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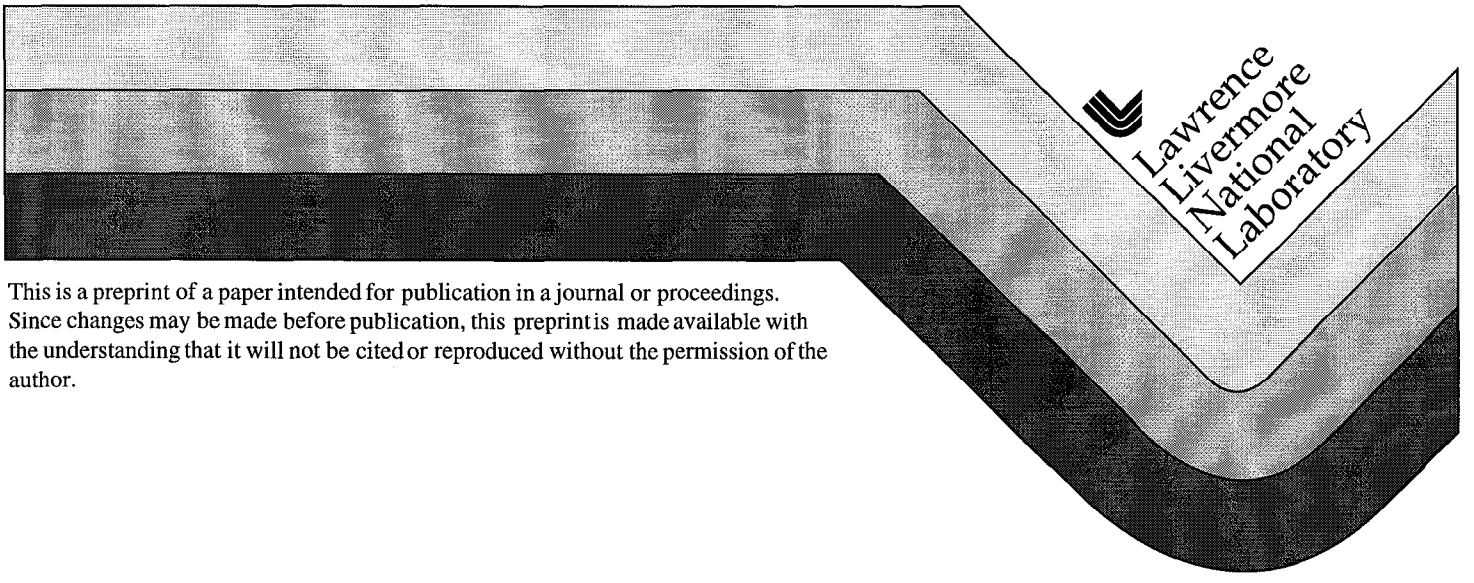

AN ANALYSIS OF PLUTONIUM IMMOBILIZATION VERSUS THE "SPENT FUEL STANDARD"

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ABSTRACT

Safe Pu management is an important and urgent task with profound environmental, national, and international security implications. Presidential Policy Directive 13 and analyses by scientific, technical, and international policy organizations brought about a focused effort within the Department of Energy (DOE) to identify and implement long-term disposition paths for surplus Pu. The principal goal is to render surplus Pu as inaccessible and unattractive for reuse in nuclear weapons as Pu in spent reactor fuel.

In the *Programmatic Environmental Impact Statement and Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials* (1997), DOE announced pursuit of two disposition technologies: (1) irradiation of Pu as MOX fuel in existing reactors and (2) immobilization of Pu into solid forms containing fission products as a radiation barrier. DOE chose an immobilization approach that includes "use of the can-in-canister option... for a portion of the surplus, non-pit Pu material." In the can-in-canister approach, cans of glass or ceramic forms containing Pu are encapsulated within canisters of HLW glass.
In support of the selection process, a technical evaluation of retrievability and recoverability of Pu from glass and ceramic forms by a host nation and by rogue nations or subnational groups was completed. The evaluation involved determining processes and flowsheets for Pu recovery, comparing these processes against criteria and metrics established by the Fissile Materials Disposition Program and then comparing the recovery processes against each other and against SNF processes.

INTRODUCTION

U.S.-Russian agreements reached during the Bush Administration extended the number of warheads to be cut from U.S. and Russian stockpiles. About 100 tonnes of Pu will be removed from the two stockpiles by year 2005. In contrast, by year 2000, there will be 1200 to 1600 tonnes of weapons-usable Pu available from commercial reactors.

The National Academy of Sciences (NAS) Committee on International Security and Arms Control[1,2,3] stated that "The 'reactor-grade' Pu..., while it could be used to make nuclear bombs, it poses much smaller risks than separated Pu ... because of the mass, bulk, and intense radiation field of the spent fuel assemblies and because of the additional technical sophistication and resources required for chemical separation ... from the accompanying fission products and uranium."

The NAS[1,2] further stated, "Options for the disposition of WPu that leave it more accessible than the Pu in spent reactor fuel would mean that the WPu would continue to pose a unique safeguards problem indefinitely. Conversely, accepting substantial costs, complexities, risks, and delays in order to go beyond the "Spent Fuel Standard" (SNF) to make the WPu significantly less accessible for weapons use than the Pu in commercial spent fuel would not be justified unless the accessibility of the global stock of Pu in spent fuel were to be similarly reduced."

The SNF does not require Pu be transformed into SF.[3] It does not require the disposition product to have all the characteristics of SF to meet the objectives of the SFS. The idea behind the SFS is to create a variety of barriers to recovery of Pu which, between them, would make it roughly as inaccessible and unattractive as Pu in SF. The SFS is a very broad target area, not a single

point on an imaginary graph of proliferation resistance.

DOE has elected to pursue a duel path strategy for Pu disposition.[4-14] One component is irradiation as a mixed oxide fuel in commercial light-water reactors. The second component is immobilization in a ceramic material surrounded by high level waste (HLW) glass. The primary isotope in the HLW glass will be ^{137}Cs; the design radiation rate is >100 rad/hr at one meter, 30 years after fabrication, or >200 R/hr at fabrication. This is roughly equivalent to 40 year old BWR fuel. As time increases, radiation dose of the forms approach each other; at 300 years they are the same.

Early in the MD program, Sandia National Laboratory was chartered to lead an independent assessment of potential proliferation resistance issues associated with Pu disposition.[15] This Proliferation Vulnerability Red Team (PVRT) performed a broad, systems-level assessment of potential proliferation vulnerabilities associated with immobilization processes under investigation. The scope of the assessment was limited by DOE/MD to a broad examination of the disposition concepts:

1. To determine the most relevant proliferation resistance factors, and
2. To identify features that represent potentially significant shortfalls from goals if not adequately compensated during system design and implementation.

The PVRT came to the following conclusions:

1. Pu from all stages of all the MD alternatives can be made weapons usable, should sufficient materials be obtained.
2. The technology for recovering Pu from SF is in the open literature. It can be easily adapted for the material forms under consideration by MD. The resources required for recovery of a significant quantity of Pu are estimated to be relatively modest.
3. The presence of a radiation barrier sufficient to require shielding and the need for chemical processing during recovery provides discrimination among the forms under consideration by the MD. However, a small, well-prepared group could recover sufficient Pu for a device within months.
4. A primary goal of the disposition program is to put the Pu in a form that meets SNF. However, the intrinsic features of SF are insufficient to protect it from sufficiently dedicated adversaries with modest resources. The institutional protection provided by domestic safeguards are necessary to augment the intrinsic barriers.
5. The intrinsic barriers for the immobilized forms are currently somewhat less than those implied by the SNF due to lower dilution and the rapid separability of cans from the surrounding radioactive matrix, although these can likely be mitigated.
6. Sealing any of the MD forms in a geologic repository imposes very long and observable requirements, and enables the institutional measures to be greatly relaxed.

As the Immobilization Program has developed various mitigating factors have been considered. Some factors have already been incorporated into the immobilization form — others can easily be incorporated into the form if a new vulnerability assessment determines that additional factors are necessary.

How Accessible Is Pu In Spent Fuel?

The difficulty of recovering Pu from SF clearly depends upon the resources of the group seeking to recover it. A weapons state, with large reprocessing plants, could recover Pu from SF with little difficulty.

In principal, it would be possible for a relatively small cadre of extremely dedicated and well-trained individuals:

- to build in a warehouse-sized building a makeshift chemical processing facility for Pu separation, with crude shielding and crude capabilities for remotely controlled operation of the facility;
- to steal SF from cooling ponds or storage casks, hauling the SF away to the processing facility by truck or helicopter;
- to cut the SF into pieces, dissolve it, and separate the Pu in the chemical processing facility over a period of a few months; and
- to build ≥1 weapon from the purified Pu.

However, a subnational group that would have to build a facility for chemical separations of Pu from SF without being detected, steal SF without being caught, complete the processing without being stymied by unexpected difficulties and without being detected, could expect to face significantly greater difficulties.

Potential Threats. When considering potential threats, it is critical to differentiate between unauthorized and host-nation because they raise very different security issues and require different measures to address them.

Given the reality of nuclear arms reduction, neither the U. S. nor Russia is likely to reuse excess materials to rebuild nuclear arsenals in the near term. In the Clinton-Yeltsin summit statement of May 1995, the U. S. and Russia publicly committed themselves never to use material declared excess in nuclear weapons. During the course of disposition, it is likely that additional commitments will be made.[3] Thus, a decision to reuse immobilized material would mean repudiating a range of commitments. This is conceivable only in the context of a radically changed international security environment that would seem to require reconstruction of the Cold War nuclear arsenals. To accomplish this, multi-tonnes of immobilized material would have to be diverted.

Published Information. Chemical and engineering information required for Pu processing was declassified over 30 years ago; it is available in the technical literature of all of the major languages.[16-23] The essential physics of the bomb is also in the open literature.

Basic Processing Assumptions. Building a one-time use facility, would take less time than building permanent facilities. For a simple, quick clandestine processing plant[24] for the recovery of ≤5 kg Pu/day from SF the base assumptions are:

1. The group is willing to receive higher radiation doses than currently allowed by Western World guidelines. It would, however, seem likely that an adversary would choose to shield operations rather than absorb lethal doses of radiation.
2. Small industries are available that can be pirated for instruments, tanks, piping, fittings, etc. (winery, dairy, textile fibers plant, food and beverage industry, pharmaceutical houses, chemical industries, or minerals processing industries.)
3. There is a sympathetic and friendly populace.
4. Adequate funds are readily available.
5. A small machine shop equipped with lathe, power tools is available.
6. A light construction firm with bulldozers, backhoe, yard crane, etc. is available.

DISCUSSION

Proliferation Resistance. Proliferation resistance is the net barrier that must be overcome to acquire nuclear weapons.[3, 15] Larger barriers impose greater risks, resources, timelines, and/or level of effort upon the threat. The relevant obstacles that are presented and factors that contribute to them will depend upon the scenarios, systems, and context under consideration. Proliferation resistance is not a measurable or unambiguously calculable quantity, nor are there unequivocal techniques for determining the adequacy of a system's proliferation resistance.

Isotopic Dilution. During the PVRT evaluation, the feed stock to immobilization was not well understood. Since then DOE has clarified the feed stock somewhat. DOE has declared ~38.2 tonnes of weapons-grade Pu to be excess to the needs of national security, ~14.3 tonnes of fuel- and reactor-grade Pu excess to DOE needs, and anticipates an additional 7 tonnes to be declared excess to national security needs. Of this 59.5 tonnes, DOE anticipates that ~ 7.5 tonnes will be dispositioned as SF at the Geologic Repository and ~ 2 tonnes will be declared below the safeguards termination limit and be discarded as TRU waste at WIPP.

Isotopic composition of excess Pu feed stocks vary from 3% ^{240}Pu to ~40% ^{240}Pu. The Pu assay varies from <10 wt% to >99 wt%. The last purification varies from the early 1960s to the late 1990s; therefore the ^{241}Am content varies from ~200 ppm to ~15 wt%. U content varies from trace DU in the Pu to trace Pu in fully enriched U (93% ^{235}U, EU). Tramp impurities are dominated by: Al, C, Ca, Cl, Cr, Fe, F, Ga, K, Mg, Mo, Na, Si, Ta, U, W, and Zn.

For planning, two cases have been defined: a case in which ~50 tonnes of Pu is immobilized, and a hybrid case, in which ~32 tonnes of Pu are dispositioned as MOX fuel and ~18 tonnes are immobilized. The hybrid options is the preferred option.

To obtain a reasonably consistent Pu feed stream, it is obvious that large scale blending will be necessary. Blending on the 40 to 50 kg Pu scale

will minimize processing and characterization costs, and will improve both product quality and reproducibility of the form.

As a result of blending, isotopics of the Pu will be altered. There will be no attempt to reach a near homogenous blend of isotopes, however, the levelization will increase the ^{240}Pu to the 9 to 12% range. While a reasonable terrorist weapon can be manufactured, this isotopic is outside the range a host country weapons would want for its weapons.

Results of the overall blending does interfere with the ability of terrorist groups to recover the Pu in high yield and purity.

Chemical Dilution. Actinide impurities includes DU, EU, Np, Th, and Am. In the hybrid case, the feedstock contains ~18 tonnes of Pu and ~17 tonnes of DU. The mineral of choice being used for ceramic immobilization is pyrochlore. To force the desired mineral composition, additional DU will be added. As a result, the DU to Pu ratio in the final product will be about 2 parts DU per part Pu. The EU, Np and Th will be added as if they were Pu. These elements will be mineralized in the same crystal lattice positions as if they were Pu. By including EU as if it were Pu, there will be no changes necessary for criticality control. This will have the following effects on the recovery of Pu by a terrorist group:

1. About 600 kg of EU is expected in the feed stock. This EU is primarily oxide; the composition varies from trace Pu in the EU to trace EU in the Pu. Since EU will be introduced to the ceramic formulation calculated as if it were Pu, the amount of DU added will dilute the EU to below 20% in all cases. This assures that the U could not be used for a weapons, if it were recovered, without re-enrichment. EU will be added in a random fashion and will displace Pu on a kg by kg bases. The effect is to decrease the amount of Pu in individual random canisters. Each canister is expected to contain about 28 kg of Pu. However, one-half of the Pu could be replaced by EU with the final ^{235}U isotopic ≤20%. As EU in the canisters will vary and the larger amounts will be totally at random, a terrorist group would not know if they were stealing a canister containing 28 kg of Pu or a canister containing 14 kg of Pu and 70 kg of 20% ^{235}U.
2. Tramp Np and Th amounts in the Pu feed has not been determined. Both will probably be only a few kgs.. Natural Th could be added at will, of course, on a random bases. Even if Th, Np, and EU were not blended into the same batch, and would not be in the same ceramic pucks, all three could be added to the same canister. Therefore, in each canister, the actinide content may vary as follows:
   - Pu: 10 to 28 kg.
   - EU: 0 to 14 kg
   - DU: ≥56 kg
   - Am: 200 ppm to 1.5 kg
   - Np: 0 to 2 kg
   - Th: 0 to 4 kg
3. Tramp impurities will also be variable, though within vary loose limits. Tramp impurities will be limited to approximately 50 wt% of the calculated Pu content. Tramp impurities will in general be ≤14 kg total per canister.
4. The ceramic formulation contains a neutron absorber to Pu ratio of 2 to 1. The neutron absorber will be a combination of hafnium and gadolinium. The mole ratios is about 1:1:1 = Pu:Hf:Gd.

The result of the actinide impurities in the feed stock is that a minimum of a two step recover-purification process will be necessary. Regardless of the purification system used, closer control of the process will be necessary than would have been the case without the added actinides. Since EU, Np, and Th are added on a completely random bases, a terrorist group must plan both the process and the process control instrumentation and process control laboratory capabilities as if the three actinides are present.

The Fe^{+2}/Fe^{+3} couple is so close to the Pu^{+3}/Pu^{+4} couple that excessive iron can interfere with the Pu valence adjustment necessary for recovery and purification. With the tramp impurity concentration being completely random, the Fe content will be completely random. In addition, additional Fe could be added, also on a completely random bases.

Chemical Dissolution. The methods developed for the recovery of Pu from the immobilized forms has, for obvious reasons, been classified.

However, this does not prevent an assessment of the relative difficulty of the processing flowsheets. The DuPont Engineering Department[25] had previously designed such a system to assess the relative merits of waste forms. A very similar system was used for this analysis. Design data from the process flowsheets, equipment's definitions, and facility layouts were used to rate each process. Units of measure are defined in Table 1. A figure-of-merit rating method was used to rate each process. The merit rating of each process was calculated by taking a weighted sum of normalized value functions:

$$R = \sum_{i=1}^{9} W_i \, (X_{i/} \, Y_{i,})$$

where:

- W_i is weight of i^{th} criterion or factor
- (X_i / Y_i) is value function for i^{th} processability factor
- X_i is value of i^{th} factor for process being considered
- Y_i is value of i^{th} factor for process having highest value for that factor

The Pu feed stock receiving the highest value for each criterion receives a process merit rating of 100. Therefore, the highest "R" value represents highest proliferation resistance.

The raw scores or process values and the weighted, normalized scores are shown in Tables 2 and 3, respectively.

For better understanding, a number of typical residues that have been recovered in the past are included in the table. With a calculated score of 99, Pu immobilized in ceramic and encased in HLW glass is the most difficult to recover and therefore has the highest proliferation resistance. The score for Pu immobilized in glass and encased in HLW glass drops to 62 but is still more difficult to recover than plutonium from spent fuel, which has a processing difficulty score of 58. As a check on the accuracy of the ordering, incinerator ash is know to be one of the more difficult residue to recover in a nitric acid dissolution system. On the other hand, SS&C is one of the easiest residues to recover, in fact, the resources required to recover incinerator ash is about twice that required to recover SS&C.

This analysis would indicate that Pu immobilized in glass and embedded into HLW glass meets the spent fuel standard and that Pu immobilized in ceramics and embedded in HLW glass would exceed the SFS.

Radiation Shield. The radiation shield will be provided by the ^{137}Cs in the HLW glass produced in DWPF. The amount of ^{137}Cs required to provide the radiation barrier was calculated using the MCNP code, a 3D monte carlo radiation transport code. For DWPF canisters, containing immobilized Pu ceramics, the amount of glass in the canister will be about 1325 kg. (A glass-only DWPF canister will contain about 1680 kg of glass.) To give a dose rate of 100 Rem/hr, one meter outboard of and at the midplane of the canister requires 5.36 kCi of ^{137}Cs. To assure a dose rate of 100 Rem/hr at one meter 30 years after fabrication, the acceptable curie loading at fabrication would be ≥10.8 kCi of ^{137}Cs.

Savannah River has made a number of waste work off projection over the years. The 1996 projection averaged 13 kCi ^{137}Cs/canister. As there is some flexibility in the way the ^{137}Cs is processed, it would be fairly easy to assure at least 12 kCi ^{137}Cs per canister containing Pu. With the start-up problems experienced by DWPF, sludge only glass will be produced for a longer time frame than originally anticipated. Depending upon the time required to

Table 1. Criteria for Processing Difficulty or Proliferation Resistance

Complexity-Reliability Factor	Relative Weight	Unit of Measure
1. Critical control parameters	**25**	**Count of control points required to maintain product quality or operability**

2.	Process cell requirements	20	Square feet (length x 60 ft width) (Modified to linear feet)
3.	Process steps	15	Count of steps accomplishing a function
4.	Equipment pieces at high temp. (>350°C) or high pressure (>150 psi)	10	Count of major equipment pieces above temp. Or press. Pieces are counted twice if both temp. & press. are exceeded.
5.	Unusual service facilities	10	Count of equivalent small facilities (1 large facility = 3 small facilities)
6.	Recycle loops	5	count of process flows returning to preceding steps
7.	Equipment pieces in covered cells	5	Count
8.	Chemical additions through walls	5	Count
9.	Dry radioactive materials transfer steps	5	Count

Table 2. Raw Data Scores for Processing Difficulty or Proliferation Resistance

Process Factor	Glass	Ceramics	Spent Fuel	Spent Salt	Incinerator Ash	SS&C
1. Critical control Parameters	8	13	8	2	2	2
2. Process Cell requirements (linear feet)	130	190	130	28	30	30
3. Process steps	25	38	23	4	6	6
4. Equipment pieces at high temp. (>350°C) or high pressure (>150 psi)	1	2	1	1	2	1
5. Unusual service facilities	6	9	3	1	1	1
6. Recycle Loops	2	3	2	1	4	1
7. Equipment pieces in covered cells	8	12	8	1	1	1
8. Chemical additions through walls	6	9	6	1	1	1
9. Dry radioactive materials transfer steps	2	4	2	1	3	1

Table 3. Weighted Scores for Processing Difficulty or Proliferation Resistance

Process Factor	Glass	Ceramics	Spent Fuel	Spent Salt	Incinerator Ash	SS&C
1. Critical control Parameters	15.4	25	15.4	3.8	3.8	3.8
2. Process Cell requirements (linear feet)	13.7	20	13.7	3.0	3.2	3.2
3. Process steps	10.0	15	9.1	1.6	2.4	2.4
4. Equipment pieces at high temp. (>350°C) or high pressure (>150 psi)	5.0	10	5.0	5.0	10.0	5.0
5. Unusual service facilities	6.7	10	3.3	1.1	1.1	1.1
6. Recycle Loops	2.5	3.8	2.5	1.3	5.0	1.3
7. Equipment pieces in covered cells	3.3	5	3.3	0.4	0.4	0.4
8. Chemical additions through walls	3.3	5	3.3	0.4	0.4	0.4

9. Dry radioactive materials transfer steps	**2.5**	**5**	**2.5**	**1.3**	**3.8**	**1.3**
Totals	**62**	**99**	**58**	**18**	**30**	**19**

solve the DWPF ^{137}Cs processing problems, it may be possible to assure 15 to 18 kCi ^{137}Cs/canister. Therefore, it may be possible to increase the dose rate, at fabrication, from ≥200 Rem/hr at one meter, to ≥ 300. Rem/hr.

Radiation Shield of Spent Fuel.[15] SF itself varies significantly in many of the SNF characteristics. SF that is 40 years old is only half as radioactive as SF that is 10 years old. At the midpoint of the Disposition Program, all SF withdrawn from U. S. reactors in the 1960's will be 40 to 50 years old. The radiation field from CANDU SF is much lower than the radiation field from LWR SF. SF from fast-neutron reactor cores contains a much larger percentage of Pu, which is closer to weapon-grade, than SF from LWRs or CANDUs; Pu in the breeding blankets of fast-neutron reactors is typically weapon-grade or even super-grade.

The magnitude of the radiation field near a SF assembly depends on a number of factors, including design, the burnup, and the decay time since irradiation. The PVRT considered three assembly designs: PWR, BWR, and CANDU. For comparison purposes, they fix the decay time at 10 years post irradiation and the radiation dose rates calculated.

The radiation field near a ten-year-old PWR fuel assembly was calculated with the code MicroShield. The calculated dose rate near the PWR assembly as a function of position. At the axial mid-plane of the assembly, the dose rate at the surface is about 22,000 Rem/hr and at 1 m from the surface the dose rate is about 1,400 Rem/hr. Off the axial mid-plane, the dose is fairly uniform except near the end of the assembly. The dose on the axis of the assembly at the surface of the end is about the same as the dose at the surface on the mid-plane. The dose drops off more sharply with distance on the axis than it does at the mid-plane. The dose is 1000 Rem/hr at about 37 cm from the surface and drops off with the square of the distance from the surface beyond that point. At 40 years the dose will have decreased to about 700 Rem/hr at one meter from the midplane surface.

The radiation field near a ten-year-old BWR fuel assembly was calculated in the same fashion. The dose contours are similar in shape to those for the PWR assembly. On the axial mid-plane of the assembly, the dose at the surface is about 17,000 Rem/hr at the surface and about 640 Rem/hr at 1 m from the surface. At 40 years the dose will have decreased to ~320 Rem/hr at one meter from the midplane.

Because the CANDU assembly contains less fuel that has a lower burnup, the dose at the surface of the assembly are less than those for the BWR and PWR assemblies. CANDU assemblies are considerably shorter (roughly 0.5 m compared to 4 m) so the source appears to be more "point-like." At the axial mid-plane, the dose at the surface is about 3,800 Rem/hr and about 33 Rem/hr at 1 m from the surface

Accessibility Barrier Provided by the Radiation Field.[15] A radiation field does not impede the ability of a host nation to retrieve Pu, since they have continuous, long-term access to the material and readily available equipment designed for that purpose.

A radiation field is a significant accessibility barrier to unauthorized parties if the field is high enough to force a thief to shield the object during the theft. The shielding material, being heavy and cumbersome, and/or remote handling would force the thief to use lifting equipment during the theft and to haul away a significantly larger mass than just the stolen object. For this to be the case, the radiation dose absorbed by a thief during the theft must be sufficient to either a) incapacitate the thief during the theft for those whom long-term survival is not important or, b) guarantee the eventual demise of the thief if the thief is one for whom survival is important.

Incapacitation can occur from the onset of symptoms of radiation sickness or from the immediate disruption of the nervous system that results with acute doses of about 5000 Rem or greater. Which of these occurs first depends on the dose rate. For very high dose rates where a 5000 Rem dose cans be delivered in minutes (≥ tens of thousands of Rem per hour), disruption of the central nervous system will occur. For lower dose rates, ~1000 Rem/hr and protracted exposure times, symptoms of radiation sickness will occur before a 5000 Rem dose is delivered.

Even if ^{137}Cs recovered and purified at Hanford were shipped to Savannah River and the combined total fed to DWPF, the radiation rate of the

immobilized Pu could only be raised to about 500 to 600 Rem/hr at one meter, at fabrication. There is not enough ^{137}Cs in the U. S. to provide a dose sufficient to disrupt the central nervous system of a thief during the clandestine theft of a canister of immobilized Pu.

By contrast, 10 year old PWR and BWR SF have slightly higher radiation dose rates, but these rates are not high enough to disrupt the central nervous system of a thief during the clandestine theft of 10 year old SF. Dose rates from CANDU SF assemblies are even less than canisters of immobilized Pu. The PVRT conclusion was that in neither case is the radiation level intense enough to force the use of shielding and remote handling during theft. The intrinsic features of SF are insufficient to protect it from sufficiently dedicated adversaries with only modest resources.

If one is to incapacitate the thief, then the inherent canister system must be designed to protract the exposure time and to assure that the thief cannot maintain a distance of one meter from the canister. Two cases can be considered: a) theft of the canister, or b) removal of the cans from the canister followed by escape with the cans of immobilized Pu.

A. Theft of the Canister.[15] Activities required during theft of the canister depends upon the intrinsic system protecting the host country workers from the radiation field.[15] There are three scenarios under which this could occur:

1. The waste glass storage building
2. While in transit to the repository
3. After placement in the repository

Analysis of each scenario requires development of additional background information. The analysis this therefore deferred until the logical sections below. The general conclusion is that there is insufficient radiation to incapacitate the thief during the theft of the canister. This, of course, assume that the thief has the resources to shield the canister during transport after the theft.

B. Removal of Cans from Canister Followed by Escape.[15] The same three scenarios to be analyzed for theft of the canister apply to this case also. The same background information is required for this case as the previous case. The analysis this therefore deferred until the logical sections below. Since the PVRT Report, the Immobilization Team has developed a number of conceptual designs that could deny the ability of on adversary to rapidly separate the required number of Pu-bearing cans from the radioactive HLW glass matrix. In the words of the PVRT "Success could be claimed when it is more trouble to separate the "cans" than to carry off the canister."[15] The general conclusion of the analysis below is that "success can be claimed."

Shaped Charge Attack.[15] The wide availability of energetic materials forces one to look carefully at potential attacks that could rapidly open a container and allow the extraction of its contents.

Proper design of an energetic attack requires knowledge of the design of the target and materials of construction. Uncertainties are usually treated by increasing the size of explosives. This works for simple targets and tasks such as perforation or fracture of homogenous materials. More complex materials such as reinforced concrete present more of a problem. Breaching charges of appropriate size to crush the concrete will not cut the reinforcing rods. If these must be cut, a second phase is necessary. The delay caused by the need to cut reinforcing rod can greatly exceed that necessary to carry out the initial breaching operation. Targets that consist of massive casks containing fragile components such as fuel elements or cans of immobilized Pu present additional challenges. Excessive explosive charge size can rupture and deform the fragile component delaying their separation.

Given adequate time and information an explosive/thermal attack can be designed to efficiently penetrate very large, complex objects. In practice, custom designs would be tailored for the specific canister design (type of steel, thickness, diameter).

Knowledge of how energetic attacks are designed, allows one to design the target, in this case the internals of the canister, to impede the attack. The can holding rake analyzed by the PVRT had been designed to allow an experiment to be carry out prior to the "hot start-up" of DWPF. It was not designed with proliferation resistance in mind, and it failed. The present thinking is shown in Figure 1. The cans are loaded into a cage of bars which run parallel to the surface of

the canister. It would be very easy to join these cans together, probably by tack welding. This "magazine" is loaded into the canister and held in place by plates which are perpendicular to the bars. A locking mechanism locks the magazines into place. By designing the cans and the rods the proper thickness, any attempt to cut the rods during the breach of the canister would cut the cans and shatter the ceramic pucks. The shape of the plates and the thickness would preclude cutting the plates during the breach of the canister.

This requires the attack group to come in closer to the radiation field to place burn bars on the rods and the plates to prevent shattering the ceramics and scattering the pieces all over the place. This adds both dose and time to the teams members.

Storage In The High Level Waste Glass Storage Facility. DWPF will pour approximately 6000 canisters of HLW glass. In the preferred hybrid option, approximately 650 to 675 of these canisters will contain Pu, calculated at 28 kg Pu per canister. (In the full option, ~1800 would contain Pu.) The Pu containing canisters will be delivered to the DWPF in small batches of three to six canisters. The DWPF is anticipated to operate at an average production rate of 500 canisters per year. In the hybrid option, the Pu immobilization facility will produce only about 60 to 75 canisters per year. As Pu-containing canisters will be poured in DWPF on a random bases, they will also be stored in the glass waste storage building on a random bases.

The filled, seal-welded, decontaminated canisters will be moved within a shielded vehicle from the mechanical cell of the DWPF to the interim waste glass storage building. The canisters will be stored in a below-grade, shielded, air-cooled vaults. The canister transporter, which travels at 3 mph, will position itself over a vault, remove the 6 ton concrete plug, store the plug within the transporter, and lowers the canister into the vault. The transporter then replaces the concrete plug before is moves from over the vault.

The superstructure over the vaults is primarily for climate control. It will not support lifting devices to lift the concrete plugs or the canisters. The transporter is heavily shielded and does not allow access to the canister. Therefore, any attack on the waste glass storage facility would require that the attack team bring portable lifting devices with them.

The attack team is then faced with determining which canisters contains Pu. As only one in ten canisters are anticipated to contain Pu, and these are interspersed with the HLW glass canisters on a random bases, insider information would be required to determine with any accuracy the canisters to extract.

The glass storage facility is on a DOE site where the security force has the authority to apply deadly force. Since the second glass storage facility has not yet been built, security as suggested by a full scale vulnerability analyses could be applied to this facility. At least, these would include motion and radiation detectors which would alarm back at a central security post. Extraction of the canister from the vault and extraction of the cans from the canister would be carried out under armed counter attack by site security forces.

Given the group would have a 1 in 10 chance of picking the correct canister, without insider information, and there is a reasonable chance the canister extracted will contain less than 28 kg of Pu, and the fact there is a high probability that the percentage of recovery by a clandestine group would be considerably less than 60%, the probability of successfully recovering enough Pu to build a weapon is very small.

An attack scenario on the glass waste storage building is just not a credible scenario.

Transportation Cask. The actual transportation cask to transport both the HLW glass and the immobilized Pu/HLW canisters has not been designed. The canisters themselves is the same as used for the DWPF HLW canisters. As these canisters have only their unique number to identify canisters from each other, it will be necessary to read the numbers to distinguish a Pu containing canister from a HLW canister. These canisters are 0.6 meter in diameter and 3 meters in length; loaded they weigh about 2 tonnes. Their size, weight, and radiation field of these canisters will require the use of a rail car shipping cask to move them from the processing facility to the geological repository. The shipping cask could be designed to contain four or five canisters.

Either system could be designed with an internal collar that fits over the four or five canisters. Large hold-down nuts could easily be placed remotely in-between the canisters about one meter below the top. Since the collar would have to be removed prior to removal of any one canister, the collar would add time to the terrorist time line for stealing canisters from the shipping package. Placing hold-down devices about one meter below the tops of the canisters should preclude the use of shaped charges to aid in the removal of the collar.

Although the second round of criticality calculation are incomplete, it appears as if no more than two Pu canister within the transportation cask will be allowed. In the preferred hybrid case, approximately one in ten canisters will contain Pu. At best, the terrorist group would have a 50% chance of picking a transportation cask that contained a Pu canister and a 20 to 50% chance of picking the correct canister on the first withdrawal from the transportation cask. Overall, without insider information,. The chance that a terrorist group would choose a canister containing Pu is one in ten.

Since EU, Np and Th are calculated as if they were Pu, there is a reasonable probability that, if the terrorist group indeed picked a canister that contained Pu, the amount of Pu in the canister could be as low as 10 to 14 kg.

The PVRT[15] gave three possible approaches to attacking the rail cask:

1. Cutting bolts with burn bars, would be the quietest but would take the longest time.
2. Penetrate the lids with a conical shaped charge, cool the hole and inject a low explosive. The low explosive need only generate a peak pressure of 10,000 to 15,000 psi to blow the lids. The canisters should only be dimpled at void areas.
3. The third approach is the same as the second except a seven inch wide linear shaped charge would be placed around the neck of the canister. It would be detonated at the same time as the low explosive and should result in the removal of the steel end with lids.

The ground person would only need to grab the neck of a canister with a tool hanging from the helicopter. He would only have to expose their head and arms for a few moments while using a pole to attach the tool to the canister.

Each scenario would remove the shipping cask lid but would not damage the hold down collar. Therefore "the ground person would not be able to simply grab the neck of a canister with a tool hanging from the helicopter." Instead of "only have to expose their head and arms for a few moments while using a pole to attach the tool to the canister," the hold down collar would have to be removed. Any attempt to lift a canister without removing the collar would result in attempting to lift the 100 ton cask. As hold down nuts could be placed a meter below the canisters tops, this would add time and exposure to the attack group.

Assuming collar removal, the question now becomes which canister to remove. After the canister is removed, do they take the canister, or remover the cans and just take the cans?

Considering that only one in ten canisters contains Pu, it would seem prudent for the group to ascertain whether or not they indeed had a canister containing Pu. Without insider information or highly sophisticated equipment, such as a ^{252}Cf shuffler, the only way to assure that there is Pu in the canister is to open it.

Opening the canisters to retrieve the cans was described above. Without knowledge of where to set the charges, the probability that some of the cans would be breached and the ceramic shattered during the energetic attack is very large. If the group took the time to set the canister breaching charges, and then the rod and plate cutting burn bars, the time inside the one meter range of the HLW glass would be at least a half hour. The dose received would depend upon a number of factors including how long a time period was between the filling of the canister and the attack. The longer the time, the lower the dose. If the attack were within the first 10 years after filling, the average dose would be expected to be in the 400 to 1200 Rem/hr range. The would put the expected dose of a well trained group at 200 to 600 Rem. For doses in this range, the symptoms of radiation sickness are pronounced, but occur after a significant, dose-dependent time delay. If the victim can be hospitalized, there is a reasonable confidence that treatment can be effective in preventing death.

Drift Storage In The Federal Repository.

Accessing Pu in the geologic repository could be accomplished with a number of methods. Drilling of vertical shafts to a depth of 200 m is a common practice. This type of drilling requires a large drilling rig with the associated pumps, compressors, fluid circulating equipment and other support items (pipe racks, mud pits, fork lifts, etc.). A typical drilling location at the Nevada Test Site was ~5000 m^2. Vertical or horizontal, conventional mining and machine mining techniques, such as the tunnel boring machine (TBM) that is currently operating at Yucca Mountain, could be utilized to access the repository. Like drilling, mining also requires a sizable surface support area for ventilation, muck handling, and other large equipment. Peterson estimated 6 months to access the Yucca Mountain repository using a TBM to mine the 1 km minimum access route. That estimate is based on a high level of understanding of the operational requirements.

After reaching the repository level, conventional mining would be used to reach the storage containers. Mining done in the very warm and highly radioactive environment of the repository drifts would be extremely difficult. Without previous knowledge, the exact location of the excess weapons Pu waste packages emplaced among the commercial SF packages would somehow have to be determined. Then the correct canister within the package would have to be determined. Even if the material were located, special handling equipment and procedures would be necessary to render the material into a manageable form that could then be retrieved. In short, it would be much easier to just steal the SF. It would also be much easier to process. Stealing the immobilized materials from the closed repository appears to be a very low probability event.

CONCLUSIONS

No matter which disposition option is chosen by DOE, Pu could still be recovered and made into a useful weapon. Pu disposition can only reduce, not eliminate, the risk that the host country will someday be returned it's excess Pu to nuclear weapons.

The barriers to a subnational group accomplishing such an effort successfully and without detection should not be underestimated. The subnational group would need to include individuals with chemical and engineering knowledge, and actual experience in nuclear materials processing would be a significant benefit to such a group. Although the processes and technology of reprocessing spent fuel is unclassified, the experience gained in operating reprocessing plants is not widely available. Experience such as this would be very beneficial in trying to modify the processes to handle the ceramic immobilized form. A subnational group that would have to recruit a knowledgeable team, develop the Pu recovery process, and build a facility to mechanically separate the immobilized Pu from the HLW glass, and for chemically separating the Pu from the ceramic, other actinides, and the neutron absorbers without being detected, steal the immobilized Pu canisters without being caught, complete the processing without being stymied by unexpected difficulties using an unproved process and without being detected, and then produce a nuclear weapons without any prior experience, could be expected to face significantly greater difficulties than a host country.

The group could be expected to encounter unexpected complications and difficulties in modifying the published technology and in separating the Pu, as several nations have.

The larger barrier may be carrying the whole operation to a successful conclusion without being detected and stopped. While a terrorist group could potentially defeat the security where the immobilized Pu forms are stored, they could not be removed covertly, without detection. The group removing the immobilized Pu would be pursued. The intense radioactivity of the canister would make the vehicle easy to detect. Even if the group succeeded in removing the canister and transporting it to the processing facility without giving away the location of the processing facility, the group would have to take into account the fact that intensive efforts would be made to find and recover the immobilized Pu in the weeks before the processing were completed.

The probability that a subnational group could accomplish such an effort successfully and without detection is very small. Even if the group beat the odds and successfully separated the Pu

and converted it to metal, without being stopped, designing and building an implosion-type nuclear weapon (the only type possible with Pu) would require knowledgeable individuals in several disciplines, and some testing of the high-explosive assembly. These would provide additional opportunities to detect the group's activities.

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