursued jointly with Russia, with one pilot plant being constructed in the US and one in Russia. A cooperative effort could

NUCLEAR NEWS

■ The DOE settled a lawsuit brought against Los Alamos National Laboratory (LANL) under the Clean Air Act by Concerned Citizens for Nuclear Safety. Under the settlement, LANL agreed to up to four audits by an independent, non-governmental team led by Dr. John Till of Radiological Assessments Corporation. IEER will monitor the adequacy of the audit.

facilitate technological exchanges as well as progress on immobilization of surplus military plutonium. ∎

For more information about plutonium vitrification, see IEER's report, *Fissile Materials in a Glass, Darkly.* The report is currently out of print, but photocopies are available for $5. Portions of the report are also available on our webpage, http://www.ieer.org/.

— *Ghost-written by Pat Ortmeyer*

Editorial, *from page 12*

to prevent diversion. Russia needs money and jobs, but while there may be jobs in MOX, there is no money in it. A net flow of money into Russia would be accomplished much more effectively by getting Russia to stop reprocessing. Additional money would come from greatly accelerating the conversion of Russian highly enriched uranium (which is also a proliferation problem) into a reactor fuel with real market value.

Of all the nuclear powers, only the United States has adopted a prudent non-proliferation and economic policy on the use of plutonium as an energy source. As a result, it is the only country that is in a position to take the lead on this issue. Instead, the Energy Department is proposing to follow Russia down a road that would increase nuclear dangers by entrenching pork-barrel interests in plutonium in Russia and creating them anew in the United States. Today, plutonium is one of the most serious security threats facing the world. It should be vitrified and further production stopped. ∎

For more information on vitrification, see the Centerfold.

Portions of this article appeared in "Heading Off the Plutonium Peril," by Arjun Makhijani, The Washington Post, December 5, 1996. Used with permission.

THANK YOU...

The Institute for Energy and Environmental Research
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Takoma Park, MD 20912

Address correction requested.

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