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Fissile Material Disposition Program

Screening of Alternate Immobilization Candidates for Disposition of Surplus Fissile Materials

February 9, 1996

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Screening of Alternate Immobilization Candidates for Disposition of Surplus Fissile Materials

February 9, 1996

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94550

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Executive Summary

A study was performed to evaluate and select the most promising waste forms for the incorporation of weapons-usable plutonium for ultimate disposal in a geologic repository.

A review of the literature identified that more than 70 waste forms have been considered for immobilizing radioactive wastes. The individual waste forms were grouped into families that share common chemical and physical characteristics, and their properties were reviewed. An approach was selected for the screening of the potential plutonium immobilization forms that provided a formal, structured mechanism for selecting a set of candidates for further analysis and development. A two-stage screening approach involving both pass-fail and multiattribute type analysis techniques was adopted.

The screening process resulted in a ranking of 16 waste forms shown in Table 5-1. Borosilicate glass ranks highest of all the immobilization forms. Titanate-based ceramic (Synroc) ranks second highest. Sensitivity analysis showed that these form family rankings are very insensitive to changes in both the attribute weights generated and the technical scores assigned.

Based on the technical rankings, borosilicate glass, titanate-based ceramic (Synroc), and metallic alloys were selected for more detailed examination as a means to further narrow the number of options for the immobilization mission.

1. Introduction

Overview of the Surplus Fissile Material Control and Disposition (SFMC&D) Program

With the end of the Cold War, the world faces for the first time the need to dismantle vast numbers of "excess" nuclear weapons and dispose of the fissile materials they contain, together with fissile residues in the weapons production complex left over from the production of these weapons. If recently agreed U.S. and Russian reductions are fully implemented, tens of thousands of nuclear weapons, containing a hundred tons or more of plutonium and hundreds of tonnes* of highly enriched uranium (HEU), will no longer be needed worldwide for military purposes. These two materials are the essential ingredients of nuclear weapons, and limits on access to them are the primary technical barrier to prospective proliferants who might desire to acquire a nuclear weapons capability. Theoretically, several kilograms of plutonium, or several times that amount of HEU, is sufficient to make a nuclear explosive device. Therefore, these materials will continue to be a potential threat to humanity for as long as they exist.

The Department of Energy (DOE) has been directed to complete a comprehensive review of long-term options for surplus fissile material storage and disposition, taking into account technical, nonproliferation, environmental, budgetary, and economic considerations. In furthering this policy, DOE's objectives include:

- Strengthening national and international arms control efforts by providing an exemplary model for storage of all weapons-usable fissile materials and disposition of surplus weapons-usable fissile materials.
- Ensuring that storage and disposition of weapons-usable fissile materials are carried out in compliance with ES&H standards.
- Minimizing the prospect that surplus U.S. weapons-usable fissile materials could be reintroduced into the arsenals from which they came, therefore increasing the prospect of reciprocal measures by Russia and other nuclear powers.
- Minimizing the risk that surplus U.S. weapons-usable fissile materials could be obtained by unauthorized parties.
- Accomplishing these objectives in a timely and cost-effective manner.

* 1 tonne = 1 metric ton = 1000 kg = 2200 lbs.

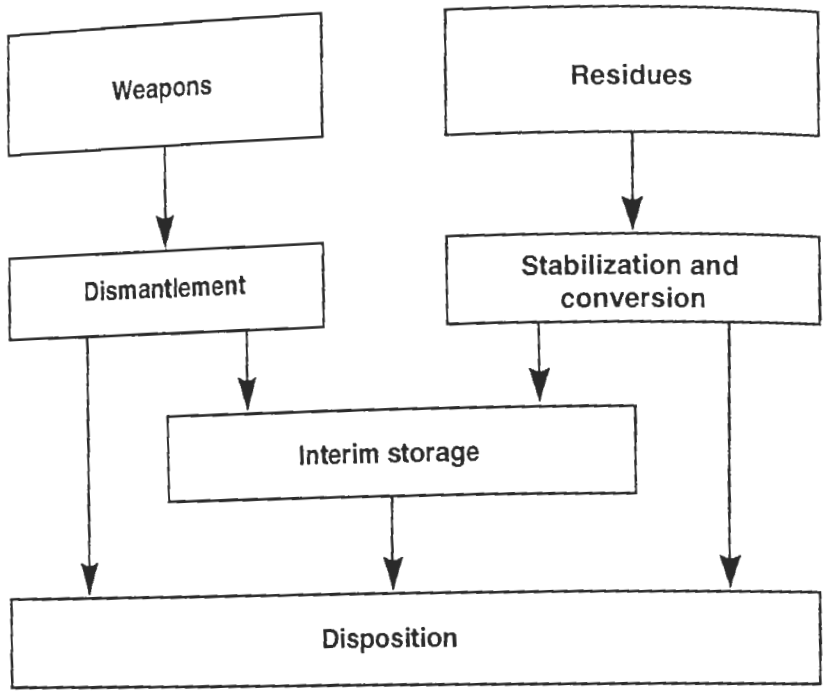

Figure 1-1. Steps in control and disposition of surplus materials.

The task of managing this reversal of the arms competition is complicated. The process (see Fig. 1-1) can be divided into three distinct but overlapping phases–dismantlement of nuclear weapons, intermediate storage of surplus fissile materials and long-term disposition of those materials. Dismantlement of weapons and storage of the resulting fissile materials are already under way. Conversion of the residue materials and disposition of all the surplus fissile materials will take far longer to accomplish. The HEU from nuclear weapons can be blended to make a reactor fuel that poses little proliferation risk and can return a substantial economic benefit, but disposition of weapons plutonium is far more problematic—hence, plutonium is the primary focus of this report. However, other actinides could be handled in much the same fashion as plutonium. The potential quantities and types of Pu-containing materials in the U.S. inventory that are subject to final disposition are indicated in Fig. 1-2.

The primary goal in choosing options for storage and disposition of surplus fissile materials should be to minimize the risks to national and international security posed by the existence of this material. This security goal can be divided into three main objectives:

- To minimize the risk that weapons or fissile materials could be obtained by unauthorized parties.

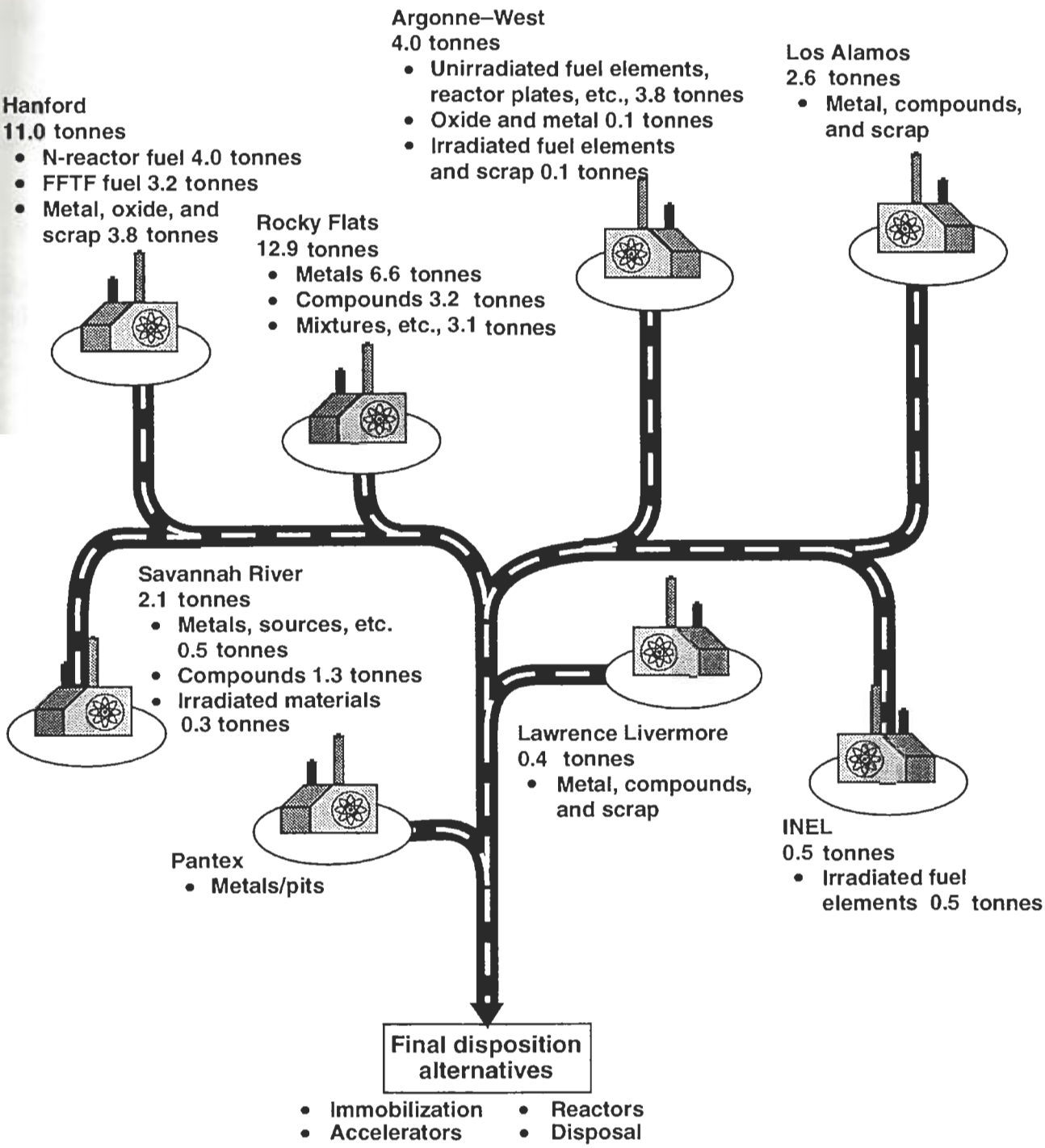

Figure 1-2. Potential types and quantities of Pu-containing materials in the U.S. inventory subject to final disposition.

- To minimize the risk that weapons or fissile materials could be reintroduc the arsenals from which they came, halting or reversing the arms reduction process.
- To strengthen the national and international control mechanisms and incen designed to ensure continued arms reductions and prevent the spread of nu weapons.

In addition to these security objectives, all options must protect worker health a the environment, and be acceptable to the public. Timing, which plays an importan part in whether the security criteria can be met, and consistency with other policies objectives will also be important criteria for choice. In addition, cost will inevitably be an important consideration.

2. Immobilization

2.1 Objectives

Immobilization is the fixation of the surplus fissile materials in an acceptable matrix to create an environmentally benign form for disposal in a geologic repository or deep borehole. In addition to the traditional requirement for an immobilization form to isolate the fissile material from the biosphere over geologic times, the immobilization form for the Fissile Materials Disposition Program must also be such that it is inherently as unattractive and inaccessible as the fissile material from spent fuel. This latter requirement is the so-called "spent fuel standard" similar to that invoked in the National Academy of Sciences (NAS) study[1] on plutonium disposition. From this perspective, high-level wastes (HLW) or other radioactive species can be added with the fissile material into the waste form to create a radiation field that can serve a proliferation deterrent. This immobilization process is shown conceptually in Fig. 2-1.

In several countries, including the U.S., radioactive HLW are to be immobilized in glass in a process known as vitrification, producing highly radioactive glass "logs" that will be stored for an interim period and then buried in geologic repositories. Such vitrification plants are in operation in several countries. Surplus fissile materials could also be vitrified, although such a process has not yet been demonstrated on an extensive scale. As in the case of HLW, other waste form matrices besides borosilicate glass were contemplated for the immobilization mission. It is important for the Fissile Materials Disposition Program to consider whether other immobilization forms may have inherent advantages over borosilicate glass for immobilization of these surplus fissile materials.[1] The purpose of this waste form evaluation study is to evaluate waste forms that may be used to immobilize surplus fissile materials for the disposition mission.

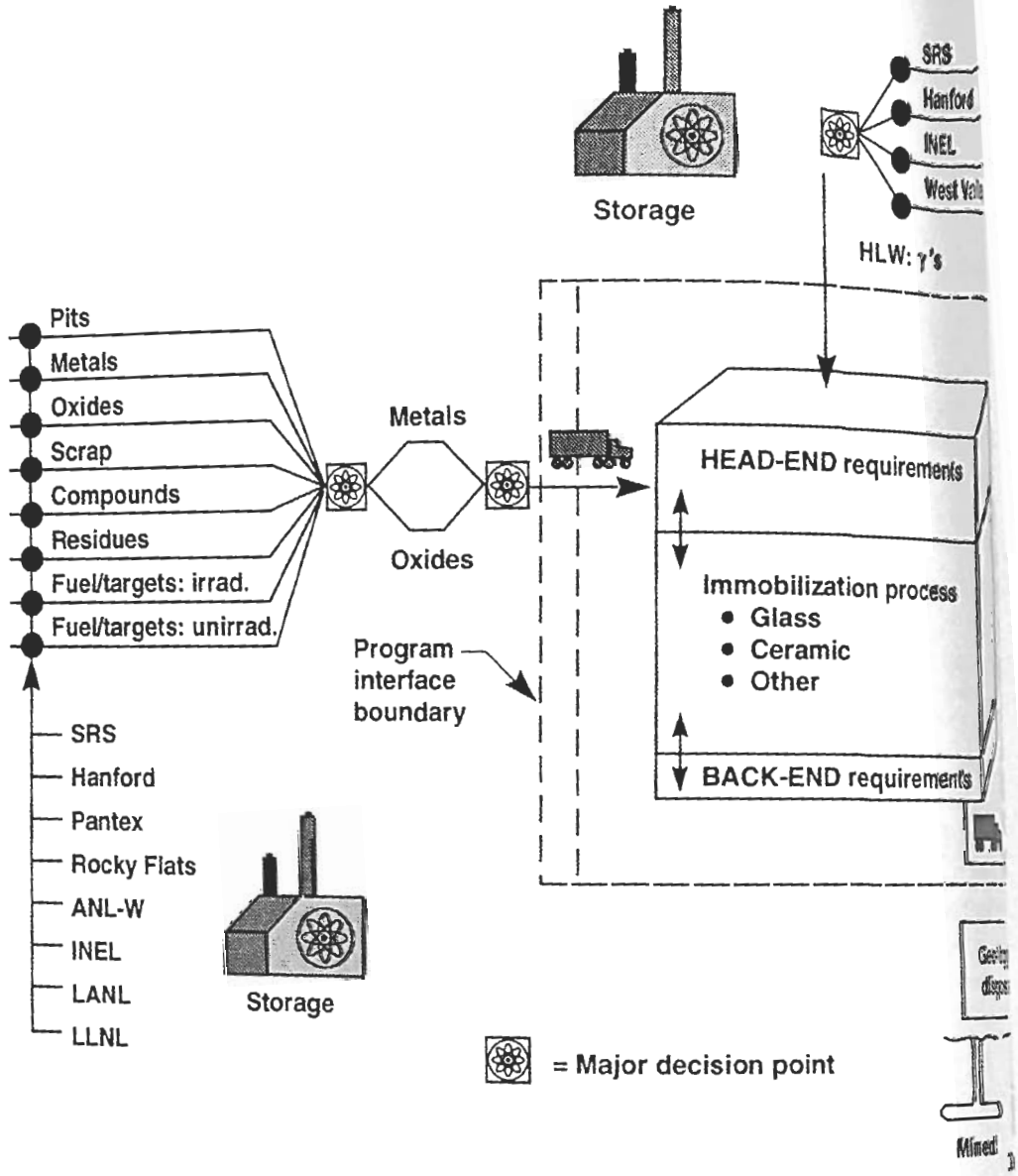

Figure 2-1. Immobilization of surplus fissile materials.

2.2 References for Section 2.

1. *Management and Disposition of Excess Weapons Plutonium* (National Academy of Sciences Press, Washington, DC, 1994).

3. Screening Process

An approach was selected for the screening of Pu immobilization forms that quickly surveyed all possible waste form alternatives and provided a formal, structured mechanism for selecting a set of candidates for further analysis and consideration.

A two-stage approach to selecting immobilization forms was adopted, based on formal decision analysis techniques. The staged approach allowed the use of more rigorous selection techniques as the number of options decreased and limited the data collection required in early steps. The first stage involved applying a small set of pass-fail screening criteria to the full list of immobilization forms and was aimed at quickly removing those forms that were clearly inappropriate for the Pu immobilization mission. The second stage evaluated more closely the remaining forms with the goal of selecting a small set (about three) of the best projected Pu immobilization forms for final consideration. This final set will be studied thoroughly in the PEIS. The prescreening process is depicted in Figure 3-1. This methodology and detailed aspects of the prescreening evaluations are presented below.

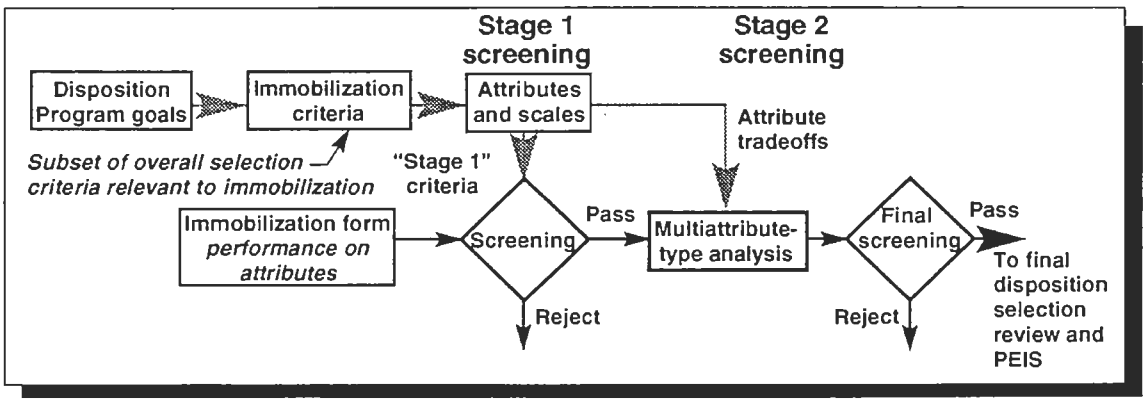

Figure 3-1. Pu immobilization task screening process.

3.1 First Level Stage—Pass/Fail Criteria

Given the time constraints of this effort, it was not feasible to evaluate every possible immobilization alternative with the care or detail called for in the PEIS. To identify the forms relevant to Pu immobilization it was necessary to review existing or proposed waste immobilization technologies and to eliminate those clearly not appropriate for the plutonium Immobilization project. The goal of this stage was to quickly remove those inappropriate technologies, while ensuring that no viable alternatives were eliminated from further consideration.

Pass-fail exclusion screening was used for this first stage. In this case, only alternatives that met all of a set of criteria were retained. This procedure expedited the screening process, since an alternative that failed any one criteria was eliminated.

3.1.1 Cutoff Levels

Cutoff levels for pass-fail screening are usually set using one of two methods. The first is to use a regulatory guideline to specify a cutoff [e.g., Codes of Federal Regulations (CFRs)] The other method is to set a level based on technical considerations. A cutoff assumes that, up to some point, a choice is acceptable and otherwise it is not. Figure 3-2 illustrates such a cutoff using a function that relates an option's desirability score with respect to a performance measure. For example, the performance measure could be the time to start the disposition and the cutoff could be 20 years.

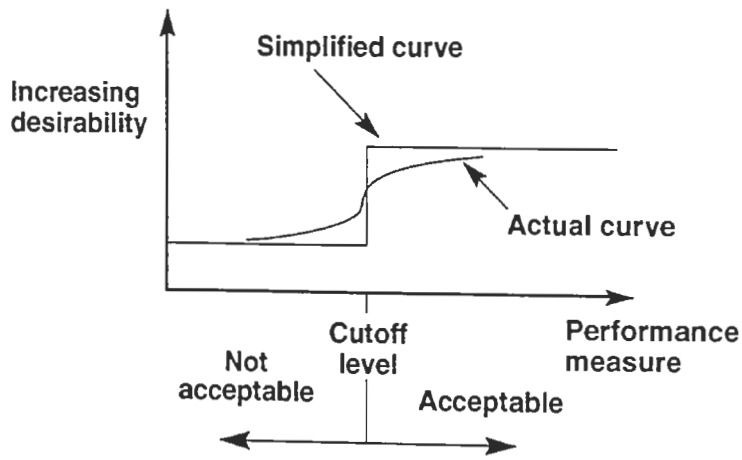

Figure 3-2. Establishment of cutoff levels.

Cutoff levels have the advantage of simplicity. To be conservative, the cutoff level could be relaxed, as shown in Fig. 3-3. This is all the more reasonable if there are several other criteria that may more appropriately eliminate the same option. The basis for setting a criterion in the first stage was that a technology should be eliminated on any given criterion only if the performance with respect to the criterion was *unacceptable* to the disposition program.

Regulatory requirements provided the majority of the first-stage screening criteria. The value judgments about acceptability of regulatory requirements are implied by the law. Consistent with eliminating unacceptable options is the assumption that within the allowable time frame there is insufficient time to obtain regulatory changes in order to adopt strategies that do not currently meet the regulations. The regulatory criteria relate primarily to the CFR requirements for long-term geologic disposal and are detailed below.

Other, nonregulatory criteria for the first-stage prescreening consisted of technical performance levels below which the results could not be tolerated for the disposition

program. These include criteria based on DOE-generated program requirements such as the maximum allowable time to start and finish dispositioning. The other, nonregulatory criteria required technical judgment to set cutoff levels. The question used to query the cutoff levels for these attributes was "what is the minimum level acceptable for the application?" Cutoff levels were set low enough to ensure that performance below this level would be so poor that the technology would not surface as a top contender *regardless* of its performance over *all other* characteristics (see Fig. 3-3).

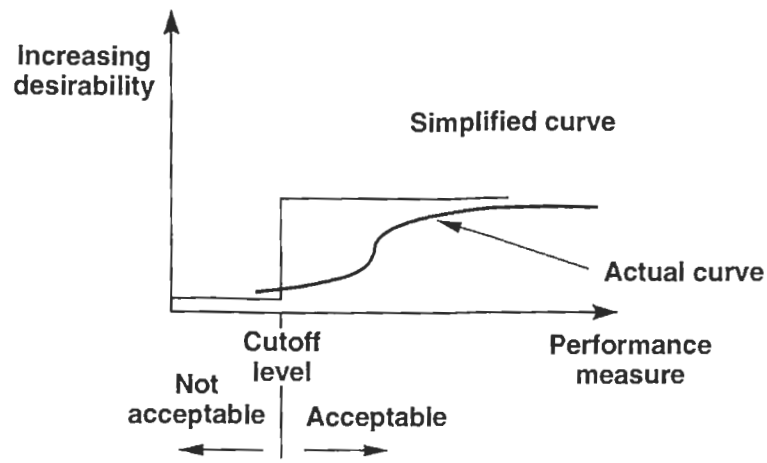

Figure 3-3. Cutoff levels can be set conservatively low.

Most of the screening criteria requires value judgments. Even though the existence of regulatory requirements implies that cut-off levels are defined, in many cases regulations require interpretation, and demonstration of compliance or noncompliance requires judgment and interpretation of the values which the regulations are intended to employ.

For some of the criteria, only objectives were specified since defining specific cutoff characteristics was often impossible, given the range of the options. It was determined that it was more appropriate for the technical reviewers to describe how forms met or did not meet the criteria, rather than provide all these definitions *a priori*.

3.1.2 First-Level Criteria

Table 3-1 shows the criteria used in the first stage of screening.

Although other characteristics have been identified as potentially equal or more important, specific cutoff levels for these attributes could not be developed. Other, performance-based attributes, do not have clearly identified unacceptable levels. These other attributes will, therefore, be used in the second stage of prescreening.

For the above exclusion criteria, failure of any one criterion results in elimination. In some cases judgment may deem it "probable" or "very likely" that a technology will fail on any given criterion. A combination of these "probable" failures for two or more criteria would also make it extremely unlikely that the technology would be selected as an option of choice. Therefore, forms were screened out in this first stage if they had

Table 3-1. First-stage pass-fail screening criteria.

Criteria	Requirement	Basis
No free water	"Shall not contain free liquids in an amount that could compromise the waste package"	10 CFR 60.13
Solidification & consolidation	"Shall be...in solid form…[and]…consolidated…to limit the availability and generation of particulate"	10 CFR 60.135(
Stability	"Shall not contain explosive or pyrophoric or chemically reactive materials in an amount that could compromise the waste package..." and "…shall be noncombustible…"	10 CFR 60.135(b)(
Criticality control	"K_{eff} must…show at least a 5% margin"	10 CFR 60.131(
RCRA metal content	Cannot contain significant quantities of the following free metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium, silver	40 CFR 261.2
Readiness	Must be technically viable for use 20 years after the record of decision (Subsequently, 10 years)	DOE-prescribed requ
Loading	Must maintain a feasible volume of waste for storage	Reasonable limit, factori increased resources requ handle excess volumes c immobilized material an storage sites/volumes.

probable failures on two or more of the criteria. The prescreening criteria were a to all waste forms, by experts for each technology. Results of the first-stage pres are described in Section 5 of this report.

3.2 Second-Level Stage—Performance-Based Screening

The objective of Stage 2 screening was to downselect, from the forms that pas Stage 1, to an appropriately small number of forms to be considered in detail (in future research and study) in the PEIS. This stage involved more formal treatme chosen attributes using a multiattribute utility analysis technique. This section d attribute selection, scales, scoring, and treatment of the data.

The goal was to maintain consistency with formal decision analysis principles. The steps in the Stage 2 process shown in Fig. 3-4 included:

- Defining the waste forms for consideration (identified from Stage 1 prescreening and described in Section 4).
- Develop the attributes (technical maturity, costs, etc.) against which the waste forms will be evaluated.
- Assess technical performance by evaluating the waste forms in terms of these attributes using a panel of experts.
- Perform trade-off assessments between attributes by accessing the opinion of decision makers to arrive at the value function (relative weighting) of the attributes.
- The result of the trade-off assessments are a set of utility functions that are then used to rank the waste forms.

The attributes and scales are presented in the next two sections, followed by a description of the scoring and value assessments. The results are presented in Section 5.

3.2.1 Attribute Selection

Attributes used in evaluating the performance of the immobilization forms were derived from goals and objectives of the overall Fissile Materials Disposition Program. This procedure ensured that immobilization forms selected will be consistent with the higher level goals of the disposition program. Although the top level program criteria have evolved over the last year, the attribute scales remain valid and appropriate.

The following discusses the attributes believed to be useful for distinguishing between immobilization forms.

1. Resistance to theft or diversion in processing/storage and resistance to retrieval, extraction and reuse

1.a Inherent attractiveness & difficulty of retrieval, extraction and reuse

The attribute will examine both inherent attractiveness for diversion and use (loading, ease of extraction, etc.) and the additional *un*attractiveness for diversion achieved by adding a radiation barrier. Though the focus of the screening committee was primarily to address diversion during processing, immobilization also creates some potential for recovery and reuse during long-term storage. Therefore, the Pu Immobilization Team felt it was necessary for this attribute to also address attractiveness during storage.

1.b Assurance of detection of retrieval & extraction

- It was determined that for immobilization form selection, it would be difficult and unnecessary to distinguish between the inherent attractiveness and difficulty of retrieval, extraction and reuse. Therefore, these are both addressed in 1.a, above.
- Minimization of transportation and sites was determined not to be applicable to the selection of immobilization forms because it is outside the analysis boundary for immobilization form selection.
- Safeguards and security assurance was determined not to vary significantly over the immobilization forms.

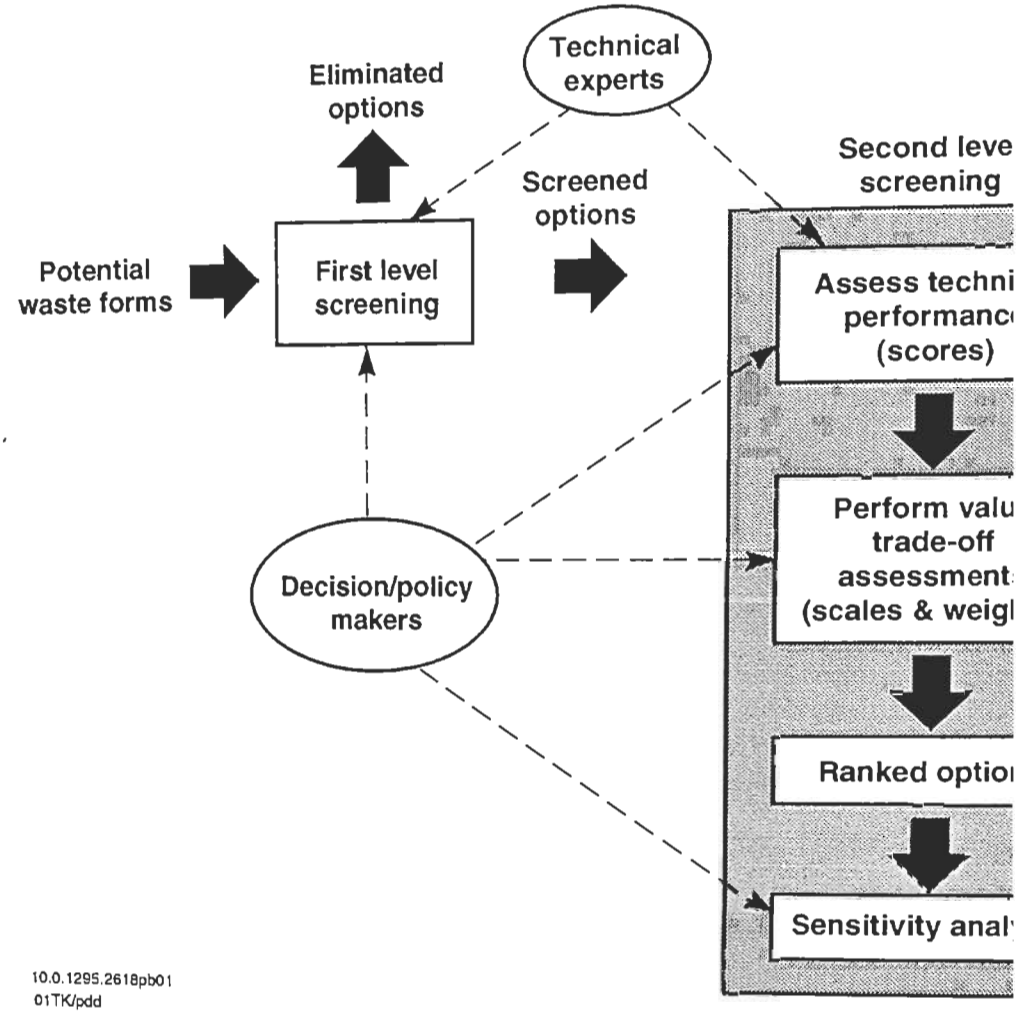

Figure 3-4. Steps used in second-level screening.

- Avoids capability for production/reprocessing was determined to not significa immobilization forms.

2. Technical viability

2.a Technical maturity

Technical maturity assesses a form's likelihood and capability to accomplish the pr and functional requirements. Maturity includes technology, design or engineering adva successful operational performance; the extent of experience with the technology and it the complexity of the technology. The likelihood of schedule delays should be considere technical maturity. Technical maturity should also reflect the form's ability to incorpora

2.b Regulatory/licensing technical requirements

This reflects regulatory and licensing requirements associated with construction an form process facility and product form. It may include problems due to poor anticipate performance.

3. Environmental, safety, and health

- For immobilization, the distinguishing aspect of environment & resource conservation is the potential environmental contamination resulting from long term storage of each waste form. The Pu Immobilization Team determined the only significant aspect of environmental isolation, for which data existed to allow assessment, was the leaching characteristics of the various forms.
  3a and 3b, radiological and hazardous exposures, were determined not to vary significantly over the immobilization forms, given the current knowledge of the form production processes. (Numbering was maintained for consistency with past revisions.)

3.c Waste minimization

This attribute examines hazardous and radioactive wastes generated as byproducts of the immobilization processes.

3.d Environment and resource conservation: leaching.

This attribute addresses the extent to which the final waste form is and will remain isolated (will not leach) by the waste form.

- Use of scarce resources is not expected to differ significantly between the immobilization forms.
- Known and manageable waste forms are considered as part of technical maturity to the extent that an immobilization form creates a new byproduct waste form and waste minimization to the extent that byproduct waste forms are unmanageable.

4. Cost effectiveness

4.a Life-cycle costs

This includes capital costs (with R&D and demonstration costs), O&M costs (startup, and O&M), post-operations' costs assuming all else equal and assuming a completion schedule of 25 years. This attribute also reflects the loading of the immobilization technology. That is, all else equal, the life-cycle cost of one material that can accept twice the Pu of a second material would be half of the cost of the second material. (Note: risk of schedule delays and cost overruns is accounted for in technical maturity). Life-cycle costs also include existing facilities that can be used for each of the forms.

4.b Investment and startup costs

Up-front research and development and capital costs for facility upgrades or construction.

- The potential for cost sharing with other DOE projects was considered as part of life-cycle costs. Other opportunities for cost sharing were determined not to vary significantly over the immobilization forms.
- Cost estimate uncertainty was included as part of technical maturity, and is otherwise viewed as an uncertainty in life-cycle costs rather than as an attribute of its own.

5. Timeliness

5.a Time to start disposition

The timeline to implement each phase of the disposition process should be consistent with the overall program goal without incurring exceptional costs for program acceleration. The time to start disposition refers to the timeline to begin the Phase II permanent disposal process, which in the program goals was set for completion in approximately 25 years from the present. Timeline considerations should include

the NEPA process, required legislation, if any, time to meet licensing and regulatory requirements, technology demonstration, start up time, and impact (if any) on the time to begin permanent disposal.

- Time to start dispositioning was considered to be the discriminating component of all the immobilization form options. Due to the conceptual stage of the form process designs, time to complete the disposition was more a factor of construction and operating costs than of the form characteristics themselves. Schedule uncertainty is considered as part of Technical Maturity.

6. Fosters international progress and cooperation

- Reciprocity and equivalence, compliance with treaties or agreements, transparency, and economic factors/defense conversion were determined not to vary significantly over the immobilization forms. Timeliness is not expected to vary to an extent to impact international progress and cooperation.

7. Public and institutional acceptance

7.a. Ability to create a sustainable consensus

Public concerns about disposition can be expected to impact institutional requirements such as licensing, legislation, perceived noncompliance with treaties and the likelihood of regulatory approval. These were considered in scoring the immobilization forms.

- Socioeconomic impacts, fuel cycle policy signal, and adherence to other policies and statutes were determined to not significantly vary over the immobilization forms.

8. Additional Benefits

- Facilitates achievement of other government missions and contributes to commercial initiatives, and potential technological spin-offs. Additional benefits, were determined not to vary significantly over the immobilization forms.

3.2.2 Scales and Scoring

Below are the scales for attributes relevant to waste form selection that measure the performance of the waste forms in terms of that attribute. The scales range from a relative low value of 1 to a relative high value of 5. At least two scale points have been defined for each attribute. In some cases, additional points have been explicitly defined, allowing interpolation to be made more consistently.

It is acceptable to assign a number that is in between the two descriptions; e.g., a 2 assignment would indicate that the proposal is approximately midway between descriptions 1 and 3. Similarly, a 2.5 would further differentiate between a 2 and a 3.

This scoring compares the performance of waste forms with respect to a specific attribute but does not make any judgments about the relative importance or weighting amongst the different attributes.

Borosilicate glass (BG) is used as a nominal baseline for many of the scales below. This reference form is used because it is the most developed waste form for immobilization of low level waste (LLW) and HLW.

Attribute Scales

1. Resistance to theft or diversion in processing/storage and resistance to retrieval, extraction and reuse.

1.a Inherent attractiveness and difficulty of retrieval, extraction, and reuse

The scale will examine both inherent attractiveness for diversion and use (loading, ease of extraction, etc.) and the additional *un*attractiveness for diversion achieved by adding a radiation barrier.

(1) Low—The combination of the material's inherent unattractiveness for diversion and the ability to add a radiation barrier are significantly lower than (less than half of) that of BG.

(3) Medium—The combination of unattractiveness for diversion and the ability to add a radiation barrier are approximately equivalent to BG.

(5) High—The combination of the material's inherent unattractiveness for diversion and the ability to add a radiation barrier are significantly higher (at least 50% higher) than that of BG.

1.b Assurance of Detection of Retrieval & Extraction

(1) Low —clandestine (undetected) retrieval and/or fabrication is possible.

(3) Medium—retrieval and/or fabrication is likely detectable by remote sensing.

(5) High—retrieval and/or fabrication is easily detected with high certainty by remote sensing.

2. Technical viability

2.a Technical maturity

Technical maturity assesses an option's likelihood and capacity to accomplish the program mission and functional requirements. Maturity includes technology, design or engineering advances necessary for successful operational performance; the extent of experience with the technology and its waste forms, and the complexity of the technology. The likelihood of schedule delays should be considered as part of technical maturity. Technical maturity should also reflect the form's ability to incorporate plutonium.

(1) Low—Technology would require 20 or more years to reach the technical maturity level of BG.

(2) Technical maturity would require greater than 15 years to reach that of BG.

(3) Medium—Technical maturity would require greater than 10 years to reach that of BG.

(4) Technical maturity would require greater than 5 years to reach that of BG.

(5) High—Technical maturity is approximately equal to that of BG.

2.b Regulatory/licensing technical requirements

This reflects regulatory and licensing requirements associated with construction and use of the waste form process facility and product form. May include problems due to poor anticipated environmental performance.

(1) Low—Basis does not exist and is not forthcoming or form will not satisfy potential basis.

(3) Medium—Regulatory basis can be created and satisfied,

(5) High—Regulatory and/or licensing basis exists and can be satisfied.

3. Environmental, safety, and health

3.c Waste minimization

This attribute examines hazardous and radioactive wastes generated as byproducts of the immobilization processes.

(1) Low— Byproduct waste generated from technology is expected to be more severe (by greater than 1.5 times), in terms of mass or level of hazard, than that generated by BG processes.

(3) Medium—Byproduct waste generated from technology is expected to be approximately equal to, in terms of mass or level of hazard, that generated by BG processes.

(5) High—Byproduct waste generated from technology is expected to be less severe (by more than 50%), in terms of mass or level of hazard, than that generated by BG processes.

3.d Environment and resource conservation: leaching

This attribute addresses the extent to which the final waste form is and will remain isolated (will not leach) from the environment.

(2.5) Low—leach rate is expected to be approximately an order of magnitude greater than BG.

(3) Medium—leach rate is expected to be approximately equivalent to BG.

(3.5) High—leach rate is expected to be approximately an order of magnitude less than BG.

4. Cost effectiveness

4.a Life-cycle costs

Including capital costs (with R&D and demonstration costs), O&M costs (startup, O&M, and post operations costs), post-operations costs assuming all else equal and assuming a completion schedule of 25 years. This attribute also reflects the loading of the immobilization technology. That is, all else equal, the life cycle cost of one material that can accept twice the Pu of a second material would be half of the cost of the second material. (Note: risk of schedule delays and cost overruns is accounted for in Technical Maturity).

(1) Low—total life cycle costs are expected to be much greater than those total life cycle costs of Synroc or glass facilities, due to lower loading abilities.

(3) Medium—total life cycle costs are expected to be approximately equal to those of a Synroc facility or a facility to produce glasses outside of DWPF.

(5) High—total life cycle costs are expected to be approximately equal to those life cycle costs anticipated for BG (given overlap with HLW processing).

4.b Investment and Startup Costs

Up-front research and development and capital costs for facility upgrades or construction

(1) Low—investment and startup costs are expected to be much greater (by more than 5 times) than those anticipated for BG.

(3) Medium—investment and startup costs are expected to be approximately equal to those anticipated for BG (on the order of a billion dollars).

(5) High—investment and startup costs are expected to be much lower (by more than 50%) of those anticipated for BG.

5. Timeliness

5.a Time to Start Disposition

Timeline considerations should include the NEPA process, required legislation (if any), time to meet licensing and regulatory requirements, technology demonstration, start up time, and impact (if any) on the time to begin permanent disposal.

(1) Low—projected schedule unlikely to meet program requirements.

(3) Medium—projected schedule meets requirements (20 years from the ROD), but with little or no slack time.

(5) High—schedule contains significant (2 or more years) slack time.

7. Public and Institutional Acceptance

7.a Ability to create a sustainable consensus

Including public concerns about disposition can be expected to impact institutional requirements such as licensing, legislation, perceived noncompliance with treaties and the likelihood of regulatory approval. These should be considered in measuring an option.

(1) Low—Public or governmental resistance to licensing, legislation, or regulatory approval is expected to be significantly higher than that anticipated for the BG option (i.e., additional interested groups may be organized and opposed to the option)

(5) High —Public or governmental resistance to licensing, legislation, or regulatory approval is expected to be approximately equivalent to that anticipated for the BG option.

3.2.3 Scoring and Downselecting

The scoring and downselection process was composed of two parts. First, technical assessments (TAs) were conducted to score the performance of each waste form with respect to the attributes; and second, value tradeoff assessments (VA) were conducted to determine the relative importance or weighing to be assigned to the set of attributes. Figure 3-5 summarizes these processes.

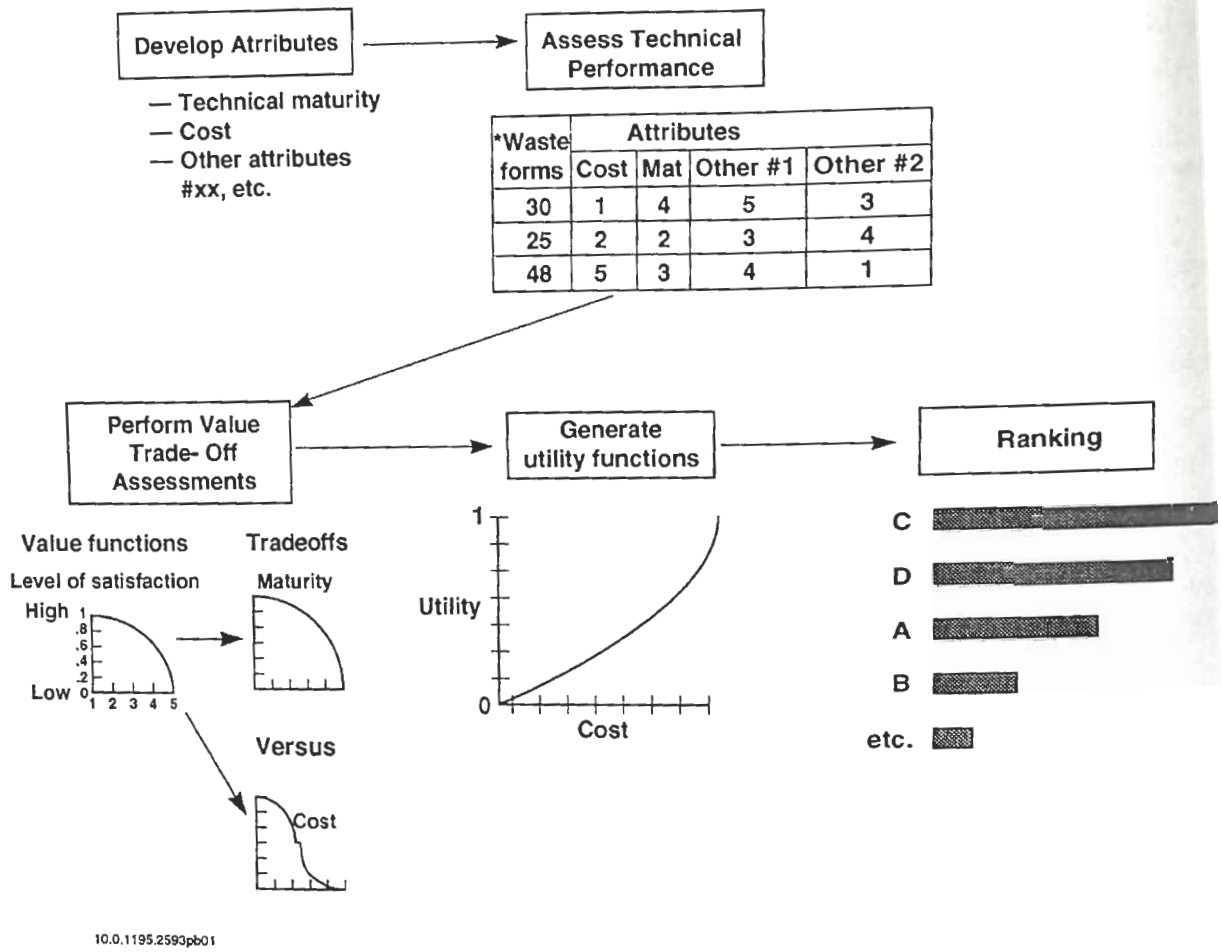

Figure 3-5. Second-level screening process summary. (*See Table 4–1 for a master list of waste forms.)

Teams were formed to perform both assessments. The TA team consisted of technical experts on the immobilization forms and the scores were determined by consensus. Members of the Disposition Integration Team and the DOE Screening Committee also participated in the TAs.

The VAs were performed to determine the relative weighting to be assigned to the various attributes by querrying the subjective value judgments of "the decision maker." A team from LLNL was used to provide a baseline value and trade-off assessment. The team consisted of the Immobilization Task Leader, the deputy task leader, and two individuals tasked with developing the same analysis for the Disposition Screening Committee. This baseline assessment could then be used to conduct a sensitivity analysis to identify areas that policy-makers may want to verify or reassess.

The VA team first examined the relative value of the range of scores. That is, a determinations as to whether a score of 5 on an attribute was twice as good as a 2.5 and five times as good as a 1, or whether the value over the range of scores was nonlinear. These assessments defined utility curves for each attribute. The VA team also assessed the value of each attribute relative to the others. This was accomplished using the trade-off approach, the most powerful and sophisticated approach available for assessing weights. The VA team was given two hypothetical alternatives related to two attributes. By defining the scores at which the alternatives were equally preferred, the VA team establishes the relative importance of one attribute over another. This process is repeated until all the attributes have been assessed.

A software package was used to translate the VAs into mathematical functions. The computer package generates an overall figure of merit based on the combined technical scores, utility functions, and tradeoffs. For each form, the scores from the TA are given a utility based on the VA utility curves. The utilities are then added, with weights determined by the outcome of the trade-off assessments. The figure of merit is based upon an additive relationship of all the attributes, as follows:

$$\text{Figure of Merit} = U = k_1 u_1 \text{score}_1 + k_2 u_2 \text{score}_2 + \ldots + k_{10} u_{10} \text{score}_{10} ,$$

where k_1 is the weighting multiplier, u_1 is the utility function determined by the VA, and score_1 is the score for an option from the TA, for the first attribute. The value U is the overall figure of merit for the option under consideration.

The overall figure of merit is then used to compare form performance. The results of the assessments are provided in Section 5.

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4. Candidate Immobilization Forms

4.1 Classification by Waste Form Family

A review of the literature showed that more than 70 waste forms have been considered for immobilizing radioactive wastes. These individual waste forms can be grouped into families that share common chemical and physical characteristics. Table 4-1 presents a master list of the waste forms and their family classifications. The families are: (1) calcine, (2) cementitious, (3) ceramic, (4) glasses, (5) glass-ceramic, (6) metallic, (7) multibarrier, and (8) polymeric. A description of each waste form family follows.

Table 4-1. Master list of waste forms considered for Pu immobilization.

Master list #	Waste form	Form family
1	Calcine	Calcine
2	Calcine Marbles	Calcine
3	Pelletized Calcine	Calcine
4	Stabilized Calcine	Calcine
5	Cement	Cementitious
6	FUETAP Concrete	Cementitious
7	Hot-Pressed Concrete	Cementitious
8	Normal Concrete	Cementitious
9	Phosphate-bonded Cement	Cementitious
10	Sludge in Concrete	Cementitious
11	Stabilized Calcine in FUETAP	Cementitious
12	Supergrout Concrete	Cementitious
13	Aqueous Silicate	Ceramic
14	Ceramic Sponge	Ceramic
15	Clay Ceramic Monoliths	Ceramic
16	Clay Ceramic Pellets	Ceramic
17	Coated Ceramic	Ceramic
18	Coated Sol-Gel Particles	Ceramic
19	Crystalline Ceramic	Ceramic
20	Disc-Pelletized Coated Particles	Ceramic
21	LOTES Process	Ceramic
22	Low-temperature Hydroxylated Ceramics	Ceramic
23	Monazite	Ceramic
24	Phosphate-bonded Ceramic	Ceramic
25	Plasma Spray Coatings	Ceramic
26	Silicon Zirconium Phosphate	Ceramic
27	Supercalcine	Ceramic
28	Supercalcine HIP	Ceramic
29	Thermite type process	Ceramic
30	SYNROC Ceramic Marbles	Ceramic
31	Synroc Ceramic Monoliths	Ceramic
32	Tailored Ceramic	Ceramic
33	Tailored Ceramic Marbles (sintered)	Ceramic
34	Tailored Ceramic Monoliths (sintered)	Ceramic
35	Titanate	Ceramic
36	Borosilicate glass (continuous melt)	Glass

Table 4-1 (Cont'd).

Master list #	Waste form	Form family
37	Borosilicate glass (in-can melt)	Glass
38	Borosilicate glass marbles	Glass
39	Borosilicate glass monoliths	Glass
40	High Silica glass	Glass
41	Lead-iron phosphate glass	Glass
42	Phosphate glass	Glass
43	Porous glass matrix	Glass
44	Sintered glass-calcine	Glass
45	Stuffed glass	Glass
46	Glass-ceramic marbles	Glass-Ceramic
47	Glass-ceramic marbles (sintered)	Glass-Ceramic
48	Glass-ceramic monoliths	Glass-Ceramic
49	Glass-ceramic monoliths (sintered)	Glass-Ceramic
50	Iron-enriched basalt	Glass-Ceramic
51	Talc-silicon glass-ceramic	Glass-Ceramic
52	Metal compounds (Z<19)	Metallic
53	Metal compounds (Z>19)	Metallic
54	Metal matrix - cast	Multibarrier
55	Metal matrix - sintered	Multibarrier
56	Metallic solid solutions	Metallic
57	Stabilized calcine in sintered metal	Metallic
58	Ceramic in concrete	Multibarrier
59	Ceramic pellets in metal matrix	Multibarrier
60	Cermet	Multibarrier
61	Glass in metal matrix	Multibarrier
62	Glass marbles in a lead matrix	Multibarrier
63	Matrix forms	Multibarrier
64	Pyrolytic C and SiC-coated particles	Multibarrier
65	Bitumen	Polymeric
66	Epoxy resins	Polymeric
67	Polyester resins	Polymeric
68	Polyethylene resin	Polymeric
69	Styrene-divinylbenzene	Polymeric
70	Sulfur polymer cement (SPC)	Polymeric
71	Urea-formaldehyde resin	Polymeric
72	Iron phosphate glass	Glass

4.2 Calcines

Calcination is the process whereby solutions are heated to a temperature below point of fusion, resulting in the evaporation of water. Most high-level radioactive wastes are dissolved in nitric acid. In addition to removing moisture, calcination o these solutions results in the conversion of nitrates to oxides. Calcination processe include use of rotary drums, fluidized beds, sprayers, and a variety of simple or complex batch processes. Depending on the type of solution and the calcination p the resultant products, called "calcines," can range from freely flowing powders t agglomerates. In general, their large surface area and high potential for airborne r renders calcines and stabilized calcines unsuitable for use as final waste forms.

4.2.1 Pelletized (Consolidated) Calcine

Consolidation techniques that have been explored for increasing leach resistan decreasing potential for airborne dispersal include cold pressing and sintering, ho pressing, and disc pelletizing. The leach performance of a consolidated calcine wo expected to be better than that of the precursor powder but less than that of glass prepared from it. Pelletized and sintered stabilized calcines have been considered phase in the multibarrier approach to waste forms.[1]

4.2.2 Stabilized Calcine

One of the first attempts to increase the leach resistance of calcine waste was t add nonradioactive substances to the liquid waste stream before calcination. The was to produce host mineral phases for some of the radionuclides in the calcine, d either the calcination process or, more often, subsequent heat treatment. The "supercalcine" process, developed at Pennsylvania State University during the 19 produced various thermodynamically stable minerals that could incorporate larg numbers of radionuclides. Several other studies included various additives to pro stabilized calcines.[2]

4.2.3 References for Section 4.2

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4.3 Cementitious

Cementitious materials consist of cements and concretes. Cements consist mainly of silicates and aluminates of lime. They react with water to yield hydroxides which, when dried, produce a monolithic form. Concretes are cements mixed with aggregates. Cementitious waste forms have been proposed and used for hazardous,[1] mixed,[2] low-level,[3–7] intermediate-level,[3–7] and high-level[6,8,9,14] wastes. The cementitious waste form immobilizes the waste by a combination of encapsulation, redox control, and chemical reaction. The cement physically surrounds the waste and separates it from the environment. Common cements are included in Table 4-2. The cements can be mixed with various additives to improve various properties such as setting time, mixing viscosity, leach rate, and strength. Table 4-3 lists various additives and the properties they improve. There are also various processing operations that can modify the properties of the cement or concretes. Some of these are listed in Table 4-4.

Table 4-2. Cement types.

Cement name	Catagory/Type
Portland Cement	Type I - general use Type II - general use plus moderate sulfate resistance Type III - high early strength Type IV - low heat of hydration Type V - high sulfate resistance Plug - Early set, expanding cement Masonry - high workability (highly alkaline)
Gypsum Cement	Plaster of Paris Environstone
Slag Cement	
Polymer-Modified Cement	Latex Cement Polymer-impregnated cements Epoxy-cement mixtures Polymer-cement mixtures
Other	Alumina-based cement Silicate cement Lime or lime-fly ash mixtures Pozzolan cement

Cementitious waste forms were among those evaluated for a high-level waste disposal form. The types of cementitious forms evaluated,[8,15–26] were hot-pressed concrete, normal concrete, Formed Under Elevated Temperature and Pressure (FUETAP) concrete, supergrout concrete, and sludge in concrete. The cementitious waste forms were rated as the easiest waste forms to make. Many of these final pro were not considered very good from the standpoint of waste loading, leach rates, thermal stability, radiation stability and mechanical strength. Only some of the mo durable cementitious waste forms will be reviewed below.

Table 4-3. Cement additives.

Additive	Property
Clay	Radionuclide/chemical retention Minimize cesium leaching
Fly ash	Radionuclide/chemical retention Increase strength Minimize strontium leaching
Silica fume	Reduce porosity
Sand	Improve thermal conductivity Increase strength
Water reducers	Minimize amount of water for pourable mixture

Table 4-4. Processing to improve performance.

Additive	Property improved
Autoclaving (FUETAP)	Increased strength[1,2]
Hot pressing	Decrease porosity, increase strength[1,3]
Dewatering	Reduced free and unbound water content

4.3.1 Supergrout Concrete

This waste form is similar to waste in concrete, except that special additives are added to decrease radionuclide leachability and improve other properties of the fina concrete. The special additives could include:

- Zeolitic clays and minerals to sorb cesium,
- Sodium titanate to sorb strontium, and
- Precipitants or scavengers for Tc and I.

4.3.2 Hot-Pressed Concrete

The waste is mixed with the cement and additives and poured into a heated press die. The concrete is pressed to 25,000–50,000 psi and heated to 150–400°C. The minimum amount of water is added and the resulting waste has very little free or unbound water.

4.3.3 FUETAP

FUETAP stands for Formed Under Elevated Temperature and Pressure. This concrete is formed in an autoclave at 100–300°C and 16–600 psi. After curing, the solid is dewatered at 250°C for 24 hours. This removes about 98% of the unbound water.

4.3.4 References for Section 4.3

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4.4 Ceramics

The ceramic approach to immobilizing the radioactive elements present in nuclear waste is to incorporate the nuclides into solid solution in an assemblage of mineral phases. The concept was originally promulgated by Hatch[1] in 1953, but was unappreciated until demonstrated by workers at Pennsylvania State University.[2,3] The

original philosophy for using crystalline host phases remains the same today; namely, that certain mineral phases containing radioactive elements have been known to be geologically stable for tens to hundreds of millions of years, some of them in contact with water for a considerable portion of that time. Thus, it is argued that analogously, synthetic mineral phases (e.g., ceramics) will also be stable over the required immobilization period. There also are a number of additional advantages to using ceramics: they can, in principle, accommodate a higher waste loading than alternative materials; they have higher thermal conductivity; and their refractory nature means that they can sustain higher radiogenic temperatures and in solid solution they can accommodate wide chemical variability. One of the perceived drawbacks of ceramics, however, is that they are, in general, more difficult to consolidate and fabricate than the currently favored glass waste form; this need not be the case (see Section 5).

Since a class of aluminosilicate-based ceramics was developed by McCarthy and colleagues at Pennsylvania State University,[2–4] a number of other mineralogical assemblages have been demonstrated for waste immobilization. Notable among these are the Sandia National Laboratories titanate-based ceramic,[5] the appropriately named "Synroc" (synthetic rock) zirconolite-hollandite-perovskite assemblage (also titanate-based) from Ringwood and his colleagues in Australia,[6,7] and the alumina-based and titanate-based ceramics, both developed at the Rockwell International Science Center.[8–10]

Implicit in the concept of manufacturing an assemblage of crystalline, synthetic mineral phases is the pivotal idea of using additives to alter or modify the actual waste composition; that is, tailoring it chemically so that the desired combination of crystalline phases will be produced after consolidation. The resulting waste forms have been called "tailored ceramics." The tailoring can be extended[7] to produce additional phases containing no radionuclides and to provide microstructural isolation of the radiophases, a strategy employed to further enhance the leach resistance of the form.

Four principal classes of oxide ceramics for the immobilization of nuclear waste can be recognized: alumina-, aluminosilicate-, titanate-, and phosphate-based waste forms.

4.4.1 Alumina-Based Ceramics

A class of high alumina-based ceramics for the immobilization of the defense waste at the Savannah River Plant was developed at the Rockwell International Science Center.[8,10] Recently, the range of ceramics has been extended to immobilize commercial wastes.[11] The high-alumina ceramic waste form consists of the compatible phases of alumina, spinel (nominally $MgAl_2O_4$), magnetoplumbite [nominally $X(Al,Fe)_{12}O_{19}$, where X = Sr, Ba, or charge substitutions such as $Cs_{0.5} + La_{0.5}$], and a fluorite-related uraninite$(U,Th)O_2$. For wastes containing a high concentration of sodium, an additional crystalline phase, nepheline, $NaAlSiO_4$, is produced to accommodate the monovalent ion. The magnetoplumbite phase acts as a host for the radionuclides Sr and Cs, and the phase assemblage is analogous to a naturally occurring placer deposit of alumina-spinel-hibonite (magnetoplumbite)-thoria found in Fort Dauphin, Malagasy, a locale of obvious prolonged exposure to water.[12]

4.4.2 Aluminosilicate-Based Ceramics

Clay-Ceramics

The use of clay (bentonite, kaolin, or pyrophyllite) to immobilize radioactive waste was studied by Barney.[17,18] This process combines clay and high alkaline waste to facilitate the formation of relatively insoluble aluminosilicates. Clay ceramics can be produced as either pellets or monoliths. For the pelletizing process, binders are added to the high-level waste (slurry, dried powder, or calcines) and clay mixture, then the mixture is extruded, cut into pellets, and sintered or calcined. Calcination produces dense (80 to 90% of theoretical) nepheline-type crystals, which have relatively high leach resistance. Monoliths can be produced by hot isostatically pressing the clay-waste mixture. The resulting crystalline structure and composition of the monoliths and the pellets are identical.

In general, the clay-ceramic product volume is high and tends to swell when soaked in water and no (or inadequate) calcination occurs. Table 4-5 summarizes the waste forms produced from mixing a simulated cesium waste slurry with each of three clays and heating the mixture at 100°C.

The leach resistance and mechanical properties of minerals formed by clay additions depend on their type, composition, and processing temperatures. The ability of clay-ceramics to accommodate small changes in waste composition by simple adjustments of waste loading and sintering temperatures is advantageous.

Table 4-5. Products of clay-ceramic processing of simulated Cs waste.[17]

Reacting clay	Product	Leach rate[a] ($g/cm^2 \cdot d$)
Bentonite	Pollucite (Cs_2O-Al_2O_3-$4SiO_2$-$2H_2O$)	5.7×10^{-4}
	Analcite (Na_2O-Al_2O_3-$4SiO_2$-$2H_2O$)	2.4×10^{-4}
	Cancrinite (Na_2O-AI_2O_3-$2SiO_2$-xSalt-yH_2O)	1.4×10^{-4}
	Sodalite ($2Na_2O$-Al_2O_3-$2SiO_2$-$2H_2O$)	
	Nepheline (Cancrinite heated to 530°C)	
Kaolin	Cs-D (Cs_2O-Al_2O_3-$2SiO_2$-$2.4H_2O$)	2.6×10^{-3}
	Cancrinite (Na_2O-Al_2O_3-$2SiO_2$-xSalt-yH_2O)	2.4×10^{-4}
	Sodalite ($2Na_2O$-Al_2O_3-$2SiO_2$-$2H_2O$)	5.4×10^{-4}
	Cs-F (Cs-D heated to 1060°C)	
Pyrophyllite	Pollucite (Cs_2O-Al_2O_3-$4SiO_2$-$2H_2O$)	5.7×10^{-4}

[a] Leaching parameters: 28 days, 23°C, 6.16 cm^2 SA, in DI water.

Clay-ceramic processes form relatively insoluble aluminosilicate minerals on calcination; permit use of lower processing temperatures, but at the cost of lower leach resistance; and permit high loading of alkali wastes. They have the following

.sadvantages: poor durability of the "non-calcined" minerals, lack of technology for ;e with multicomponent wastes, potential for uncontrolled partitioning of .dionuclides within the crystalline phases, and limited control of microstructure.

4.3 Titanate-Based Ceramics

utile

Rutile (TiO_2) forms a highly durable ceramic matrix with low processing mperature and adequate properties.[16] Rutile matrix waste is produced by mixing :gh-level waste slurry with TiO_2. The mixture is calcined at 900°C and hot isostatically ressed (HIP) at 1200° to 1500°C. An overpack material, such as metal or TiO_2, can ɜ used.

Adelheim investigated the waste loading of TiO_2 up to 12 wt% (~9.5 vol%) mulated waste oxides (comparable to a 15 wt%, or ~8.0 vol%, waste-loaded ɔrosilicate glass). At least up to that level, waste particles remained isolated in the ıatrix. The waste-loading limit is reached when waste agglomerates to large ɔntinuous volumes in the matrix. Leaching occurs where waste particles intersect acture surfaces in the matrix. If the particles form a large, continuous network in the ighly leach-resistant TiO_2 matrix, the product will have low leach resistance.

The advantages of TiO_2 matrix waste form are high chemical durability and little ɜquirement for chemical pretreatment. The disadvantages are the need for process evelopment and the form's limited waste loading capacity.

ynroc

Another range of ceramic materials, developed by Ringwood et al.[19-22] at the .ustralian National University, is based on the incorporation of radioactive waste .ements as dilute solid solutions in predominantly titanate-rich phases. Ringwood ɔined the generic term Synroc (synthetic rock) to describe these materials. The two rincipal forms, Synroc-C and Synroc-D, were formulated to accommodate high-level ɔmmercial and defense wastes. respectively. Ringwood originally envisaged that the 'aste loadings would be low(~10 wt%) so that the remaining inert additives (~90 wt%) 'ould determine the nature of the phase assemblages, with the radionuclides simply ıbstituting within the crystal lattices, as occurs in nature.[6,7]

The reference form of Synroc consists of an assemblage of four main titanate ıinerals—zirconolite $CaZrTi_2O_7$, "hollandite" $Ba_{1,2}(Al,Ti)_8O_{16}$, perovskite $CaTiO_3$, and tanium oxide(s) Ti_nO_{2n-1}. These minerals have the capacity to incorporate nearly all of ıe elements present in HLW or plutonium containing materials into their crystal :ructures as solid solutions. Similar minerals have survived in a wide range of natural ɜochemical-geological environments for up to 2 billion years. It is this evidence of ɜological stability provided by nature, combined with experimental observations ıowing that these minerals are highly resistant to attack by hydrothermal solutions, ıat shows that Synroc should provide a superior method of immobilizing HLW. In

fact, the Synroc strategy for immobilizing HLW is similar to the way in which nature immobilizes radioactive elements on a scale vastly greater than will ever be contemplated by the nuclear industry. All rocks contain small amounts of radioactive elements (e.g., ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb) that become distributed among coexisting minerals as dilute solid solutions. Many of these minerals (e.g., zircon, feldspar) have demonstrated their ability to lock up small amounts of radioactive elements for millions of years. In Synroc, the radioactive waste elements are likewise immobilized as solid solutions in the crystalline structures of their host minerals.

Several distinct Synroc formulations have been developed for a range of radioactive wastes (see Section 1.6); however, this review is primarily concerned with immobilization of HLW derived from reprocessing spent nuclear fuel from commercial power reactors. The principal formulation developed to immobilize these wastes is Synroc-C, the composition of which is given in Table 4-6. Synroc-C is designed to contain about 20 wt% of calcined HLW. It comprises an assemblage of titanate phases, hollandite + zirconolite + perovskite + titanium oxide(s) and/or minor calcium-aluminum titanates, plus small amounts of metallic alloys and a calcium-rich phosphate.

Table 4-6. Composition and mineralogy of Synroc-C.

Composition		Mineralogy	Approx. wt%
TiO_2	57.0[a]	Hollandite	30
ZrO_2	5.4[b]	Zirconolite	30
Al_2O_3	4.3	Perovskite	20
BaO	4.4[b]	Ti oxides and Ca-Al-titanates	15
CaO	8.9		
HLW	20.0	Alloy, phosphate	5
Sum	100.0		

[a] Does not include 2% added Ti

[b] Does not include contribution from HLW

4.4.4 Phosphate-Based Ceramics

Monazite

Monazite is a mixed lanthanide orthophosphate mineral. It occurs naturally as an ore that contains uranium and much of the world supply of thorium. Thorium content ranges as high as 20 % ThO_2 in natural ore.[13] Monazites over 2 billion years old have been found in Brazil. Other deposits in France are said to be 570 million years old.[14] Lanthanides behave very similarly to actinides such as plutonium. Thus, it is reasonable to expect that a monazite waste form would be extremely stable during the time it must contain plutonium. Monazite can be synthesized by first reacting an actinide oxide with ammonium hydrogen phosphate to form an orthophosphate, which

ı precipitated using molten urea. The precipitate is calcined at 800°C. The ɜd product can be formed into pellets by hot pressing, or by cold pressing ntering.

m Zirconium Phosphate

dium zirconium phosphate was proposed by Roy as a single-phase waste form for Its advantage is the ability to accommodate wide variations of waste ›sition. At high waste loadings, monazite forms as a second phase.[19]

›hate-bonded Ceramics

osphate-bonded ceramics are chemically similar to phosphate-bonded cement. rincipal difference is that the ceramic is fired to remove water and produce a le crystalline structure.

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4.5 Glasses

Glasses are noncrystalline inorganic solids made in a high-temperature press. Although they are thermodynamically metastable and may devitrify under cer conditions, they can be very durable. Obsidian and basaltic glass are two naturally occurring glasses that have endured over geologic time.[1]

4.5.1 Borosilicate Glass

Borosilicate glass is an amorphous material formed by melting silica and boric ide together with other constituents such as soda. Borosilicate glass was chosen as the waste form for virtually all HLW worldwide because it combines high waste solubili and high tolerance to waste variability, with excellent leach resistance, and high thermal and radiation stability and good mechanical integrity.[2] Borosilicate glass was chosen over other types of glasses because of these properties, and because it could be produced at temperatures well below more conventional glasses, thus minimizing volatility and dose to workers.[3]

These same properties make incorporation of plutonium into borosilicate glass an option for the disposition of excess plutonium. Incorporation of Pu into borosilicate glass containing HLW would provide a form which would be relatively easy to produce, but which would render retrieval of the plutonium more difficult. This form would be suitable for indefinite storage, or for disposal in a geologic repository.

Virtually every major country which is producing HLW has selected borosilicate ıss as the preferred waste form. The French have been immobilizing waste from ɔrocessing spent fuel for both themselves and other nations since 1978, first at arcoule, then at La Hague. The British are vitrifying their own HLW, as well as the ıste from reprocessing spent nuclear fuel from Japan at their Sellafield facility. In the S., the Defense Waste Processing Facility (DWPF) at Savannah River will be the tion's first, and the world's largest, HLW immobilization facility, when it begins ·eration in fiscal 1996. For each of these facilities, borosilicate glass was selected as the ıste form because of its excellent combination of reliable processing properties and ceptable product performance.

ɔmposition of DWPF Glass

The compositions of HLW glasses of the type which will be made in the DWPF are own in Table 4-7. Since the late 1960s, SRS has conducted an ongoing waste aracterization program. This has led to the definition of generic waste compositions r current waste. These generic waste compositions have been combined according to e SRS tank farm waste processing schedule to produce four projected waste types. ıese represent the material which will be vitrified during the first 15 years of DWPF oduction. These glass compositions are designated Batch 1, Batch 2, Batch 3, and ıtch 4. The DWPF design-basis glass, designated "Blend," has also been included in ıble 4-7.

Two additional projected glass compositions have also been defined, based on waste ·neration processes used at SRS. These are the Purex and HM glasses, which represent 'pothetical extreme glass compositions. The Purex waste glass has been specifically rmulated to represent a credible bounding composition (worst case in terms of ırability) for the facility. It represents the maximal flow of alkali and boron to the WPF, and is based on a glass frit composition which would yield a less durable glass an the current generation of waste glasses because of its higher alkali and lower silica ncentrations. All of the projected compositions, including the worst case (Purex) mposition, are significantly more durable than the benchmark glass in the product ·ecifications.[4]

In Table 4-8, the radionuclide inventory of nominal average canisters of Batches 1 rough 4 are presented. The radionuclide inventory of a "future" (year 2015) waste ass, assumed to be identical to the design-basis glass, is also included. The number of nisters to be produced of each waste type is also included.[5]

Table 4-7. Projected DWPF waste glass compositions.

Waste glass composition	Constituent sludge type (weight %)						
	Blend	Batch 1	Batch 2	Batch 3	Batch 4	HM	Purex
Al_2O_3	3.95	4.83	4.42	3.22	3.29	7.02	2.87
B_2O_3	7.95	7.63	7.64	7.63	8.04	6.88	10.13
$BaSO_4$	0.27	0.22	0.24	0.26	0.38	0.18	0.29
CaO	0.96	1.16	0.99	0.92	0.82	0.99	1.01
$CaSO_4$	0.08	0.12	0.11	0.10	0.0034	trace	0.12
Cr_2O_3	0.12	0.10	0.12	0.13	0.14	0.085	0.14
Cs_2O	0.12	0.079	0.081	0.079	0.13	0.073	0.080
CuO	0.44	0.40	0.41	0.40	0.46	0.25	0.42
Fe_2O_3	10.33	12.42	10.52	11.07	11.23	7.32	12.64
Group A	0.14	0.10	0.14	0.10	0.20	0.20	0.077
Group B	0.36	0.22	0.44	0.25	0.60	0.88	0.083
K_2O	3.83	3.46	3.47	3.44	3.96	2.12	3.55
Li_2O	4.36	4.38	4.38	4.38	4.29	4.58	3.09
MgO	1.34	1.35	1.34	1.34	1.37	1.44	1.32
MnO_2	2.47	2.50	1.97	2.20	3.74	2.52	2.42
Na_2O	8.66	8.55	8.54	8.44	8.81	8.10	12.04
Na_2SO_4	0.10	0.10	0.12	0.095	0.13	0.14	0.12
NaCl	0.19	0.31	0.23	0.22	0.089	0.092	0.26
NiO	0.88	0.74	0.89	1.06	1.08	0.40	1.20
SiO_2	49.80	49.41	49.77	49.58	48.89	53.95	44.20
ThO_2	0.19	0.36	0.62	0.76	0.24	0.55	0.011
TiO_2	0.89	0.65	0.66	0.65	1.01	0.55	0.64
U_3O_8	2.12	0.53	2.28	3.13	0.78	1.00	2.87
Ag	0.0076	0.0022	0.0022	0.019	0.011	0.0019	0.0023
$Ca_3(PO_4)_2$	0.064	0.050	0.068	0.076	0.079	0.037	0.084
CoO	0.0025	0.0039	0.0036	0.0034	0.00011	trace	0.0041
MoO_2	0.00036	0.00037	0.00036	0.00036	0.00039	0.00026	0.00055
Na_3PO_4	0.013	0.013	0.015	0.012	0.016	0.019	0.014
NaF	0.062	0.071	0.083	0.065	0.044	0.066	0.064
PbO	0.033	0.0062	0.016	0.040	0.077	0.0066	0.049
PbS	0.069	0.119	0.072	0.066	0.056	0.058	0.079
Pd	0.016	0.0079	0.017	0.014	0.030	0.031	0.0095
PuO_2	0.020	0.0025	0.0060	0.0064	0.0043	0.058	0.00022
Rh	0.0068	0.0038	0.0078	0.0056	0.012	0.015	0.0031
Ru	0.035	0.021	0.042	0.026	0.058	0.082	0.0099
SrO	0.043	0.027	0.054	0.030	0.070	0.11	0.0088
TcO_2	0.013	0.0092	0.015	0.0083	0.019	0.029	0.0033
Y_2O_3	0.015	0.0094	0.019	0.0099	0.025	0.038	0.0031
ZnO	0.075	0.088	0.092	0.098	0.096	0.016	0.11

Table 4-8. Radionuclide inventory of single canisters of each type of DWPF glass in 2015.

Radionuclide	Batch 1	Batch 2	Batch 3	Batch 4	Future
Ni-59	1.05×10^{-2}	2.08×10^{-2}	1.20×10^{-2}	2.81×10^{-2}[a]	2.39×10^{-2}
Ni-63	1.14	2.34	1.39	3.26[a]	2.97
Se-79	1.55×10^{-1}	2.13×10^{-1}	1.63×10^{-1}	3.18×10^{-1}[a]	1.70×10^{-1}
Sr-90	4.60×10^{3}	3.52×10^{4}	3.19×10^{4}	2.21×10^{4}	4.82×10^{4}[a]
Zr-93	4.66	9.21	5.28	1.24×10^{1}[a]	1.12
Nb-93m	2.37	5.59[a]	2.00	4.70	6.51×10^{-2}
Tc-99	2.01	3.16	1.81	4.02[a]	3.07
Pd-107	6.09×10^{-3}	1.32×10^{-2}	1.08×10^{-2}	2.30×10^{-2}[a]	1.47×10^{-2}
Sn-126	2.98×10^{-1}	5.89×10^{-1}	3.38×10^{-1}	7.94×10^{-1}[a]	4.38×10^{-1}
Cs-135	1.11×10^{-1}[a]	6.21×10^{-2}	4.54×10^{-2}	2.57×10^{-2}	9.92×10^{-2}
Cs-137	3.06×10^{4}	1.92×10^{4}	1.57×10^{4}	8.89×10^{3}	4.33×10^{4}[a]
Sm-151	4.49×10^{2}	9.22×10^{2}	5.50×10^{2}	1.29×10^{3}[a]	2.39×10^{2}
Th-230	3.21×10^{-6}	9.18×10^{-6}[a]	7.12×10^{-6}	1.79×10^{-6}	2.01×10^{-6}
Np-237	6.49×10^{-2}	1.28×10^{-1}	7.35×10^{-2}	1.73×10^{-1}[a]	8.86×10^{-3}
U-234	8.22×10^{-3}	3.60×10^{-2}	4.94×10^{-2}[a]	1.24×10^{-2}	3.42×10^{-2}
U-238	2.53×10^{-3}	1.10×10^{-2}	1.52×10^{-2}[a]	3.80×10^{-3}	1.05×10^{-2}
Pu-238	3.31×10^{1}	1.27×10^{2}	8.51×10^{1}	1.76×10^{2}	1.48×10^{3}[a]
Pu-239	2.03	4.64	5.13	3.26	1.29×10^{1}[a]
Pu-240	1.36	3.12	3.45	2.19	8.67[a]
Pu-241	2.81	2.75×10^{1}	9.94×10^{1}	2.59×10^{2}	1.66×10^{3}[a]
Pu-242	1.92×10^{-3}	4.39×10^{-3}	4.85×10^{-3}	3.09×10^{-3}	1.22×10^{-2}[a]
Am-241	2.29×10^{1}	4.54×10^{1}	2.60×10^{1}	6.11×10^{1}[a]	1.10×10^{1}
Am-243	1.82×10^{-1}	3.60×10^{-1}	2.06×10^{-1}	4.84×10^{-1}[a]	5.79×10^{-3}
Cm-244	4.76×10^{1}	1.14×10^{2}[a]	7.91×10^{1}	9.29×10^{1}	1.07×10^{2}
TOTAL	3.57×10^{4}	5.56×10^{4}	4.85×10^{4}	3.29×10^{4}	9.50×10^{4}[a]
No. of canisters	910	987	1002	751	3532[b]

[a] Upper limits for each radionuclide in any DWPF canistered waste form.

[b] Number of canisters is a conservative upper bound. Calculations based on the assumption that future waste at SRS will have the same radionuclide content as DWPF design-basis glass.

4.5.2 High-Silica Glass

The oldest glasses found in nature have high-silica content. A high-silica porous glass process was originally developed at Catholic University of America for

immobilizing high-sodium HLW. This process (which is identified as the porous glass matrix or "stuffed glass" process in some reports) loads a slurry of HLW sludge and porous glass frit into high silica glass tubes, which are then sintered at 900 to 1100 C.[6] The Alternative Waste Form Peer Review Panel noted that the low vacuum and relatively high temperature needed for densification of the frit causes a substantial loss of cesium, which must be recovered by an off-gas treatment system. The panel ranked this process as third in a group of eight waste forms it considered for Savannah River HLW.[7]

Dunson et al. have stated that high-silica porous glass only encapsulates sludge hydroxides, whereas borosilicate glass actually dissolves them.[8] Schulz et al. reported that leaching tests on samples of simulated Savannah River Plant (SRP) waste indicated a leach rate of 5×10^{-10} g/cm^2-day.[6] Stone et al. claimed that leachability could be about 10^{-12} g/cm^2-day with a glass layer around the core.[9]

A 1982 study for the DWPF indicated that investment for a plant to produce a high silica waste form would cost $797 million, compared to $585 million for borosilicate glass. Although this represents a 36 percent increase, it should be noted that the estimates include 35 percent contingency for the high silica facility and only 15 percent contingency for borosilicate glass. Estimates were based on 3rd Quarter 1980 costs.[8]

4.5.3 Lead-Iron Phosphate Glass

The lead-iron phosphate (LIP) nuclear waste glasses were discovered at Oak Ridge National Laboratory (ORNL) in 1984 while Boatner and Sales were attempting to find a sintering aid for certain types of crystalline monazite ceramic high-level nuclear waste forms. LIP glasses are corrosion resistant in aqueous solutions at temperatures below 100° C. They can be melted and poured at temperatures that are relatively low in comparison with the processing temperatures required for borosilicate glass compositions. Unlike the phosphate glasses investigated previously, LIP glasses do not suffer from alteration due to devitrification during realistic and readily achievable cooling periods. Additionally, LIP glass melts are not nearly as corrosive as the sodium phosphate melts.[10]

Vitreous LIP appears to have substantially better chemical durability than borosilicate glass. However, severe crystallization leading to deteriorated chemical durability would result if this glass were poured into large canisters, as is presently done with borosilicate glass. Cesium leach rates from this crystallized material are orders of magnitude greater than those from borosilicate glass. Therefore, to realize the performance advantages of the LIP material in a nuclear waste form, it would be necessary to process it so that it is cooled rapidly, thus retaining its vitreous structure.[11]

Investigation of this glass for vitrifying SRP waste demonstrated that the LIP glass is incompatible with current borosilicate glass processing. Although the durability of the LIP glasses in deionized water was comparable to current borosilicate waste glass formulations, many defense waste constituents have low solubility in the phosphate melt, producing a nonhomogeneous or nonvitreous product. LIP glass is highly

:osive, which prevents the use of current borosilicate glass melter materials such as ›nel and alumina, and requires more exotic materials of construction such as :inum.[12]

The use of lead in manufacturing LIP glass would be likely to complicate the mitting of a plant. Lead is regulated by the Resource Conservation and Recovery (RCRA). Thus, the waste form could be classified as a mixed waste under federal s unless tests based on the Toxicity Characteristic Leaching Procedure (TCLP) ved that leached lead does not exceed the legal threshold. Failure to pass the TCLP may make the waste unacceptable to a repository.

No cost estimates have been published for LIP glasses.

4 Iron-Phosphate Glass

Although iron-phosphate glass would eliminate concerns about using lead to nufacture the LIP glass waste form, the literature search found no published reports ›ut this form. Plodinec indicates that it readily devitrifies and has a narrow phase d for operation.[13]

5 Phosphate Glass

Phosphate glasses have been used to immobilize radioactive wastes in the former 'iet Union. However, this waste form tends to devitrify readily. The process is also y corrosive, which causes frequent costly equipment failures. All western countries 'e abandoned work on this waste form.[14]

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4.6 Glass Ceramics

Glass ceramics are partially crystalline materials formed during controlled devitrification of glass.[1,2] They are more thermodynamically stable and usually more mechanically and chemically durable than the parent glass. A critical step in formation of glass ceramics is to form a crystalline phase that will contain the radionuclides. Radionuclides remaining in the amorphous phase will be more susceptible to leaching. The amorphous phase remaining in a glass ceramic tends to be slightly more soluble than that of the parent glass. As with any glass, partial devitrification during cooling can degrade the body structure and properties of the original glass.[1] Controlled devitrification of glass ceramics minimizes the danger of accidental devitrification.

The conversion of glass to glass ceramic is sensitive to composition, requiring careful monitoring of the raw materials added to the batch glass. Lutze, Borchardt, and De report a typical waste-loading in glass ceramics of 0.6 to 0.8 g/cm^3 for light water reactor (LWR) waste.[3]

ceramic monoliths are formed by pouring the molten glass into a canister then ing the cooled container to nucleate the crystalline microstructure and g the growth process. Marbles are cast in the same way as other glass forms, it the molten glass is fed to a marble-making machine. The solidified marbles eat treatment to form their crystalline microstructure and need to be placed in containment. The void spaces between the spheres increase the bulk volume s by about 40% over that of monoliths. Because of their greater mass, require longer heat treatments than do marbles and are much more difficult .

ceramic waste forms also can be prepared by sintering. The starting material is lass or gel, prepared by melting or sol-gel techniques, blended with waste, nd other required additives. The mixture is then pressed and slowly heated to iquid-phase sintering of the compact yields a body with <1% open porosity. of glass ceramics can produce a durable waste form at low temperatures, nimizes the problems of radionuclide volatilization and melter refractory .

lc-Silicon Glass Ceramics

-silicon glass-ceramic (TSGC) waste form has been proposed by Vinjamuri.[4] e form is designed to immobilize fluorinel-sodium blend calcine waste at the Idaho Chemical Processing Plant (ICPP) by the addition of talc, silicon, inum metals. The final waste form is a durable MgO Al_2O_3-SiO_2 glass with crystalline phases.

SGC process has been experimentally tested using 70 wt% fluorinel-sodium ine, 28–23 wt% talc ($Mg_3Si_4O_{10}[OH]_2$), 0–5 % Si, and 2 % Al metal. The talc ie were preheated to 1200° and 600°C, respectively, to remove volatile nts. The four components were mixed, precompacted, and hot pressed at nalysis of seven samples showed a glass phase with the following on: Al_2O_3 (17–29 wt%), B_2O_3 (7–9 wt%), SiO_2 (23–49 wt%), MgO (0–18 wt%), (4–20 wt%); embedded crystalline phases included CaF_2, ZrO_2, $MgSiO_3$, , $Ca_4Si_2O_7F_2$, and $Ca_3ZrSi_2O_9$.

operties of the final products where good and their density was high cm^3). No evidence suggested microcracking due to thermal expansion es in the glass ceramics. The products had relatively low durability, however, was observed to increase with increasing Si additions.

ntages of TSGC process include low-temperature processing, very high loading el-sodium blend waste (70 wt%), and high density (~3.23 g/cm^3).

vantages are the difficulty of the process, including precalcination and hot ressing, and low durability for 70 wt% fluorine-sodium waste loading. The ity of this waste form and process to plutonium immobilization is ble at best.

4.6.2 Iron-Enriched Basalt

Iron-enriched basalt (IEB) glass ceramic is being developed at Idaho National Engineering Laboratory. This waste form is primarily intended to immobilize radioactive wastes from soil remediation, although it has been considered for immobilizing certain Three Mile Island wastes. Process temperature is relatively high (1400 to 1500°C), which would make cesium impractical as a radiation barrier for plutonium immobilization.[1]

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4.7 Metals

An electrometallurgical treatment process has been developed by Argonne National Laboratory to convert various types of spent nuclear fuels into stable storage forms and waste forms for repository disposal.[1,2] The process produces a mineral waste form[3] and a metal waste form.[4] Two concepts for the metal waste form were investigated during the process development: (1) encapsulation of metallic wastes in a copper–aluminum alloy matrix and (2) alloying metal waste constituents into a uniform, corrosion-resistant iron–zirconium (Fe-Zr) alloy. The Fe–Zr alloy waste form has been selected over copper encapsulation. The following sections describe metal options for surplus plutonium immobilization, including copper alloys (5.7.1), iron-zirconium, or Fe–Zr, alloys (5.7.2), and other metal forms (5.7.3), but the primary plutonium immobilization form being considered is the Fe–Zr alloy waste form.

4.7.1 Copper Alloys

In this approach, surplus plutonium would be dispersed in a copper alloy matrix as intermediate phases. The plutonium would be uniformly distributed to alleviate criticality concerns. For most alloys, processing would be carried out at relatively low temperatures, <1200°C, in an inert atmosphere. For the electrometallurgical treatment metal waste form, several alloy compositions were prepared to obtain corrosion information and other data useful in selection of optimal composition. Copper–aluminum alloys with 80, 67, 60, 45 and 40 wt % Al were tested, but Cu-45Al and

40Al were eliminated due to their extreme brittleness. Alloys with high Cu :entrations (>70 wt % Cu, aluminum bronze) were suggested as attractive alloys due ıeir superior corrosion resistance, but they have not been tested. Work on the Cu-Al ıl waste form was discontinued as it became evident that the Fe–Zr metal waste ı was superior in corrosion resistance, uniformity, mechanical properties, waste imization and other categories.

: Iron–Zirconium Alloys

:he selected method for consolidation and stabilization of the electrometallurgical :ess metal waste stream is melting and casting into a uniform, corrosion-resistant /. Both stainless steel and Zircaloy clad fuel types are being considered for :rometallurgical treatment, thus stainless-steel-rich and Zircaloy-rich waste forms ɔeing developed. The nominal waste form compositions that have been selected for development are stainless steel—15 wt % zirconium (SS-15Zr) and Zircaloy—8 wt% ıless steel (Zr-8SS), respectively, with each containing 1 to 5 wt% noble metal fission ducts (e.g., Ru, Rh, Pd, and Tc). Characterization of phase compositions and crystal ctures for baseline and off-normal alloys is essentially complete and performance uation is continuing.

:xperiments have shown that both the SS-15Zr and Zr-8SS alloys have potential as onium immobilization alloys. Nine small-scale (~30 g) simulated waste form alloys :aining uranium, plutonium, and neptunium have been generated. Uranium and tunium were included because actinides in the metal waste form is a possible, but kely, option for the electrometallurgical treatment process. The cast compositions vt%) include six SS-15Zr alloys with 0.5U-0.5Pu, 2U-2Pu, 6Pu, 10Pu, 6Pu-2Np, and ı and three Zr-8SS alloys with 4, 7, and 10Pu. The SS-15Zr alloys were generated ıg Type 316SS and the Zr-8SS alloys were generated using Type 304SS.

n both alloys, the actinide metals do not form separate, pure actinide phases, but ɜad are uniformly distributed in that alloy microstructure. In the SS-15Zr alloy, Pu the other actinides form an intermetallic phase that is miscible with the 'e,Cr,Ni)$_2$ intermetallic present in the baseline alloy. This phase was observed in all ıe SS-15Zr alloys with TRU additions, irrespective of the actinide or group of ıides present; increasing the actinide content resulted in a higher volume fraction of phase. In the Zr-8SS alloy, plutonium was observed in solution in an α-Zr solid ıtion phase, but it also was found in higher concentrations at the α-phase lath ndaries. Increasing the amount of Pu added to the alloy resulted in higher amounts u both in the α-Zr matrix phase and at the lath boundaries for the compositions that e examined.

The above descriptions are for as-cast structures, but homogenization studies are ıg carried out to further develop the microstructure. In addition, corrosion results n the baseline Fe–Zr alloys indicate a high resistance to corrosion from groundwater is as good or better than 316 stainless steel or zirconium metal. Leach testing of the nide-bearing alloys is in progress and comparisons are being made to the baseline ı. For both alloys, loadings in excess of 10 wt% Pu are physically possible.

4.7.3 Other Metallic Forms

The following is a very brief description of other metallic waste forms that have been investigated in the past. These other forms are included in this present discussion for reference.

Past studies of metallic HLW forms have considered techniques for encapsulating vitrified or calcined wastes or spent fuel. Jardine et al. made an extensive survey of metallic encapsulation of calcined high-level waste.[5,6] The waste forms considered were (1) a thick-walled container for stabilized calcine, (2) dispersing stabilized calcine in a metal matrix, and (3) converting the calcine into glass beads that are dispersed in a metal matrix. Methods considered for fabricating metal matrices included vacuum casting, extrusion casting, and powder metallurgical techniques, such as cold pressing, cold and hot extrusion, and hot uniaxial and isostatic pressing. Based upon their ease of fabrication and potential resistance to groundwater attack, the matrix materials identified as promising candidates were aluminum and its alloys, copper and its alloys, low-alloy steels, austenitic and ferritic stainless steels, and nickel and its alloys. In Europe, there was a brief study of encapsulating vitrified HLW in lead and aluminum alloys.[7] Specimens of surrogate waste glass beads and calcine particles dispersed in metal matrices were prepared by vacuum casting. Investment casting of lead, zinc, and aluminum alloys was investigated for Canadian spent fuels.[8,9] Preliminary corrosion tests of lead alloys at conditions simulating the basalt, salt, and tuff repositories have been performed.[10] Encapsulation of spent LWR fuels in a dense copper matrix in a thick-walled copper container has been investigated in Sweden.

4.7.4 Preferred Metal Waste Forms

Based on the information available on metal alloys as immobilization forms, it was judged that the most promising candidate is the Fe–Zr alloy system developed for the electrometallurgical treatment process. The Fe-Zr alternative actually consists of two compositions, SS-15Zr and Zr-8SS, both of which appear equally promising at this time. In addition, no information is available for copper–aluminum alloys to warrant their off-hand rejection. Therefore, the primary reference metal waste forms for plutonium immobilization are the Fe–Zr alloys, but Cu–Al alloys may be considered a secondary option. There is considerable data on the corrosion resistance of copper and its alloys under repository conditions, and there is a growing database on the corrosion resistance of the Fe–Zr alloys. The continued development of the electrometallurgical treatment process will yield additional information relevant to the immobilization program. Since the initial preparation of this screening document, glass bonded zeolite has become the preferred electrometallurgical form and is retained as a reasonable alternative.

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4.8 Multibarrier

The multibarrier waste form was developed to encapsulate waste streams not readily vitrifiable and to encourage development of options for encapsulation of fission-product waste.[1–16] The aim is to dispose or separate the radioactive waste as a low-leaching phase in a metal matrix or to isolate it with coatings. Multibarrier waste forms are composite materials with layers of protection for the radioactive waste form. Multibarrier waste forms employ two or more of the other families described here (excluding calcine). One family serves as the interior carrier (core) for the radioactive material and the other serves as an inert (nonradioactive) exterior shell. The process for making multibarrier waste forms is obviously more complex than for a single form. Some techniques that have been employed for applying the shell include plasma coating, chemical vapor deposition, vacuum casting, and simply pouring molten metal over the primary waste form. Theoretically, this approach combines strengths and mitigates weaknesses of the individual families to improve the overall performance of the finished product. For example, coating supercalcine waste with pyrolitic carbon/silicon carbide (PyC, SiC) improved leach resistance more than an order of magnitude.[4] The matrix serves as a physical barrier to isolate the waste from the

biosphere and to provide mechanical stability. Enhanced leach resistance, improved thermal stability, and increased mechanical strength are advantages of these composite waste forms.[2]

4.8.1 Ceramic in Concrete

After radioactive waste has been incorporated in a ceramic such as clay ceramic, Supercalcine, or Synroc, it can then be incorporated in a cement matrix. The technique has been described by Schulz et al.[14] It may be useful when the ceramic waste form is small (e.g. pellets or marbles), to minimize dispersion if the external container were breached. However, there is little performance data available and no active research for this waste form.

4.8.2 Glass or Ceramic in Metal Matrix

An alternative to storing waste glass as monoliths or marbles in a canister is to fill the void space with molten metal. The waste form can be glass, glass ceramic, or ceramic (e.g., supercalcine, Synroc, tailored ceramics, clay ceramic) in monolith, marble, or pellet form.

Ewing[4] discussed a composite waste form (Vitromet) in which glass beads or marbles (occupying as much as 66% of the total volume) are embedded in a metal matrix. Molten glass is made into marbles and rapidly cooled to minimize devitrification. The marbles are loaded into a canister, and the void space is filled with a low-melting metal alloy, such as lead-tin, lead-antimony, aluminum-zinc, or aluminum-silicon, or pure lead or copper.[5,7] The metal matrix provides an additional barrier to leaching or air dispersion of waste material. For Vitromet, the corrosion rate of the encapsulating metal matrix or the glass in the metal/solution environment controls leaching. The metal matrix provides mechanical strength to the waste form and enhances dissipation of heat from the glass by increasing the thermal conductivity of the waste package.

Waste loading is the same as for the original waste form. However, since void spaces filled with metal can account for 50% to 70% of waste-form volume, effective loading per canister would be approximately 30% to 50% of that for the glass monoliths.

Use of lead[8,9] as the metal matrix will provide some shielding from radioactivity in the canister. Lead is a toxic metal that is regulated under RCRA and thus may present more difficulties in obtaining permits than other metals. RCRA metals may not be acceptable in a geologic repository. The addition of the melting and pouring steps will slightly increase the complexity of the waste processing. Encapsulation can be accomplished by gravity sintering of metal powders, casting at ambient pressure vacuum casting, pressure casting, or vacuum and pressure casting.

Additional research needs to be conducted to evaluate the compatibility of different metal matrix compositions with waste forms and canister materials. Ewing[2] noted that one of the greatest difficulties has been to find metal compositions and processes that

effectively wet and encapsulate the dispersed "fines" in the matrix.[4] Vitromet and Cermet are the two most-developed waste forms that incorporate radionuclides in a metal matrix.

Ceramic pellets prepared from a calcined mixture of waste and tailored additives are sintered (900°–1300°C) and loaded into a canister, and the void space is filled with a low-melting metal alloy. Waste loadings are similar to those of ceramic waste forms. As with glass marbles, filling the void spaces with metal reduces the effective waste-loading per canister to only about half that of a canister containing a hot pressed or hot isostatic pressed ceramic. A major disadvantage of ceramic pellets would be the difficulty in reworking the potentially nonuniform products. The need to crush or pulverize the pellets before rework would create a potential for problems with dust. Furthermore, variation in feed composition could lead to formation of pellets with poor physical quality and sintering characteristics.

4.8.3 Plasma Spray Coatings

The storage properties of calcined nuclear waste can be significantly enhanced by coating the particles with tougher, more leach-resistant materials. Rusin and associates found that chemical-vapor deposited (CVD) coatings of pyrolytic carbon (PyC) and silicon carbide (SiC) can double or triple the leach resistance of supercalcine waste.[10] Very dense, impermeable PyC coatings are produced by decomposing acetylene at 1000°C in an argon atmosphere. SiC coatings are produced by decomposing methylsilane at 900°C. Both types of coatings have shown excellent structural integrity in irradiation tests. Researchers at ORNL estimated that PyC-coated zeolite particles would be stable in water at 100°C for 3×10^5 years or 1×10^{13} years in air at 100°C.[16]

In 1981, Oma and colleagues introduced the use of a plasma torch for calcine coating.[11] In this method an inert-gas plasma is used to vaporize coating material, which is then deposited on the surface of a substrate, such as supercalcine waste. The plasma spray coating processes proved preferable to the CVD (high and low temperature) PyC coating process in complexity, deposit rate, leach resistance, coating porosity, coating bond strength, and thermal expansion mismatch.[11] This process has been successfully applied to coating of more than 300 kg of high level waste glass marbles. This technique has been used only to coat small particles and probably would not be applicable to large monoliths. Small particles can be dispersed easily. Hence, this waste form may need to be incorporated with an external barrier as described in Section 4.8.1.

Plasma spray coatings increase leach resistance of waste-glass marbles by two- to three-fold, may enhance the mechanical properties of waste forms, and have been successfully used in large-scale demonstrations. On the other hand, their line-of-sight mechanism requires agitation of waste particles (or marbles) for an even coating, and the coating process adds complexity to the process.

4.8.4 Cermet

Cermet fixes HLW as multimicron-sized ceramic particles in a continuous, corrosion-resistant, thermally conductive, metal-alloy matrix.[12] The composite is formed by mixing waste with additives in molten urea, which promotes homogen mixing. The mixture is then spray calcined, a process in which a precipitate contai homogeneously distributed waste and additives is calcined into component oxide Spray calcining produces near spherical particles approximately 10 µm in diamete oxides are mixed with water and extruded into rods or pellets. Liquid-phase sinte (~1000°C) in a hydrogen atmosphere quickly densifies the pellets, reduces metal (e Cu, Ni, Fe) oxides, and encapsulates the wastes in a continuous metal matrix havi little microporosity.[13] The ceramic contains oxides tailored to retain specific radionuclides. The matrix is formed of metal ions in the waste or added in the solu during formulation of the feed.

The exact ceramic and metal compositions are unique to each waste type and loading. According to Ewing, the greater the proportion of alloy material, the mor effectively the ceramic phases are encapsulated in the metal matrix.[2] The alloy composition can be easily modified, and any combination of reducible metals may added to the waste. Ceramic formers, such as Al and Si, are added to fix specific s (e.g., Na, K, Rb, and Cs) in the waste as insoluble ceramics. Likewise, Ti is added t waste to fix Ba and Sr as titanates.[13]

Schulz and colleagues extensively reviewed this waste form for use in encapsu Hanford high-level waste.[2,9,14] They identified the following advantages and disadvantages. As reported by Westsik, the added leach barrier from metal matrix minimizes leaching.[15] The material is stable to ionizing radiation, and mechanical stability and fire resistance provide good transportation safety. Kobisk et al. repor low volatility during processing.[12] Thermal conductivity is high. The alloy is prim composed of hydrogen-reducible metals, already in the waste. Finally, certain was compositions have the potential for high waste-loading. The disadvantages are as follows. The dispersed radioactive oxide phase has a large surface area; on corrosi metal matrix, fine particles will be easily dispersed into aqueous medium. The me alloy matrix is poorly resistant to corrosion and may swell if high radiation waste encapsulated. Waste-loading for high alkali wastes is poor.

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12. E. H. Kobisk, T. C. Quinby, and W. S. Aaron, *Final Report on Cermet High-Level Waste Forms*, ORNL-5760, Oak Ridge National Laboratory, Oak Ridge, TN (1981).
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15. W. A. Ross and J. E. Mendel, *Annual Report on the Development and Characterization of Solidified Waste Forms for High-Level Wastes*, PNL- 3060, Pacific Northwest Laboratory, Richland, WA (1979).
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4.9 Polymerics

Polymeric matrices are currently in use at nuclear power plants and reprocessing facilities around the world for the immobilization of various low and intermediate level (doses < 10 rad) radioactive waste sources.[1] The polymer waste forms have chemical and physical properties that make them compatible for the above application over a

wide range of conditions. Many polymeric matrix materials cannot retain liquids, so that the waste must undergo a dewatering pretreatment before being incorporated into the polymer. The polymer materials may be sensitive to the pH of the waste, which may require pretreatment to obtain the optimal chemical properties for polymerization. Polymeric materials are generally not suitable for HLW applications.

4.9.1 Epoxy Resins

Viscosities of epoxy resins range from liquids to high-melting solids. They usually contain several additives, such as hardeners, which can significantly affect their properties and processing rates. Unlike most other polymers, some epoxies (e.g., Polymer B) can immobilize wastes with high water content and incorporate large volumes (50 to 56 wt%) of waste.

4.9.2 Polyester Resins

Commercial polyester resins are composed of a linear polyester resin, a cross-linking monomer, and inhibitors to retard premature cross-linking; they may contain other additives that alter the temperature of polymerization. Styrene is often used as the cross-linking monomer in radioactive waste immobilization because it is highly resistant to radiation. Polyester resins can be formulated with a wide range of physical properties; they can be hard and brittle, tough and resilient, or soft and flexible. Chemical additions can impart fire resistance, chemical durability, or weather resistance.

4.9.3 Polyethylene Resins

Polyethylene is formed through the polymerization of ethylene gas. The crystallinity of the polymer determines its density, which affects the material properties. Low-melting polyethylene is usually preferred for radioactive waste immobilization to reduce the volatilization or decomposition of radionuclides or other waste components. The structure of polyethylene makes it resistant to chemical attack. Removing water from the waste before it is mixed with polyethylene will prevent foaming during processing.

4.9.4 Styrene-Divinylbenzene Copolymer

Small amounts of divinyl benzene are added to styrene monomer to create a cross-linked copolymer. The resulting cross-linked copolymer is more elastic and has better solvent resistance than the uncross-linked polymer.

4.9.5 Urea-Formaldehyde Resins

Urea-formaldehyde (UF) resins are viscous emulsions of urea and formaldehyde that are miscible with water. During polymerization, the byproduct water and the waste are physically trapped in the honeycomb polymer matrix. The waste-form volume is the sum of the volumes of the waste and the polymer. Between 1970 and 1980, UF was a

principal solidification agent in the U.S., but regulations concerning the amount of free water allowed in the waste package have resulted in its phase out as a waste form.

4.9.6 Bitumen

Bitumen is made by mixing radioactive waste slurry with asphalt and evaporating the mixture to dryness. This waste form, which is also called asphalt immobilization, has been used to immobilize low-and intermediate-level radioactive wastes in Europe, where it replaced concrete. The world's first asphalt solidification system began operating in France in 1965. The advantages over concrete include much higher waste loadings, much lower water content, reprocessability, high impact resistance, and low leach rates.[2] This waste form has many disadvantages for plutonium immobilization, including (1) low softening temperature, (2) sensitivity to attack by radiolysis, and (3) low density. Storage temperature should be limited to 50°C to prevent long-term stratification of the radioactive solids.[3]

4.9.7 Sulfur Polymer Cement

Sulfur polymer cement (SPC) consists of 95 wt% sulfur, 2.5 % dicyclopentadiene, and 2.5 % oligomers of cyclopentadiene. Both DOE and the Commission of European Communities have tested SPC for stabilizing radioactive and hazardous wastes. SPC does not support combustion and resists attack by most acids, salts, and sulfates that destroy hydraulic concretes. Processing temperatures are only 130–140°C, which is a strong advantage if cesium must be encapsulated in the waste form. SPC does not tolerate water in the mix. SPC should not be used if the disposal site temperature exceeds 100°C or if it could be contacted with strong alkali.[4]

4.9.8 References for Section 4.9

1. *Immobilization of Low and Intermediate Level Radioactive Wastes with Polymers*, International Atomic Energy Agency, Technical Report Series No. 289, Vienna (1988).
2. Stewart, J. E. and R. Herter. 1975. "Solid Radwaste Experience in Europe Using Asphalt." ASME-IEEE Joint Power Generation Conference. Portland, OR.
3. W. W. Schulz, et al. 1980. *Preliminary Evaluation of Alternative Forms for Immobilization of Hanford High-Level Defense Wastes*. Rockwell International Energy Systems Group. Richland, WA. RHO-ST-32.
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5. Screening Results

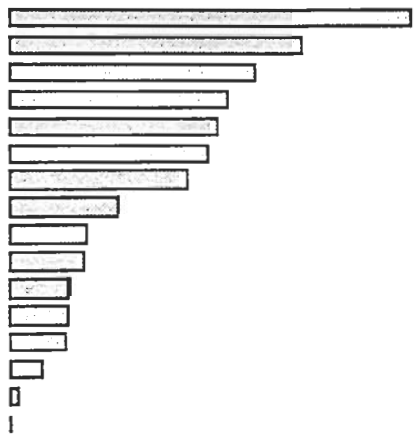
5.1 Final Screening Results Summary

The results of the combined first- and second-level screening process is shown in Table 5-1 as a ranking of 16 waste forms. Utility is the figure of merit for each waste form.

Table 5-1. Final ranking of waste forms.

Ranking for Best Form for Base-line Preference Set

Form	Utility
Borosilicate Glass	0.89
Synroc	0.66
Phosphate Glass	0.55
Monazite	0.49
Metallic Alloy	0.47
High Silica Glass	0.44
FUETAP Concrete	0.40
Hot-Pressed Concret	0.24
Phos.-bnded Ceramic	0.17
Silicon-Zirc Phosph	0.17
Ceramics in Concret	0.14
Iron-Enriched Basal	0.13
Ceramic Pell. in Me	0.13
Supercalcine	0.08
Glass-Ceramic Monol	0.03
Cermet	0



Borosilicate (BG) glass ranks highest, and Synroc second. Within the glass family, BG ranks higher than phosphate glass, and high-silica glass. Similarly, Synroc outranks Monazite and all other ceramics. Sensitivity analysis showed that these form family rankings are very insensitive to changes in both the attribute weights generated and the technical scores assigned.

The detailed results of first and second level screening together with descriptions of the individual technical assessments (TA) and value assessments (VA), as well as combined results and sensitivity analysis are presented in this section.

5.2 Elimination of Redundant or Geometrically Different Waste Forms

The master list of waste forms was edited to eliminate redundancies. For the purposes of this study, waste forms are distinguished by unique physical and chemical properties. Different names or shapes, for example, do not represent unique waste

forms. In the case of borosilicate glass, monoliths and marbles are geometric variants that need not be considered separately for screening. The process for making the waste form (e.g., LOTES, Plasma Spray, and Thermite) does not need to be evaluated separately either. Table 5-2 lists the unique forms that remain.

Table 5-2. List of unique waste forms remaining after removing redundancy.

Master list #	Waste form	Form family
1	Calcine	Calcine
6	FUETAP Concrete	Cementitious
7	Hot-Pressed Concrete	Cementitious
8	Normal Concrete	Cementitious
9	Phosphate-bonded Cement	Cementitious
12	Supergrout Concrete	Cementitious
13	Aqueous Silicate	Ceramic
15	Clay Ceramic Monoliths	Ceramic
23	Monazite	Ceramic
26	Silicon Zirconium Phosphate	Ceramic
27	Supercalcine	Ceramic
31	Synroc Ceramic Monoliths	Ceramic
39	Borosilicate glass monoliths	Glass
40	High Silica glass	Glass
41	Lead-iron phosphate glass	Glass
42	Phosphate glass	Glass
44	Sintered glass-calcine	Glass
48	Glass-ceramic monoliths	Glass-Ceramic
50	Iron-enriched basalt	Glass-Ceramic
51	Talc-silicon glass-ceramic	Glass-Ceramic
52	Metal compounds (Z<19)	Metallic
53	Metal compounds (Z>19)	Metallic
56	Metallic solid solutions	Metallic
58	Ceramic in concrete	Multibarrier
59	Ceramic pellets in metal matrix	Multibarrier
60	Cermet	Multibarrier
61	Glass in metal matrix	Multibarrier
64	Pyrolytic C and SiC-coated particles	Multibarrier
65	Bitumen	Polymeric
66	Epoxy resins	Polymeric
67	Polyester resins	Polymeric
68	Polyethylene resin	Polymeric
69	Styrene-divinylbenzene	Polymeric
70	Sulfur polymer cement (SPC)	Polymeric
71	Urea-formaldehyde resin	Polymeric
72	Iron phosphate glass	Glass

5.3 Results of First Level Screening

At the present time, federal laws and regulations do not specifically address the disposition of plutonium, but there are laws covering the disposal of high level radioactive wastes in geologic repositories.[1] It is assumed that disposition of plutonium must meet these requirements as a minimum. Any waste form that could not pass these minimum requirements would be construed to have a fatal flaw and should be eliminated from further consideration.

In addition, the waste form containing plutonium would be subject to leaching in a repository. Waste forms that could release toxic metals regulated under the RCRA would present an additional regulatory obstacle.[2] Because this reduces the likelihood of timely permitting, this could also be a fatal flaw for forms containing high concentrations of the following free metals:

- Arsenic
- Barium
- Cadmium
- Chromium
- Lead
- Mercury
- Selenium
- Silver

A draft guidance document describing the anticipated requirements for a plutonium disposition waste form in more detail is given in Ref. 3.

Table 5-3 restates the first level screening criteria, presented in Section 3, along with a brief interpretation of the screening activity.

References for Section 5.1

1. Code of Federal Regulations, 10 CFR 60.131 and 135.
2. Code of Federal Regulations, 40 CFR 261.24.
3. *Waste Form Requirements for the Potential Disposition of Weapons-Usable Fissile Materials in a Deep Geological Repository*. Prepared for U.S. Department of Energy Office of Civilian Waste Management by TRW Environmental Safety Systems Inc. Preliminary Draft August 18. 1994. Report No. A00000000-00811-1708-00004.

5.3.1 Results of First-Level (Pass/Fail) Screening

Table 5-4 presents the edited list of 37 waste forms and their scoring in the first level screening process. The 16 forms that passed the first level screening appear first on the list.

All members of the calcine and polymeric families were eliminated in the first level of screening. Table 5-5 identifies the 16 waste forms that passed the first level. Only these were considered in subsequent evaluations.

Table 5-3. Criteria for first level screening.

Criteria	Requirement	Interpretation
No free water	"Shall not contain free liquids in an amount that could compromise the waste package"	Chemically bound water is exempt from this requirement.
Solidification & consolidation	"Shall be...in solid form ...[and]... consolidated ... to limit the availability and generation of particulate"	Eliminate forms that are friable or consist of small particles.
Stability	"Shall not contain explosive or pyrophoric or chemically reactive materials in an amount that could compromise the waste package..." and "...shall be noncombustible..."	This includes gases that might be generated by radiolysis.
Criticality control	K_{eff} must...show at least a 5% margin.	Incorporation of neutron poison can satisfy this requirement.
RCRA metal content	Cannot contain significant quantities of the following free metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium, silver	Eliminate forms containing high concentrations of RCRA-regulated metals.
Readiness	Must be technically viable for 20 years after record of decision	Unlikely to be ready if bench-scale research is not complete now.
Loading	Must maintain a feasible volume of waste for storage	Must not occupy an unreasonable amount of storage volume.

Table 5-4. First level screening results for edited list of waste forms.

Master list No.	Waste form	Form family	Prescreening result	Free water	Pu loading	Structural integrity	Criticality control	Solidification & consolidation	Stability	Readiness	RCRA problem potential
6	FUETAP concrete	Cementitious	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Pass	Pass
7	Hot-pressed concrete	Cementitious	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Pass	Pass
23	Monazite	Ceramic	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Not well developed	Pass
24	Phos-phate-bonded ceramic	Ceramic	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Pass
26	Sodium zirconium phosphate	Ceramic	Pass							Not well developed	Pass
27	Super-calcine	Ceramic	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
31	Synroc ceramic monolith	Ceramic	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail	Pass
39	Borosilicate glass monoliths	Glass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Commercial process	Pass
40	High-silica glass	Glass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Not well developed	Pass
42	Phosphate glass	Glass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Not well developed	Pass
48	Glass-ceramic monoliths	Glass-ceramic	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Not well developed	Pass
50	Iron-enriched basalt	Glass-ceramic	Pass	Pass	Unknown	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Pass
56	Metallic alloys	Metallic	Pass	Pass	Pass	Pass	Pass	Pass	Unknown	Not well developed	Some metals fail
58	Ceramic in concrete	Multi-barrier	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Pass
59	Ceramic pellets in metal matriz	Multi-barrier	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Some metals fail
60	Cermet	Multi-barrier	Pass	Pass	Pass	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Pass
1	Calcine	Calcine	Fail	Pass	N/A	Fail	Fail	Fail	Fail	Fail	Pass
8	Normal concrete	Cementitious	Fail	Pass	Pass	Pass	Pass. Must add poison	Pass	Fail	Pass	Pass
9	Phos-phate-bonded cement	Cementitious	Fail	Fail	Pass	Pass	Pass. Must add poison	Pass	Pass	Not well developed	Pass

Table 5-4. (Cont'd.)

Master list No.	Waste form	Form family	Prescreen-ing result	Free water	Pu loading	Structural integrity	Criticality control	Solidifica-tion & consolida-tion	Stability	Readiness	RCRA problem potential
12	Super-grout concrete	Cementi-tious	Fail	Fail	Pass	Pass	Pass. Must add poison		Fail	Fail	Pass
13	Aqueous silicate	Ceramic	Fail	Fail	Unknown	Fail		Pass	Fail	Not well developed	Pass
15	Clay ceramic monoliths	Ceramic	Fail	Pass	Pass	Fail	Pass. Must add poison	Pass	Pass	Pass	Pass
41	Lead-iron phosphate glass	Glass	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Not well developed	Fail
72	Iron phosphate glass	Glass	Fail	Pass	Pass	Fail	Pass	Pass	Fail	Not well developed	Pass
44	Sintered glass-calcine	Glass	Fail	Pass	Probably fail	Pass	Pass		Probably fail	Not well developed	Pass
51	Talc-silicon glass-ceramic	Glass-ceramic	Fail		Probably fail					Not well developed	Pass
52	Metal compunds (Z < 19)	Metallic	Fail	Pass	Pass	Fail	Unknown	Poor	Unknown	Not well developed	Some metals fail
53	Metal compunds (Z > 19)	Metallic	Fail	Pass	Pass	Fail	Unknown	Poor	Unknown	Not well developed	Some metals fail
61	Glass in metal matrix	Multi-barrier	Fail	Pass	Pass	Pass		Pass	Pass	Commercial process	Pass
64	Pyrolytic C and SiC-coated particles	Multi-barrier	Fail	Pass	Pass	Pass	Pass	Fail	Pass		Pass
65	Bitumen	Polymeric	Fail	Pass	Fail	Fail		Pass	Fail	Not well developed	Pass
66	Epoxy resins	Polymeric	Fail	Pass	Fail	Pass		Pass	Fail	Not well developed	Pass
67	Polyester resins	Polymeric	Fail	Pass	Fail	Pass		Pass	Fail	Not well developed	Pass
68	Poly-ethylene resin	Polymeric	Fail	Pass	Fail	Pass		Pass	Fail	Not well developed	Pass
69	Styrene-divinyl-benzene	Polymeric	Fail	Pass	Fail	Pass		Pass	Fail	Not well developed	Pass
70	Sulfur polymer cement (SPC)	Polymeric	Fail	Pass	Fail			Pass	Fail	Not well developed	Pass
71	Urea-formalde-hyde resin	Polymeric	Fail	Pass	Fail	Pass		Pass	Fail	Not well developed	Pass

Table 5-5. Waste forms that passed first-level screening.

Master list #	Waste form	Form family
6	FUETAP Concrete	Cementitious
7	Hot-Pressed Concrete	Cementitious
23	Monazite	Ceramic
24	Phosphate-bonded Ceramic	Ceramic
26	Sodium Zirconium Phosphate	Ceramic
27	Supercalcine	Ceramic
31	SYNROC Ceramic Monoliths	Ceramic
39	Borosilicate Glass Monoliths	Glass
40	High Silica Glass	Glass
42	Phosphate Glass	Glass
48	Glass-Ceramic Monoliths	Glass Ceramic
50	Iron-enriched Basalt	Glass Ceramic
56	Metallic Alloys	Metallic
58	Ceramic in Concrete	Multibarrier
59	Ceramic Pellets in Metal Matrix	Multibarrier
60	Cermet	Multibarrier

5.4 Results of Second-Level (Performance-Based) Screening

The methodology for second-level screening was described in Section 3.2. The following sections detail the results of the assessments and multi-attribute analysis used to evaluate the 16 waste forms.

5.4.1 Results of the Technical Assessment

Table 5-6 summarizes the results of the TAs. Notes related to the numerical scores are contained in Appendix A.

5.4.2 Results of the Value Assessments

This section presents the results of the VA assessments.

Table 5-6. Summary of TA numerical scores, Part A.

Immobilization form	1.a	1.b	2.a	2.b	3.c
39. Borosilicate glass monoliths	3	3	5	5	3
40. High-silica glass monoliths	3	3	2	3	3
42. Phosphate glass	3	3	4	3	3
31. Synroc ceramic monoliths (titanate-based)	4	3.5	3.5	3.5	3
27. Supercalcine (aluminosilicate-based)	3	3	2	1	3
23. Monazite	4	3	2.5	3	3
24. Phosphate-bonded ceramic	3.5	3	1.5	1	3
26. Silicon zirconium phosphate	3.5	3	1	1	3
48. Glass-ceramic monoliths	3	3	1	1	1
50. Iron-enriched basalt	3	3	2	1	3
6. FUETAP concrete	3	3	3.5	2	3
7. Hot-pressed concrete	3	3	2.5	2	3
56. Metallic alloy	3	3	3	3	3
58. Ceramics in Concrete	4	3.5	2.5	2.5	1
59. Ceramic pellets in metal matrix	4	3.5	2	2.5	1
60. Cermet	3	3	1	1	1

1.a Attractiveness & difficulty of retrieval
1.b Assurance of detection
2.a Technical maturity
2.b Regulatory/licensing requirements
3.c Waste minimization

Value Assessments to Develop Utility Curves

A normalized 0–1 utility scale was adopted over the technical performance range for each attribute. During the technical assessment, the entire technical performance range was assessed over the alternatives for most attributes (such as technical maturity). Each utility curve is described below.

Attractiveness and difficulty of retrieval (see Fig. 5-1). For this measure, responses varied only between 3 and 4. The VA team felt utility was linear over this range.

Assurance of detection (see Fig. 5-2). For this measure, responses varied only between 3 and 3.5. The VA team felt utility was linear over this range.

Table 5-6. Summary of TA numerical scores, Part B.

Immobilization form	3.d	4.a	4.b	5.a	7.a
39. Borosilicate Glass Monoliths	3	5	3	5	5
40. High Silica Glass Monoliths	3	3	2	3	3
42. Phosphate Glass	2.5	3	2.5	4	3
31. Synroc Ceramic Monoliths (Titanate-based)	3.5	3	2	4	4
27. Supercalcine (Aluminosilicate-based)	2.5	1	1.5	1	2
23. Monazite	3.5	3	1.5	3	3.5
24. Phosphate-bonded Ceramic	2.5	3	1.5	1	2.5
26. Silicon Zirconium Phosphate	2.5	3	1.5	1	2.5
48. Glass-Ceramic Monoliths	2.5	2	1	1	3
50. Iron-enriched Basalt	2.5	2	1.5	1	2
6. FUETAP Concrete	2.5	2	3.5	3	2
7. Hot-Pressed Concrete	2.5	1	3	2	2
56. Metallic Alloy	2.5	4	3	3.5	3
58. Ceramics in Concrete	2.5	1	1.8	2	2
59. Ceramic Pellets in Metal Matrix	2.5	1	1.8	2	3
60. Cermet	2.5	1	1	1	2

3.d Environment and resource conservation: leaching
4.a Life-cycle costs
4.b Investment and startup costs
5.a Time to start disposition
7.a Ability to create a sustainable consensus

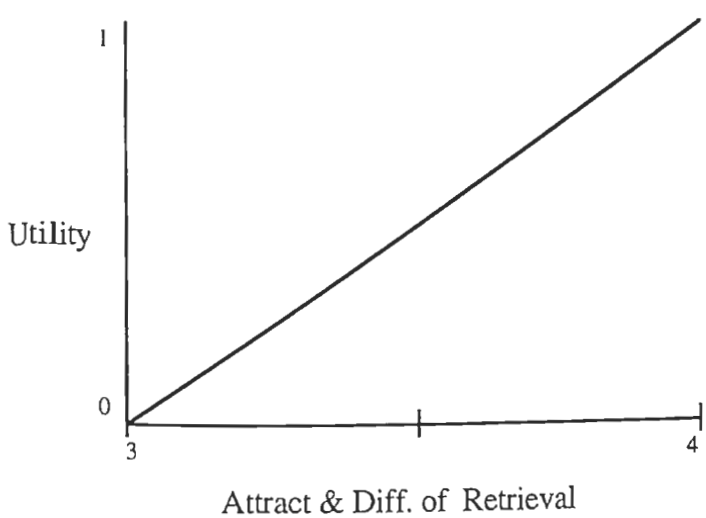


Figure 5-1. Attractiveness and difficulty of retrieval.

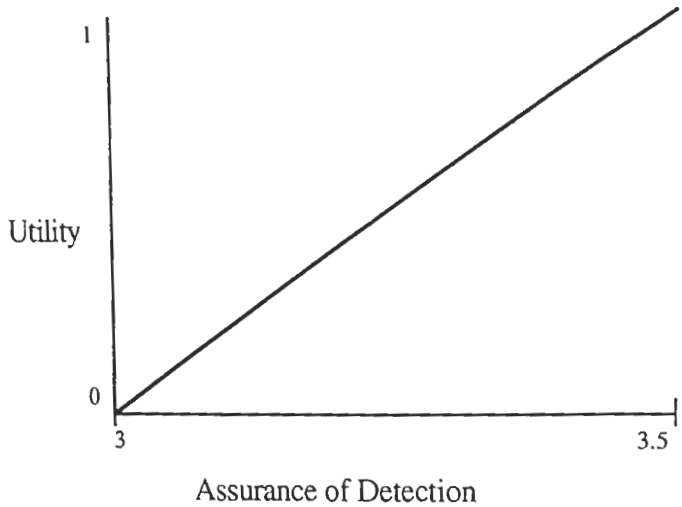


Figure 5-2. Assurance of detection.

Technical maturity (see Fig. 5-3). The team felt that the utility curve for technical maturity was non-linear; that values much below 3 (Technical maturity requiring greater than 10 years to reach that of BG) would be of little utility. Similarly, the increase in utility from 4 to 5 (between 5 years less mature than BG and equivalent maturity to BG) was small. This behavior results in an S-shaped utility curve.

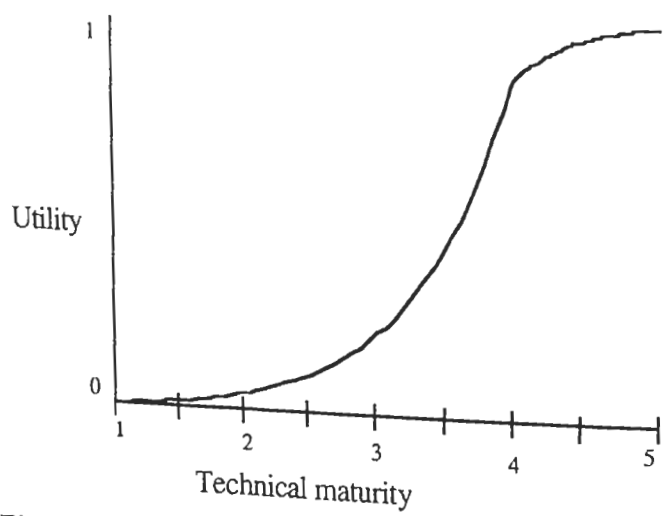


Figure 5-3. Technical maturity.

Regulatory requirements (see Fig. 5-4). The regulatory requirements utility curve was also viewed as non-linear. Scores from 1 to 2.5 (low likelihood of meeting regulatory requirements and worse) received low utility values. The largest change in utility occurs around the values representing the ability to meet a regulatory requirement.

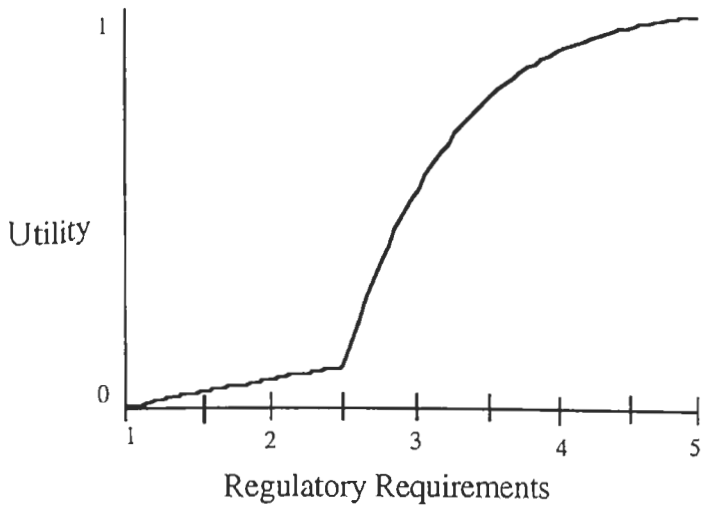


Figure 5-4. Regulatory requirements.

Waste minimization (see Fig. 5-5). For this measure, the VA team felt utility was linear.

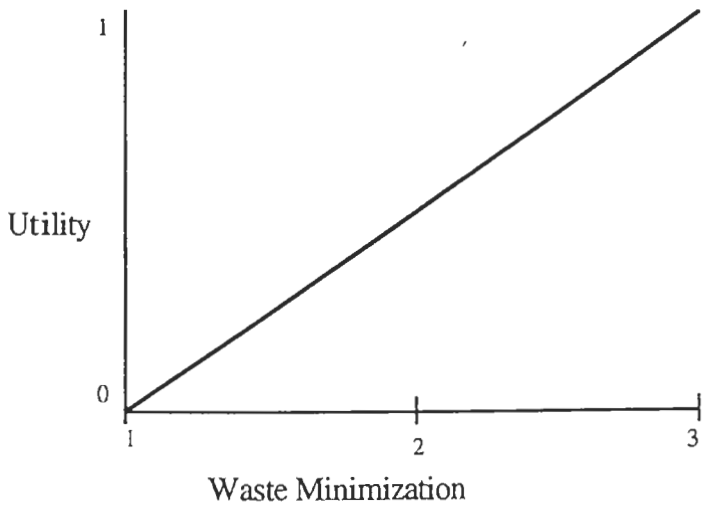


Figure 5-5. Waste minimization.

Leaching (see Fig. 5-6). The leaching curve was nonlinear for scores below 3 and linear above this value. The leaching behavior of BG (score of 3) was viewed as adequate. Utility exponentially decreases for scores below 3, as leaching behavior worse than BG are seen as inadequate. Scores higher than BG were judged to have incrementally lower increase in utility than increases below BG.

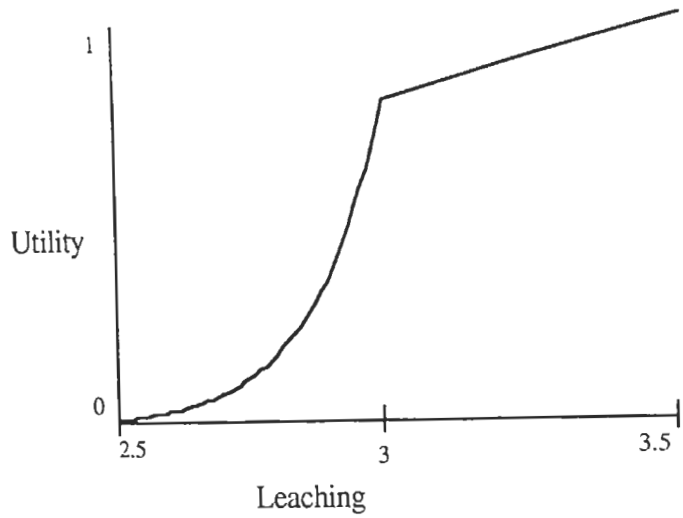


Figure 5-6. Leaching

Life-cycle costs (see Fig. 5-7). The utility curve increases linearly from 1 to 4. A score of 4 (the score representing costs between a new glass or ceramic facility and the reduced costs for the case where BG can be made in an existing facility making use of an overlap with a HLW disposal mission. A score of 4 receives a large fraction of the utility.

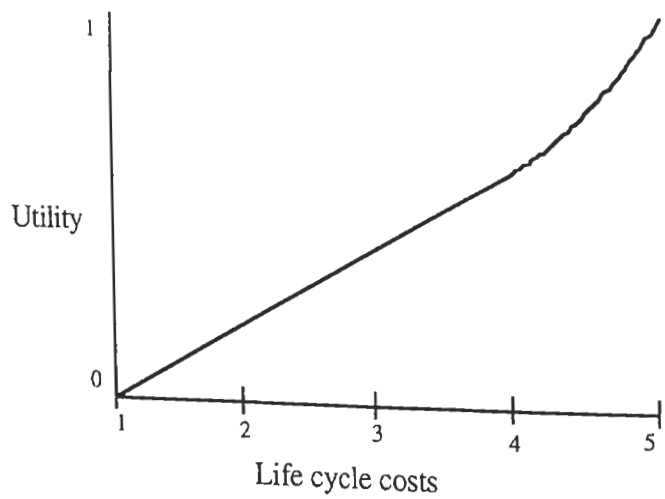


Figure 5-7. Life-cycle costs.

Investment and startup costs (see Fig. 5-8). This utility curve was assessed as linear over the scores of 1 (investment and startup costs are expected to be much greater (by more than 5 times) than those anticipated for BG) to 3 (investment and startup costs are expected to be approximately equal to those anticipated for BG (on the order of a billion dollars).

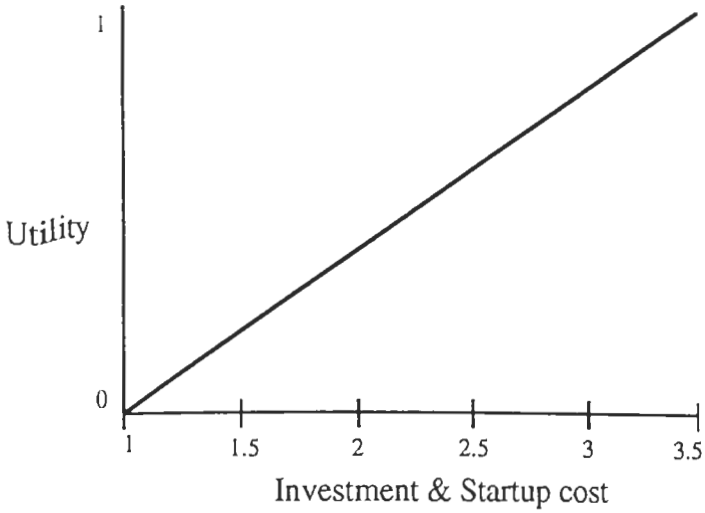


Figure 5-8. Investment and startup costs.

Time to start disposition (see Fig. 5-9). This utility curve is based on the premise that meeting project schedule is adequate and completion any sooner is of little value. Utility increases as scores move from a likelihood that schedule requirements will not be met (1), to meeting schedule requirements with little or no slack time (3). Scores above 4 were given only slightly higher utility (never greater than 10% utility improvement).

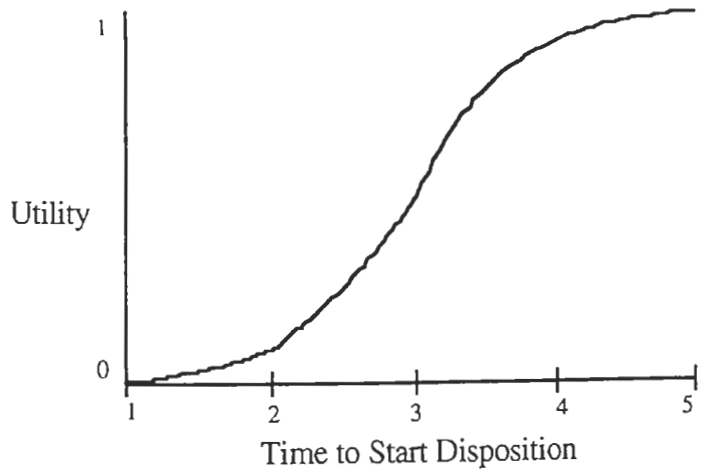


Figure 5-9. Time to start disposition.

Consensus (see Fig. 5-10). A score of 3 was given the majority of the utility. The increase in utility from a score of 1 (public or governmental resistance to licensing, to the "acceptable" score of 3 (regulatory approval is expected to be similar to that anticipated for the BG option) was seen as great, whereas scores greater than 3 received only slightly higher utilities.

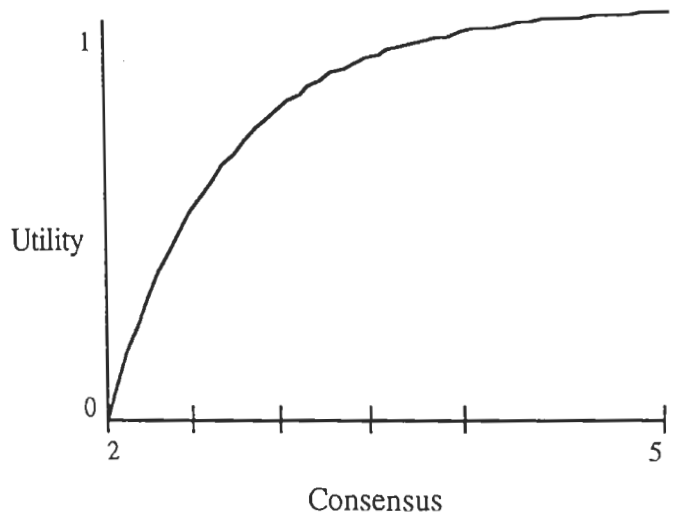
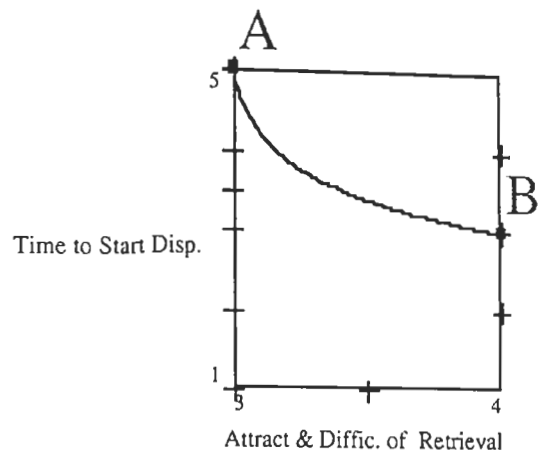


Figure 5-10. Consensus.

Tradeoff Assessments for Attribute Weighting

To define the relative importance of the attributes in this analysis, attribute weights were also assessed from the VA team. These formed the scaling constants used to compute the utilities for the multiattribute utility functions, to calculate the overall figures of merit for each form over all the attributes.

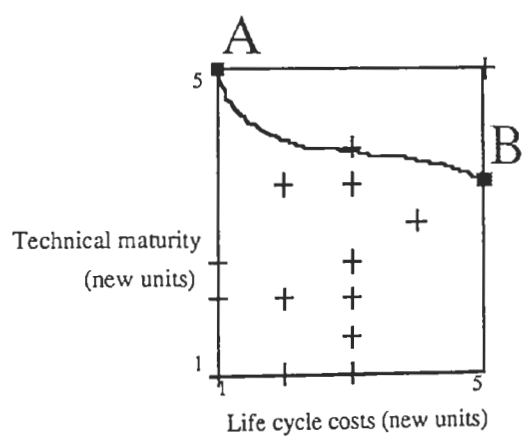
The trade-off method was used to assess the weights, comparing two attributes at a time. The two endpoints on the curve (labeled A and B, below and detailed under each graph) were determined to be equally preferred. The trade-off curves resulting from these assessments are shown below. The trade-off question used to determine the curve endpoints are also shown below each curve. The curves below also incorporate the utility curves described above. Thus trade-off curves may be nonlinear, given nonlinear utility curves. The specific trade-off curves are shown below.



	A	B	A-B
Attract & Diff. of .	3	4	-1
Time to Start Disp.:	5	3	2

Attract & Diff. of Measure Weight:Time to Start Disp. Measure Weight = 0.5:1

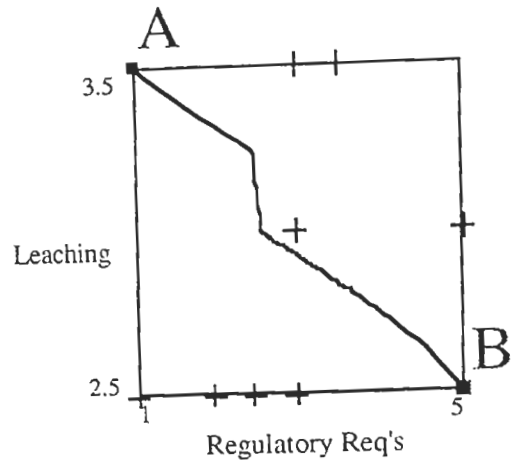
Figure 5-11a. Trade-off of time to start disposal vs attractiveness and difficulty of retrieval.



	A	B	A-B
Life cycle costs (new units):	1	5	-4
Technical maturity (new units):	5	3.5	1.5

Life cycle costs Measure Weight:Technical maturity Measure Weight = 0.584266:1

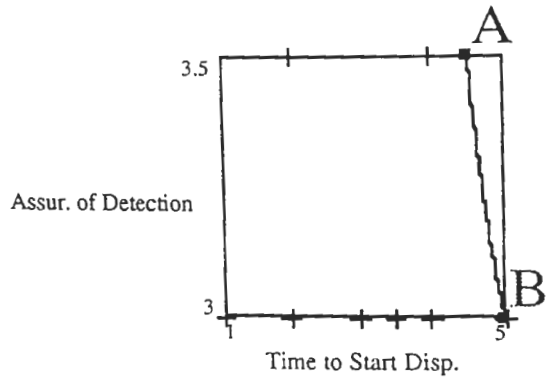
Figure 5-11b. Trade-off of technical maturity vs life-cycle costs.



	A	B	A-B
Regulatory Req's:	1	5	-4
Leaching:	3.5	2.5	1

Regulatory Req's Measure Weight:Leaching Measure Weight = 1:1

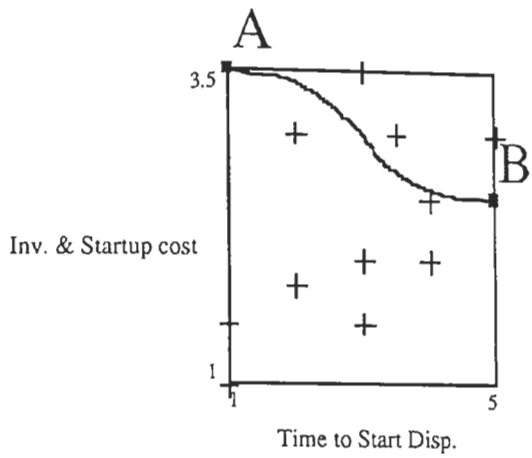
Figure 5-11c. Trade-off of leaching vs regulatory requirements.



	A	B	A-B
Time to Start Disp.:	4.5	5	-0.5
Assur. of Detection:	3.5	3	0.5

Time to Start Disp. Measure Weight:Assur. of Detection Measure Weight = 41.6277:1

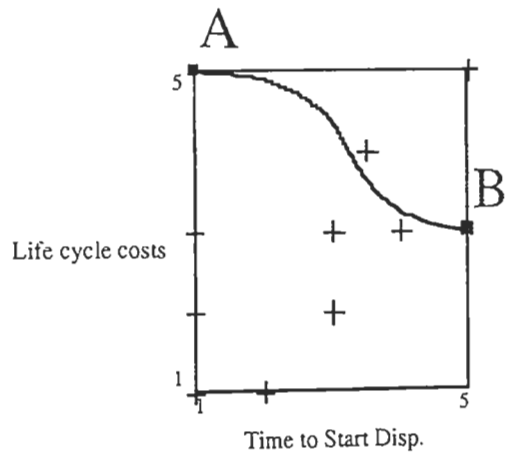
Figure 5-11d. Trade-off of assurance of detection vs time to start disposition.



	A	B	A-B
Time to Start Disp.:	1	5	-4
Inv. & Startup cost:	3.5	2.5	1

Time to Start Disp. Measure Weight:Inv. & Startup cost Measure Weight = 0.4:1

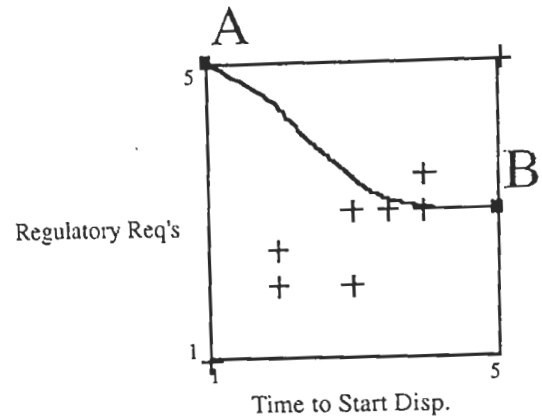
Figure 5-11e. Trade-off of investment and startup costs vs time to start disposition.



	A	B	A-B
Time to Start Disp.:	1	5	-4
Life cycle costs:	5	3	2

Time to Start Disp. Measure Weight:Life cycle costs Measure Weight = 0.6:1

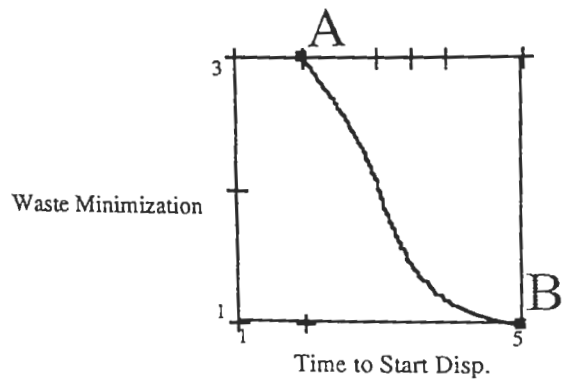
Figure 5-11f. Trade-off of life-cycle costs vs time to start disposition.



	A	B	A-B
Time to Start Disp.:	1	5	-4
Regulatory Req's:	5	3	2

Time to Start Disp. Measure Weight:Regulatory Req's Measure Weight = 0.457624:1

Figure 5-11g. Trade-off of regulatory requirements vs time to start disposition.



	A	B	A-B
Time to Start Disp.:	2	5	-3
Waste Minimization:	3	1	2

Time to Start Disp. Measure Weight:Waste Minimization Measure Weight = 1.0988:1

Figure 5-11h. Trade-off of waste minimization vs time to start disposition.

5.4.3 Combined Results: Output of the Multiattribute Utility Analysis

- **Attribute Weights.** The above value and trade-off assessments resulted in the following relative attribute weights:

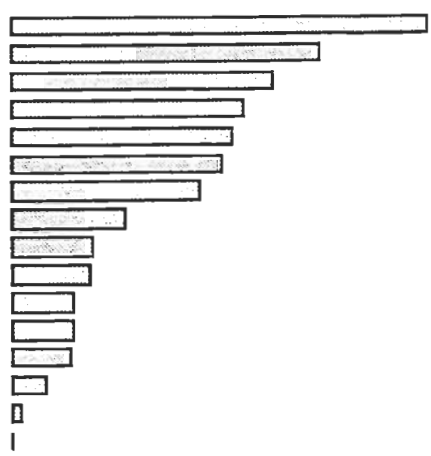
Technical maturity	20.52
Investment and startup costs	17.98
Leaching	15.72
Regulatory requirements	15.72
Life-cycle costs	11.99
Time to start disposition	7.19
Waste minimization	6.55
Attractiveness and difficulty of retrieval	3.60
Consensus	0.57
Assurance of detection	0.17

- **Overall Ranking.** When the above weightings and the utility curves are applied to the technical data obtained during the technical assessments, the forms rank as shown in Table 5-1 which is reproduced below also as Table 5-7.

Table 5-7. Ranking of forms according to weightings and utility curves.

Ranking for Best Form for Base-line Preference Set

Form	Utility
Borosilicate Glass	0.89
Synroc	0.66
Phosphate Glass	0.55
Monazite	0.49
Metallic Alloy	0.47
High Silica Glass	0.44
FUETAP Concrete	0.40
Hot-Pressed Concrct	0.24
phos.-bnded Ceramic	0.17
Silicon-Zirc Phosph	0.17
Ceramics in Concrct	0.14
Iron-Enriched Basal	0.13
Ceramic Pell. in Mc	0.13
Supercalcine	0.08
Glass-Ceramic Monol	0.03
Cermet	0



As shown above, BG ranks the highest, with ceramic second. A comparison of the weighted performance of these two forms is shown in Table 5-8.

Table 5-8. Comparison of BG and Synroc performance.

Overall Utility for		
Borosilicate Glass (Alt1)	= 0.8949	
Synroc (Alt2)	= 0.6592	
Difference	= 0.2357	

Measure	Alt1 Level	Alt2 Level	% Contribution to Difference	Total Contribution
Technical maturity	5	3.5	50.9	0.1199
Inv. & Startup cost	3	2	30.5	0.07193
Life cycle costs	5	3	30.5	0.07193
Attract & Diff. of	3	4	-15.3	-0.03596
Regulatory Req's	5	3.5	14.9	0.03516
Leaching	3	3.5	-13.3	-0.03143
Time to Start Disp.	5	4	2.4	0.005706
Assur. of Detection	3	3.5	-0.7	-0.001728
Consensus	5	4	0.1	0.0002373

Phosphate glass ranks third. However, if a portfolio of forms is to be recommended, it is not clear that choosing the three highest ranking forms provides the best portfolio. The comparison below shows that BG out-performs Phosphate glass on every attribute (BG strictly dominates PG). Thus, if the team were to pursue a glass form, it should always pursue BG. High-silica glass is also strictly dominated by BG.

Table 5-9. Comparison of BG and phosphate glass performance.

Overall Utility for		
Borosilicate Glass (Alt1)	= 0.8949	
Phosphate Glass (Alt2)	= 0.5516	
Difference	= 0.3433	

Measure	Alt1 Level	Alt2 Level	% Contribution to Difference	Total Contribution
Leaching	3	2.5	36.6	0.1257
Regulatory Req's	5	3	21.0	0.07193
Life cycle costs	5	3	21.0	0.07193
Inv. & Startup cost	3	2.5	10.5	0.03596
Technical maturity	5	4	9.0	0.03078
Time to Start Disp.	5	4	1.7	0.005706
Consensus	5	3	0.4	0.001264

Similarly, Synroc always outperforms Monazite, as shown below. (Synroc strictly dominates Monazite.) For this reason, the best portfolio of forms should likely not include Monazite in addition to Synroc.

Table 5-10. Comparison of Synroc and Monazite performance.

Overall Utility for	Synroc (Alt1)	= 0.6592
	Monazite (Alt2)	= 0.4879
	Difference	= 0.1713

Measure	Alt1 Level	Alt2 Level	% Contribution to Difference	Total Contribution
Technical maturity	3.5	2.5	38.7	0.06625
Regulatory Req's	3.5	3	21.5	0.03677
Inv. & Startup cost	2	1.5	21.0	0.03596
Time to Start Disp.	4	3	17.7	0.03026
Assur. of Detection	3.5	3	1.0	0.001728
Consensus	4	3.5	0.2	0.0003333

The next highest-ranking forms, not dominated by Synroc or BG, are metallic alloy (MA) and FUETAP (F). The comparison of these forms is shown below. MA outperforms FUETAP on the heavily weighted measures and therefore ranks higher. However, many of the scores of these two forms are very close together.

Table 5-11. Comparison of metallic alloy and FUETAP performance.

Overall Utility for	Metallic Alloy (Alt1)	= 0.4690
	FUETAP Concrete (Alt2)	= 0.4014
	Difference	= 0.0676

Measure	Alt1 Level	Alt2 Level	% Contribution to Difference	Total Contribution
Regulatory Req's	3	2	110.0	0.07434
Life cycle costs	4	2	70.9	0.04795
Technical maturity	3	3.5	-65.5	-0.04426
Inv. & Startup cost	3	3.5	-53.2	-0.03596
Time to Start Disp.	3.5	3	31.2	0.0211
Consensus	3	2	6.6	0.004442

Sensitivity analysis was performed to investigate the effect of variation in numbers on the ranking. Variations in single values for both the weights and the technical scores were examined. Sensitivity analysis and its implications are contained in Appendix B.

6. Immobilization Forms Selected for Development

The following forms were selected to be developed further: borosilicate glass, titanate-based ceramic (Synroc), and metallic alloys.

Borosilicate glass was chosen because it is consistently the highest performing form and because it dominates all glasses. Synroc-like ceramics were selected because they dominate all the other glasses with the exception of borosilicate glass. This ceramic was selected over the other glasses to provide a well-balanced portfolio of forms being studied. In other words, since borosilicate glass out performs all other glasses on all attributes, developing a crystalline ceramic is expected to yield a larger benefit than scoring another, poorer performing glass.

For the same reason, a nonglass, nonceramic form was chosen as the third form to develop. Metallic alloy was chosen over FUETAP concrete, and metallic alloy ranked higher than FUETAP. The team felt this ranking was rather insensitive to the attribute weighting and that the changes in weights needed for FUETAP to rank higher were incredible. The ranking of these two forms was relatively sensitive to TA scores: some metallic scores do not have to decrease by much, and some FUETAP scores do not have to increase substantially to result in FUETAP's higher ranking. After reviewing the scores, however, the team felt that the relative scoring of metallic alloy and FUETAP was correct. In other words, the team did not expect metallic alloy's scores to decrease without FUETAP's scores also decreasing. Similarly, on those sensitive attributes, they did not expect FUETAP's scores to increase without metallic alloy's scores increasing. Therefore, the team felt confident that metallic alloys would rank higher than FUETAP.

Since the initial preparation of this screening document, glass-bonded zeolite has become the preferred electrometallurgical form and is retained as a reasonable alternative.

In addition, upon reviewing the TA scores, immobilization team members felt that, if anything, these scores overstated FUETAP's performance. FUETAP can be associated with past histories of cement failures and has made no regulatory progress for immobilizing Pu. The fact that there are no ongoing efforts here in the United States to develop FUETAP's use as a Pu immobilization form gave the team additional incentive to select metallic alloys over the FUETAP form.

7. Acronyms

;	borosilicate glass
;R	Code of Federal Regulations
/D	chemical-vapor deposited
)E	Department of Energy
/PF	Defense Waste Processing Facility
;&H	Environmental, Safety & Health
JETAP	Formed Under Elevated Temperature and Pressure
EU	highly enriched uranium
LW	high-level wastes
:PP	Idaho Chemical Processing Plant
B	iron-enriched basalt
P	lead-iron phosphate
;W	Low-level waste
A	metallic alloy
AS	National Academy of Sciences
EPA	National Environmental Protection Act
RNL	Oak Ridge National Laboratory
EIS	Programmatic Environmental Impact Statement
G	phosphate glass
CRA	Resource Conservation and Recovery Act
OD	record of decision
?C	sulfur polymer cement
A	technical assessments
SGC	talc-silicon glass-ceramic
F	urea formaldehyde
A	value trade off assessments

Appendix A. Technical Assessment Notes

Form	Score	Section/Notes
		1.a Attractiveness & difficulty of retrieval
39	3	Per the scale's definition.
40	3	Requires a similar type of operation as BG. The effort requires breaking down the silica structure. Overall, not much more difficult than BG.
42	3	Does not require a significantly different effort than BG. Devitrification potential was noted.
6, 7, 27, 23, 24, 26	3	Some felt ceramic reprocessing is more difficult than glass. It cannot be done on a bench scale with a beaker. For all the ceramics (except supercalcine), the extractability of Pu was argued as more difficult, costly, and or time consuming than from glass. Synroc and Monazite were viewed as better yet. The need to use capital intensive chloride volatility, carbochlorination and metal reduction processes, or long term nitric and hydrofluoric acid dissolution at high temperature and pressure, was discussed. It would be more difficult for a terrorist to come up with the resources to process Pu out of ceramics. It requires a more sophisticated process that would probably take 10 times as much time. Synroc and Monazite may be harder to grind up than the other 3 ceramics. Monazite has a difficult commercial process for extraction. Synroc has no commercial process to date. Rich Van Konynenburg thinks it would be greater than 50% more difficult (but numbers assigned do not reflect his judgment). Wicks thinks given the big picture it's not 50% more difficult. Group agrees that Synroc and Monazite are more difficult than other. Supercalcine a 3, approximately equal to glass.
31	3.5	See note above.
39, 40, 42	3	All can contain HLW, therefore each is equally detectable. Other differences in forms are not distinguishers for detection.
6, 7,	3	Similar to supercalcine because they have different materials in them. For lower loading they play a big role.
48, 50	3	Similar to glasses, for 1.a. and 1.b. No distinguishing factors for 1.a. and 1.b.
56	3	Radiation barrier is expected to be achieved with fission products in metallic alloy. No known easy defeat system exists.
58, 59	4	Same proliferation resistance as the inherent ceramic you made it in. (Group assumed Synroc would be used.) Ceramic may add additional step to processing Pu out. The fact that the ceramic is in little particles it may be faster to leach out. Rich Van Konynenburg says it could be harder to get out due to the cement. Matrix materials allow for intermediate QA with particles. No worse than 3 (the worst glass). Not necessarily worse than Synroc. Could be higher than a 4 if one could show that the concrete would provide an additional deterrent.

Appendix A. (Cont'd)

Form	Score	Section/Notes
40	3	Similar type of operation to BG. Big effort is knocking down silica structure.
60	3	Cermet: same as supercalcine.
		1.b Assurance of detection
		A form using HLW as a radiation barrier will be easier to detect than a pure cesium glass because there will be more elements in the waste streams. It is difficult to protect against environmental releases of all the radionuclides in HLW. SRL says reference form (BG) would use HLW, as would as all other glasses.
6, 7, 27, 23, 24, 26		Higher pressure processes means more volatility which means more radionuclides may be released. Cesium would be less likely to be released but it is much more volatile. Higher vapor pressure means higher releases. Thus, Cs would give higher potential of detection. This argument implies slightly higher (3.5) score for Synroc because of the higher temperatures required by Synroc.
39,40, 42	3	All can contain HLW, therefore each is equally detectable. Other differences in forms are not distinguishers for detection. Forms could be likely detected by remote sensing.
48, 50	3	Similar to glasses, for 1.a. and 1.b. No distinguishing factors for 1.a. and 1.b.
58, 59	3.5	1.b if the ceramic is Synroc detection should be 3.5. If another ceramic is used it would be 3.
60	3	Cermet: Same as Supercalcine.
		2.a Technical maturity
39	5	Five by definition
40	2	Phase separated glass, different operation, very large process to demonstrate.
42	4	Demonstrated process in plant in Russia, with tiny amounts of Pu. No QA, no sampling in Russian process. Glass form has been assessed. Give it a 4, suggesting 5 years out.
31	3.5	Synroc has better attributes. Australians have built pilot plant and have designed a process plant. Doped to 5% Pu both at LLNL and Australia. Synroc seems to be between 5 and 10 years.
27	2	Author doesn't believe in it anymore. No one is pursuing.
23	2.5	For Pu, Monazite is a first choice (good form) because you can dissolve a lot in it, occurs in nature, can handle radiation damage. Pu would go in easily. Easy to hold Pu, but not any easier to make. Ammonia and water vapor to be handled. A sintering process must be developed. Score 2.5 for 10-15 years out.
24	1.5	Nobody has put Pu in. It's in the bench scale at Argonne. 1.5 since it is less than #40 and #27.

Appendix A. (Cont'd)

Form	Score	Section/Notes
26	1	Not much work been done. No current research or demonstration scale facility.
48	1	Tricky process and not much work has been done recently or for Pu.
50	2	Have worked on it. Have made batches. Have recently incorporated titanium. Is being pursued. Don't know if Pu has been put into it. More specific to cleaning up contaminated soil with low Pu.
6	3.5	Some quantities made with Pu. While low Pu loading anticipated, 1% viewed as OK. Further along in development because it's simple process. Process is more advanced but waste form is less well known.
7	2.5	Similar product to FUETAP but a more difficult process. Not much waste has been incorporated into it. Higher pressure range used to reduce porosity. A lot more development work to do. More is known about it than monazite. See papers by Roy, Gouda, et. al.
56	3	Current research (funding) under way. Facility exists with equipment at ANL-W. Score as 3.5 (between 5 and 10 years). Synroc has gone through peer review, where this form has not. Having facility puts metal ahead, but hasn't had the same national backing. Further ahead in process development but behind in backing. Development of performance data has progressed in 1995, and they have extensive experience with radioactive materials. Some leaching tests have been done.
58	2.5	Less than ceramics and less than concrete.
59	2	Composites should be lower than constituents.
60	1	Worse in terms of development. Tough experience at Savannah River. SRS unable to replicate Irwin, TN process for Naval fuel. Making good ones is very difficult. Has never been turned from artistic procedure to process. High rejection rates, high reprocess rates.
		2b. Regulatory/Licensing Requirements
		The sense was that this should include waste form as well as processing facility. Some believe that natural analog benefits exist, because 10 CFR 60 specifically cites natural analogs. Others do not believe natural analogs will help that much.
		Almost directly related to technical maturity. Regulations were written for glass. Other forms will have more difficulty. Incremental changes to get Pu in glass are a lot smaller than to get Pu in a form that has not already been approved for HLW. What about criticality in the waste form? A mechanism is needed to account for quality control.
39	5	Significant basis exists for BG. Consensus that it could be satisfied.
40	3	Basis exists. Not proven. Not sure current regulations will work for glass.
42	3	Regulations exist.

Appendix A. (Cont'd)

Form	Score	Section/Notes
31	3.5	Natural analogs should enhance the probability of licensing, but no regulations exist to date. Regulatory requirement for 10,000 years can be satisfied by ceramic. Majority felt Synroc score should be 3.5, but there was one holdout for 3.
27	1	Predictability of phase distribution. Highly variable. Can't predict with confidence.
23	3	Natural analog and good one (better than Synroc). Amount of development on process is lower than Synroc.
24, 26, 48, 50	1	No analogs. No basis.
6, 7	2	Complex, gas generation. WIPP-type acceptance criteria exists. Large database exists.
56	3	Spent fuels in repository could serve as an analog. Suggests one can create basis and satisfy it with a metal form.
58	2.5	Harder to qualify than ceramics or cements as far as developing basis.
59	2.5	A little more complex than metals alone.
60	1	No natural analogs, no data. Difficult process.
		3c. Waste Minimization
All		If form handles HLW, you can put more of your waste streams back into the product than for forms that use cesium alone. Cermet is so tough to make it would likely generate more wastes. Ceramics and matrix forms may generate more waste because they are more difficult to process. Composites are generally difficult. Liquid feed streams usually generate more waste streams. What processes are remotable. Last processes are less remotable. The more steps in the process the worse. Liquid vs. powder feed will also be important. Cements benefit over glass and ceramic because of lower processing temperatures. Forms that use cesium capsules may generate more waste byproducts. Given current status, we can generalize to say there is no distinction. All we can do now is spot the outliers. We have no reason to believe that others are significantly better or significantly less. We also assume that the volume of waste form (due to loading) does not vary among the forms to the extent of requiring an additional repository. Therefore, the volume of primary waste will be entirely accounted for by cost.
60, 48, 58, 59	1	Difficult processes at end of chain. Difficulty in recovery.
31	3	Touchy (complex) process and no recycle processes.
23	3	However, more equipment with hydraulic and other hazardous chemicals.
		This process may generate a lot of ammonia, but ammonia is not a big problem. Also sold to incorporate HLW.

Appendix A. (Cont'd)

Form	Score	Section/Notes
56	3	Recycle process meant to minimize waste. Pyroprocess are thought to minimize waste streams over aqueous process. Generates fission gasses.
		3d. Leach rate
		Issue was of consequences and uncertainty originally. Three waste forms are wild cards because there are no data to show performance. Most forms have 10 times lower leaching rate than spent fuel. Pu criticality is a big factor and the potential show stopper. If boron is criticality control, water intrusion in the repository means potential leaching of neutron poisons. At low loading (around a few percent), criticality control has been shown to be maintained even if boron leaches out. Otherwise, group felt unable to provide any quantitative scores. They may be able to tell you which forms "win" but would be unable to describe what "win" means. Criticality control can be adapted to any of the forms. If considered in isolation, Synroc and Monazite followed by silicates followed by everything else, as estimated by natural analogs. This would describe which you would be least concerned about and which ones most, given no repository environment. Change it to release from waste form. Regs mean short lived radionuclides will decay. We ended up assessing leach rates, though group felt that glasses and ceramics would both meet acceptable levels of risk. Leachability of titanate is three orders of magnitude better than silicate. Leach rate not critical in Pigford and LLNL models. Need to verify 1×10^{-5} /yr for 10,000 years with substantially complete containment with reasonable assurance. Pu comes out orders of magnitude more slowly than already acceptable HLW materials.
39	3	By definition.
40	3	Similar to BG
31, 23	3.5	Approximately an order of magnitude better than BG.
All others	2.5	Approximately an order of magnitude worse than BG.
		4a. Life-cycle costs

Appendix A. (Cont'd)

Form	Score	Section/Notes
39	5	One major factor not considered in the rest of these suggests you're not going to make any new canisters. Wild card is repository cost. Will there be additional repository costs if new containers introduced? Cost sharing exists with other programs in that they are going to use the HLW that was going to be processed anyway. Worth up to a half a billion $. This savings only applies to use in DWPF site. New sites would probably not be timely enough to recognize the cost savings from using the DWPF HLW because of timing and transportation costs. Assumes that program can move fast enough to use the opportunity window of using the HLW, relative to programmatic timing. This tends to skew cost very low for the base case BG, whereas all others fall within a few categories, with much higher costs than BG.
7, 58, 59, 27	1	Higher life cycle costs due to substantially increased volumes as a result of low ability to load.
60	1	Cermet is the very worst. Low loading, difficult process.
40	3	Some extra steps required. Slightly more costly.
42	3	
6	2	Low loading, but easier to run than some of the other cementitious plants.
31	3	Similar cost to Synroc and glass plants without the costs benefit which DWPF has. Similar to what greenfield site for a vitrification plant, though some of an infrastructure exists.
56	4	Metallic alloy: 4. Better than other group because it consumes spent fuel in the process, thereby saving other processing and storage costs.
23, 24, 26	3	Similar costs to 31 over the described range and given the current level of data.
48, 50	2	More costly than 31.
		4b. Investment costs
6	3.5	FUETAP is lowest cost, that's why it was selected. But it still requires development
39	3	By definition. However, there was discussion about whether the modifications to DWPF for BG are going to be cheaper than a greenfield site. SRS personnel felt the estimates clearly indicated this was the case. It was noted that the infrastructure for a greenfield site is extensive, e. g., front end, feed handling, spent fuel handling, storage, back end, analytical support, etc. P. Rhoads noted in the past DOE experience was that was not necessarily the case. He also noted the screening committee baseline for BG was a greenfield case.
6	4	Process is simple and form is easy to make.

Appendix A. (Cont'd)

Form	Score	Section/Notes
7	3	Requires much higher pressure facilities than FUETAP.
31	3	Existing facility has to be cheaper than Synroc, as far as investment costs. Report quoted that up-front costs would be less than a factor of 2.
60	1	Experience shows that Cermet is very expensive to make work.
56	3	Plant already exists. Already has added fission products. Will process with present facilities. Need larger front end operation to handle the quantities of spent fuel. Clean facility, but needs for front-end additions imply approximately the same investment as BG. Large off-gas system. Need storage facility for interim. Same ballpark felt by some. Scored a 3. by consensus. Fred Nichols felt score should be 3.5.
40	2	Phase-separated glass suggests extra steps.
42	2.5	
23, 27	1.5	More development work for other forms. Might require lower loading.
24, 25	1.5	
48	1	New facility new development.
50	1.5	Higher temperature than other glasses. Requires more development and special components than glasses or Synroc.
58, 59	1.8	If the ceramic is Synroc, then cost of composite facility would be greater than Synroc, but not on the order of magnitude of $1 billion.
		5a. Time to start disposition
		Note: If the importance is on an accelerated schedule. The ability to create an intermediate product will allow starting in a much shorter time frame. That form will also allow other forms to use the glass-immobilized form to shorten their costs and time frames. The intermediate process would be a highly immobilized source. It appears that constraints are on regulatory processes, rather than technical merits alone. For immature processes you tack on time prior to that before regulations can be begun. Obtaining up-front product laboratory and experimental data on the waste form to support the regulatory process is a key step. For some forms the sense was that the difficulty of making "good" product will make it difficult for them to meet the schedule. For other waste forms it's likely you could make the time frame.
39	5	By definition. They're expecting 8-10 years, including permitting, building etc.
27, 24, 26, 48, 50, 60	1	These forms that are not qualified such that the paperwork can be accomplished in time. Supercalcine has more hazardous inputs.
6	3	Easier to build, but no regulatory basis.
58, 59	2	Not yet finalized

Appendix A. (Cont'd)

Form	Score	Section/Notes
7	2	A little worse than FUETAP since higher pressure processes would take longer to develop.
31	4	Synroc has some sort of regulatory basis. It's been looked at, studied, reviewed. Natural analog. Wicks suggested a 3 for Synroc. But consensus was that a lot of steps can be done in parallel.
23	3	Difficult to make, but better process.
56	3.5	Experience with Pu helps, but not in same category with Synroc.
40	3	
42	4	Phosphate glass plant running. Practical experience.
		7a. Ability to create consensus
39	5	Glass forms have been considered the only acceptable waste. All anti-nuclear groups are now going for the glass waste options. All other countries have based their waste forms on glass. Public probably doesn't care much between other options.
6, 7, 58	2	May be interveners for putting Pu in cements. Previous histories of cement failures could invite objections.
42	3	It's being done but by the Russians, which hurts the reputation because of secrecy surrounding the operation.
31	4	Can be presented such that it's more well accepted. Rich Van Konynenburg. thinks it would be easy to sell.
23	3.5	Development hasn't been demonstrated on the scale as Synroc.
27	2	Sponsor has even backed away from this form. It has no advocate.
24, 26	2.5	
48	3	Similar to Corningware® glass. Easy to promote.
50	2	
56	3	
59	3	Assumes that Synroc is the ceramic.
60	2	
40	3	Similar to Pyrex.

Appendix B. Sensitivity Analysis

Sensitivity analysis gives insight into how the outcome of the analysis would be affected if key variables were changed. It is especially valuable when assessments—such as the ones performed here—provide the basis for a decision, as differences of opinion always exist. The objective of this sensitivity analysis is to identify the factors to which the outcome is sensitive. In doing so, those relevant factors can be identified and re-examined if necessary, further validating the outcome of this analysis.

Table B-1. Sensitivity analysis summary.

Attribute weight sensitivity summary:
• BG ranking over other forms is insensitive to changes in individual weights.
• BG is *always* preferred to PG, and HSG, regardless of attribute weighting.
• Synroc is *always* preferred to Monazite and other ceramics, regardless of attribute weighting.
• If the Investment and Startup Costs' weight increased from 18% to approximately 50%, F would rank higher than MA.
• If the Technical Maturity's weight increased from its assessed value of about 20% to about 40%, F would rank higher than MA.
• If the weight of life-cycle costs increased from 12% to 60%, MA—an inexpensive form—ranks higher than Synroc.
Technical sensitivity summary:
• BG ranking over other forms is insensitive to changes in individual technical scores.
• BG is *always* preferred to PG, HSG, and other glasses, regardless of changes in the individual technical scores of BG or PG.
• Synroc is *always* preferred to Monazite and other ceramics, regardless of changes in Synroc's individual technical scores.
• Technical maturity has to be scored higher for Monazite than for Synroc for Monazite to rank higher.
• Metallic alloy and FUETAP ranking is the pair most sensitive to technical scoring. This ranking is especially sensitive to changes in MA's regulatory requirements score and FUETAP's investment and startup and leach rate scores. Other attribute's scores also result in a ranking change, but require a substantial change in scores before ranking is affected.

Details of the sensitivity analysis over the attribute weights and the technical scores are presented below.

Sensitivity to Changes in Attribute Weights

The following section discusses the effect changes in weighting, due to small differences in value judgments, for example, would have on the ranking of the immobilization waste forms. In general, the top ranking set of forms (BG through Monazite) remain the top ranking forms relative to the lower ranking forms (hot-pressed concrete through Cermet) over all possible variations in attribute weighting. Exceptions to this are limited to setting attributes assessed to have very low weights to very high weights. (For example, assurance of detection of reuse was assessed to have a weight of 0.17% given the range of performance of the various forms. If that weight was judged to be 90% instead, the outcome of the analysis changes dramatically.) Since the likelihood that weights were misjudged by such large amounts is very unlikely, the low performance of the lower-ranked alternatives is viewed as being insensitive to changes in attribute weights.

Additionally, the fact that BG is a "good performer" over all other glasses is insensitive to attribute weighting. Synroc's higher ranking over other ceramics is also insensitive to the weighting. Similarly, ranking within form families is insensitive to the weightings; BG *always* ranks higher than phosphate glass (PG) and high-silica glass (HSG), and Synroc *always* ranks higher than Monazite. The analysis outcome most sensitive to attribute weighting is the ranking between metallic alloy (MA) and FUETAP (F). The effects of variations in attribute weighting on the ranking of these attributes, as well as any other significant sensitivities are detailed below.

Attribute weighting sensitivity plots are shown for those attributes with relative high importance. The charts show the utility of the top options and how those utilities would change as the attribute's weight is changed. The vertical line shows the weight as it was assessed.

Sensitivity to Investment and Startup Costs Weighting

As described above, the top ranking forms are insensitive to small changes in investment and startup costs. Over the entire range of possible weights (0–100%), BG is always preferred over all other glasses, including PG, and Synroc is always preferred over all other ceramics. A reassessment of the tradeoffs would have to result in investment and startup costs carrying approximately 50% of the weight before F would rank higher than MA.

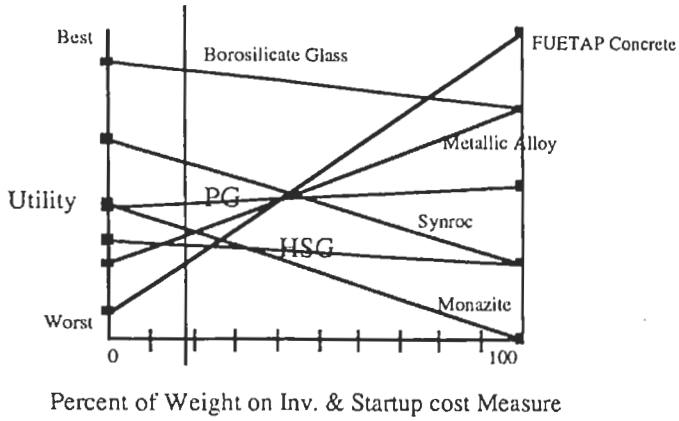


Figure B-1. Sensitivity to investment and startup costs weighting.

Sensitivity to Technical Maturity Weighting

Ranking within form families is insensitive to changes in technical maturity weighting. At very low weights, the figure of merit for MA and F would approach that of Synroc (S). A reassessment of the trade-offs would have to result in technical maturity carrying approximately 40% of the weight before F would rank higher than MA.

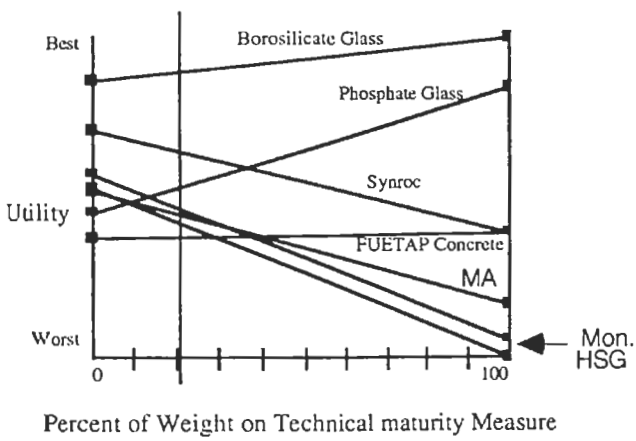


Figure B-2. Sensitivity to technical maturity weighting.

Sensitivity to Leaching Weighting

Ranking within form families and between MA and F is insensitive to changes in leaching weighting. At very low weights the figure of merit for MA and F would approach that of Synroc (S).

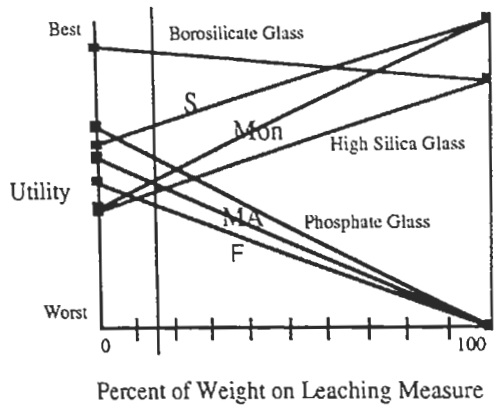


Figure B-3. Sensitivity to leaching weighting.

Sensitivity to Regulatory Requirements Weighting

If regulatory requirements weight were to go to zero, F ranking would approach MA ranking. All other ranking is insensitive to changes in regulatory requirements weighting.

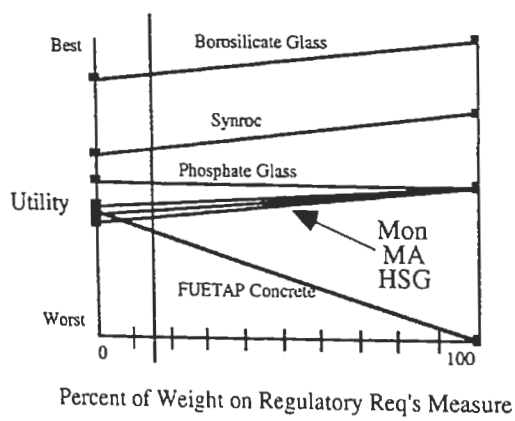


Figure B-4. Sensitivity to regulatory requirements weighting.

Sensitivity to Life-Cycle Cost Weighting

If life-cycle cost weight were to go to zero, F ranking would approach MA ranking. At very high weights (60% of total) MA, an inexpensive form, ranks higher than Synroc.

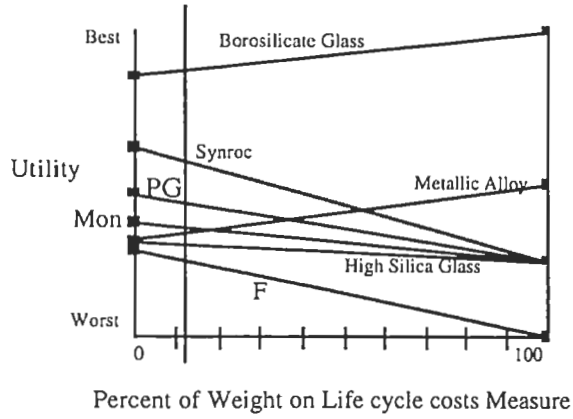


Figure B-5. Sensitivity to life cycle cost weighting.

Sensitivity to Time to Start Disposition Weighting

Ranking within forms and between MA and F are insensitive to changes in time to start disposition weighting.

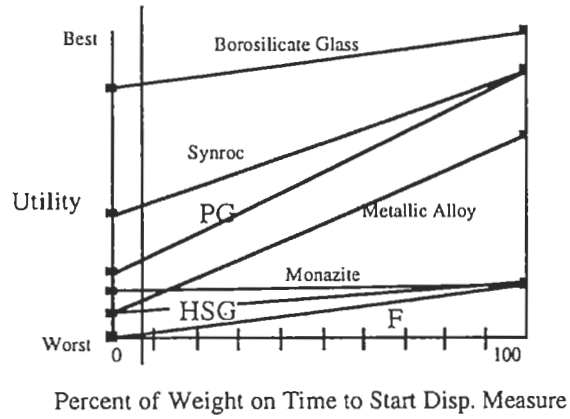


Figure B-6. Sensitivity to time to start disposition weighting.

Sensitivity to Waste Minimization Weighting

Ranking is insensitive to changes in waste minimization weighting.

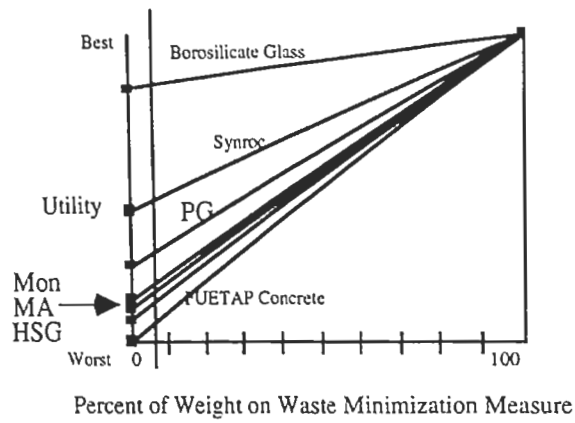


Figure B-7. Sensitivity to waste minimization weighting.

Sensitivity to Attractiveness and Difficulty of Retrieval Weighting

The ceramics (Synroc and Monazite) scored (technically) slightly higher on this attribute than did other forms; as the weighting goes up (would have to increase from about 4% to ≥20%) Synroc and Monazite rank higher than the glasses. Ranking within forms and between MA and F are insensitive to changes in attractiveness and difficulty of retrieval weighting.

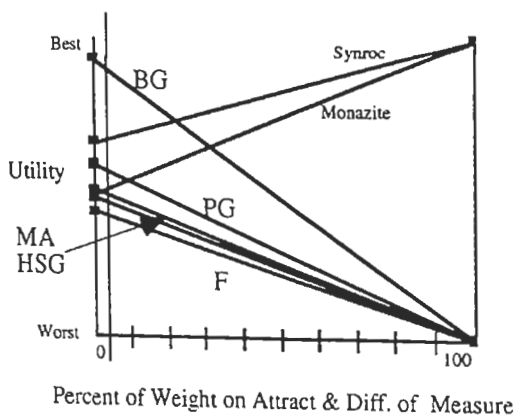


Figure B-8. Sensitivity to attractiveness and difficulty of retrieval weighting.

Sensitivity to Consensus Weighting

The weight was assessed at less than 1% for this measure. Ranking within forms and between MA and F are insensitive to changes in consensus weighting.

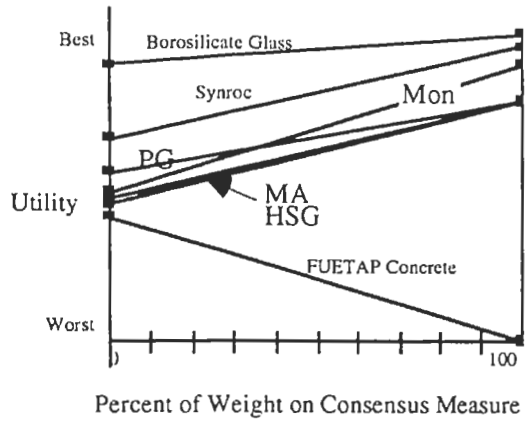


Figure B-9. **Sensitivity to consensus weighting.**

Sensitivity to Assurance of Detection During Reuse Weighting

The weight was assessed at less than half a percent for this meas insensitive to changes in this weighting other than Synroc exceedin increases by more than 100 × its assessed value.

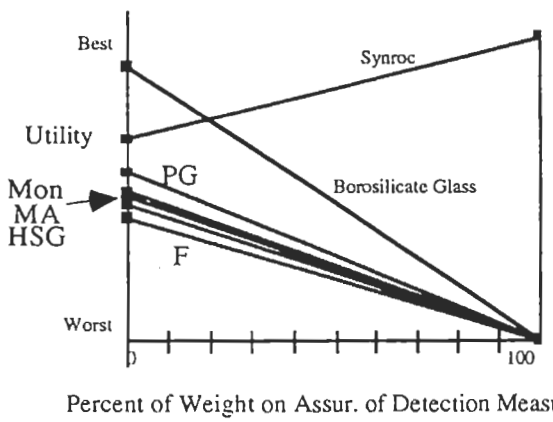


Figure B-10. **Sensitivity to assurance of detection weighting.**

Sensitivity to Changes in Technical Scores

Individual technical scores were varied over their assessed rang degree to which ranking outcomes are dependent upon specific sco are discussed, by form type, below.

Borosilicate Glass Technical Sensitivity. Borosilicate glass is a performer over all the important attributes. When technical perforn varied from that assessed to the worst case for each attribute weigh 7%, the ranking of the top five forms remained unchanged. Althou utility for BG decreased, it still remained higher than all other form

Tables B-2 through B-7 show the ranking results when BG technical scores are varied.

Table B-2. BG technical maturity from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.6897
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-3. BG investment costs from best (3) to worst (1).

Form	Utility
Borosilicate Glass	0.7511
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-4. BG leaching from best (3)to worst (2.5).

Form	Utility
Borosilicate Glass	0.7692
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-5. BG regulatory requirements from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.7377
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Tables B-2 through B-7 show the ranking results when BG technical scores are varied.

Table B-2. BG technical maturity from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.6897
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-3. BG investment costs from best (3) to worst (1).

Form	Utility
Borosilicate Glass	0.7511
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-4. BG leaching from best (3)to worst (2.5).

Form	Utility
Borosilicate Glass	0.7692
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Mc	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-5. BG regulatory requirements from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.7377
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Mc	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-6. BG Life-cycle costs from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.775
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

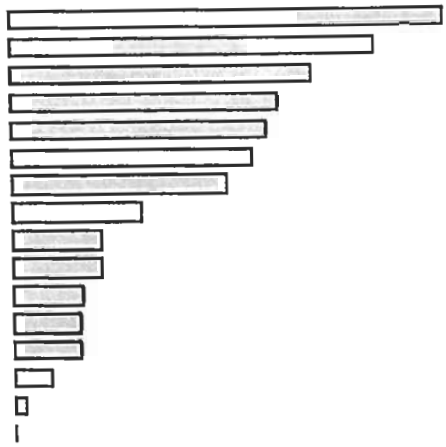
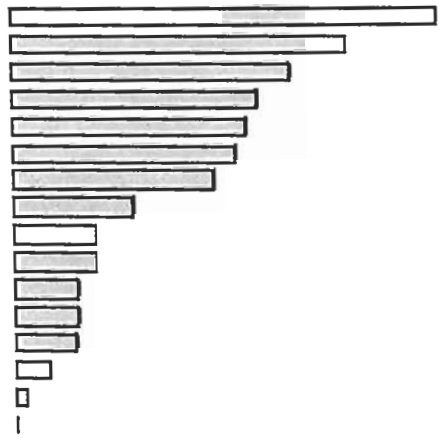


Table B-7. BG time to start from best (5) to worst (1).

Form	Utility
Borosilicate Glass	0.823
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0



Synroc Technical Sensitivity. Technical sensitivity analysis also was performed for Synroc, varying scores from assessed values to lower values to see if the ranking of Synroc would rank lower among the forms due to changes in ranking.

Synroc also is a robust performer over all important (>7% weight) attributes. Synroc ranks higher than all other ceramics even if scores are varied to their worst case. When leaching was varied from its assessed score of 3.5 to the worst case of 2.5, and when the regulatory requirements score was individually varied from its assessed score of 3.5 to the worst case of 1, PG ranked slightly higher than Synroc. Otherwise, Synroc remained ranked second to all other forms as its scores were varied from assessed values to worst-case values, as shown in Tables B-8 through B-13.

Table B-8. Synroc technical maturity from best (3.5) to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.5739
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-9. Synroc investment and startup costs from best (2) to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.5873
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-10. Synroc leach rate from best (3.5) to worst (2.5).

Form	Utility
Borosilicate Glass	0.8949
Phosphate Glass	0.5516
Synroc	0.502
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-11. Synroc regulatory requirements from best (3.5) to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Phosphate Glass	0.5516
Synroc	0.5372
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-12. Synroc life-cycle cost from best (3) to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6113
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-13. Synroc time to start from best (4) to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.593
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Phosphate Glass Technical Sensitivity. Sensitivity analysis was performed on phosphate glass, varying its scores upward to see the effect changes in the scores would have on the relative ranking of Phosphate Glass and BG.

PG exceeded Synroc ranking when its leach rate was improved to the level of Synroc's. At this level, however, PG still ranked lower than BG. PG's ranking below BG is insensitive to changes in individual performance scores (see Tables B-14 through B-19).

Table B-14. PG technical maturity from 4 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5824
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

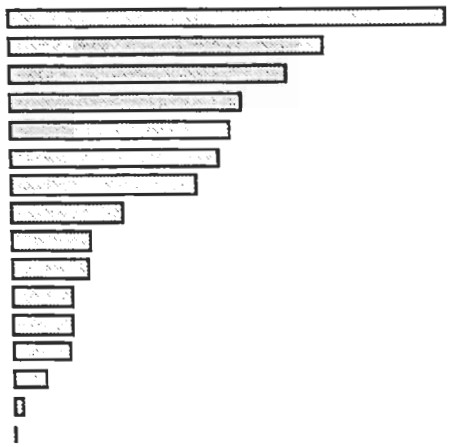


Table B-15. PG investment and startup costs from 2.5 to best (3.5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.6235
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

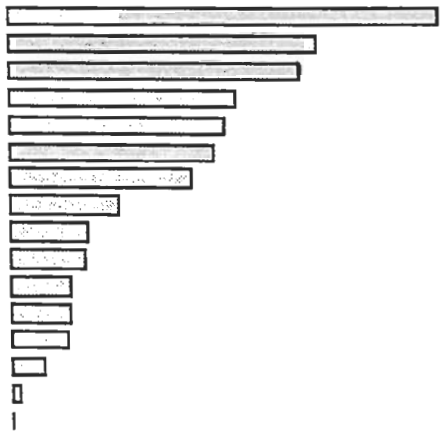


Table B-16. PG leach rate from 2.5 to best 3.5.

Form	Utility
Borosilicate Glass	0.8949
Phosphate Glass	0.7088
Synroc	0.6592
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-17. PG regulatory requirements from 3 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.6235
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-18. PG life-cycle cost from 3 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.6235
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-19. PG time to start disposition from 4 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5573
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Monazite Technical Sensitivity. Monazite ranks over Synroc only when its Technical Maturity score is raised above 4. However, in this case the maturity of Monazite is considered to be higher than that of Synroc, which is unlikely. Since it is likely that the technical maturity of both Monazite and Synroc would be correlated, variations in technical maturity would not result in Monazite's ranking higher than Synroc.

The ranking from this analysis and others performed for Monazite are shown in Tables B-20 through B-24.

Table B-20. Monazite technical maturity from 2.5 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Monazite	0.674
Synroc	0.6592
Phosphate Glass	0.5516
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

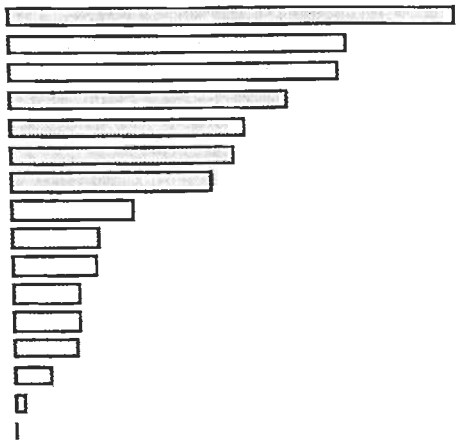
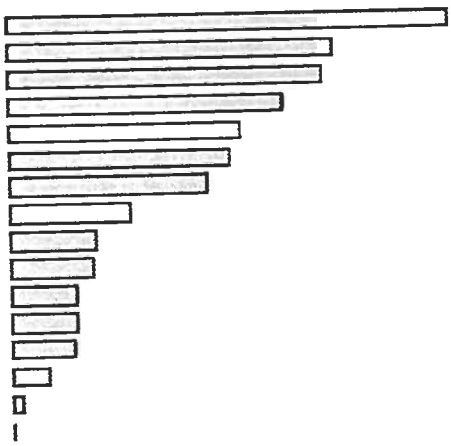


Table B-21. Monazite's investment and startup costs from 1.5 to best (3.5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Monazite	0.6318
Phosphate Glass	0.5516
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0



Monazite leaching scored the highest originally.

Table B-22. Monazite regulatory requirements.

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Monazite	0.5598
Phosphate Glass	0.5516
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-23. Monazite life-cycle costs from 3 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Monazite	0.5598
Phosphate Glass	0.5516
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-24. Monazite time to start from 3 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.5239
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Metallic Alloy Technical Sensitivity. Sensitivity analysis was performed on MA, varying its scores downward to see the effect changes in the scores would have on the relative ranking of MA and forms other than BG and Synroc. Metallic alloy ranks below FUETAP when MA's scores are lowered for the following attributes:

- MA investment and startup cost score is decreased from its assessed value of 3 to below 1,
- MA regulatory requirements score is decreased from 3 to 2.5, and
- MA life-cycle costs are decreased from 4 to below 1.5.

For other attributes, decreases in MA scores do not result in MA ranking lower than FUETAP. The outcomes of the analyses are shown in Tables B-25 through B-29.

Table B-25. MA technical maturity from 3 to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
High Silica Glass	0.4449
Metallic Alloy	0.428
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

Table B-26. MA investment and startup costs from 3 to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Metallic Alloy	0.3252
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

MA was scored at the lowest Leaching score.

Table B-27. MA regulatory requirements from 3 to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Metallic Alloy	0.3838
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

F ranks higher than MA when MA's Regulatory Requirements score drops to 2.5.

Table B-28. MA life-cycle costs from 4 to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
High Silica Glass	0.4449
FUETAP Concrete	0.4014
Metallic Alloy	0.3971
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

MA costs have to score below 1.5 before FUETAP ranks higher.

Table B-29. MA time to start disposition from 3.5 to worst (1).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
High Silica Glass	0.4449
Metallic Alloy	0.412
FUETAP Concrete	0.4014
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

FUETAP Technical Sensitivity. Sensitivity analysis was performed on FUETAP scores, improving its scores over the important (>7% weight) attributes to see to what extent changes in scores ranked F above MA.

FUETAP ranks above Metallic Alloy when F's scores are raised for the following attributes:

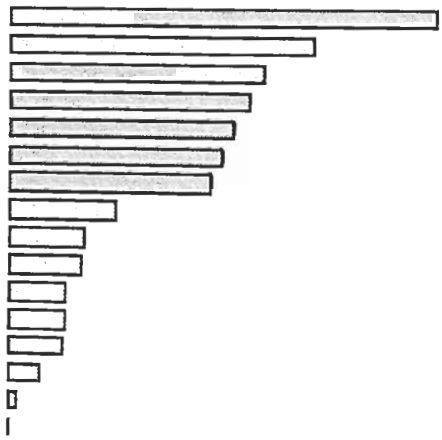
- Technical Maturity score greater than its assessed score of 3.5.
- Investment and Startup costs of 4 or greater (scored at 3.5).

- Leach rate of 3 or higher (scored at 2.5),
- Regulatory Requirements of 3 or higher (scored at 2), and
- Life-cycle cost of 4 or higher (scored at 2).

The outcomes of the analyses are shown in Tables B-30 through B-35.

Table B-30. F technical maturity from 3.5 to best (5).

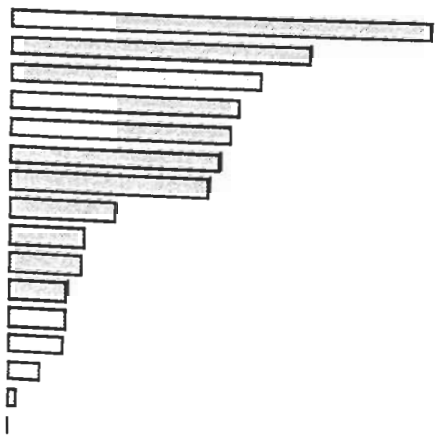
Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
FUETAP Concrete	0.5213
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0



F technical maturity scores greater than 3.5 result in a higher ranking for F tha

Table B-31. F investment and startup costs from 3.5 to best.

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
FUETAP Concrete	0.5093
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0



F Investment and Startup Costs score would have to be 4 or greater to be ranke better than MA.

Table B-32. F leaching from worst (2.5) to best (3.5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
FUETAP Concrete	0.5586
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

F would have to score approximately 3 or higher to be ranked above MA. This is unlikely because F has been known to have very high leach rates.

Table B-33. F regulatory requirements from 2 to best (5).

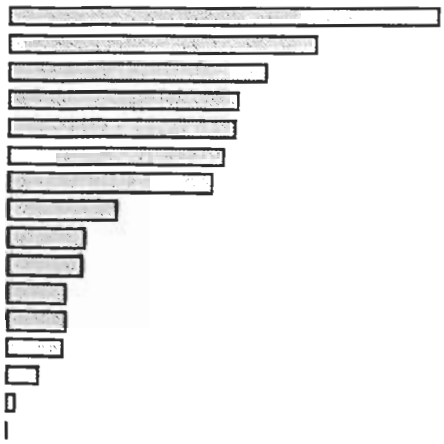
MA.

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
FUETAP Concrete	0.5477
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0

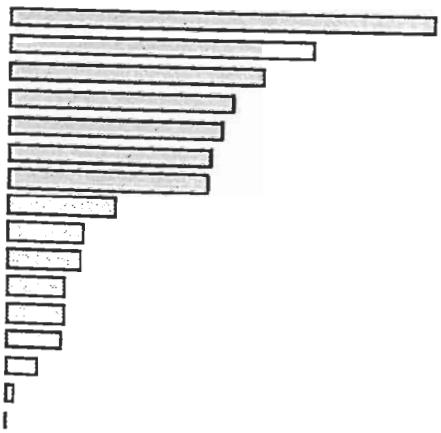
F would have to receive a regulatory requirements score of 3 or greater to rank higher than MA.

Table B-34. F life-cycle costs from 2 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
FUETAP Concrete	0.4973
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0



F would have to score higher than 4.5 on life-cycle costs to be ranked above M

Table B-35. F time to start from 3 to best (5).

Form	Utility
Borosilicate Glass	0.8949
Synroc	0.6592
Phosphate Glass	0.5516
Monazite	0.4879
Metallic Alloy	0.469
High Silica Glass	0.4449
FUETAP Concrete	0.4374
Hot-Pressed Concret	0.2457
phos.-bnded Ceramic	0.1731
Silicon-Zirc Phosph	0.1704
Ceramics in Concret	0.1365
Iron-Enriched Basal	0.1335
Ceramic Pell. in Me	0.13
Supercalcine	0.07682
Glass-Ceramic Monol	0.02842
Cermet	0