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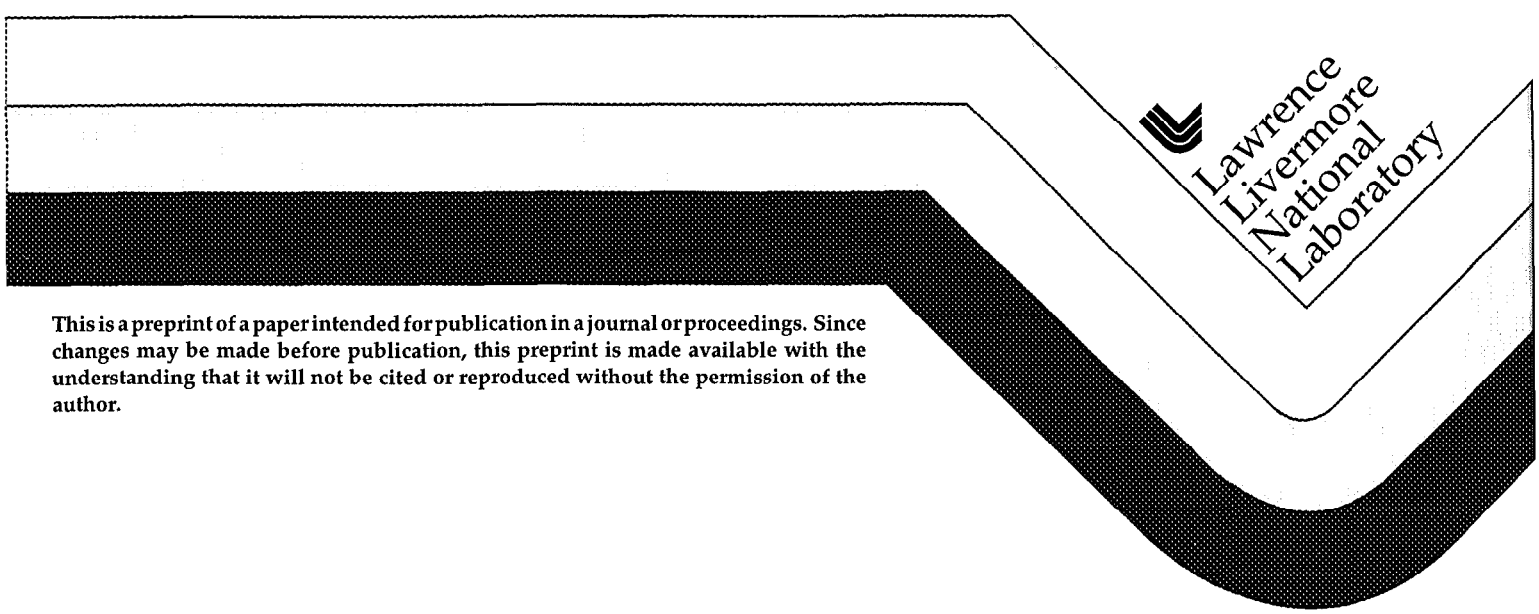

Plutonium Immobilization Form Evaluation

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ABSTRACT

The 1994 National Academy of Sciences study and the 1997 assessment by DOE's Office of Nonproliferation and National Security have emphasized the importance of the overall objectives of the Plutonium Disposition Program of beginning disposition rapidly. President Clinton and other leaders of the G-7 plus one ("Political Eight") group of states, at the Moscow Nuclear Safety And Security Summit in April 1996, agreed on the objectives of accomplishing disposition of excess fissile material as soon as practicable. To meet these objectives, DOE has laid out an aggressive schedule in which large-scale immobilization operations would begin in 2005.

Lawrence Livermore National Laboratory (LLNL), the lead laboratory for the development of Pu immobilization technologies for the Department of Energy's Office of Fissile Materials Disposition (MD), was requested by MD to recommend the preferred immobilization form and technology for the disposition of excess weapons-usable Pu. In a series of three separate evaluations, the technologies for the candidate glass and ceramic forms were compared against criteria and metrics that reflect programmatic and technical objectives:

- Evaluation of the R&D and engineering data for the two forms against the decision criteria/metrics by a technical evaluation panel comprising experts from within the immobilization program.
- Integrated assessment by LLNL immobilization management of the candidate technologies with respect to the weighted criteria and other programmatic objectives, leading to a recommendation to DOE/MD on the preferred technology based on technical factors.
- Assessment of the decision process, evaluation, and recommendation by a peer review panel of independent experts.

Criteria used to assess the relative merits of the immobilization technologies were a subset of the criteria previously used by MD to choose among disposition options leading to the Programmatic Environmental Impact Statement and Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials, January 1997. Criteria were: (1) resistance to Pu theft, diversion, and recovery by a terrorist organization or rogue nation; (2) resistance to recovery and reuse by host nation; (3) technical viability, including technical maturity, development risk, and acceptability for repository disposal; (4) environmental, safety, and health factors; (5) cost effectiveness; and (6) timeliness.

On the basis of the technical evaluation and assessments, in September, 1997, LLNL recommended to DOE/MD that ceramic technologies be developed for deployment in the planned Pu immobilization plant.

INTRODUCTION

Endorsed with highest priority by the presidents of both countries, the U. S. and Russia have under-taken programs to develop and implement approaches to ensure secure management of Pu made surplus as a result of nuclear weapons reduction agreements. To demonstrate U.S. commitment President Clinton declared in March, 1995 that approximately 50 tonnes of Pu was surplus to U.S. needs. Russia has also indicated that a similar quantity of Pu will be made surplus.

The goal of the Office of Fissile Materials Disposition (MD), created in 1994 to manage DOE activities relating to the management, storage, and disposition of surplus fissile materials, is to "make Pu as

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The goal of the Office of Fissile Materials Disposition (MD), created in 1994 to manage DOE activities relating to the management, storage, and disposition of surplus fissile materials, is to "make Pu as unattractive and inaccessible for retrieval and weapons use as residual Pu in spent fuel from commercial reactors. " This goal, referred to as the "Spent Fuel Standard," was originally stated by the U.S. National Academy of Sciences (NAS) (Ref. 1).

MD has evaluated promising disposition technologies leading to a choice of the best technologies for implementation. In the *Record of Decision (ROD) for the Storage and Disposition of Weapons-Usable Fissile Materials*, January 1997 (Ref. 2), DOE announced its decision to pursue two alternative technologies: (1) irradiation as MOX fuel in existing power reactors, and (2) immobilization into large solid forms containing fission products as a radiation barrier. The immobilization alternative will be used

for the disposition of impure Pu materials and could, if desired, be used for the larger quantity of pure Pu materials from retired weapon components.

Previously, six variants had been chosen for study (Ref. 3-9). In the PEIS/ROD, DOE expressed preference for deploying the can-in-canister [CIC] technology at the Savannah River Site. In this approach, cans of either glass or ceramic forms containing Pu are encapsulated within canisters of HLW glass. Consequently, glass and ceramic technologies were the focus of an aggressive R&D program aimed at selecting the final form by September of 1997 (original plan November, 1998).

Evaluation Process

The evaluation process is depicted in Figure 1. The overall evaluation, excluding the R&D work and criteria development, was conducted over seven weeks in July and August of 1997.

Figure 1 goes here

Documentation Supporting the Immobilization Technology Evaluation

Numerous published and unpublished reports and presentation materials were used in evaluating immobilization technologies. This large body of information was distilled into the following reports:

- Immobilization Technology Down-Selection: Radiation Barrier Approach, May 23, 1997 (Ref. 10).
- Technical Evaluation Panel Assessment of Glass and Ceramic Immobilization Technologies (Final Draft), August 28, 1997 (Ref. 11).
- Fissile Material Disposition Program Final Immobilization Form Assessment and Evaluation, August 29, 1997 (Ref. 12).

TECHNOLOGY BASES AND METHODOLOGY

Research and Development Program

The R&D program was restructured in October 1996 to reflect the importance of expediting implementation of Pu disposition technologies. The R&D needed to choose between candidate immobilization technologies was re-scoped and rescheduled so that this R&D could be prior to the evaluation. This rescoping cut 14 months from the original schedule. The R&D effort involved (Ref. 13):

- Glass and ceramic formulation development - developing composition and fabrication parameters for a range of expected Pu feed materials, and characterization of important macrostructure and microstructure properties of resulting experimental forms.
- Preliminary process development - definition of processing parameters, identification of equipment development needs, and early scale-up tests of key fabrication steps for both performance under accelerated and simulated repository conditions; development of thermodynamic data for repository modeling studies.
- Preconceptual engineering studies - studies to support parallel Pu Disposition EIS activities and to provide a rough estimate of facility configuration and cost differences between the glass and ceramic technologies.

Experimental, analytical, and engineering studies provided data on both forms and their processes that were used in evaluating both technologies against criteria and metrics.

The integrated Immobilization R&D plan (Ref. 13) couples R&D activities to overall project schedule. It defines tasks for development of form, process parameters, and equipment needed to support design of the immobilization plant, and schedules waste form qualification activities required to get the form accepted into the Civilian Radioactive Waste Management System.

Five laboratory organizations are involved, with the following responsibilities (some shared):

- Lawrence Livermore National Laboratory (LLNL) - overall technical lead, ceramic form development lead, glass form development support, process/equipment development with Pu, and form characterization and qualification.
- Westinghouse Savannah River Company's (WSRC) Technology Center and glass form development lead, ceramic formulation support, and process/equipment development.
- Argonne National Laboratory (ANL) - form characterization, and glass formulation support.
- Australian National Science and Technology Organisation (ANSTO) - ceramic form development support.
- Pacific Northwest National Laboratory (PNNL) - form characterization and glass formulation support.

Evaluation Criteria

The criteria used to evaluate immobilization variants are a subset of those previously used by MD (Ref. 14), namely:

- *Resistance to theft and diversion by unauthorized parties.* Each disposition process step must be capable of providing for comprehensive protection and control of weapons-usable fissile materials.
- *Resistance to retrieval, extraction, and reuse by the host nation.* Surplus material must be made resistant to potential use in weapons to reduce reliance on institutional controls, and demonstrate that arms reduction can not be easily reversed.
- *Technical viability. There must be a h*igh degree of confidence that the alternative will be technically successful.
- *Environmental, safety, and health (ES&H).* High standards of public/worker safety and environmental protection must be met; significant additional ES&H burdens should not be created.
- *Cost effectiveness.* Disposition should be accomplished in a cost-effective manner and be compatible with reasonable long-term storage alternatives.
- *Timeliness.* There is an urgent need to begin Pu disposition and to minimize the time period the surplus fissile materials remain in weapons-usable forms.

Three non-technical criteria used by MD in previous assessments (fostering cooperation with Russia, public and institutional acceptance, and additional benefits) were not considered in these evaluations. Political and institutional considerations in making the final decision on the immobilization form, rests with the ultimate decision maker, DOE.

Metrics. Factors and metrics for each criterion were developed by a committee of experts from the Immobilization Development Team and the Office of Civilian Radioactive Waste (RW) M&O contractor. Criteria and major factors are summarized in Table 1; they are described fully in References 10 and 11.

Spent Fuel Standard. Criteria 1 and 2 are related to the NAS Spent Fuel Standard (Ref. 1) adopted by MD. That is, the immobilization form must "make Pu as unattractive and inaccessible for retrieval and weapons use as residual Pu in spent fuel from commercial reactors". Attributes include:

- High radiation dose rate: Use of fission products to achieve doses > 100 rem/hour one meter from the canister surface 30 years after fabrication.
- Large and heavy integral assembly: Impossible for individual to move without heavy equipment.

Table 1 Goes Here

- Diluted, substantially homogeneous solid matrix: Concentrations of a few weight percent effectively dispersed with the fission products within the waste form's solid matrix.
- Higher concentration of heavier Pu isotopes than weapon-grade Pu.

The Pu isotopic composition has only secondary effects on proliferation resistance, because non weapon-grade Pu can be used to fabricate nuclear devices. Nevertheless, lower isotopic quality may make reuse by the host nation less attractive.

Technical Evaluation Panel (TEP) Review

The initial step in evaluating the relative merits of immobilization technologies was a comprehensive review during a two-week period in July 1997. A panel of experts from the five participating labs performed the review. The TEP reviewed the performance of glass and ceramic form technologies relative to the criteria and metrics. The TEP received data in oral briefings and in written format. Members evaluated attributes of glass and ceramic technologies for each of the criteria-metrics, based on the information provided, and then documented their findings in a detailed report (Ref. 11).

Bounding Conditions, Uncertainties and Assumptions

Three major constraints that placed limitations on the evaluations were: the availability of data; the specificity and clarity of the criteria and metric; and a severe time limit for the evaluation process. Because the decision was accelerated by one year, some experiments/engineering studies could not be completed. Still, there was sufficient information to make comparisons for most decision factors.

Because of programmatic uncertainties, assumptions had to be made. They were: 1) the preferred immobilization implementation paths expressed in the ROD (Ref. 2); 2) MD program interfaces with DOE Environmental Management (EM) and Civilian Radioactive Waste Management (RW) programs; and 3) the planned project schedule.

ROD Related Assumptions

1. The PEIS-ROD and May 1997 Notice of Intent for the Pu Disposition EIS (Ref. 18) identified can-in-canister variants (glass and ceramic) as the preferred immobilization technology. In this approach (Figure 3), cans of glass or ceramic forms containing Pu are encapsulated within canisters of HLW glass

Figure 3 Goes Here

2. The May 1997 Notice of Intent (Ref. 19) identified SRS as the preferred site for the immobilization mission. The evaluators assumed that the Pu (first stage) immobilization plant would be located at SRS, that standard DWPF canisters would be used as vessels for cans of Pu forms and HLW glass, and that the immobilization program would have minimal impacts on the overall DWPF mission.

Expected Pu Feed Materials and DOE-EM Interface. Two Pu feed cases were considered, based on the possible partitioning of surplus Pu between the immobilization and reactor-MOX alternatives:
Non-pit materials comprise impure metals, alloys, and predominately oxide materials, currently within the DOE Environmental Management (EM) stabilization program, pure metal and oxides still under the control of DOE Defense Programs. Other EM Pu residues may be candidates for immobilization. In general, it was assumed that EM materials would be stabilized. Tables 2 and 3 summarize categories and quantities of expected feed materials; additional details on impurity contents are given in Reference 16.

Two cases were considered:

1. 50 MT case: all the surplus Pu materials come to the immobilization plant;
2. 18.2 MT, commonly referred to as the "17 MT case:" Only non-weapons-pit materials come to the immobilization plant.

Tables 2 and 3 Go Here

Plutonium feed materials will be grossly blended to levelize the 17 MT of uranium from the unirradiated fuel materials. Blending will degrade the Pu isotopic composition by mixing weapons grade with fuels grade. Limited blending will be performed to reduce tramp impurity concentrations. The non-U impurities represent about 2.6 wt. % and 4.5 wt. % of the bulk feed for the 50MT and 17 MT cases, respectively.

High Level Waste Repository. It was assumed that the immobilized form would be combined with HLW-glass canisters for disposal in the Federal Repository. Repository acceptance requirements have not been established. Existing acceptance criteria for vitrified HLW were based on the waste package and repository system having to retain the fission products in HLW for several half lives, or several hundred years. The immobilization form will contain significantly larger quantities of fissile elements, primarily ^{239}Pu which decays with a half-life of ~24,000 years to the fissile isotope ^{235}U which has a half-life of ~700 million years. Therefore, the primary concern for repository performance is the possibility of a criticality event occurring in the lifetime of the repository system. Migration of immobilization radionuclides to the biosphere is not to be a major issue due to the relatively small radionuiclide inventory associated with the immobilized Pu.

As a consequence of the criticality issue, it is possible that more stringent durability requirements could be placed on Pu forms than exist for HLW-glass.

Schedule. It was assumed that the immobilization plant would begin fabricating forms in CY2005. The R&D plan (Ref. 15) lays out development activities needed to meet this aggressive schedule. Significant delays in development of form/processing technology or in characterization, testing, and qualification for repository acceptance would delay startup.

Brief Descriptions of Immobilization Forms and Processes

The proposed glass form was a single-phase (baseline formulation) lanthanide borosilicate (LaBS) glass specially formulated to accommodate high concentrations of actinide elements (~ 16 wt %). The proposed ceramic form was a multi-phase titanate-based crystalline ceramic that is based on durable titanate minerals existing in nature. These titanate phases can accommodate up to 50 wt. % actinide in their crystalline structures. Both forms were quite robust with respect to non-actinide impurities. A comparison of the baseline ceramic and LaBS glass fabrication processes is given in Table 4.

Table 4 Goes Here

Glass. Borosilicate glasses have been used to immobilize HLW and LLW in the U.S. and Europe (see Ref. 11 for citations to numerous publications). Glasses were chosen for their high flexibility to accommodate a broad range of chemicals, combined with acceptable durability for retaining fission products over their lifetimes under expected repository conditions. Borosilicate glasses developed for waste disposal missions do not contain significant concentrations of actinide elements, because these materials were separated from the HLW during spent fuel processing. Generally, borosilicate glasses are melted and cast at 1050° to 1150° C.

LaBS glass was developed by WSRC to provide a storage form for Am and Cm, and subsequently to provide an immobilization form for surplus Pu. The objective was to find a glass composition that could accommodate large actinide concentrations and the impurity elements in the surplus Pu materials, as well as demonstrate acceptable durability. This was accomplished through the modification of lanthanide-containing Löffler glass (Löffler -1932, U.S. Patent #2150694). LaBS glass can accept actinide concentrations of up to 16 wt. % along with the expected range of impurity elements. Leaching tests indicate that LaBS glass has higher durability than both EA Standard Glass and DWPF HLW glass as measured in a PCT-A test. The LaBS glass processing temperature is 1500°C, much higher than traditional HLW borosilicate glasses.

Ceramic. The proposed titanate-based crystalline ceramic form originated from SYNROC (synthetic rock) forms developed and tested by the Australian National Science and Technology Organisation (ANSTO). (Ref.11 cites references for these forms). These forms are much more durable than glasses under simulated repository conditions, but are not as flexible as borosilicate glass in accommodating the broad range of

chemical constituents contained in HLW streams. Furthermore, the hot pressing fabrication technology for SYNROC proved to be more complex than the glass forming operations for shielded cell operations with HLW (Ref. 17).

Ceramic

With advent of the Pu immobilization mission, the SYNROC concept of incorporating radioactive elements into titanate phases was readily adapted to Pu. Both ANSTO and LLNL explored zirconolite and pyrochlore titanate ceramics for incorporating Pu and U. These phases can accept high concentrations of actinides and the expected range ofimpurities in Pu feedstock. They also proved to be more durable than SYNROC C and D. LLNL chose pyrochlore-rich ceramic that contains zirconolite, brannerite, and rutile as secondary and tertiary phases. A cold press and sinter process, very similar to European MOX fuel processes, was developed for both the ceramic form. As a consequence, for the Pu immobilization mission, the ceramic technology offers a compositionally flexible form with extremely high durability, fabricated by a process that is no more complex than the LaBS glass process

OVERALL ASSESSMENT

Integrated Evaluation of Forms Against Criteria

The following sections summarize the evaluations made for candidate forms with respect to their advantages for specific factors under the decision criteria areas. (from Table 1). Both technologies would provide acceptable Pu immobilization forms. However, the ceramic form was judged to be superior, as a consequence of an accumulation of small to moderate advantages for important decision factors. These are: Proliferation resistance, repository performance/acceptability, potential worker dose, and cost effectiveness. Glass has only a slight advantage for one non-proliferation factor.

Resistance to Theft and Diversion

The objective is to provide for comprehensive control and protection, external and intrinsic, of Pu. A parallel study (see Table 5) of the non-proliferation effectiveness of the can-in-canister immobilization approach provided input to assessments for Criteria 1 and 2 (Ref. 17).

Table 5 Goes Here

Difficulty of Retrieval and Extraction by Rogue Party: - A small to moderate advantage exists for ceramic as a consequence of the higher degree of difficulty in the processes needed to separate Pu from the ceramic form versus the glass form. The key findings (Ref. 17) are:

- Both glass and ceramic can-in-canister forms meet the Spent Fuel Standard based on the degree of difficulty, time, and cost for recovering Pu.
- Several design modifications to the original concept could be made that would effectively retard or preclude access to the Pu cans for both glass and ceramic forms. These include mechanical enhancements, such as welding cans to the rack and armoring, and designs that allow the HLW glass to intimately contact the glass or ceramic forms.
- Because of its density (volumetric) advantage, the ceramic form would more readily allow for structural enhancements to the can-in canister configuration, such as armoring.

The ceramic form has an advantage over the glass form with respect to the difficulty of Pu recovery. The importance of this advantage could be reduced should DOE decide to employ one of the proliferation-resistive measures mentioned above to thwart retrieval.

Technical Maturity

Ceramics and glass technologies are of similar overall technical maturity for plutonium immobilization (assuming the can-in-canister radiation barrier system). Both forms are sufficiently mature that eventual plant implementation can be expected to be successful. However, several of the individual process steps for

both technologies differ in maturity. A comparison of process steps for each form is given in Table 6. Both technologies require further development before implementation.

Table 6 Goes Here

Viability Risk

Risks are associated with advancing the program from where it is today through RD&T to plant operation and closeout. Table 7 summarizes the risks involved with individual process steps for the ceramic and glass technologies. Sl;ght differences are evident in the risk for the two forms. The ceramic technology's defined data requirement for the development of a product control model has a rating of medium, differentiating it from the glass product control maturity afforded by the HLW glass model. The glass technology has an engineering cost and schedule risk of medium in the area of glass melter development and testing, discriminating it from the corresponding ceramic process steps of pressing and sintering which are low risk.

Technical Viability: Repository Acceptability

The findings were:

- Both forms should be acceptable to the repository from the standpoint of criticality. Because total radionuclide inventory in immobilization forms would be small compared to total projected inventory in the repository, the release of constituents from immobilization forms is not expected to affect results of the total system performance assessment (Ref. 25).
- Dissolution rates of the ceramic for matrix elements Ca, Hf, Pu, and neutron absorbers Hf and Gd are substantially lower (>two to four orders of magnitude) lower than their counterparts for glass.
- Radiation damage from alpha-decay is expected to have minor effects on the glass form's dissolution rates. The ceramic form will become metamict, which is expected to increase its dissolution rate by a factor of 10 to 15. Consequently, available data suggest that the long-term durability of the ceramic form (after it becomes metamict) should be more than an order of magnitude superior to LaBS glass.

Environmental, Safety, and Health Compliance

The objective is to ensure that high standards of public and worker safety and environmental protection are achieved. There were three factors considered in assessing the expected performance of the two technologies with respect to this criterion: (1) public and worker health and safety; (2) waste minimization; and (3) known and manageable waste forms.

Public and worker health and safety: - There is a significant difference between the two forms with respect to potential worker dose. Ceramic has a significant advantage over glass as a consequence of a much higher neutron source strength associated with the glass form. This stems from the (a, n) reaction that occurs with ^{11}B, a key constituent in LaBS glass. A comparatively high neutron generation rate occurs in the glass beginning with glass frit-Pu feed milling and blending step through canister operations.

To assess potential dose implications of higher neutron generation rates for glass, LLNL and WSRC calculated comparative doses for both processes for various shielding configurations and distances (Refs. 18 and 19).

The baseline glass form generates between 7 to 8 times higher radiation field than the ceramic form and is dominated by the neutron dose. If isotopically enriched ^{10}B is used, then the potential exposure differences would decrease to a factor of 3 to 4 times higher for glass than ceramic.

Table 7 Goes Here

For ceramic and the powder-conditioning portion of the glass process, equipment and automation techniques can be adapted from the MOX fuel industry. Even with this overall design approach, there are significant implications of the higher glass dose rate:

- There are a few troublesome operations that might benefit from limited operator handling, such as can extraction from the glove box (decontamination of the weld area). With the ceramic form, such "hands on" operations would be possible (see Figure 3). For glass, such "hands on" operations would be much more restricted. In some areas, this could translate into simpler ceramic equipment designs. This is a potential cost impact.
- The glass line, after milling. will require more shielding than the ceramic line to achieve comparable dose rates to operational and maintenance personnel. To avoid significant deinventorying when maintenance operations need to be performed on a piece of equipment, additional shield barriers and space may need to be provided for the glass process. This also is a potential cost impact.
- Finally, the DOE goal of "As Low As Reasonably Achievable" (ALARA) exposure to personnel can more easily be achieved with the ceramic process. The ALARA principle would favor the ceramic immobilization process.

In giving ceramic a small, rather than a moderate, advantage for this important ES&H factor, it was assumed that appropriate facility design measures, such as shielding/spacing, would be used to meet exposure goals.

Cost Effectiveness

Investment and Life Cycle Cost: - This metric shows a small to moderate cost advantage for ceramic due primarily to the cost associated with the extra HLW canisters that will be required and the design and operational impacts associated with the higher radiation source term for the glass alternative.

Potential areas of distinct cost differences were identified: (1) additional canisters of HLW forms for glass; (2) facility design and operational impacts for factor of eight higher neutron dose source for glass; (3) differences in waste form qualification and product control reflecting the glass experience with the DWPF "model"; (4) potential higher development costs for the melter versus the MOX-based ceramic formation process; (5) provision for recycling failed glass melts; and (6) rawmaterial (frit versus ceramic precursors) and equipment replacement costs. Life cycle cost differences in these areas are summarized for the two forms in Table 8.

Table 8 Goes Here

Conclusion

On the basis of comprehensive technical evaluations of the immobilization technologies, both technologies were found by to be acceptable for the Pu immobilization mission, but ceramic offers a number of important advantages over glass, notably:

- The ceramic form is expected to be much more durable in the repository environment and should retain Pu and its decay products for longer periods than the glass form.
- The ceramic process has a significantly lower source term and potential for worker exposure, which enhances its preference by reason of the ALARA standard.
- The ceramic form and process offer significant cost savings relative to the glass technology.
- The ceramic form is somewhat more robust to the threat of theft and diversion by terrorists or rogue nations.

Maturity of the ceramic technology, found to be comparable to glass, is sufficient to provide DOE with a reasonably high confidence that Pu immobilization can be carried out successfully on the desired schedule. There were no "show stopper" issues identified for either technology.

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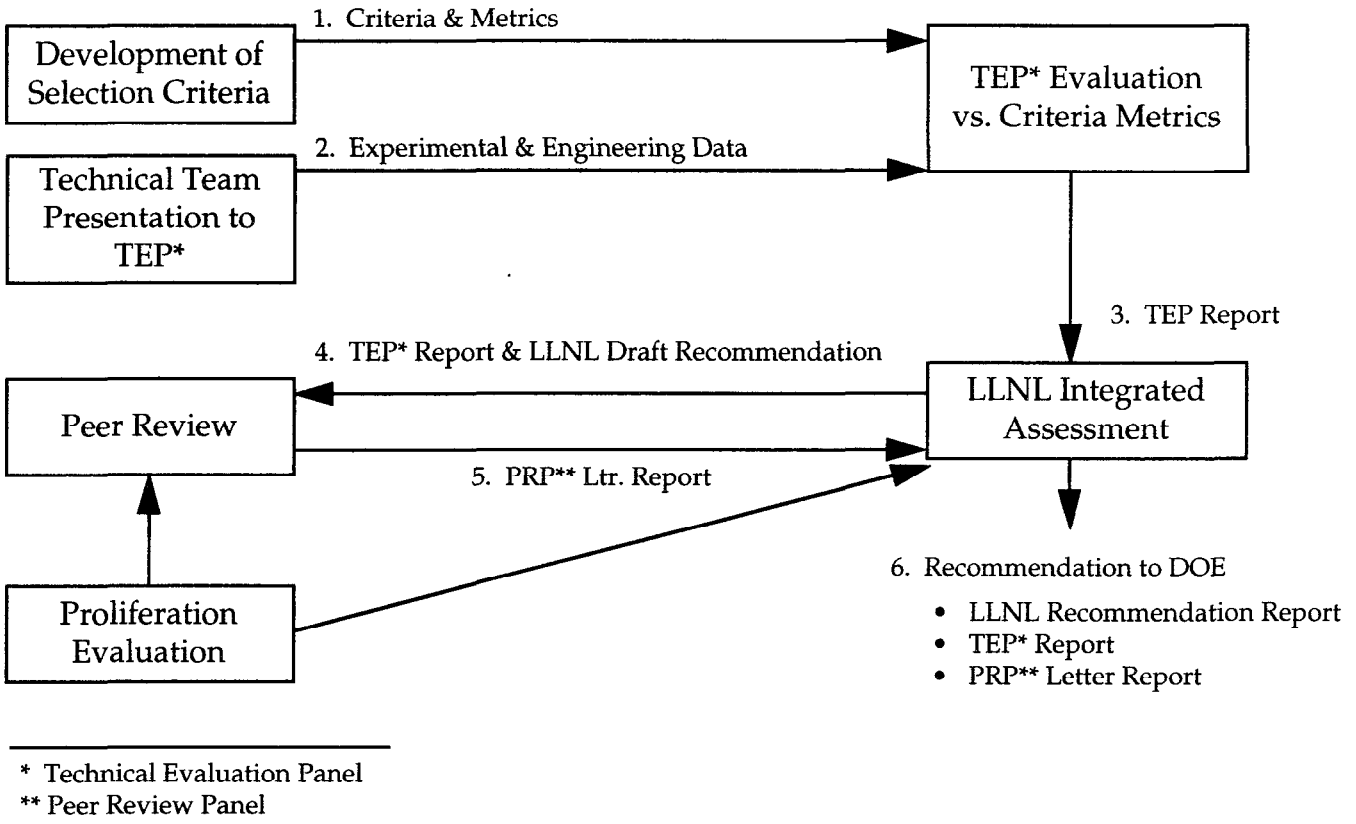
Figure 1. Immobilization Form Evaluation Process



* Technical Evaluation Panel
** Peer Review Panel

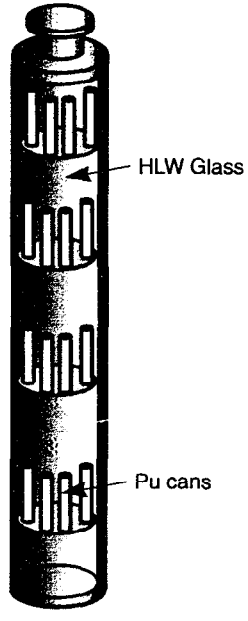


Figure 2. Schematic Diagram of the can-in-canister configuration

Figure 3. Working Hours Per week for Canned Forms for Different Operating Conditions

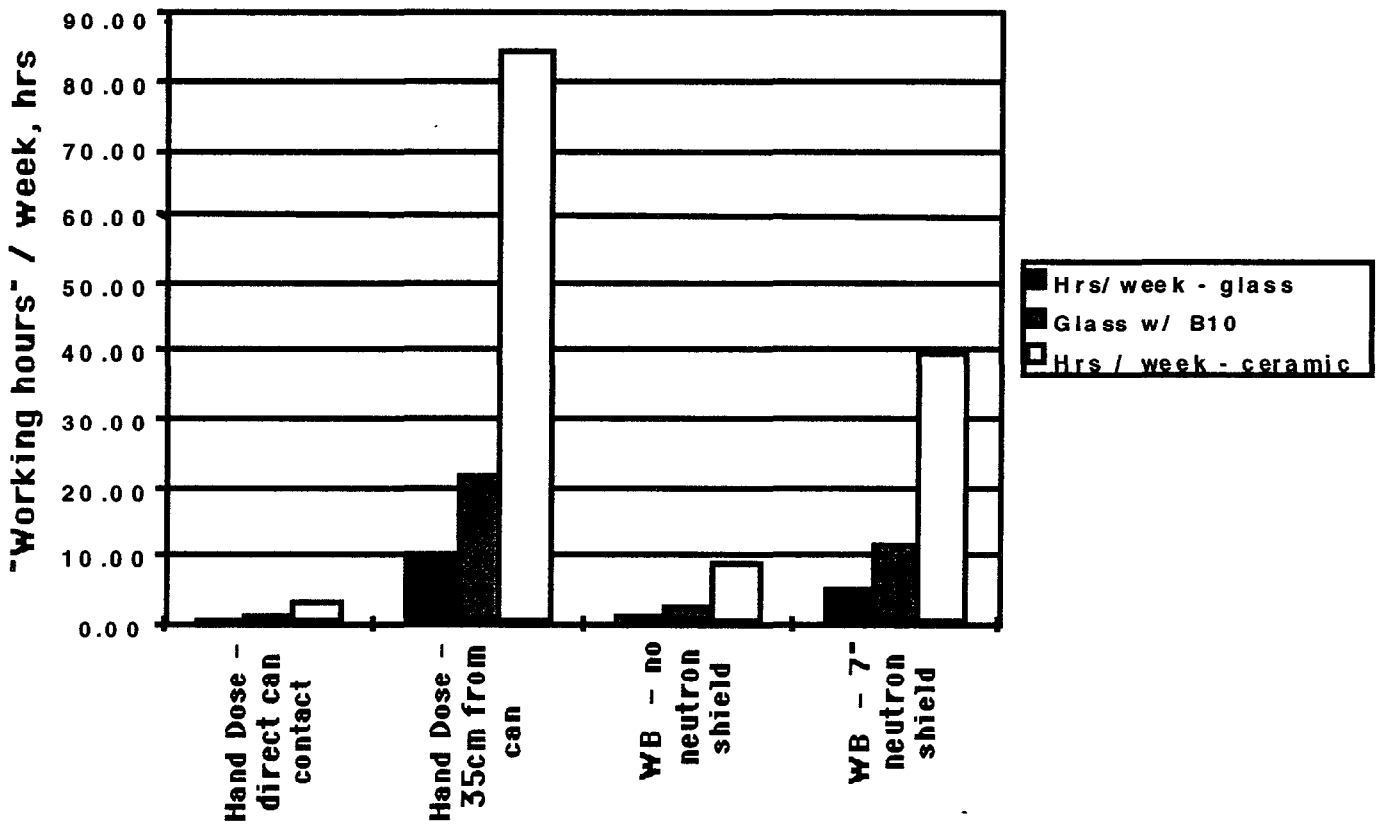


Table 1. Decision Criteria and Factors

Criterion 1. Resistance to Theft or Diversion by Unauthorized Parties
- a. Low Inherent Attractiveness
- b. Minimization of Transportation, Facilities, and Sites
- c. Minimization of Processing
- d. Safeguards and Security Assurance
- e. Difficulty of Retrieval, Extraction, and Use by a Clandestine Group or Rogue Nation

Criterion 2. Resistance to Retrieval, Extraction, and Reuse by the Host Nation
- a. Difficulty of Retrieval, Extraction, and Reuse
- b. Assurance of Detection of Diversion and Extraction

Criterion 3. Technical Viability
- a. Technical Maturity (considered as impacts on cost and timeliness)
- b. Viability Risks (considered as impacts on cost and timeliness)
- c. Repository Acceptability of Disposal Form

Criterion 4. Environmental, Safety, and Health Compliance
- a. Public and Worker Health and Safety
- b. Waste Minimization
- d. Known and Manageable Waste Forms

Criterion 5. Cost Effectiveness
- a. Life Cycle Cost:
- b. Investment and Start-up Cost
- c. Establish Product Acceptability Requirements
- d. Potential for Cost Sharing. Dollars
- e. Utilization of Existing Infrastructure
- f. Cost Estimate Certainty

Criterion 6. Timeliness
- a. Time to Start Disposition/Time to Open Facility
- b. Time to Complete
- c. Impacts to Existing or Future Missions

Table 2. General Categories and Quantities of Surplus Pu (Ref. 20)

Category	MT Pu	MT U	MT Other
Weapons Pits	31.8	0	0
Oxide			
Metals	3.4	0	0.1
Non-pit Oxides	9.0	2.0	1.2
Alloys	1.0	0.3	0.1
Fuels (unirradiated)	4.8	14.5	0.1
Total	50	17	1.5

Table 3. Identified Individual Feed Streams for the Pu Immobilization

Pu Source	%Pu	%U	%	Minor Components
Clean Metal (A)	98.0	0.0	2.0	Ca, Mg, Ga, Zn
Impure Metal (A)	78.6	0.0	21.4	Ca, Mg, Fe, Cr, Ni, K, Ta, W, Al
Pu Alloy	65.3	32.6	2.1	Ca, Mg, Fe, Mo, Al, Zr
Clean Oxide	98.5	1.1	0.4	Al
U/Pu Oxide	33.4	60.4	6.3	Ca, Mg, Fe, Ni, K,Na, Mo, Ta, Ba, W
Pu/U Compounds &Impure Oxide (A)	47.1	0.0	52.9	Ca, Mg, Cl, Fe,Cr, Ni, F, K,Na, Mo, Ba, W, Si
Impure Oxide (T)	86.4	0.0	13.6	Ca, Mg, Cl, Fe,Cr, Ni, F, K,Na, Mo, Ba, W, Si
ZPPR Fuel	28.0	69.0	3.0	Mo

Table 4. Comparison of Baseline Ceramic and LaBS Glass Processes

Ceramic	LaBS Glass
Conditioning mill to size reduce UO_2 and PuO_2	
Attritor mill to blend PuO_2/UO_2 and Oxide precursor	Attritor mill to co-grind PuO_2/UO_2 and glass making frit
Granulator	Screw feeder to seven melters
Feed hopper to single press	Melter feed hopper
Cold press	Melters for vitrification including off-gas system
Conveyer to six furnaces	Glass pour into cans
Sintering furances including off-gas system and Ar purge	Can cool down
Disc cool down	Trim can
Inspection	Inspection
Load discs into can	Load glass can in outer can
Bagless loadout	Bagless loadout

Table 5. Summary Comparison of Ceramic and Glass Pu Immobilization Forms for Criterion I: Resistance to Theft or Diversion by Unauthorized Parties.

Metric	Ceramic Form	Glass Form	Spent Fuel
1. Time to reprocess			
a. Development time	6 to 12 months depending upon the level of expertise	Documented in open literature	Documented in open literature
b Design, procurement & construction time	10 to 42 months	6 to 30 months	6 to 30 months
c Process equipment	Specialized	Piratable from many small industries	Piratable from many small industries
d. Actual processing time	4 to 14 weeks	3 to 12 weeks	3 to 12 weeks
2. Process Parameters			
a U/Pu ratio	2 for 50 tonne case 2 for hybrid case	0 3 for 50 tonne case 0.95 for hybrid case	>19
b Processing steps required	14 for minimal yield 18 for higher yield	12	11
c Anticipated yield (from one canister containing)	5 6 to 18 6 kg (35 1 kg)	15 to 21 kg (23 6 kg)	88 ± 44 kg (100 ± 50 kg)*
d Hypothetical number of weapons that could be produced	1 to 3	3 to 4	8 to > 30 **
3. Cost to reprocess	Within capability	Within capability	Within capability
4. Detectability of reprocessing activities	Purchase of specialized equipment and process chemicals	Purchase of process chemicals	Purchase of process chemicals
5. Separability from radiation barrier	Feasible	Feasible	Feasible

*For spent fuel waste package

** Depends upon the fuel in the spent fuel waste package

Table 6. Summary of technical maturity by process step for glass (G) and ceramic (C) forms.

	TEP assessment		Confidence in data/information		Clarity of the metric		Assessment of overall impact	
Process step	**Ceramic**	**Glass**	**Ceramic**	**Glass**	**Ceramic**	**Glass**	**Ceramic**	**Glass**
Formulation (G, C)	H	H	H	H	M	M	H	H
Grinding (G, C)	H	H	H	H	M	M	L	L
Blending (G, C)	H	H	H	H	M	M	H	L
Granulation (C)	H	N/A	H	N/A	M	N/A	L	N/A
Pressing (C)	H	N/A	H	N/A	M	N/A	H	N/A
Sintering (C)	H	N/A	H	N/A	M	N/A	H	N/A
Melting (G)	N/A	M	N/A	H	N/A	M	N/A	H
Automation (G, C)	M	M	L	L	M	M	M	M
Process control (G, C)	H	H	H	H	M	M	H	H
Product control (G, C)	L	M	M	H	L	L	H	H
HLW glass pour (G, C)	M	M	L	L	M	M	H	H
Product recycle (G, C)	H	H	L	L	L	L	L	L

H = high; M = medium; L = low; N/A = not applicable

Table 7. Summary of technical risk by process step for glass (G) and ceramic (C) forms.

	TEP assessment		Process summary (key points)		Required development		Backup technology	
Process	**Ceramic**	**Glass**	**Ceramic**	**Glass**	**Ceramic**	**Glass**	**Ceramic**	**Glass**
Formulation (G, C)	L	L	Pyrochlore/rutile	LaBS frit B	Optimize	Optimize	Other SYNROC blends	Other glass compositions
Grinding (G, C)	L	L	Attritor	Attritor	Optimize	Optimize	Jet mill	Jet mill
Blending (G, C)	L	L	Attritor	Attritor	Optimize	Optimize	V-blender	V-blender
Granulation (C)	L	L	Spherodiser	none	Optimize	Demonstrate	V-blender	Spherodiser
Pressing (C)	L	N/A	Hydraulic	N/A	Hot demo	N/A	None	N/A
Sintering (C)	L	N/A	Argon furnace	N/A	Select, optimize, demonstrate	N/A	Tunnel kiln	N/A
Melting (G)	N/A	M	N/A	Platinum induction	N/A	Modify, test	N/A	Alternative design
Automation (G, C)	L	L	Pick/place	Screw, pick/place, cutter	Design, test	Design, test	Alternative design, worker	Alternative design
Process control (G, C)	L	L	T/C, actuators, valves, etc.	T/C, actuators, valves, etc.	Design, test	Design, test	Alternative design	Alternative design
Product control (G, C)	M	L	Composition and parameter control	Composition control, continuous properties models	Develop, test	Modify, test	Further development	Development
HLW glass pour (G, C)	M	M	Baseline canister design	Baseline canister design	Generate data, optimize model, determine criteria	Generate data, optimize model, determine criteria	Alternative design	Alternative design
Product recycle (G, C)	L	L	Adjust at attritor, off-line crusher	Adjust at attritor, off-line crusher	Demo	Demo	In-line equipment	In-line equipment

H = high, M = medium, L = low; N/A = not applicable.

Table 8. Areas of Cost Differences between Glass and Ceramic Processes

Cost Category	Est. LC Cost Difference	Advantage to:
• Additional Canisters	~$24M to $70M [1]	Ceramic
• Higher Neutron Rate		
- Enriched B-10	~$17M to $50M [1]	Ceramic
- D Automation	Not evaluated	Ceramic
- D Shielding and Space for Maintenance	Not evaluated	Ceramic
- ALARA	Not evaluated	Ceramic
• Form Qualification	Not evaluated	Glass
• Melter Development	Not evaluated	Ceramic; offset glass advantage above
• Glass Recycle	Within preconceptual design uncertainty	No discernible difference
• D Raw Materials & Equipment Replacement	$(6+X)M to $(18+Y)M [1] [2]	Ceramic

[1] Range reflects the 17 MT and 50 MT feed cases

[2] Estimates reflect difference in estimated glass frit and ceramics precursor costs and yet-to-be-determined costs for replacing glass melter crucibles versus sintering furnace replacement (X and Y).

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