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4. Revision No.	5. Description of Revision
	This version contains extensive revision of Sections 7.2 and 7.3. Original Sections 7.4 and 7.5 were not used and Sections 7.8 and 7.9 were deleted and other sections renumbered. Revisions are indicated by left margin sidebars where appropriate and some of the sections numbers were changed in other parts of the text to reflect changes in the section numbers.
01	Issued approved.

Table of Contents

1. Purpose

This analysis is prepared by the Mined Geologic Disposal System (MGDS) Waste Package Development department to provide documented justification for the materials selections for preliminary design of the waste package.

The objective of this analysis is to recommend materials for use in preliminary design of the waste package. The purpose of this analysis is to provide documentation of the preliminary selection and associated justification for these selections.

2. Quality Assurance

The Quality Assurance program applies to this analysis. The work reported in this document is part of the preliminary design of the waste package. This activity can affect the proper functioning of the Mined Geologic Disposal System waste package. The *Classification of Permanent Items* QAP-2-3 evaluation entitled *Classification of the Preliminary MGDS Repository Design* (Ref. 5.1) has identified the waste package as an MGDS item important to safety, waste isolation, and physical protection of materials. The Waste Package Operations responsible manager has evaluated this activity in accordance with the QAP-2-0, *Conduct of Activities*. The work performed for this analysis is subject to *Quality Assurance Requirements and Description* (Ref. 5.3) requirements. As specified in NLP-3-18, *Documentation of QA Controls on Drawings, specifications, Design analyses, and Technical Documents*, this activity is subject to QA controls.

All design inputs which are identified in this document are for preliminary design and shall be treated as unqualified data; these design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. This document will not directly support any construction, fabrication or procurement activity and therefore does not require TBV (to be verified) tracking. However, use of any data from this analysis for input into documents supporting procurement, fabrication, or construction is required to be controlled as TBV in accordance with the appropriate procedures.

3. Method

The method used in this analysis is as follows. The waste package is divided into components, and the functions that each waste package component performs are identified. In light of the functions, materials characteristics are selected that will be helpful in performing those functions. The materials are rated against grading scales for these characteristics and suitable weighting factors are applied, according to the importance of the criteria in assuring that the component will perform its functions. By this process, a material is chosen that is believed to be the most conducive to successful design. The following paragraphs describe the process in more detail.

Four types of waste packages are considered. Additional types may be required if new waste streams are to be accommodated. Preliminary versions of disposal containers for Zircaloy-clad, uncanistered boiling water reactor (BWR) and pressurized water reactor (PWR) spent nuclear fuel (SNF) are considered (Ref. 5.4). Design work on disposal containers for canistered fuel has been suspended due to funding priorities. At the time this work was started, only SNF and HLW glass waste (including DOE SNF being codisposed with HLW) streams were being considered, and this materials selection analysis applies to both waste streams. Subsequent reference to HLW in this document will include codisposed DOE SNF unless otherwise specified.

The configuration item architecture for the Engineered Barrier System waste disposal containers for a variety of SNF and HLW (Ref. 5.6, p. A-6). Each of these will in turn be constructed of smaller components that have not yet been defined in the configuration item architecture. Many of these smaller components will have similar designs and similar functions even if the types of disposal container are different. Because of the similarities and the limited depth of the current configuration item architecture, the approach in this analysis is to lump similar components. The components considered are as follows:

- Waste package components
  - Corrosion allowance barrier
  - Corrosion resistant barrier
  - Waste container fill gas
  - Fuel basket plates
  - Fuel basket tubes
  - Basket guides (structural support)
  - Canister guide for HLW and DOE SNF codisposed canister

Waste package supports are addresses in a separate design analysis document (Ref. 5.93)

Fuel basket plates are those components depicted in Ref. 5.86 and Ref. 5.90. Basket guides are those components depicted in Ref. 5.87 and Ref. 5.88. These references are representative of selected component drawings. Complete lists of components for PWR and BWR waste packages are provided in Ref. 5.91 and 5.92.

Filler material has previously been considered as a criticality control material for canistered fuel, but design for canistered fuel has been suspended, so no discussion of filler material is included.

Because of the similarity between the PWR, BWR, and canistered fuel waste forms, corresponding components in the two designs have very similar functions, and a single analysis is used for corresponding components for these waste forms. In addition the containment barrier materials selection analysis for the HLW including DOE SNF is implicitly included in this document.

Requirements have been assigned specifically to the waste package (Ref. 5.25, Sec. 3.7.1) and its components. In this analysis, however, materials selection is not based directly on the requirements. Instead, selection criteria are chosen that are more closely related to materials properties. For example, controlled design assumption EBDRD 3.7.1.2.A (see Section 4.3 below and Ref. 5.26) requires that the waste package be able to withstand certain external loads, but performance of materials is measured against the criterion "mechanical performance," which includes strength and ductility.

For each component, candidate materials are chosen from the commonly available materials (or, in the case of fill gas, from common gases). Some of these materials may be eliminated because of constraints. Here "constraints" means reasons for rejection that are so strong that the materials may be rejected immediately. By analyzing requirements for the components, selection criteria and grading scales are established, and a weighting factor (level of importance) is assigned to each criterion. In choosing the weighting factors, qualitative arguments are used to justify estimates of the importance of the criteria in assuring that the component will perform its functions.

To determine the overall performance of the material, the expected performance of the material is determined for each criterion. For each criterion, a utility score is assigned to each material. The utility score can vary from zero (lowest performance) to the weighting factor (highest performance). The highest possible score is therefore equal to the sum of the weighting factors. Total utility scores for each material are calculated by adding the individual utility scores. Where it is appropriate, uncertainties in materials performance are included by explicit comparison with the criteria "predictability of performance" and "previous experience." Note that the mathematical procedure described above differs slightly from that used in Ref. 5.8; in that document each utility score was the product of a weighting factor and a rating that varied from 0 to 10. The two approaches are equivalent, but the current approach simplifies the mathematics.

In a previous report on materials selection (Ref. 5.9), seven selection criteria were identified as contributing to the performance of materials for containment barriers:

- Mechanical performance
- Chemical performance
- Predictability of performance
- Compatibility with other materials
- Fabricability
- Cost
- Previous experience

Since this analysis includes additional components, these criteria were supplemented by two others:

- Thermal performance
- Neutronic performance

Correspondence between the selection criteria and the functions, and descriptions of how the criteria are applied to each component, are discussed in Section 7.1. Weighting factors for components not discussed in Ref. 5.9, subdivisions of weighting factors within each selection criterion, details of the application of the selection criteria, and grading scales are developed within the analysis on the basis of the expert opinion of the author. Another author might use different grading scales and arrive at different ratings which may lead to different selections.

The analysis given here has distinct limitations. First, the designs of the Engineered Barrier Segment and underground facilities are subject to change and therefore uncertain. Thermal loads may change. Emplacement drift backfill may or may not be used. Second, even if the final design were known, the environment to which the materials would be exposed would be both variable and uncertain. Some waste packages will be hotter than others. Some may be exposed to dripping groundwater; others may not. Third, even if the environment were known, the materials performance would be uncertain. Any material tests will by necessity be of short duration in comparison to the expected life of a repository. However, these limitations do not provide a reason for dismissing the method; they apply to any method that involves prediction. The situation is well summarized by Title 10, U.S. Code of Federal Regulations, Part 60.101(a)(2) (Ref. 5.10): "Proof of the future performance of engineered barrier systems and the geologic setting over time periods of many hundreds or many thousands of years is not to be had in the ordinary sense of the word." In view of that, materials that provide acceptable performance under a variety of conditions have been sought, but no guarantee of performance can be provided. It is expected that future materials research, which should include long-term corrosion testing on various candidate materials as well as studies of natural and historical analogs, will help to reduce the uncertainty in predictions of materials performance. Finally, it is noted that the work presented here has not been subjected to peer review. During later stages of design, such a review may be helpful in developing consensus and showing reasonable assurance that the performance objectives will be met.

The International System of Units (SI) is used throughout this analysis, but materials specifications or other sources of information might be written in SI units, U.S. customary units, or both. For example, steel plate might be ordered to specifications of the American Society for Testing and Materials (ASTM) according to either the designation ASTM A 516 or the designation ASTM A 516M. In the latter designation, "M" denotes a metric (SI) standard. Section 1.4 of Ref. 5.14 describes the usage of units in that specification: "The values stated in either inch-pound [U.S. customary] or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other." For consistency, all the material specifications used herein are the versions written in U.S. customary units. For example, Ref. 5.14, Table 2 states that ASTM A 516 Grade 55 requires a minimum yield strength of 30 ksi [= 30,000 pounds per square inch] = 207 MPa, but the equivalent SI specification ASTM A 516M Grade 380 requires a minimum yield strength of only 205 MPa. Since the material under discussion here is ASTM A 516 Grade 55, the higher value of yield strength applies. Quantities taken from the specifications or other sources of information have been converted to SI without comment in the text. Conversion factors were taken from ASTM E 380 (Ref. 5.24).

Many different systems are used to designate materials. For the purposes of this analysis, ASTM specifications are used whenever possible to denote the candidate materials. However, the various sources of information use a variety of designations for their materials. For clarity of referencing, the designations used in the source of information are repeated in the text, and a note is made regarding the equivalent ASTM specification. A few materials are proprietary; for these the vendor's designation is used.

Selection of materials for long-term testing, modeling, and performance assessment is beyond the scope of the present analysis. The results of such testing, modeling, and performance assessment should provide the basis for future confirmation or revision of the recommendations in this analysis.

4. Design Inputs

All design inputs that are identified in this document are for preliminary stage design of the design process; all of these design inputs will require subsequent confirmation (or superseding inputs) as the waste package design proceeds. This document will not directly support any construction, fabrication, or procurement activity and therefore is not required to be procedurally controlled as TBV (to be verified), per NLP-3-15. In addition, the inputs associated with this analysis are not required to be procedurally controlled as TBV. However, the use of any data from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled as TBV in accordance with the appropriate procedures.

4.1 Design Parameters

Weighting factors for corrosion allowance barrier materials:
Mechanical performance: 10 (Ref. 5.9, p. 5, Table 2)
Chemical performance: 15 (Ref. 5.9, p. 5, Table 2)
Predictability of performance: 20 (Ref. 5.9, p. 5, Table 2)
Compatibility with other materials: 15 (Ref. 5.9, p. 5, Table 2)
Fabricability: 30 (Ref. 5.9, p. 5, Table 2)
Cost: 10 (Ref. 5.9, p. 5, Table 2)
Previous experience: 10 (Ref. 5.9, p. 5, Table 2)

(Weighting factors for other components including the corrosion resistant barrier are developed within this analysis and summarized in Table 7.1-1.)

Minimum strength for candidate materials:

Corrosion Allowance barrier materials

Material	Yield strength, MPa	Reference
ASTM A 387 Grade 22	207	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	207	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	262	Ref. 5.14, Table 2.
ASTM B 127	193	Ref. 5.16, Table 3, hot-rolled plate, annealed.
ASTM B 171 C71500	124	Ref. 5.17, Table 3.

Corrosion Resistant Barrier Materials

Material	Yield Strength, MPa	Reference
ASTM B 265 Grade 12	345	Ref. 5.18, Table 3.
ASTM B 265 Grade 16	276	Ref. 5.18, Table 3.
ASTM B 443	379	Ref. 5.20, Table 3, Grade 1, hot-rolled plate.
ASTM B 575 N06022	310	Ref. 5.22, Table 3..
ASTM B 575 N06455	276	Ref. 5.22, Table 3.

Internal Component materials:

Material	Yield Strength, MPa	Reference
ASTM A 887 Type 304B3 Grade A	207	Ref. 5.15, Table 2.
ASTM A 887 Type 304B4 Grade A	207	Ref. 5.15, Table 2.
ASTM A 887 Type 304B5 Grade A	207	Ref. 5.15, Table 2.
ASTM A 887 Type 304B6 Grade A	207	Ref. 5.15, Table 2.
Neutronit A976	300	Ref. 5.56, p. 16.
Neutronit A978	300	Ref. 5.56, p. 16.

Minimum elongation for candidate materials:

Material	Elongation, %	Reference
ASTM B 265 Grade 12	18	Ref. 5.18, Table 3.
ASTM B 265 Grade 16	20	Ref. 5.18, Table 3.
ASTM B 443	30	Ref. 5.20, Table 3, Grade 1 hot-rolled plate/
ASTM B 575 N06022	45	Ref. 5.22, Table 3.
ASTM B 575 N06455	40	Ref. 5.22, Table 3.

Material	Elongation, %	Reference
ASTM A 387 Grade 22	18	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	27	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	21	Ref. 5.14, Table 2.
ASTM B 127	35	Ref. 5.16, Table 3, hot-rolled plate, annealed.
ASTM B 171 C71500	30	Ref. 5.17, Table 3.

Material	Elongation, %	Reference
ASTM A 887 Type 304B3 Grade A	31	Ref. 5.15, Table 2.
ASTM A 887 Type 304B4 Grade A	27	Ref. 5.15, Table 2.
ASTM A 887 Type 304B5 Grade A	24	Ref. 5.15, Table 2.
ASTM A 887 Type 304B6 Grade A	20	Ref. 5.15, Table 2.
Neutronit A976	10	Ref. 5.56, p. 16.
Neutronit A978	10	Ref. 5.56, p. 16.

Characteristics of J-13 groundwater:

pH = 7.41, chloride (Cl^-) concentration = 7.14 mg/L (Ref. 5.29, vol. 2, p. 38, mean values)

Corrosion rate of carbon steel in lake water for 16-year exposure:

39.7 μm/yr to 44.5 μm/yr (Ref. 5.30, Table III-B (Key letters A, B, and C))

Short-term corrosion rate of 1020 carbon steel for high aeration:

434 μm/yr (Ref. 5.32, Table III; arithmetic mean)

Short-term corrosion rate of 2-1/4 Cr - 1 Mo alloy steel for high aeration:

362 μm/yr (Ref. 5.32, Table III; arithmetic mean)

Corrosion depth of Cu 70 - Ni 30 in lake water for 16-year exposure:

33 μm (Ref. 5.33, vol. 2, p. 44, Table 13)

Corrosion rate of Alloy 400 exposed to aerated 10% acetic acid at 30°C:

8 μm/yr (Ref. 5.31, p. 648, Table 9)

Chloride concentration of seawater:

18980 parts per million (Ref. 5.36, p. F-206)

Corrosion rate of Monel 400 in dilute sulfuric acid saturated with air:

30 mpy = 760 μm/yr (Ref. 5.34, p. 17, Fig. 14)

Corrosion rate of neutron-absorbing materials in short-term corrosion tests in aqueous solution containing 0.01 molar HCOOH, 0.01 molar NaCOOH, 0.02 molar $Na_2C_2O_4$, 0.01 molar HNO_3, 0.01 molar NaCl, and 0.01 molar H_2O_2:

Böhler A976 SD: 41 μm/yr (general corrosion) (Ref. 5.21, Table 3)
Neutrosorb Plus base metal: 60 μm/yr (general corrosion) (Ref. 5.21, Table 3)
Neutrosorb Plus welded metal: 880 μm/yr (pitting corrosion) (Ref. 5.21, Table 3)

Maximum galvanic potential in seawater versus a saturated calomel electrode (SCE):

Low-carbon steel and low-alloy steel: −570 mV SCE (Ref. 5.31, p. 235, Fig. 1)
70-30 copper nickel: −170 mV SCE (Ref. 5.31, p. 235, Fig. 1)
Nickel-copper alloy 400: −20 mV SCE (Ref. 5.31, p. 235, Fig. 1)
Nickel-iron-chromium alloy 825: +40 mV SCE (Ref. 5.31, p. 235, Fig. 1)
Stainless steel type 304 (passive): −30 mV SCE (Ref. 5.31, p. 235, Fig. 1)

Minimum galvanic potential in seawater versus a saturated calomel electrode (SCE):

Titanium: −50 mV SCE (Ref. 5.31, p. 235, Fig. 1)
Stainless steels types 304 and 316 (passive): −100 mV SCE (Ref. 5.31, p. 235, Fig. 1)

Cost of materials: Note: The cost figures have not been updated and do not include fabrication costs. The following values are being used only for comparing materials.

Material	Cost, $/kg	Reference
ASTM A 516 Grade 55	0.79	Ref. 5.63, p. 14, Table 1, Bethlehem Steel.
ASTM A 516 Grade 70	0.79	Ref. 5.63, p. 14, Table 1, Bethlehem Steel.
ASTM B 127	9.92	Ref. 5.39, vol. 1, p. 56, Monel 400.
ASTM B 171 C71500	7.17	Ref. 5.39, vol. 1, p. 56, C715 70/30 Cupronickel; arithmetic mean.

Material	Cost, $/kg	Reference
ASTM B 265 Grade 12	18.10	Ref. 5.39, vol. 1, p. 56, Titanium Grade 12.
ASTM B 265 Grade 16	22.13	Ref. 5.39, vol. 1, p. 56, Titanium Grade 16.
ASTM B 575 N06022	13.56	Ref. 5.39, vol. 1, p. 56, Inconel 622.
ASTM B 575 N06455	19.51	Ref. 5.39, vol. 1, p. 56, Hastelloy C-4.

Material	Cost, $/kg	Reference
ASTM A 887 Type 304B3 Grade A	22.05	Ref. 5.57, "balanced cost."
ASTM A 887 Type 304B4 Grade A	24.25	Ref. 5.57, "balanced cost."
ASTM A 887 Type 304B5 Grade A	26.46	Ref. 5.57, "balanced cost."
ASTM A 887 Type 304B6 Grade A	28.66	Ref. 5.57, "balanced cost."
Neutronit A976	24.00	Ref. 5.58.
Neutronit A978	27.00	Ref. 5.58.

Thickness of corrosion resistant barrier = 20 mm (Ref. 5.89)

Thickness of fuel basket plates:
21 PWR disposal container: 7 mm (Ref. 5.90)
44 BWR disposal container: 10 mm (Ref. 5.86)

Amount of Neutronit produced to date:
more than 2000 tons (Ref. 5.59, p. 14 of attachment)

Thermal conductivities of solids:

Material	Conductivity, W/m·K	Reference
ASTM A 387 Grade 22	36.1	Ref. 5.39, vol. 2, p. 40, Table 2-36, 2 1/4 Cr - 1 Mo steel, 70°F.
American Iron and Steel Institute 1020 carbon steel	51.9	Ref. 5.39, vol. 2, p. 37, Table 2-28, 0°C.
American Iron and Steel Institute 1020 carbon steel	51.0	Ref. 5.39, vol. 2, p. 37, Table 2-28, 100°C.
ASTM B 127	21.8	Ref. 5.39, vol. 2, p. 43, Table 2-44, alloy 400, 70°F.
ASTM B 171 C71500	29	Ref. 5.39, vol. 2, p. 43, Table 2-46, C71500, 68°F.
Neutronit A976 and A978	10.3	Ref. 5.56, p. 18, 20°C.
American Iron and Steel Institute Type 304	14.9	Ref. 5.60, p. 671, 300 °K.
American Iron and Steel Institute Type 316	13.4	Ref. 5.60, p. 671, 300 °K.

Arithmetic mean of minimum and maximum boron content:

Material	Boron, %	Reference
ASTM A 887 Type 304B3 Grade A	0.87	Ref. 5.15, Table 1.
ASTM A 887 Type 304B4 Grade A	1.12	Ref. 5.15, Table 1.
ASTM A 887 Type 304B5 Grade A	1.37	Ref. 5.15, Table 1.
ASTM A 887 Type 304B6 Grade A	1.62	Ref. 5.15, Table 1.

Thermal conductivity of gases at 600 K and 101 kPa:

Material	Thermal conductivity, W/m·K	Reference
Helium	0.2524	Ref. 5.61, p. 6-251.
Carbon dioxide	0.0416	Ref. 5.61, p. 6-251.
Nitrogen	0.0440	Ref. 5.61, p. 6-251.
Argon	0.0306	Ref. 5.61, p. 6-251.
Dry air	0.0457	Ref. 5.61, p. 6-251.

4.2 Criteria

The selection of waste package materials is an undertaking with far-reaching consequences. Compliance with many requirements, including those for containment, controlled release, criticality control, mechanical strength, and durable labeling, are affected by the materials selection. It is beyond the scope of this analysis to demonstrate compliance with all of these requirements as these are addressed in a number of other documents relating to waste package design and criticality analysis. As is discussed in Section 3 above, the approach taken here is to identify the materials that are believed to be the most conducive to successful design. Therefore, only those requirements that directly apply to materials selection are listed here. The requirements are taken from the *Engineered Barrier Design Requirements Document* (EB-DRD) (Ref. 5.25). Traceability to higher-level requirements is documented in the EB-DRD. In the quotations below, "TBD" denotes "to be determined". Based on the rationale that the conclusions derived by this analysis are for preliminary design that will not be used as input to documents supporting construction, fabrication, or procurement, the TBD and TBR designations in Ref. 5.25 will not be carried to the conclusions of this analysis.

> "Engineered Barrier Segment structures, systems, and components important to safety shall be designed so that the effects of anticipated natural phenomena and environmental conditions will not interfere with necessary safety functions."
>
> [EB-DRD 3.2.6.1.A]

The preceding requirement is considered to the extent that the selection criterion "mechanical performance" favors strong, ductile materials and that the selection criteria "chemical performance" and "predictability of performance" favor materials that will corrode slowly in the near-field environment, as far as it is understood.

> "To the extent practicable, the Engineered Barrier Segment components shall be designed to incorporate the use of non-combustible and heat-resistant materials."
> [EB-DRD 3.2.6.2.2]

The preceding requirement is considered in that all of the candidate materials are non-combustible and heat-resistant.

> "Alternative designs shall be prepared for major engineering features important to waste isolation, with particular attention to the alternatives that would provide longer radionuclide containment and isolation. These alternatives are for use in the analysis required by [Title] 10 [, U.S. Code of Federal Regulations, Part] 60.21(c)(1)(ii)(D)."
> [EB-DRD 3.3.1.A]

The preceding requirement is considered to the extent that several candidate materials have been considered for each component and several design options have been considered.

> "When evaluating design concepts, materials, and process alternatives, consideration shall be given to cost effectiveness. This consideration shall be secondary to realization of designs that will be technically conservative and meet the regulatory performance objectives."
> [EB-DRD 3.3.1.I]

The preceding requirement is considered to the extent that cost was included as on of the selection criterion for many of the components.

> "Packages for [spent nuclear fuel] and [high-level waste] shall be designed so that the in situ chemical, physical, and nuclear properties of the waste package and its interactions with the emplacement environment do not compromise the function of the waste packages or the performance of the underground facility or the geologic setting."
> [EB-DRD 3.7.1.A]

The preceding requirement is considered to the extent that physical properties of materials and chemical interactions between waste package components (including the waste form) are discussed.

> "The design of waste packages shall include, but not be limited to, consideration of the following factors: solubility, oxidation/reduction reactions, corrosion, hydriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radionuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions."
> [EB-DRD 3.7.1.B]

The preceding requirement is considered to the extent that oxidation/reduction reactions and corrosion are considered by means of the selection criterion "chemical performance," thermal effects are considered by means of the selection criterion "thermal performance," mechanical strength is considered by means of the selection criterion "mechanical performance," and synergistic effects are considered by means of the selection criterion "compatibility with other materials."

> "The waste packages shall not contain explosive or pyrophoric materials or chemically reactive materials in an amount that could compromise the ability of the underground facility to contribute to waste isolation or the ability of the geologic repository to satisfy the performance objectives."
>
> [EB-DRD 3.7.1.C]

The preceding requirement is considered in that the candidate materials (and therefore the selected materials) for waste package components other than the waste form are all standard engineering materials, which are not considered to be explosive, pyrophoric, or chemically reactive.

> "The waste package shall not contain free liquids in an amount that could compromise the ability of the waste package to achieve the performance objectives relating to containment of radioactive waste (because of chemical interactions or formation of pressurized vapor) or that could result in spillage and spread of contamination in the event of waste package perforation during the period through permanent closure."
>
> [EB-DRD 3.7.1.D]

The preceding requirement is considered in that the candidate materials (and therefore the selected materials) for waste package components other than the waste form are all solid (or, in the case of fill gas, gaseous) and not liquid.

> "Processes specified for the fabrication, assembly, closure, and inspection of waste packages shall be based on technology reasonably available at the time of final design. These processes need not be reduced to commercial practice in all applicable details and shall not require significant extensions of the technology"
>
> [EB-DRD 3.7.1.G]

The preceding requirement is considered to the extent that currently available technology for fabrication is discussed under the fabricability criterion.

> "Containment of radioactive material within the waste packages shall be substantially complete (TBD) for a period of years (TBD) after permanent closure of the geologic repository."
>
> [EB-DRD 3.7.1.I]

The preceding requirement is considered to the extent that the selection criteria "chemical performance" and "predictability of performance" are used to favor materials that will provide a long containment lifetime.

"The container shall contain the radioactive waste materials during all normal handling and emplacement operations and, in the event of accidents or other dynamic effects, contribute to limiting the dispersal of the waste. The container shall also have the mechanical integrity to sustain routine handling and transportation loads (TBD)."

[EB-DRD 3.7.1.2.A]

The preceding requirement is considered to the extent that the selection criterion "mechanical performance" is used to favor materials that are strong and ductile. Such materials will contribute to containment, limiting dispersal, and sustaining routine loads.

"The container shall contribute to the waste package such that containment of the enclosed radionuclides is substantially complete (TBD) during the containment period of not less than 300 to 1,000 years after permanent closure of the geologic repository"

[EB-DRD 3.7.1.2.B]

The preceding requirement is considered to the extent that the selection criteria "chemical performance" and "predictability of performance" are used to favor materials that will provide a long containment lifetime.

"The container shall contribute (TBD) to controlling the release of radionuclides during the period of isolation."

[EB-DRD 3.7.1.2.C]

The preceding requirement is considered to the extent that the selection criteria "chemical performance" and "predictability of performance" are used to favor materials that will control release by providing a long containment lifetime.

"The container shall be designed to limit the amount of liquid water (TBD) allowed to contact the waste form."

[EB-DRD 3.7.1.2.D]

The preceding requirement is considered to the extent that the selection criteria "chemical performance" and "predictability of performance" are used to favor materials that will provide a long containment lifetime.

"The container shall maintain lifting and handling capabilities through the loading, emplacement, and retrieval phases."

[EB-DRD 3.7.1.2.F]

The preceding requirement is considered to the extent that the selection criterion "mechanical performance" is used to favor materials that are strong and ductile.

"The container shall be designed so that neither its in situ chemical, physical, and nuclear properties, nor its interactions with the waste form and emplacement environment, compromise the function of the waste package or the performance of the natural barriers or engineered barriers."

[EB-DRD 3.7.1.2.G]

The preceding requirement is considered to the extent that chemical interactions between waste package components (including the waste form) are discussed.

> "The internal structure shall provide separation of the waste forms such that nuclear criticality shall not be possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. The calculated effective multiplication factor (k_{eff}) must be sufficiently below unity to show at least a 5% margin after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation."
> [EB-DRD 3.7.1.3.A]

The preceding requirement is considered to the extent that the selection criteria "neutronic performance," "chemical performance," and "predictability of performance" are used in evaluating materials for components that will have a criticality control function.

> "The internal structure shall be capable of withstanding handling, emplacement, and retrieval loads (TBD)."
> [EB-DRD 3.7.1.3.D]

The preceding requirement is considered to the extent that the selection criterion "mechanical performance" is used to favor materials that are strong and ductile.

> "The internal structure shall not degrade the performance of components in the waste package which have long term containment requirements."
> [EB-DRD 3.7.1.3.E]

The preceding requirement is considered to the extent that galvanic interactions between the internal structure and the containment barriers are discussed.

> "The material used for the internal structure shall not cause adverse galvanic reactions inside the waste package."
> [EB-DRD 3.7.1.3.F]

The preceding requirement is considered to the extent that galvanic interactions between the internal structure and the containment barriers are discussed.

> "The internal structure shall maintain functionality under the thermal and chemical conditions generated by the waste form."
> [EB-DRD 3.7.1.3.G]

The preceding requirement is considered to the extent that, for components with heat transfer functions, the selection criteria "thermal performance" is used to favor materials with high thermal conductivity.

4.3 Assumptions

The following assumptions from the *Controlled Design Assumptions Document* (Ref. 5.26) were used in the development of this document:

> Key 011: Waste packages will be emplaced in-drift in a horizontal mode.

The assumption above is used in Sections 7.3 through 7.10 in selecting weighting factors for the criterion "mechanical performance" and evaluating materials against that criterion.

> Key 039: The Criticality Control Period lasts to the end of the period of regulatory concern, which is currently undefined. It is presently assumed that the time of concern is greater than 10,000 years after closure.

The assumption above is used in Section 7.7 in selecting weighting factors for the criteria "chemical performance," "predictability of performance," and "neutronic performance" and evaluating materials against those criteria.

> EBDRD 3.7.1.I: Containment of radioactive material within all but 10 waste packages shall be substantially complete for at least 3,000 years after permanent closure of the geologic repository (i.e., fewer than 10 of the waste packages shall be breached within the first 3,000 years after permanent closure of the geologic repository).

The assumption above is used in Sections 7.3 and 7.7 in selecting weighting factors for the criteria "chemical performance" and "predictability of performance" and in evaluating materials against those criteria.

> EBDRD 3.7.1.2.A: The disposal container shall have the mechanical integrity to sustain a static load at least equal to its own weight during routine handling and transportation.

The assumption above is used in Sections 7.3 through 7.7 and 7.9 and 7.10 in selecting weighting factors for the criterion "mechanical performance" and in evaluating materials against that criterion.

> EBDRD 3.7.1.2.B: The container shall contribute to the waste package such that containment of the enclosed radionuclides is substantially complete for 3000 years (with less than 10 waste packages failing within 3000 years after permanent closure of the geologic repository).

The assumption above is used in Sections 7.3 through 7.7 in selecting weighting factors for the criteria "chemical performance" and "predictability of performance" and in evaluating materials against those criteria.

> EBDRD 3.7.1.2.C: The container shall contribute to controlling the release rate of radionuclides during the period of isolation.

The assumption above is used in Sections 7.3 through 7.7 in selecting weighting factors for the criteria "chemical performance" and "predictability of performance" and in evaluating materials against those criteria.

> Key assumption 075: As a goal the Engineered Barrier System, when exposed to the environments based on assumptions TDSS 025 and TDSS 026, should prevent seeping water that is entering the emplacement drift from directly contacting the waste form at all but 10 waste form locations, for a period of at least 10,000 years after permanent closure of the repository.

The assumption above is used in Sections 7.3 in selecting weighting factors for the criteria "chemical performance" and "predictability of performance" and in evaluating materials against those criteria.

> EBDRD 3.7.1.3.A: The internal structure shall provide separation of the waste forms such that nuclear criticality shall not be possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. The calculated effective multiplication factor (k_{eff}) must be sufficiently below unity to show at least a 5% margin after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.

The assumption above is used in Sections 7.6 and 7.7 in selecting weighting factors for the criteria "chemical performance," "predictability of performance," and "neutronic performance" and in evaluating materials against those criteria.

> EBDRD 3.7.1.3.D: For Viability assessment (VA), the loads imposed on the internal structure are similar to the waste package loads.
>
> - Static load on the waste package due to its own weight during handling and transportation.
>
> - Withstand a drop of 2 m.

The assumption above is used in Sections 7.3 through 7.7 and 7.10 in selecting weighting factors for the criterion "mechanical performance" and in evaluating materials against that criterion.

> DCWP 001: Limit the fuel cladding temperature to less than 350°C.

The assumption above is used in Sections 7.6 through 7.9 in selecting weighting factors for the criterion "thermal performance" and in evaluating materials against that criterion.

The bases for all of the assumptions above are given in Ref. 5.26.

Based on the rationale that the conclusions derived by this analysis are for preliminary design that will not be used as input to documents supporting construction, fabrication, or procurement, any TBVs carried by Ref. 5.26 will not be carried to the conclusions of this analysis.

4.4 Codes and Standards

Ref. 5.10 is cited, but it is not used as a source of design input. The various references published by the American Society for Testing and Materials (Ref. 5.11 through Ref. 5.20 and Ref. 5.22 through Ref. 5.24) are used as sources of information in the analysis.

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6. Use of Computer Software

Not applicable.

7. Design Analysis

This section is organized as follows. In the first subsection, functions for the waste package are discussed, and the selection criteria that directly support each function are listed. Each of the following subsections treats one component. Components for different types of disposal containers are combined as discussed in Section 3. For each component, candidate materials are listed, any applicable constraints are applied to eliminate unsuitable materials, rating scales are described for each criterion, the individual materials are rated against the rating scales, and the resulting utility scores are used to determine the best materials.

In Ref. 5.8, selection criteria and weighting factors were developed for container materials. These criteria were for the containment barrier of a single-barrier disposal container that was intended for emplacement in a vertical borehole. Ref. 5.8 also provides grading scales. The criteria were modified and extended in Ref. 5.9, which gives criteria and weighting factors for the containment barriers of a multi barrier disposal container. Since the designs for containment barriers considered in Ref. 5.9 were quite similar to those considered here, a similar approach was used.

The weighting factors that are obtained from Ref. 5.9 are referenced as such. For example, the weighting factors recommended for the corrosion allowance barrier were used without changes. Weighting factors for the corrosion resistant barrier and other components not discussed in Ref. 5.9, subdivisions of weighting factors within each selection criterion, details of the application of the selection criteria, and grading scales are based on the expert opinion of the author. The analysis has not received a formal peer review.

7.1 Justification of selection criteria for waste package components

Several functions (Ref. 5.7, p. 4-2) and requirements (Ref. 5.25, Section 3.7.1 and its subsections) have been allocated to the waste package, but neither functions nor requirements have been allocated to the individual components of a waste package. The discussion below describes a possible allocation of requirements to the various waste package components, functions that the components perform, and selection criteria that could be used in selecting materials that are conducive to successful design. As a summary of the discussion, the selection criteria for each component are listed in Table 7.1-1. Although the table lists weighting factors, these are not justified in this section. Weighting factors for the corrosion allowance and corrosion resistant barriers are based on the approach described in Ref. 5.9, p. 5, Table 2. Justification for the values of the weighting factors for other components is provided in Sections 7.6.3, 7.7.3, 7.8.3, 7.9.3, and 7.10.3.

All of the solid (i.e., not gaseous) components must be fabricated. The selection criterion "fabricability" is, therefore, applied to all solid components except as noted below.

Corrosion allowance barrier:

This barrier contributes to meeting the containment requirement of EB-DRD 3.7.1.2.B. To provide a containment function that will satisfy this requirement, the corrosion allowance barrier must be designed to provide the functions of maintaining structural and material integrity; that is, they must tolerate mechanical loads, such as those from handling accidents or rock falls, and exposure to corrodents, such as humid air and dripping groundwater. The selection criteria "mechanical performance" and "chemical performance" reflect the need to design for these conditions. In addition, chemistry of the near-field environment is uncertain, so the criterion "predictability of performance" is used to reflect the need to design for a variety of near-field chemistries, such as those that would be present if the groundwater chemistry is altered. For this component, "mechanical performance" includes the strength and ductility of the material, because both of these are important in resisting rock falls. "Chemical performance" is related to the corrosion rate under the "base case" environment, which is described in Section 7.3.1.3.2. "Predictability of performance" is related (1) to the decrease in performance that occurs if the near-field environment is not the "base case" but one of the "bounding cases" described in Section 7.3.1.3.2 and (2) to the amount of corrosion data that is available. Prior use of a material in a variety of applications will help to provide reasonable assurance that all of the significant degradation modes for a material are known. The selection criterion "previous experience" is used to favor materials for which such a base of experience exists. "Previous experience" reflects the existence of standards, which are indicative of widespread use of a material, and the variety of applications that the material has seen.

The corrosion allowance barrier also contributes greatly to meeting the requirement of EB-DRD 3.7.1.2.F to maintain lifting and handling capabilities. To meet this requirement, the corrosion allowance barrier must perform the function of maintaining structural integrity. The criterion "mechanical performance" addresses this requirement.

It is clearly good practice to choose materials so that no component causes unwanted degradation of another, and consideration of such effects is required by EB-DRD 3.7.1.B through its reference to synergistic interactions. If it is possible, the characteristics of one component should enhance the performance of other components. For example, it is beneficial for the corrosion allowance barrier to provide the function of galvanically protecting the corrosion resistant barrier. The criterion "compatibility with other materials" is used to favor corrosion allowance materials that work well with the candidate materials for the corrosion resistant barrier. This selection criterion includes compatibility with the corrosion resistant barrier and with the waste form.

For this component, "fabricability" includes the formability, weldability, and inspectability of the material. Ratings of inspectability consider the closure weld; this is the most difficult weld to inspect because only one side of the weld will be accessible and the radiation field will require remote operations.

Corrosion resistant barrier:

The requirements, functions, and selection criteria are the same for this component as for the corrosion allowance barrier. However, the level of emphasis on the various functions differs. For example, for the corrosion resistant barrier in the case of dual barrier design option described in section7.2, the weighting factors for "mechanical performance" and "chemical performance" are, respectively, lower and higher than those for the corrosion allowance barrier. In addition to differences in emphasis, there are some differences in the details of the selection criteria. First, since this component is much thinner than the corrosion allowance barrier, formability is much less significant to fabricability. As a result, the selection criterion "fabricability" includes only weldability and inspectability. Second, "compatibility with other materials" refers to compatibility with the corrosion allowance barrier and with the waste form. Compatibility of the containment barriers with the internal components of the disposal container was not addressed, because the containment barriers must fail before corrodents can reach the internal components.

For the corrosion resistant barriers for the other two options identified in Section 7.2, namely the dual barrier option with two corrosion resistant barriers (two CRMs) and the single barrier option, the requirements are different. For example, the outer barrier of the two CRMs option, the outer barrier will have to be able to provide structural strength as well as corrosion resistance. These differences are addressed in the respective sections of the analysis of the design options.

Fuel basket tubes:

Fuel basket tubes are included in the design for PWR spent fuel primarily to provide an additional path for conduction of heat from the fuel to the containment barriers. Such a component was found to be needed for compliance with controlled design assumption DCWP 001, which limits fuel cladding temperatures. To favor materials that conduct heat well, the selection criterion "thermal performance" was applied to this component.

During the period when conduction of heat to the containment barriers is important, the containment barriers are expected to be intact, and the environment inside the waste package will be inert. As a result, the selection criteria "chemical performance" and "predictability of performance" are not applied. Again, since the internal environment is inert, there is little reason to expect that there are significant unknown degradation modes, so the criterion "previous experience" is likewise not applied.

The criteria "mechanical performance" and "compatibility with other materials" were applied. Requirements and the definitions of the selection criteria are generally similar to those for the containment barriers; differences are noted below.

EB-DRD 3.7.1.3.D requires that the internal structure be able to sustain mechanical loads due to handling, emplacement, and retrieval, and this component must perform the function of maintaining its own structural integrity, so the criterion "mechanical performance" is applied.

EB-DRD 3.7.1.3.F sets limits on galvanic reactions caused by the internal structure, and, in response to this requirement, the tubes are allocated the function of corroding sacrificially to protect the fuel basket plates. In addition, the plates should not degrade the waste form. To address these functions, the criterion "compatibility with other materials" is applied. This component will not be exposed to corrodents until the containment barriers fail, so compatibility with the barrier materials is not considered.

The welds in this component will be fully accessible to the entire range of nondestructive testing methods, so inspectability is expected to be of little significance, and "fabricability" includes only formability and weldability.

Fuel basket plates:

The fuel basket plates perform the function of controlling criticality to provide for compliance with the requirements of EB-DRD 3.7.1.3.A. To favor the use of materials that are effective in controlling criticality, the criterion "neutronic performance" is applied. Since boron is the neutron absorber in all of the candidate materials, neutronic performance depends on boron concentration.

Like the fuel basket tubes, the fuel basket plates also perform the function of conducting heat to the containment barriers, so the selection criterion "thermal performance" is applied to favor materials that will promote compliance with DCWP 001. Unlike the tubes, no forming or joining of the plates is required, so the criterion "fabricability" is not applied.

For the remaining selection criteria, the definitions of the criteria are like those for the containment barriers except as noted.

To assure continued performance of the function of controlling criticality, and thus compliance with the requirements of EB-DRD 3.7.1.3.A over long times, it is necessary to assure that neutron absorbing materials remain in place and effective in controlling criticality. To favor materials that provide corrosion resistance, the criteria "chemical performance" and "predictability of performance" are applied. Because of the similarity of all the candidate materials for this component, the criterion "chemical performance" has been modified to allow a distinction between the materials. The criterion "previous experience" is applied to help provide reasonable assurance that all of the significant degradation modes for a material are known.

EB-DRD 3.7.1.3.D requires that the internal structure be able to sustain mechanical loads, so the plates must perform the function of maintaining structural integrity. For PWR designs this component will support much of the load in the basket, and for BWR designs this component will support all of the load in the basket. The criterion "mechanical performance" is applied.

In galvanic reactions between basket tubes and basket plates, the plates are given preference, that is, the tubes are expected to corrode and thus protect the plates. This arrangement is in response to EB-DRD 3.7.1.3.F. The selection criterion "compatibility with other materials" is applied, but only reactions between the plates and the waste form are considered for this component.

Waste container fill gas:

The fill gas contributes to the functions of limiting waste form temperature and to controlling synergistic interactions by providing an inert environment for the waste form while at least one containment barrier is intact. These functions promote compliance with DCWP 001 and EBDRD 3.7.1.B. Two selection criteria have been applied to the fill gas to assure that these functions are provided. "Thermal performance" is applied to favor gases that conduct heat well and promote compliance with DCWP 001. "Compatibility with other materials" is used to favor inert gases.

Basket guides:

Requirements, functions, and selection criteria are similar for the basket guides and the fuel basket tubes. For compliance with EB-DRD 3.7.1.3.D, the basket guides must provide the function of maintaining structural integrity. To address this function, the selection criterion "mechanical performance" is applied. To promote compliance with DCWP 001, the guides must provide the function of limiting waste form temperature by conducting heat to the containment barriers. Therefore, the criterion "thermal performance" is applied. There is a difference in emphasis, however, as regards the selection criterion "mechanical performance." For the fuel basket tubes, the requirements of EB-DRD 3.7.1.3.D are incidental, whereas for the basket guides, the requirements are essential because the basket guides are the component that transfers loads between the basket and the containment barriers.

Although their wording differs, EB-DRD 3.7.1.B and EB-DRD 3.7.1.3.F both require the function of controlling synergistic interactions. To address these functions, the criterion "compatibility with other materials" is applied. Like the fuel basket tubes, however, this component will not be exposed to corrodents until the containment barriers fail, so this criterion addresses reactions with the fuel basket plates and the waste form.

As with the containment barriers, the selection criterion "fabricability" is applicable. However, the welds in this component will be fully accessible to the entire range of nondestructive testing methods, so inspectability is expected to be of little significance, and "fabricability" includes only formability and weldability.

Canister guide:

Requirements, functions, and selection criteria are generally similar for the basket guides for SNF waste forms. An exception is that the criterion "thermal performance" is not applied. There are temperature limits for HLW glass, but the canister guide is ineffective in conducting heat to the containment barriers because of its small size and limited contact with the waste form.

For compliance with EB-DRD 3.7.1.3.D, the canister guide must provide the function of maintaining structural integrity. To address this function, the selection criterion "mechanical performance" is applied. EB-DRD 3.7.1.B and EB-DRD 3.7.1.3.F both require the function of controlling synergistic interactions. To address these functions, the criterion "compatibility with other materials" is applied. However, the canister guide will not be exposed to corrodents until the containment barriers fail, so this criterion addresses reactions with the waste form. The selection criterion "fabricability" is also applicable. However, the welds in this component will be fully accessible to the entire range of nondestructive testing methods, so inspectability is expected to be of little significance, and "fabricability" includes only formability and weldability.

Table 7.1-1 Selection criteria and weighting factors for materials selection

	Waste package Components						
Selection criterion	Corrosion allowance barrier	Corrosion resistant barrier **	Fuel basket tubes	Fuel basket plates	Fill gas	Basket guides	HLW canister guide
Mechanical performance	10	**	10	10		25	40
Chemical performance.	15	**		20			
Predictability of performance	20	**		10			
Compatibility with other matl.	15	**	20	10	60	20	20
Fabricability	30	**	20			20	20
Cost	10	**	25	10	15	20	20
Previous experience	10	**		5			
Thermal performance		**	25	15	25	15	
Neutronic performance		**		20			

** Selection criteria and weighting factors for the corrosion resistant barriers were changed from those in Ref. 5.9 to the following:

Critical parameters for crevice/pitting corrosion = 30
Environmentally accelerated cracking = 15
Predictability of performance = 20
Formation of brittle phases = 5
Mechanical performance = 5
Fabricability = 25

7.2 Containment barriers

In determining the appropriate materials for the waste package containment barriers, three different design options were considered. Each option was evaluated using separate selection criteria applicable to that design. Following are the design options for the waste package containment barriers evaluated in this analysis.

-Dual-barrier design consisting of a corrosion allowance material (CAM) for the outer barrier and a corrosion resistant material (CRM) for the inner barrier (CAM-CRM option) ---Option 1

-Dual-barrier design consisting of two corrosion resistant materials for both inner and outer barriers (two CRMs)---Option 2

-Single barrier design with a corrosion resistant material---Option 3

Sections 7.3 addresses the materials selection analysis for the dual-barrier and single barrier design options as well as the comparative evaluation of the options and recommendation for the preferred option.

7.3 Containment barrier selection

7.3.1 Dual-barrier design -- Option 1

This option provides for defense in depth concept with each barrier degrading by a different mechanism. The outer corrosion allowance barrier is expected to corrode by a slow, uniform process at a predictable rate. This delays the exposure of the inner corrosion resistant barrier to the near-field environment long enough for the waste package temperatures to be low and thus reduce the corrosion rates for the inner barrier.

7.3.1.1 Corrosion allowance barrier

7.3.1.1.1 Candidate materials

Candidate materials were taken from Ref. 5.27, p. 12. The corrosion allowance and moderately corrosion resistant materials listed in this document are ASTM A 516 Grade 55, ASTM A 27 Grade 70-40, ASTM A 387 Grade 22, ASTM B 127, and ASTM B 171 C71500. One material, ASTM A 516 Grade 70, was added to the list because of its greater mechanical strength.

7.3.1.1.2 Constraints

Plans for fabrication are that the corrosion allowance barrier is to be made by forming from plate

| and welding (Ref 5.94, p. 7). This is evidenced by the citation of "A516 Carbon Steel" (ASTM A 516) in Ref. 5.63, p. 17, because that specification is for plate. Since ASTM A 27 is a specification for steel castings (Ref. 5.11), this analysis will not consider that material further. Some common names for the remaining candidate materials are given below.

Material	Common names
ASTM A 387 Grade 22	2 1/4 Cr - 1 Mo alloy steel (Ref. 5.27, p. 12)
ASTM A 516 Grade 55	carbon steel (Ref. 5.14)
ASTM A 516 Grade 70	carbon steel (Ref. 5.14)
ASTM B 127	Alloy 400, Monel 400 (Ref. 5.27, p. 12)
ASTM B 171 C71500	70-30 copper nickel (Ref. 5.27, p. 12)

7.3.1.1.3 Selection criteria and ratings

Selection criteria for the corrosion allowance barrier for SNF waste forms were given in Ref. 5.9, p. 5, Table 2. Although those criteria were intended for the advanced conceptual design phase, they are used here without change because (1) current designs still call for an outer barrier of a corrosion allowance material and an inner barrier of a corrosion resistant material, and the thicknesses of these barriers are unchanged from those specified in Ref. 5.9; (2) what is called a high thermal load in Ref. 5.9 approximates the current reference thermal load (83 metric tons of uranium per acre) (Ref. 5.26, p. 6-22). For reference, the weighting factors are given in Table 7.1-1. It is noted that Ref. 5.9 does not treat the criteria "thermal performance" and "neutronic performance," so in effect it assigns a zero weighting factor to these criteria.

7.3.1.1.3.1 Mechanical performance

Weighting factor = 10 (Ref. 5.9, p. 5, Table 2)

Mechanical performance score is the sum of scores for strength and ductility. "Strength" is minimum yield strength as given in the appropriate ASTM specification. "Ductility" is the minimum elongation (for tensile testing of a sample with a 2-inch gage length) as given in the specification. In general, higher strength and higher ductility are preferable. The yield strength provides a measure of the loads that the container can withstand without significant permanent distortion. Yield strength and ductility together provide a conservative estimate of the amount of energy that the material can withstand without failing. Tensile strength provides an alternative measure of mechanical performance and may be considered in future materials selection analyses.

Strength:

Rating	Characteristics
5	Yield strength > 250 MPa
4	250 MPa ≥ Yield strength > 200 MPa
3	200 MPa ≥ Yield strength > 150 MPa
2	150 MPa ≥ Yield strength > 100 MPa
1	100 MPa ≥ Yield strength > 50 MPa
0	50 MPa ≥ Yield strength

Material	Yield strength, MPa	Rating	Reference
ASTM A 387 Grade 22	207	4	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	207	4	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	262	5	Ref. 5.14, Table 2.
ASTM B 127	193	3	See text below.
ASTM B 171 C71500	124	2	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

Ductility:

Rating	Characteristics
5	Elongation > 25%
4	25% ≥ Elongation > 20%
3	20% ≥ Elongation > 15%
2	15% ≥ Elongation > 10%
1	10% ≥ Elongation > 5%
0	5% ≥ Elongation

Material	Elongation, %	Rating	Reference
ASTM A 387 Grade 22	18	3	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	27	5	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	21	4	Ref. 5.14, Table 2.
ASTM B 127	35	5	See text below.
ASTM B 171 C71500	30	5	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

7.3.1.1.3.2 Chemical performance

Weighting factor = 15 (Ref. 5.9, p. 5, Table 2)

The chemical performance of waste package materials will depend on the near-field environment. What the near-field environment will be is a subject of ongoing research. In the absence of conclusive evidence, a "base case" environment and three "bounding" environments have been chosen (Ref. 5.28, p. 18). The base case is J-13 groundwater, for which the composition is given in Ref. 5.29, vol. 2, pp. 38-39. That reference lists the following characteristics of J-13 water that are particularly significant for corrosion: pH = 7.41 and chloride (Cl^-) concentration = 7.14 mg/L (Ref. 5.29, vol. 2, p. 38, mean values). For the purposes of this analysis, "chemical performance" is taken to be the abiotic corrosion performance in this environment. The base case environment is intended to simulate that of a typical waste package, whereas the bounding environments are intended to simulate the more aggressive conditions that some packages may encounter. It is possible that the environments of some waste packages will be substantially more benign than even the base case. This may be particularly true at short times, if decay heat is effective in drying the repository.

The three bounding environments are as follows (Ref. 5.28, p. 18): (1) a concentrated groundwater, which is like J-13 but 20 to 100 times as concentrated, (2) an acidified, concentrated groundwater, like the first bounding environment but with pH as low as 2, and (3) an alkalized, concentrated groundwater, like the first bounding environment but with pH as high as 12. These three bounding environments are intended to simulate (1) the effects of dry-out and concentration of dissolved species, (2) acidification as a result of degradation of introduced materials or microbial metabolism, and (3) water conditioning by concrete or grout, respectively. In view of the uncertainty in the near-field environment, materials performance in these bounding environments must also be considered. For the purposes of this analysis, the corrosion performance for the bounding environments is considered in the criterion "predictability of performance."

To make accurate predictions of the relative performance of the different candidate materials, it is necessary to measure corrosion in well-controlled experiments with identical conditions. At the time this analysis was prepared, such experiments had not been completed, so estimates of chemical performance were based on literature values.

There have been numerous measurements of corrosion of steel. Many of these are reviewed in Ref. 5.30. The following observations are made with regard to corrosion of steel. First, the various carbon steels, including ASTM A 516 Grades 55 and 70, are so lightly alloyed that they have similar corrosion rates (Ref. 5.31, p. 509). Second, the corrosion rate of carbon steels at near-neutral pH increases with increasing aeration (Ref. 5.31, p. 515, fig. 11). Third, the corrosion rate of carbon steels at near-neutral pH decreases with increasing exposure time (Ref. 5.30, Table III-B) if a protective oxide layer accumulates.

For the purposes of this analysis, it is argued that the 16-year Gatun Lake exposures of carbon steel reported in Ref. 5.30, Table III-B (Key letters A, B, and C) are most representative. These are long exposures and, because they were in a lake, are expected to have been at moderate aeration and flow rate. These range from 39.7 μm/yr to 44.5 μm/yr, and, on the basis of the first observation above, are judged to be applicable to ASTM A 516 Grades 55 and 70. Higher corrosion rates, up to 531 μm/yr, were observed by McCright and Weiss (Ref. 5.32, p. 5, Table III) for 1020 carbon steel, but these rates were for shorter times and high aeration (Ref. 5.32, p. 4). ASTM A 387 Grade 22 is judged to be slightly more corrosion resistant than ASTM A 516 Grades 55 and 70. Ref. 5.32, Table III gives an average general corrosion rate over the 50°C to 100°C temperature range of 434 μm/yr for 1020 carbon steel, which is similar in composition to ASTM A 516 Grades 55 and 70. The same table gives an average general corrosion rate for the same temperature range of 362 μm/yr for 2-1/4 Cr - 1 Mo alloy steel, which is similar in composition to ASTM A 387 Grade 22. Applying the ratio of these corrosion rates to those for the Gatun Lake exposures gives a corrosion rate of 33 µm/yr to 37 µm/yr for ASTM A 387 Grade 22.

Cu 70 - Ni 30 was also tested in 16-year exposures in Gatun Lake. This material has a composition very similar to that of ASTM B 171 C71500. Ref. 5.33, vol. 2, p. 44, Table 13 specifies a penetration of 33 µm over 16 years for this material, or an average penetration rate of 2.1 µm/yr. The use of this average rate, rather than the final rate of 1.0 µm/yr reported in the same table, appears to be consistent with the approach taken for steels in the previous paragraph.

Information on long-term corrosion of ASTM B 127 exposed in Gatun Lake gives a corrosion rate of 0.95 µm/yr (Ref. 5.95). Ref. 5.34, p. 16 states only that the corrosion rates are usually less than 25 µm/yr. Ref. 5.33 does not appear to consider the material. Ref. 5.31, p. 648, Table 9 gives a value of 8 µm/yr for Alloy 400 exposed to aerated 10% acetic acid at 30°C.

Rating	Characteristics
15	0.1 µm/yr ≥ Corrosion rate
12	1 µm/yr ≥ Corrosion rate > 0.1 µm/yr
9	10 µm/yr ≥ Corrosion rate > 1 µm/yr
6	100 µm/yr ≥ Corrosion rate > 10 µm/yr
3	1000 µm/yr ≥ Corrosion rate > 100 µm/yr
0	Corrosion rate > 1000 µm/yr

Material	Corrosion rate, µm/yr	Rating	Reference
ASTM A 387 Grade 22	40 to 45	6	See text above.
ASTM A 516 Grade 55	40 to 45	6	See text above.
ASTM A 516 Grade 70	33 to 37	6	See text above.
ASTM B 127	0.95	12	See text above.
ASTM B 171 C71500	2.1	9	See text above.

7.3.1.1.3.3 Predictability of performance

Weighting factor = 20 (Ref. 5.9, p. 5, Table 2)

Scores for predictability of performance were taken to be the sum of scores for performance in bounding environments (as is mentioned in Section 7.3.1.1.3.2, Chemical performance) and availability of corrosion data.

Performance in bounding environments:

Rating	Characteristics
15	Severe loss of performance, relative to the base case, in none of the three bounding environments of Ref. 5.28, p. 18.
10	Severe loss of performance, relative to the base case, in one of the three bounding environments.
5	Severe loss of performance, relative to the base case, in two of the three bounding environments.
0	Severe loss of performance, relative to the base case, in all of the three bounding environments.

Material	Rating	Reference
ASTM A 387 Grade 22	10	See text below.
ASTM A 516 Grade 55	10	See text below.
ASTM A 516 Grade 70	10	See text below.
ASTM B 127	10	See text below.
ASTM B 171 C71500	10	See text below.

Ref. 5.35, pp. 307-308 notes large increases in the corrosion rate of iron in acid environments, but a decrease in corrosion rate in alkaline environments. Carbon steels, including ASTM A 516 Grades 55 and 70, are so lightly alloyed that their corrosion rates are similar to those of iron (Ref. 5.31, p. 509). As discussed in Section 7.3.1.1.3.2, Chemical performance, the corrosion rate of ASTM A 387 Grade 22 is similar to that of ASTM A 516 Grades 55 and 70.

Comparison of results in Tables III-B and III-C of Ref. 5.30 shows that seawater is more corrosive than fresh water for carbon steel, nickel steel, chromium steel, and low alloy steel. For 16-year exposures, the greatest corrosion enhancement is 4.7 × for 3% chromium steel. However, this corrosion enhancement results from a chloride concentration of 18980 parts per million (Ref. 5.36, p. F-206), versus only 714 parts per million for J-13 water concentrated 100 × (Ref. 5.29, vol. 2, p. 38). On the basis of these results, it is concluded that ASTM A 387 Grade 22 and ASTM A 516 Grades 55 and 70 show severe loss of performance in only one bounding environment, the acidified concentrated groundwater.

Monel 400 (ASTM B 127) is said to give excellent service in seawater or brackish water (Ref. 5.34, p. 16). Severe loss of performance is therefore not expected in concentrated J-13 water. However, loss of performance is expected in acidified concentrated J-13 water. Ref. 5.34, p. 17, Fig. 14 shows corrosion rates of about 30 mpy = 760 μm/yr for dilute sulfuric acid saturated with air. This is a severe loss of performance in comparison to the value of 8 μm/yr reported in Section 7.3.1.1.3.2, Chemical performance. The alloy is said to be highly satisfactory for handling most alkalies (Ref. 5.34, p. 20), so loss of performance in alkalized concentrated J-13 water is not expected. Severe loss of performance is therefore expected in only one bounding environment, acidified concentrated groundwater.

Copper nickels, which include ASTM B 171 C71500, are said to give excellent service in brines and seawater (Ref. 5.31, pp. 617-618), so severe loss of performance is not expected in concentrated J-13 water. In contrast, they are said to give poor performance in acidic mine water (Ref. 5.31, p. 618), so severe loss of performance is expected in acidified concentrated J-13 water. Finally, they are said to give excellent performance in alkalies including sodium hydroxide and potassium hydroxide (Ref. 5.31, p. 618), so severe loss of performance is not expected in alkalized concentrated J-13 water. Severe loss of performance is therefore expected in only one bounding environment, acidified concentrated groundwater.

Availability of corrosion data:

Rating	Characteristics
5	Large amounts of corrosion data available.
2	Limited amounts of corrosion data available.
0	No corrosion data available.

Material	Rating	Reference
ASTM A 387 Grade 22	5	See text below.
ASTM A 516 Grade 55	5	See text below.
ASTM A 516 Grade 70	5	See text below.
ASTM B 127	5	See text below.
ASTM B 171 C71500	2	See text below.

ASTM A 516 Grades 55 and 70 are carbon steels, and ASTM A 387 Grade 22 is an alloy steel. Large amounts of corrosion data are available for carbon and alloy steels. This is attested by Ref. 5.30, pp. I-vi, which lists 96 references. Similarly, Ref. 5.31, pp. 529-530 lists 72 references on corrosion of carbon steels and Ref. 5.31, pp. 545-546 lists 30 references on corrosion of alloy steels.

Extensive corrosion data are also available for ASTM B 127 and ASTM B 171 C71500. These two alloys are discussed in sections on nickel-base alloys and copper and copper alloys in Ref. 5.31, and these two sections contain 92 references (Ref. 5.31, pp. 656-657) and 101 references (Ref. 5.31, pp. 639-640), respectively. However these two sections each cover a wide range of alloys. The section on nickel-base alloys includes nickels, nickel-copper alloys, nickel-molybdenum alloys, nickel-chromium-iron alloys, nickel-chromium-iron-molybdenum alloys, nickel-chromium-molybdenum-tungsten alloys, nickel-silicon alloys, and precipitation-hardening alloys (Ref. 5.31, p. 644). The section on copper and copper alloys includes the following classes of wrought copper alloys: coppers, high-copper alloys, brasses, leaded brasses, tin brasses, phosphor bronzes, leaded phosphor bronzes, copper-phosphorus and copper-silver phosphorus alloys, aluminum bronzes, other copper-zinc alloys, copper-nickels, and nickel silvers (Ref. 5.31, p. 611). The coverage of each of these classes is clearly lighter than that for carbon and alloy steels.

7.3.1.1.3.4 Compatibility with other materials

Weighting factor = 15 (Ref. 5.9, p. 5, Table 2)

Scores for compatibility with other materials were taken to be the sum of scores for compatibility with the corrosion resistant barrier and for compatibility with the waste form.

Compatibility with the corrosion resistant barrier:

Design discussions have often focused on the benefits of having the corrosion resistant barrier galvanically protected by the corrosion allowance barrier. The effectiveness of galvanic protection has been determined according to the galvanic series (Ref. 5.31, p. 235, Fig. 1).

Rating	Characteristics
10	Expected to provide galvanic protection: Entire galvanic potential range for corrosion allowance material is below the range for any candidate corrosion resistant material.
5	May or may not provide galvanic protection: Galvanic potential range for corrosion allowance material overlaps the range for some candidate corrosion resistant material(s) but does not extend above the top of the range for any candidate corrosion resistant material.
0	Not expected to provide galvanic protection: Galvanic potential range for corrosion allowance material extends above the top of the range for some candidate corrosion resistant material(s).

Material	Rating	Reference
ASTM A 387 Grade 22	10	See text below.
ASTM A 516 Grade 55	10	See text below.
ASTM A 516 Grade 70	10	See text below.
ASTM B 127	5	See text below.
ASTM B 171 C71500	10	See text below.

According to Ref. 5.31, p. 235, Fig. 1, the maximum galvanic potential for low-carbon steel and low-alloy steel in seawater are about −570 mV versus a saturated calomel electrode (SCE). These materials are comparable to ASTM A 387 Grade 22 and ASTM A 516 Grades 55 and 70. Similarly, 70-30 copper nickel (ASTM B 171 C71500) has a maximum galvanic potential of about −170 mV SCE, and nickel-copper alloy 400 (ASTM B 127) has a maximum galvanic potential of about −20 mV SCE.

The corrosion resistant candidate materials are comparable to four materials near the top of the series: Ni-Cr-Mo alloy C, titanium, Ni-Cr-Mo-Cu-Si alloy G, and nickel-iron-chromium alloy 825. The lower end of the galvanic potential range for these may be as low as −50 mV SCE (for titanium), and the upper end may be as low as +40 mV SCE (nickel-iron-chromium alloy 825). From the data given here and in the previous paragraph, it is seen that ASTM B 127 may not provide galvanic protection, but all of the other materials are expected to provide galvanic protection.

It is noted that the ratings above do not follow the conventional approach of choosing metals that have similar galvanic potentials. Since a long containment lifetime is desired and the environment is uncertain, it is preferable for the corrosion allowance barrier to have a galvanic potential that is well below that of the corrosion resistant barrier so that, regardless of the environment, the corrosion allowance barrier will corrode sacrificially and protect the corrosion resistant barrier.

Another aspect of possible incompatibility between the two barrier materials is discussed in Section 7.3.1.2

Compatibility with waste form:

Rating	Characteristics
5	No evidence of degradation of waste form by candidate material or its products of corrosion.
0	Evidence of degradation of waste form by candidate material or its products of corrosion.

Material	Rating	Reference
ASTM A 387 Grade 22	5	See text below.
ASTM A 516 Grade 55	5	See text below.
ASTM A 516 Grade 70	5	See text below.
ASTM B 127	5	See text below.
ASTM B 171 C71500	5	See text below.

No evidence has been found that any of the corrosion allowance materials or their corrosion products will cause degradation of the waste form.

7.3.1.1.3.5 Fabricability

Weighting factor = 30 (Ref. 5.9, p. 5, Table 2)

Scores for fabricability were taken to be the sum of scores for formability, weldability, and inspectability.

Formability:

Rating	Characteristics
10	Forms easily.
5	Forms with slight difficulty.
0	Forms with great difficulty.

Material	Rating	Reference
ASTM A 387 Grade 22	10	See text below.
ASTM A 516 Grade 55	10	See text below.
ASTM A 516 Grade 70	10	See text below.
ASTM B 127	5	See text below.
ASTM B 171 C71500	5	See text below.

Ref. 5.37, p. 217 discusses three-roll forming of steel plate; this is an appropriate method for forming the outer containment barrier. The reference states "most of the steels formed by this process conform to one of the plate specifications: either plain carbon or low-alloy steels, such as A516 grade 70. For the most successful three-roll forming, steels having a minimum elongation of 18% are preferred." All three of the steels under consideration (ASTM A 387 Grade 22, ASTM A 387 Grade 55, and ASTM A 516 Grade 70) fall into the classes discussed here, and, as documented in Section 7.3.1.1.1, have adequate ductility. This information is judged to mean that these materials will form easily.

Ref. 5.37, p. 432 rates the formability of nickel alloys, which include ASTM B 127, to range from moderately easy to moderately difficult. This is judged to mean that ASTM B 127 is formable with slight difficulty. Ref. 5.37, p. 406, table 1 rates the formability of Alloy C715 (ASTM B 171

C71500) as good on a scale of excellent, good, fair, and poor. This is judged to mean that it is formable with slight difficulty.

Weldability:

Rating	Characteristics
10	Welds easily.
5	Welds with slight difficulty.
0	Welds with great difficulty

Material	Rating	Reference
ASTM A 387 Grade 22	10	See text below.
ASTM A 516 Grade 55	10	See text below.
ASTM A 516 Grade 70	10	See text below.
ASTM B 127	10	See text below.
ASTM B 171 C71500	10	See text below.

Ref. 5.38, p. 667 discusses welding of low-alloy steels, and Table 8 in the reference specifically refers to ASTM A 387 Grade 22. The reference goes on to say that "All the common arc welding processes can be used to join low-alloy steels." This is judged to mean that ASTM A 387 Grade 22 welds easily.

Ref. 5.38, p. 641 states, in a discussion of carbon steels, "In the range of 0.15 to 0.30% [carbon], the steels are generally easily welded." Such steels include ASTM A 516 Grades 55 and 70.

Ref. 5.38, p. 766 discusses welding of copper-nickel alloys, which include ASTM B 171 C71500. The reference states "Copper-nickel alloys are readily welded by [gas-tungsten arc welding], [gas-metal arc welding], and [shielded metal arc welding]." Ref. 5.33, vol. 8 considers weldability of Alloy C715 (ASTM B 171 C71500) at some length, and pays particular attention to the question of hot cracking, though it notes (Ref. 5.33, vol. 8, p. 14) that with gas-tungsten arc welding, "cracking is not a serious problem."

Inspectability:

The containment barriers are expected to have several weld joints. The most difficult weld to inspect will be the closure weld, because its inspection must be performed remotely and because it is not accessible to radiography. All of the candidate materials provide surface inspectability (e.g., visual inspection). Therefore, inspectability is rated according to the applicability of ultrasonic testing to the material, as rated in Ref. 5.38, p. 1086, Table 1.

Rating	Characteristics
10	Ultrasonic testing is "most applicable."
5	Ultrasonic testing is "applicable."
0	Ultrasonic testing is "least applicable."

Material	Rating	Reference
ASTM A 387 Grade 22	10	See text below.
ASTM A 516 Grade 55	10	See text below.
ASTM A 516 Grade 70	10	See text below.
ASTM B 127	5	See text below.
ASTM B 171 C71500	0	See text below.

Ref. 5.38, p. 1086, Table 1 rates the applicability of ultrasonic testing to low-carbon steel as "most applicable." ASTM A 387 Grade 22 and ASTM A 516 Grades 55 and 70 are all low-carbon steels. The reference rates the applicability of ultrasonic testing to copper alloys as "least applicable." ASTM B 171 C71500 is a copper alloy. ASTM B 127 is a nickel-base alloy, but the reference does not rate such alloys. Among the metals listed in the reference, ultrasonic testing is rated "most applicable" only for low-carbon steel and "least applicable" only for copper alloys. In the absence of additional information, ultrasonic testing is rated to be "applicable" for ASTM B 127. It is noted that the materials selection in Section 7.3.1.1.4 would remain the same regardless of the inspectability rating for ASTM B 127

7.3.1.1.3.6 Cost

Weighting factor = 10 (Ref. 5.9, p. 5, Table 2)

For the purposes of this analysis, "cost" is defined as the price per kilogram of raw material. Details of price estimates may vary from one material to another.

Rating	Characteristics
10	Cost < \$2/kg
8	\$2/kg ≤ Cost < \$4/kg
6	\$4/kg ≤ Cost < \$6/kg
4	\$6/kg ≤ Cost < \$8/kg
2	\$8/kg ≤ Cost < \$10/kg
0	\$10/kg ≤ Cost

Material	Cost, \$/kg	Rating	Reference
ASTM A 387 Grade 22	0.95	10	See text below.
ASTM A 516 Grade 55	0.79	10	See text below.
ASTM A 516 Grade 70	0.79	10	See text below.
ASTM B 127	9.92	2	See text below.
ASTM B 171 C71500	7.17	4	See text below.

Costs for ASTM A 516 Grades 55 and 70 follow the cost estimate from Bethlehem Steel given in Ref. 5.63, p. 14, Table 1 (\$0.36/lb). Cost for ASTM A 387 Grade 22 is estimated to be the cost of ASTM A 516 Grade 70 plus 20% for the more costly alloying elements (chromium and molybdenum). Cost for ASTM B 127 that from Ref. 5.39, vol. 1, p. 56 for Monel 400 (\$4.50/lb). Cost for ASTM B 171 C71500 is the arithmetic mean of the maximum and minimum prices in Ref. 5.39, vol. 1, p. 56 for C715 70/30 Cupronickel (\$3.00/lb to \$3.50/lb).

7.3.1.1.3.7 Previous experience with the material

Weighting factor = 10 (Ref. 5.9, p. 5, Table 2)

Scores for previous experience with the material were taken to be the sum of scores for existence of ASTM standards and variety of applications.

Existence of ASTM standards:

Rating	Characteristics
4	ASTM standard exists for material.
0	No ASTM standard exists for material.

Material	Rating	Reference
ASTM A 387 Grade 22	4	Ref. 5.13.
ASTM A 516 Grade 55	4	Ref. 5.14.
ASTM A 516 Grade 70	4	Ref. 5.14.
ASTM B 127	4	Ref. 5.16.
ASTM B 171 C71500	4	Ref. 5.17.

Variety of applications:

Rating	Characteristics
6	Material or similar materials are used in a wide variety of applications.
3	Material or similar materials are used in a limited variety of applications.
0	Material or similar materials are used in an extremely limited variety of applications.

Material	Rating	Reference
ASTM A 387 Grade 22	6	See text below.
ASTM A 516 Grade 55	6	See text below.
ASTM A 516 Grade 70	6	See text below.
ASTM B 127	6	See text below.
ASTM B 171 C71500	6	See text below.

Ref. 5.40, p. 181 states that "Steel plate is used mainly in the construction of buildings, bridges, ships, railroad cars, storage tanks, pressure vessels, pipe, large machines and other heavy structures." This is taken to be a wide variety of applications. ASTM A 387 Grade 22 and ASTM A 516 Grades 55 and 70 are materials of this type.

Ref. 5.41, pp. 133-134 lists the following applications for Monel 400 (ASTM B 127): "Valve and pump parts, propeller shafts, marine fixtures and fasteners, electronic components, chemical-processing equipment, gasoline and fresh-water tanks, petroleum-processing equipment, boiler feedwater heaters and other heat exchangers.". This is taken to be a wide variety of applications.

Ref. 5.42, pp. 373-378 lists the following applications for C 71500 (ASTM B 171 C71500): "Condensers, condenser plates, distiller tubes, evaporator and heat-exchanger tubes, ferrules, salt water pipe." This is taken to be a wide variety of applications.

7.3.1.1.4 Summary

Results from Sections 7.3.1.3.1 through 7.3.1.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria. The column "Total" gives the total score for the material.

Table 7.3.1.1.4-1. Ratings of materials for corrosion allowance barrier for SNF waste forms

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
ASTM A 387 Grade 22	7	6	15	15	30	10	10	0	0	93
ASTM A 516 Grade 55	9	6	15	15	30	10	10	0	0	95
ASTM A 516 Grade 70	9	6	15	15	30	10	10	0	0	95
ASTM B 127	8	12	15	10	20	2	10	0	0	77
ASTM B 171 C71500	7	9	12	15	15	4	10	0	0	72

ASTM A 516 Grade 55 and ASTM A 516 Grade 70 tie for the highest score. Either of these materials could be used; a choice between them will require additional engineering analysis. Inspection of the ratings for each material has not revealed any single rating that is so low that the material should be disqualified without further consideration. It is noted that the uncertainty in the inspectability of ASTM B 127 does not affect the final selection.

7.3.1.2 Corrosion resistant barrier

7.3.1.2.1 Candidate materials

The primary functional requirement for the corrosion resistant barrier is to act as an ultimate containment barrier between the environment and the waste form. Therefore, corrosion resistant properties of the barrier are significantly more important than other properties such as mechanical strength. This aspect is reflected in the selection of candidate materials and the criteria for evaluating them. Based on the functional requirement, the following materials were selected as candidates for further evaluation and ranking.

Common Names of Candidates	UNS Designation/ASTM Specification
Alloy 625/Inconel 625	N06625/ASTM B 443
Alloy C-4	N06455/ASTM B 575
Alloy C-22	N06022/ ASTM B 575
Titanium Grade 12	ASTM B 265 Grade 12
Titanium Grade 16	ASTM B 265 Grade 16

7.3.1.2.2 Constraints

A number of other alloys could have been selected as candidates. These include alloys such as Alloy C-276, and titanium Grade 7. It was, however, believed that the list should be based on the information obtained from prior screening efforts. Lawrence Livermore National Laboratory (LLNL) staff have reviewed degradation modes of a number of potential candidate materials for the waste disposal containers and have developed a list of candidate materials. Results of these studies are presented in References 5.8, 5.9, 5.21, 5.27, 5.28, 5.30, 5.44, and 5.95. Long-term corrosion tests were initiated on many of the candidate materials in support of the waste package development. This information forms the basis for the selection of candidate materials for this analysis.

Nickel-rich alloys such as Alloy 825 and Alloy G-30 were eliminated because preliminary results from corrosion testing at LLNL demonstrated that they are not sufficiently resistant to localized corrosion, and Alloy G-3 was eliminated because it is no longer available.

7.3.1.2.3 Selection criteria and ratings

All of the above listed candidates have good to excellent general corrosion resistance in a wide range of environments. If these materials suffer severe degradation, it is by a form of localized corrosion such as pitting or crevice corrosion (Ref. 5.27). Even these forms of corrosion occur only under most aggressive corrosive environments.

The selection criteria developed for evaluation of the candidate materials fall into two major groupings; performance related and engineering related. Each of these groupings has several subcriteria as shown below:

Performance related criteria (75 percent)
- -Critical parameters for initiation of crevice/pitting corrosion
- -Susceptibility to environmentally accelerated cracking
- -Formation of detrimental post-weld microstructure
- -Predictability of performance
- -Mechanical performance

Engineering related criteria (25 percent)
- -Weldability
- -Inspectability

7.3.1.2.3.1 Critical parameters for initiation of crevice/pitting corrosion

Weighting factor = 30 (total)

During fiscal year 97, an expert panel was convened by the Yucca Mountain Project to develop a better understanding of the waste package materials degradation processes. Based on a detailed review of the waste package design and the available definition of the near-field environment, this panel concluded that the most likely failure mode for the corrosion resistant barrier was crevice corrosion with the possibility of high aspect ratio pitting and stress corrosion cracking (Ref. 5.66, p. 3-11). Based on this observation, this criterion was assigned the highest weighting factor.

This criterion deals primarily with the chemical environment that develops on the surface of the corrosion resistant barrier. The crevice between the outer and the inner barrier will develop a "water chemistry" that can be significantly different from the bulk environment. The chemical conditions in the crevice between the outer and the inner barriers will be largely governed by the choice of outer barrier material and the fabrication process used for making the two-barrier container. The expert panel also concluded that the probability of initiation of crevice or pitting corrosion is a function of the availability of water, temperature, chloride ion concentration, pH, ferric ion concentration, crevice geometry, and oxygen (Ref. 5.66, p. 3-11). Many of these variables are independent of the material selected for the inner barrier. Examples include crevice geometry (determined by the fabrication process), waste package temperature (determined by the decay heat load), and availability of water (determined by water percolation rates). In addition, the chemical conditions within the crevice are also, to a large extent, independent of the inner barrier material for the following reasons. The water entering the repository drift is modified by the soluble salts from the rocks and the cementitious materials in the concrete liner. This water is further modified by the corrosion products from the degradation of the outer barrier. Therefore, the selection of the inner barrier will have to be made on the basis of the susceptibility of the material to the initiation of the crevice/pitting corrosion in an aggressive environment that could develop in the crevice.

The critical parameters for the initiation of the crevice/pitting corrosion are pH, temperature, and crevice chemistry. The crevice chemistry and pH may vary widely but are bound by hydrolysis and solubility constants and other equilibrium parameters, as well as diffusion kinetics of oxygen and other chemical species. However, as mentioned earlier, these parameters are independent of the inner barrier material and so they will be common to all of the inner barrier candidate materials. As a result, the critical (threshold) temperatures for the initiation of crevice/pitting corrosion for each of the candidate material becomes a reasonable basis for selection.

Since the critical temperatures for crevice corrosion and pitting are different for each candidate material, and since the two corrosion modes are equally important, the weighting factor for this criterion was divided equally between the two modes.

One of the requirements for the onset of crevice/pitting corrosion is the availability of liquid water. Therefore, the maximum temperature of interest is the boiling point of water. Ref. 5.67 (chart 6) shows that for reference waste package containing 21 PWR fuel assemblies, the waste package temperature decreases from about 100°C to about 30°C over a period of 1000 to 30,000 years after emplacement. Therefore, it is reasonable to evaluate the corrosion behavior of the candidate materials over this temperature range. Accordingly, the distribution of the ratings over this temperature range for the two corrosion mechanisms is shown below.

Rating for Crevice Corrosion	Critical Temperature for Initiation, T^0C	Rating for Pitting
15	$T > 100$	15
12	$100 \geq T > 80$	12
9	$80 \geq T > 60$	9
6	$60 \geq T > 40$	6
3	$40 \geq T > 20$	3

There have been several crevice corrosion studies on Ni-Cr-Mo alloys in a variety of environments. Unfortunately the test conditions for all of the candidate materials are not always the same. Ref. 5.68, Table 25, and Ref. 5.69, p. 9, show comparative data on critical temperatures for crevice and pitting corrosion for Alloy C-22 and Alloy 625. The test environment in the latter case was a solution containing 4% NaCl + 0.1% ferric sulfate + 0.021M HCl. This solution contained 24,300 ppm chloride and had a pH value of 2. The critical pitting and crevice corrosion temperatures for Alloy C-22 were >150^{0}C and 102^{0}C, respectively. For Alloy 625, these temperatures were 90^0 C and 50^0 C. No data were reported for Alloy C-4 for this environment. However, based on the critical crevice corrosion temperatures reported for all three alloys in a different environment (6% ferric chloride solution), the critical temperatures for alloy C-4 are expected to be the same as that for Alloy 625. It is to be recognized that the test environments are not representative of the repository conditions, and such aggressive environments may never develop in the crevice. The data are useful, however, for evaluating the relative susceptibilities of the candidate materials.

Titanium and its alloys are reported to be highly resistant to crevice and pitting corrosion. Ref. 5.70-5.73 provide consistent information on crevice corrosion and pitting of Ti alloys. Ref. 5.73, p. 12, states that "while extremely rare, pitting has been observed in hot anhydrous organic solvent streams, in high temperature oxidizing bromide solutions, in hot salt evaporators at T [temperature] >130^0 C and associated with embedded iron or steel particles" and "Pitting due to embedded iron particles has been observed during hot (>80^{0}C) brine exposure but is more appropriately considered as a special case of crevice corrosion [Covington 1976]. It can be avoided by proper handling techniques or by the use of alloys Ti-12, Ti-7 and Ti-16". Regarding crevice corrosion in titanium alloys, Ref. 5.70, Section 9.1 states "Ti Gr. 12 becomes susceptible above 75^0 C, however, pH levels must be below 2.5 in order for crevice corrosion to occur". Based on the above, it is concluded that critical pitting and crevice corrosion temperatures for Ti Grades 12 and 16 for the repository relevant conditions are 75^0 C and >100^0 C respectively. On the basis of above discussion, the following scores are derived for the candidate materials.

Material	Score		Total Rating
	Crevice	Pitting	
Alloy 625	6	12	18
Alloy C-4	6	12	18
Alloy C-22	15	15	30
Ti-12	9	9	18
Ti-16	15	15	30

7.3.1.2.3.2 Susceptibility to environmentally accelerated cracking

Weighting factor = 15

Included in this criterion are the susceptibility of the candidate materials to stress corrosion cracking, hydrogen-induced cracking, hydriding or hydrogen embrittlement. Unrelieved stresses from the welding operations could initiate cracking under corrosive crevice conditions. The source of hydrogen for potential hydriding or hydrogen embrittlement is believed to be corrosion of the outer barrier. Therefore, this criterion also addresses the compatibility between the inner and the outer barriers.

For ease of evaluation, the degradation mechanisms listed above were grouped into two broad categories: stress corrosion cracking (SCC) and hydrogen embrittlement. Of the two, SCC is believed to be less likely because the shrink-fit fabrication process used to assemble the inner and outer cylinders will result in compressive stresses on the inner barrier, and both barriers (cylinders) will be stress relieved after welding. Accordingly, the weighting factor of 5 was selected with the rating scale shown below.

Rating	Characteristic
5	Not susceptible to SCC
3	Slight susceptibility to SCC
0	Susceptible to SCC

Nickel alloys have been found to be not susceptible to SCC in a variety of chloride solutions. Ref. 5.68, Table 11 shows that Alloy 625 and C-22 showed no cracking compared to stainless steels when exposed to a number of different corrosive environments. Some alloys, such as Alloy 625, have shown SCC under high stress intensities and aggressive acid chloride solutions (Ref. 5.78).

It is possible that such high stress intensities may develop in the waste package closure weld regions. Therefore, it is concluded that the candidate nickel alloys may be slightly susceptible to SCC under highly corrosive environments and with residual stresses from welding operations.

Ref. 5.71 (P. 9) states that Ti Grade 1 and Grade 2 (both commercially pure) are essentially immune to SCC in sea water environment. This is also confirmed by Ref. 5.70 which states that "Ti gr. 2, 7, and 12 are immune to SCC except in a few specific environments and in these cases a small amount of water will effectively inhibit against SCC". The repository environment is expected to include water in the form of liquid and/or vapor. Based on the above discussion following scores are awarded.

Material	Rating
Alloy 625	3
C-4	3
C-22	3
Ti-12	5
Ti-16	5

Hydrogen Embrittlement (HE) -- Weighting factor = 10

Susceptibility to HE in the inner barrier is considered to be a significant disadvantage because the aqueous corrosion of the carbon steel outer barrier in the crevice is likely to produce hydrogen on the inner barrier surface if the two barriers are galvanically coupled. If the hydrogen is absorbed by the inner barrier, its effectiveness as the corrosion resistant barrier will be compromised.

Rating	Characteristic
10	No potential for HE
7	Slight potential for HE
4	Modest potential for HE
0	Great potential for HE

Ref. 5.68, Section 5.1, summarizes the potential for HE in the high Ni alloys. For failure to occur by HE, a number of factors are necessary, some of which may not be present under repository conditions. The alloys are highly resistant to HE in annealed conditions and require very high stress levels (cold-worked state) and galvanic coupling with carbon steel and aggressive environments for failure. Since it is possible that not all of the weld stresses may be relieved and

the material is in contact with the carbon steel outer barrier, it is concluded that a slight potential exists for HE in the candidate Ni alloys.

Titanium alloys, on the other hand, are susceptible to HE. While Ti is being used in many applications where process streams contain hydrogen, a more serious problem occurs when cathodically impressed or galvanically induced currents generate atomic hydrogen on the surface of titanium. The presence of moisture does not inhibit hydrogen absorption of this type (Ref. 5.71, p. 28). In addition, Ref. 5.71, p. 29, states the following:

> "Because titanium is usually the cathodic member of any galvanic couple, hydrogen will be evolved on its surface proportional to the galvanic current flow. This may result in the formation of surface hydride films that are generally stable and cause no problems. If the temperature is above 170° F (77°C), however, hydriding can cause embrittlement.
>
> In order to avoid problems with galvanic corrosion, it is best to construct equipment of a single metal. If this is not practical, use two metals that are close together in the galvanic series, insulate the joint or cathodically protect the noble metal".

These statements are taken to mean that the Ti alloys are not suitable when used in combination with the carbon steel outer barrier. The ratings shown below reflect this conclusion.

Material	Rating
Alloy 625	7
Alloy C-4	7
Alloy C-22	7
Ti-12	0
Ti-16	0

7.3.1.2.3.3 Formation of detrimental post-weld microstructure

Weighting factor = 5

This criterion deals with the potential formation of either corrosion-prone or more brittle phases due to the transformation of the unstable phases formed during container welding process and long term aging in the repository. It is expected that the formation of the undesirable phases during welding will be eliminated through a weld process qualification program. However, the potential for the development of these phases during the long post-emplacement period, when the waste package materials experience a moderate temperature aging process, is of concern. The data available on the phase stability of the candidate materials during aging is very limited. As a result, comparative ranking of materials will have to be based on qualitative evaluation of the available data.

Rebak and Koon (Haynes International Inc.) have studied the change in the mechanical properties of wrought and welded Alloy C-22 and Alloy C-4 due to long-term aging at low temperatures (Ref. 5.74). After aging for 40,000 hours at 427°C, Alloy C-22 showed a slight increase (10%) in mechanical properties. Alloy C-4 showed no change in mechanical properties but exhibited a slight increase in corrosion rate in the welded region in comparison to the base metal area. All of the C-alloys tested after aging for 40,000 hours at 427° C showed no evidence of μ phase precipitation. Aging at slightly higher temperatures (540°C) appear to cause significant hardening of the Alloy C-4 with doubling of yield strength (Ref. 5.68, Table 7).

Ref. 5.68 also addresses phase stability in nickel alloys. Section 2.4 of Ref. 5.68 states that "In terms of phase stability, Alloy C-4 is superior to Alloys C-22, C-276 and 625. Alloys C-22 and C-276 are susceptible to intermetallic and carbide precipitation. Alloy 625 is susceptible to carbide precipitation and microstructural ordering".

Ref. 5.75 presents data on the effects of long term service at about 500° C on Alloy 625. After 50,000 hours of service as feed stock superheater tubes in a petrochemical plant, the material was found to be severely age hardened. Room temperature elongation decreased from 46% to 7% with associated increase in tensile strengths.

While it is recognized that the data reported on the aging effects are for temperatures higher than those expected in the repository, the information available allows for qualitative comparison among the nickel alloys. It is concluded that of the three candidate nickel alloys, Alloy C-4 has the most phase stability and Alloy 625 the least with Alloy C-22 in the middle.

In the case of titanium alloys, Ti-16 is a single phase material and is expected to be stable at temperatures up to about 900° C (Ref. 5.70, Section 2.3). Ti-12 contains small additions of Mo (0.3 wt.%) and Ni (0.8 wt.%). Nickel solubility in α-titanium is less than 0.05 wt.% at 300° C, and below 760° C for nickel concentrations greater than 0.1 wt.%, an intermetallic phase Ti_2Ni forms (Ref. 5.70, Section 2.2). A similar situation exists for molybdenum, and at temperatures below 400°C, the alloy contains α-Ti and β(Mo,Ti). Thus the Ti-12 microstructure is a mixture of α-Ti, Ti_2Ni intermetallic and β-Ti. The β-phase is primarily located at the grain boundaries and grain boundary triple points. On the basis of this information, it is concluded that Ti-16 has a higher degree of phase stability compared to Ti-12.

As mentioned earlier, the lack of data on aging and phase stability at temperatures relevant to repository conditions does not allow for a rigorous quantitative ranking of the candidate materials. However, based on a qualitative evaluation of the available information, the following scores are assigned.

Material	Rating
Alloy 625	1
Alloy C-4	4
Alloy C-22	3
Ti-12	4
Ti-16	5

7.3.1.2.3.4 Predictability of performance

Weighting factor = 20

This includes availability of information on the candidate materials and the possibility of extrapolation of short term data to predict long term performance. The alloys that are historically older and have been more widely used are expected to have a larger database than the newer or less widely used alloys. However, the list of candidate materials includes only alloys which are derivatives of or improvements on older alloys. Therefore, comparative evaluation of the older and newer "improved" alloys under similar conditions of exposure would provide a reasonable basis for ranking these materials.

As mentioned earlier, all of the candidate materials have excellent corrosion resistance to variety of environments. As a result, the available database does not include meaningful data from tests using repository relevant environments. The tests typically involve exposure to highly aggressive environments and for relatively short periods. Prediction of long term performance under more benign conditions, based on short term testing in aggressive conditions is a complicated process and requires a thorough understanding of the effects of the test variables. It is, however, possible to develop mechanistic models for predicting long term behavior from short term test results.

<u>Availability of corrosion data</u>

Availability of corrosion information is reflected in coverage in handbooks.

In the article "Corrosion of Nickel-Base Alloys" (Ref. 5.31, pp. 641-657), corrosion data for the following alloys are given in the following places:

Alloy 625 (ASTM B 443): Figures 3, 5, 12, Tables 2, 3, 5, 7, 10, 11, 13, 14, 16, 19, 20
Alloy C-22 (ASTM B 575 N06022): Figures 3, 5, 6, 10, 11, 12, 13, Tables 2, 3, 5, 7, 14
Alloy C-4 (ASTM B 575 N06455): Tables 2, 7, 11, 13, 14, 20, 16

In addition, manufacturer's literature with significant corrosion data is also available:

Inconel Alloy 625 (ASTM B 443): Ref. 5.45, pp. 11-15
Hastelloy Alloy C-22 (ASTM B 575 N06022): Ref. 5.48, pp. 7-12
Inconel Alloy 622 (ASTM B 575 N06022): Ref. 5.49, pp. 2-3
Hastelloy Alloy C-4 (ASTM B 575 N06455): Ref. 5.50, pp. 5-9

In the article "Corrosion of Titanium and Titanium Alloys (Ref. 5.31, pp. 669-706), corrosion data for the following alloys are given in the following places:
Grade 7 (ASTM B 265 Grade 7): Figures 10, 14, 15, 16, 21, 22, 23, 24, 31, Table 7, 12, 13, 19, 21, 23, 24
Grade 12 (ASTM B 265 Grade 12): Figures 3, 10, 14, 15, 16, 21, 22, 23, 24, 31, Table 7, 11, 13, 19, 21, 23, 24

In addition, manufacturer's literature with significant corrosion data is also available:
Timetal 50A Pd (ASTM B 265 Grade 7): Ref. 5.71, text pp. 4, 7, 9, 12, 13, 17, 18, 20, 23, 25, 26, 27, Tables 4, 13, 15, 17, 21, Figures 4, 5, 7, 10, 11, 12, 25
Timetal Code-12 (ASTM B 265 Grade 12): Ref. 5.47, text pp. 4, 7, 9, 12, 13, 17, 18, 20, 23, 25, 26, 27, Tables 4, 13, 15, 17, 21, Figures 3, 5, 7, 9, 11, 12, 25

ASTM B 265 Grade 7 is mentioned here, even though it is not a candidate material, because it is similar to ASTM B 265 Grade 16 but has a higher palladium content. This can be seen from Ref. 5.18, Table 1; the composition requirements are the same except that ASTM B 265 Grade 7 has palladium content of 0.12% to 0.25%, whereas ASTM B 265 Grade 16 has a palladium content of 0.04% to 0.06%.

From the preceding information, it is clear that large amounts of corrosion data are available for ASTM B 265 Grade 12. Although no data were found for ASTM B 265 Grade 16, large amounts were found for the similar alloy ASTM B 265 Grade 7, so it is judged that sufficient amounts of corrosion data are available for ASTM B 265 Grade 16.

On the basis of this information, it is judged that large amounts of corrosion information are available for all three nickel alloys and titanium alloys. Nevertheless, predictions of waste package containment life will require additional data because systematic corrosion tests for conditions that are relevant to waste package degradation have not been reported in the literature.

Variety of applications

Another aspect of predictability of performance relates to the variety of application of the candidate materials.

Ref. 5.45, p. 1 lists seawater applications for Alloy 625, "wire rope..., propeller blades..., submarine auxiliary propulsion motors, submarine quick-disconnect fittings, exhaust ducts..., sheathing for undersea communication cables, submarine transducer controls, and steam line bellows;" aerospace applications, "aircraft ducting systems, engine exhaust systems, thrust-reverser systems, ... honeycomb structures..., fuel and hydraulic line tubing, spray bars, bellows, turbine shroud rings, and heat-exchanger tubing;" chemical processing applications, "bubble caps, tubing, reaction vessels, distillation columns, heat exchangers, transfer piping, and valves;" and nuclear applications, "reactor-core and control-rod components." This is judged to be a wide variety of applications.

Ref. 5.49, p. 1 lists the following applications for Inconel Alloy 622 (ASTM B 575 N06022): "chemical processing, flue gas desulfurization, hazardous waste incineration and pulp and paper processing." Ref. 5.48, p. 3 lists the following "areas of present or potential use" for Alloy C-22 (ASTM B 575 N06022): "• Acetic Acid/Acetic Anhydride • Cellophane Manufacturing • Chlorine Spargers • Chlorination Systems • Circuit Board Etching Equipment • Complex Acid Mixtures • Fans and Blowers • Galvanizing Line Equipment • Geothermal Wells • HF Furnaces • Incineration Systems • Nuclear Fuel Reprocessing • Pesticide Production • Phosphoric Acid Applications • Pickling System Components • Plate Heat Exchangers • Selective Leaching Systems • SO_2 Cooling Towers • Sulfonation Systems • Tubular Heat Exchangers." This is judged to be a wide variety of applications.

Ref. 5.71 lists numerous uses for titanium alloys: "in chlor-alkali cells; dimensionally stable anodes; bleaching equipment for pulp and paper; heat exchangers, pumps, piping and vessels used in the production of organic intermediates; pollution control devices; and even for human body prosthetic devices" (p. 5), "nearly twenty years of trouble-free seawater service for the chemical, oil refining, and desalination industries" (p. 8), "in wet SO_2 scrubber environments of power plant [flue gas desulfurization] systems" (p. 23), and "in molten aluminum for pouring nozzles, skimmer rakes and casting ladles" (p. 24). The reference also notes that Timetal Code-12 (ASTM B 265 Grade 12) and 50A Pd (ASTM B 265 Grade 7) "extend the usefulness of unalloyed titanium to more severe conditions" (p. 4). In view of the applications listed above and the many citations of these two grades in manufacturer's literature (see Section 7.3.3.3), ASTM B 265 Grade 12 is judged to have a wide variety of applications. In contrast, ASTM B 265 Grade 16 is not mentioned in Ref. 5.47, so it is judged to have a limited variety of applications. However, in view of it similarity to Grade 7 it is considered equally acceptable.

Based on the above discussion, it is concluded that adequate amounts of corrosion data are available on the candidate materials and they or their equivalent alloys have been used in a variety of applications. However, the data available are not readily applicable to predictability of performance in the repository, as the data involve tests in highly aggressive conditions for very short duration. Excellent corrosion resistance of the candidate materials precludes collection of meaningful corrosion data under relatively benign conditions expected in the repository even after exposures for months or years. Nevertheless, in recognition of the limitation of the data relevant to repository conditions, all of the candidate materials were assigned significantly less than the maximum rating possible as shown below.

Material	Rating
Alloy 625	10
Alloy C-4	10
Alloy C-22	10
Ti-12	10
Ti-16	10

7.3.1.2.3.5 Mechanical performance

Weighting factor =5

It was mentioned earlier that mechanical properties of the inner barrier are not as important as the corrosion resistance as the barrier is not needed for structural strength of the waste package. However, under certain circumstances such as rock fall, it is desirable to have a barrier that can withstand the dynamic load and offer some physical protection to the waste form. The weighting factor of 5 reflects the level of importance assigned to this criterion.

One method of determining the relative abilities of different materials to withstand dynamic loads is to compare their energy absorbing characteristics. The concept of strain energy in the elastic and plastic regions of the stress-strain curve is used to determine a quantitative dynamic impact energy absorption property for the materials. The strain energy per unit volume of a material is a function of the stress and strain developed in the subject material. Considering a unit length for the material, the cross sectional area times the strain energy per unit volume of a specific material gives the total strain energy stored by elastic and plastic deformations. The following rating scale was selected for comparing the strain energy of the candidate materials.

Rating	Strain Energy SE, MPa
5	250 ≥ SE ≥ 200
4	200 ≥ SE ≥ 150
3	150 ≥ SE ≥ 100
2	100 ≥ SE ≥ 50
1	50 ≥ SE ≥ 0

The equations used for deriving the strain energy for the materials are given below:

Elastic strain energy per unit volume = $(\frac{1}{2})(S_y)^2 / E$
Plastic strain energy per unit volume = $(e - S_y / E)(\frac{1}{2})(S_u + S_y)$

where:
S_u = Tensile strength
S_y = Yield strength
E = Modulus of elasticity
e = Elongation

The first relation is the area below the elastic region of the stress strain curve, whereas the second relation is obtained from the plastic region of the same curve. The total strain energy is the summation of the elastic and plastic energies. Since the total strain energy is only a function of the material properties listed above, it can be determined for all materials for comparison of their dynamic impact energy absorption characteristics. Table below contain a list of materials and corresponding properties at room temperature and the total strain energy calculated for the candidate materials.

Total strain energy calculated for the candidate materials

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Modulus of Elasticity (GPa)	% Elongation	Density (kg/m³)	Poisson's Ratio	Total Strain Energy, MPa
Alloy 625	758[1]	379[1]	208[2]	30[1]	8442[1]	0.278[2]	169.51
C-4	690[3]	276[3]	211[6]	40[3]	8636[3]	0.278[5]	192.57
C-22	690[3]	310[3]	203[4]	45[3]	8691[3]	0.278[5]	224.24
Ti-16	345[7]	275[7]	107[8]	20[7]	4512[8]	0.32[8]	61.56
Ti-12	483[7]	345[7]	107[8]	18[7]	4512[8]	0.32[8]	73.74

Notes:
1. Ref. 5.20
2. Ref. 5.79
3. Ref. 5.22
4. Ref. 5.80
5. Poisson's ratio was not available for this material. Since the chemical composition is similar to Alloy 625, Poisson's ratio of Alloy 625 can be used for this material.
6. Ref. 5.50
7. Ref. 5.18

8. Ref. 5.81
It is noted that the total strain energies of all three nickel alloys (625, C-22 and C-4) are significantly higher than those of the titanium alloys. Based on the ratings scale, the following scores are obtained for the candidate materials.

Material	Score
Alloy 625	4
Alloy C-4	4
Alloy C-22	5
Ti-12	2
Ti-16	2

7.3.1.2.3.6 Fabricability

Scores for fabricability were taken to be the scores for weldability and inspectability.

Weldability: weighting factor = 20

Weldability is an important factor in the fabrication of the waste packages. While most of the welding operations in fabricating the waste packages are expected to be performed using conventional operations, the final closure welds will require remote operations. This makes the weldability of the material particularly important because the remote operations introduce additional complications. Materials which are difficult to weld outside the hot cells are likely to take much longer to weld remotely and are likely to exhibit a larger fraction of weld flaws because of the difficulties in keeping the weld areas clean between weld passes.

Rating	Characteristic
20	Welds easily
15	Welds with slight difficulty
5	Welds with great difficulty

ASTM B 265 Grades 12 and 16 are both classified as unalloyed or commercially pure titanium.

This is evidenced by Ref. 5.54. On p. 8, the alloy Ti-50 with Pd (ASTM B 265 Grade 7) is referred to as "commercially pure"; on p. 9, Ti-Code 12 (ASTM B 265 Grade 12) is referred to as "commercially pure". ASTM B 265 Grade 16 is not discussed in Ref. 5.54, but should also be considered "commercially pure" because its composition specifications are the same as those for Grade 7 except that the palladium content is lower. Ref. 5.38, p. 508 describes commercially pure (unalloyed) titanium products as "highly ... weldable." However, p. 512 of the same reference notes of titanium that "At temperatures exceeding 500 C (930 F), its oxidation resistance decreases rapidly, and the metal becomes highly susceptible to embrittlement by oxygen, nitrogen, and hydrogen, which dissolve interstitially in titanium. Therefore, the melting, solidification, and solid state cooling associated with fusion welding must be conducted in completely inert or vacuum environments. ... In addition to proper shielding, welded component cleanliness (including filler metals) is necessary to avoid weld contamination." These statements are taken as evidence that ASTM B 265 Grades 12 and 16 can be welded with slight difficulty.

Ref. 5.38, pp. 593-597 discusses the welding of nickel-base corrosion resistant alloys containing molybdenum. This class of alloys includes alloys C-22 (ASTM B 575 N06022), C-4 (ASTM B 575 N06455), G-30 (ASTM B 582 N06030), and G-3 (ASTM B 582 N06985), as is indicated by Table 1 on p. 593 of the reference. The reference goes on to state (p. 594) "Gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW), and shielded metal arc welding (SMAW) are commonly used to join this family of [corrosion resistant] alloys. ... Proper preparation of the weld angles is a very important part of welding these nickel-base [corrosion resistant] alloys. It is necessary to condition all thermal cut edges to bright, shiny metal prior to welding. ... In addition to the weld angle, a 25 mm (1 in.) wide band on both the top and bottom (face and root) surface of the weld zone should be conditioned to bright metal... The welding surface and adjacent regions should be thoroughly cleaned with an appropriate solvent prior to any welding operation. All greases, oils, cutting oils, crayon marks, machining solutions, corrosion products, paints, scale, dye-penetrant solutions, and other foreign matter should be completely removed." In addition, Ref. 5.38, p. 596 notes that "C-type alloys" (C-4 and C-22, ASTM B 575 N06455 and ASTM B 575 N06022, respectively) are subject to hot cracking. However, recently, a number of manufacturers were contacted as part of industry survey on weldability of Alloy C-22 (Ref. 5.76). None of the fabricators had experienced any problems welding C-type alloys and Alloy C-22 in particular. Some of the fabricators also stated that welding of C-22 was no different from that of Alloy 625. Ref. 5.45, p. 1 states that Alloy 625 has "excellent weldability". This statement is taken to as evidence that the candidate nickel alloys weld easily.

On the basis of above discussions, the scores obtained for the candidate materials are shown in the following table.

Material	Rating
Alloy 625	20
Alloy C-4	20
Alloy C-22	20
Ti-12	15
Ti-16	15

Inspectability: weighting factor = 5

Inspectability is rated according to the applicability of ultrasonic testing, as rated in Ref. 5.38, p. 1086, Table 1.

Ref. 5.38, p. 1038, Table 1 rates ultrasonic testing as "applicable" for titanium alloys. This class of materials includes ASTM B 265 Grades 12 and 16.

The reference does not rate the applicability of ultrasonic testing to the candidate nickel alloys. The most closely related alloys mentioned in the reference are the duplex stainless steels, for which ultrasonic testing is rated as "applicable." In the absence of other evidence, ultrasonic testing is rated as "applicable" for the six candidate nickel alloys (ASTM B 424 N08825, ASTM B 443, ASTM B 575 N06022, ASTM B 575 N06455, ASTM B 582 N06030, and ASTM B 582 N06985).

Material	Rating
Alloy 625	5
Alloy C-4	5
Alloy C-22	5
Ti-12	5
Ti-16	5

7.3.1.2.4 Summary

Results from Sections 7.3.2.3.1 through 7.3.2.3.6 are summarized in the following table. The column "Total" gives the total score for the material.

Table 7.3.1.2-1. Ratings of materials for corrosion resistant barrier for SNF waste forms

Material	Rating								
	Corr.	SCC	HE	Ph.	Pred.	Mech	Weld.	Insp	Total
Alloy 625	18	3	7	1	10	4	20	5	68
Alloy C-4	18	3	7	4	10	4	20	5	71
Alloy C-22	30	3	7	3	10	5	20	5	83
Ti-12	18	5	0	4	10	2	15	5	59
Ti-16	30	5	0	5	10	2	15	5	71

In the table above, Alloy C-22 received the highest score. This material is selected for use as the corrosion resistant material for the design incorporating ASTM A 516 carbon steel as the outer barrier. It is to be noted that a different choice for the outer barrier may result in different ratings for the candidate materials.

7.3.2 Dual-barrier design -- Option 2

This option involves the use of two corrosion resistant materials as barriers. The primary purpose of this design option is to improve the waste package lifetimes significantly beyond the current requirements.

7.3.2.1 Constraints

The concept of defense in depth requires that the materials chosen for the inner and outer containment barriers have different degradation modes. However, because of the excellent resistance to general corrosion, the primary mode of degradation for all of the candidate materials is localized corrosion. A possible approach to maintaining a certain degree of defense in depth is to choose different classes of materials for the inner and outer barriers, in this case, one barrier each from nickel and titanium alloys.

7.3.2.2 Candidate materials

The design option requires a high degree of corrosion resistance for both barriers. The candidate materials selected for the corrosion resistant barrier for the Design Option 1 includes materials with excellent corrosion resistance and materials from two different classes of materials (nickel and titanium alloys). From this list, two of the nickel alloys, C-4 and C-22 and the two titanium alloys, grades 12 and 16, are selected as candidates for further evaluation for this design option.

7.3.2.3 Selection criteria and ranking

7.3.2.3.1 Outer barrier

The functional requirements for the outer barrier include high degree of corrosion resistance and adequate mechanical strength to meet handling requirements. This barrier should also be strong enough to absorb dynamic loading from rockfall and accidental drops and tip over during handling operations. Accordingly, the following criteria are considered applicable to selection of the outer barrier.

-Corrosion resistance (general and local corrosion)
-Mechanical properties
-Compatibility with other interfaces
-Fabricability

All of the above criteria have been evaluated quantitatively for the candidate materials in Section 7.3.1.2. Therefore, it is not necessary to repeat those numerical ratings for each of the selection criteria in this section. Qualitative assessment of the candidate materials against the criteria is believed to be sufficient for the selection process and is summarized below.

Corrosion resistance: While all of the candidate materials have excellent corrosion resistance, C-22 and Ti-16 have been rated as superior to other materials. Both these materials have high threshold temperatures for pitting and crevice corrosion and both are resistant to stress corrosion cracking.

Mechanical properties: Of the four candidate materials, C-22 exhibits the highest energy absorption property as shown in Section 7.3.1.2.3.5. This property is important because it represents the ability of the material to withstand dynamic loads such as rockfall in the emplacement drifts and not perforate. Both titanium alloys fare poorly in this category. All of the candidate materials have adequate mechanical strengths but the titanium alloys have much lower ductility.

Compatibility with other interfaces: The primary interface for the outer barrier consist of the waste package handling equipment, waste package supports, and the transporter. All of these will be made from different steels and nickel alloys are highly compatible with them. Titanium alloys on the other hand, suffer from a potential for localized corrosion due to embedded or smeared iron particles (Ref. 5.73). While this form of corrosion is rare and requires highly aggressive conditions, use of titanium for the outer barrier may require modifications to the handling equipment to mitigate this problem.

Fabricability: As discussed in Section 7.3.1.2.3.6, nickel alloys have better weldability than the titanium alloys. This aspect is particularly important for the remote welding operations required for the closure welds.

Summary: Based on the qualitative assessments of the candidate materials against the selection criteria and the information presented in Section 7.3.1.2, Alloy C-22 is selected as the material for the outer barrier for Design Option 2.

7.3.2.3.2 Inner barrier

The functional requirements for the inner barrier are different from those of the outer barrier. The inner barrier does not have to serve as the primary a structural component of the waste package and so the mechanical properties are not as important as for the outer barrier. The inner barrier also serves as the ultimate containment barrier to the release of radionuclides to the environment. Therefore, the most important selection criterion is the corrosion resistance (both general and local) of the material. Other criteria important for selection are the compatibility with the outer barrier and interfaces and fabricability.

Corrosion resistance: As in the case of the outer barrier selection, C-22 and Ti-16 emerge as leading candidate materials. Ti-16, however, has greater corrosion resistance in acidic environments and has high threshold for pitting and crevice corrosion. In addition, the absence of a carbon steel outer barrier makes this material more attractive in that the potential for hydrogen embrittlement and smeared surface iron pitting will not be present.

Compatibility with other interfaces: The primary interface for the inner barrier is the outer barrier. Both nickel and titanium alloys are compatible with each other from the galvanic corrosion standpoint.

Fabricability: Ease of fabrication is equally important for the inner barrier as the outer barrier. As mentioned earlier, nickel alloys are easier to weld than titanium alloys.

Summary: Based on the above discussion and based on the selection of C-22 for the outer barrier, Ti-16 is selected for the inner barrier for the Design Option 2 consisting of two corrosion resistant materials.

7.3.3 Single barrier design -- Option 3

In this option, the two barriers are replaced with a single barrier. The functional requirements for this barrier include those of the inner and outer barriers of Design Options 1 and 2. This option has several advantages over the others. This design constitutes a simpler design and provides for ease of fabrication. It also eliminates the crevice between the inner and the outer barriers (cylinders) and the associated risks of developing aggressive crevice chemistries.

7.3.3.1 Constraints

Use of a single barrier design results in the loss of the defense in depth concept. The barrier will have to act both as a structural component and as the ultimate barrier for radionuclide release to the environment. Therefore, the mechanical properties and the corrosion resistance are the two most important criteria in material selection.

7.3.3.2 Candidate materials

In view of the corrosion resistance requirements, all of the materials selected for the Design Option 2 (dual-barrier design with two corrosion resistant materials) will be appropriate candidates. Accordingly, alloys C-4, C-22, Ti-12, and Ti-16 are selected as candidate materials.

7.3.3.3 Selection criteria and ranking

For a single barrier design, the following criteria are considered most important:

-Corrosion resistance (general and local)
-Mechanical properties
-Compatibility with other interfaces

-Fabricability

As mentioned earlier in the previous sections, both C-22 and Ti-16 are excellent choices based on corrosion resistance requirements.

From the mechanical property standpoint, C-22 is superior to Ti because of its high ductility and strain energy property. It is, however, possible to provide adequate structural strength, to some extent, by increasing the material thickness used. This may not always be desirable in some cases due to fabricability and possible increase in cost. For example, preliminary calculations show that the thickness of titanium required to withstand a 25 metric ton rock fall is about 3.5 times that required for C-22. These calculations also show that the weight of titanium required is about twice that of C-22 (e.g., 15,351 kg for 120 mm thickness vs 8,026 kg for a 35 mm thickness for a 21 PWR uncanistered fuel waste package) to withstand a 25 metric ton rock fall (Ref. 5.77). Informal contacts with several of the alloy manufacturers suggest that the costs per kg of titanium (grade 16) is about 1.5 times that of Alloy C-22. This shows that a single barrier waste package fabricated with Ti-16 will cost about three as much as that fabricated with C-22 for the same mechanical property requirements based on the 25 ton rock drop criterion.

Another criterion of importance is the material compatibility with the interfaces. As mentioned earlier, titanium barriers require careful handling to avoid embedded iron or smeared iron particles which could cause enhanced local corrosion. Alloy C-22 has a high degree of compatibility with the steels used for handling equipment and waste package supports and does not have the same problem as titanium.

Fabricability is another important criterion in the selection of materials. While it appears that all of the candidate materials should be weldable based on the wide variety of applications that all of the candidate materials or their equivalents have been used, titanium alloys require more care during welding than others. Welding of titanium requires inert atmospheres and thorough cleaning of weld areas after each pass to prevent contamination. These requirements make remote welding process more complicated for titanium than that for the nickel alloys.

7.3.3.4 Summary

It is clear that C-22 and Ti-16 are best suited for a single barrier design from a corrosion resistance standpoint. Titanium, however, has potential problems due to difficulties in welding and compatibility with handling equipment made of steel. Based on this evaluation, C-22 is selected as the containment barrier material for the single barrier design.

7.3.4 Evaluation of the design options

A comparative evaluation of the three design options is necessary in order to select the optimal design which meets current goals and requirements with a significant performance margin in a cost effective manner. Criteria for evaluation have been selected with this objective in mind.

Of the three design options under consideration, the single barrier option may be the least viable. This option, while providing a simpler design and apparent ease of fabrication, has a significant shortcoming. The option does not provide for the defense in depth concept which is important for providing added performance margin. Use of a single barrier requires this barrier to provide both structural strength and excellent corrosion resistance and does not allow for any margins for fabrication and operational errors. There are other problems associated with this option. For example, the thickness of the single containment barrier required to provide sufficient structural strength and corrosion protection is expected to be significantly large. Preliminary calculations show that at least 35 mm of C-22 and/or 120 mm of Ti Grade 16 will be needed to withstand dynamic loads from 25 metric ton rock falls (Ref. 5.77). At this time, there is no industrial experience base for fabricating components involving these thicknesses of titanium. Ref. 5.83 indicates that capability for welding titanium plates is limited to about 50 mm at this time. It is also uncertain that titanium plates of 120 mm thicknesses are readily available. In addition, use of single barrier titanium may also require modifications of handling equipment made of steel in order to avoid potential for enhanced corrosion associated with the smeared surface iron particles. On the basis of the above discussion, it is concluded that the single barrier option is not viable at this time and will not be considered for further evaluation.

The remaining two design options (using the dual barrier concept) were evaluated using the following criteria.

- -Performance of the barriers (waste package lifetime)
- -Fabrication issues
- -Cost

Evaluation of each option against the criteria are provided below.

Barrier performance:

It is expected that the waste package barriers will be designed to meet the structural requirements including those for drops, tip-overs, and rock fall scenarios. These functional requirements are common to both design options being evaluated. Discriminating parameters which could help in the selection process are then limited to corrosion performance of the barriers and the associated waste package lifetime predictions. Prediction of waste package lifetimes require corrosion models based on data obtained under repository relevant conditions and unfortunately these are often unavailable. However, using the data from tests under highly aggressive environments, models have been developed for calculating corrosion rates and waste package lifetimes (Ref. 5.84).

CAM-CRM design -- Option 1: For this option, a definition of the near-field environment as a function of time is important because of the relatively low corrosion resistance of the carbon steel outer barrier. Based on the current waste package emplacement schemes (83 MTU/acre, no backfill, 6.2 mm/yr water infiltration), it is expected that the waste package surface temperatures will reach about 100°C at about 3000 years after emplacement (Ref. 5.67). The relative humidities at the waste package surface is estimated to be in the range 90-100%. The water contacting the waste package surface at this time is expected to be near-neutral pH and not modified by concrete as the concrete drift liner is expected to have collapsed onto the waste package. Under these conditions, the dominant corrosion mode for the barrier material is general aqueous corrosion and not localized pitting. This is expected to increase the lifetime of this barrier.

A recent calculation examined the corrosion lifetime of this waste package design option. In this calculation, the contribution of the corrosion allowance material was neglected. Instead, it was conservatively assumed that corrosion of the corrosion resistant material begins as soon as the surface of the waste package cools to 100°C. The total depth of penetration was taken to be the sum of the contributions from general and localized corrosion. The standard inner barrier thickness of 20 mm was used. Under these assumptions, the corrosion life of the inner barrier was calculated to be about 530,000 years (Ref. 5.85).

Two CRM design (Option 2): For this option, the definition of the near-field environment is not nearly as important as for the other design option. Water contacting the outer barrier is again expected to be at near neutral pH and under these conditions, the Alloy C-22 is highly corrosion resistant. The containment lifetime of this design option was also calculated using the same rate equations. As for Option 1, it was assumed that corrosion of the outer corrosion resistant material begins as soon as the surface of the waste package cools to 100°C. The assumption is conservative for both options, but it is not as conservative for Option 2 as for Option 1 because there is no corrosion allowance barrier. For a C-22 barrier with a thickness of 55 mm, the corrosion lifetime was calculated to be about 1,500,000 years (Ref. 5.85). Models of titanium corrosion have been developed for the Canadian repository programs but were not used in the calculations because of the uncertainties in the potential crevice conditions from the C-22 barrier. In addition, the long lifetimes calculated for C-22 makes it unnecessary for calculating Ti corrosion as it is clear that the corrosion lifetime of the combined barriers is at least as long as that of the outer barrier alone.

It is clear from the calculated barrier lifetimes, both design options meet the 3000 year lifetime requirements/goals with sufficient margin. It is also clear that the two CRM design is superior to the CAM-CRM design option in terms of corrosion performance. It is to be noted that corrosion rates calculated for the CRMs is based on very aggressive environments and the lifetimes expected for the realistic repository conditions may be significantly higher.

Fabrication issues: The fabrication issues of concern are all associated with weldability of the barrier materials and have been addressed at various levels of detail in the previous sections. It has been shown earlier that nickel alloys are significantly easier to weld than the titanium alloys.

The CAM-CRM design option is expected to have no fabrication problems due to material weldability.

The two CRM design option may have significant problems because of the difficulty in welding titanium. A recent industry survey (Ref. 5.83) of fabricators showed that welding of titanium requires a high degree of process control to prevent contamination of the weld areas. Contamination of the welds from minute impurities are said to potentially cause weld embrittlement. In addition, welding operations need to be done in inert atmospheres to prevent oxidation of weld areas. These problems are expected to be compounded for the remote welding operations required for the closure lid weld. The extreme measures required for welding titanium raises concerns for the quality of the weld produced by remote operations. In addition, welding of thick sections (25 mm) may require intermediate stress relieving operations resulting in longer fabrication times and higher costs.

Cost: Costs of the CRMs have not been addressed previously as they were considered secondary to the performance related issues. However, in evaluating different design options which meet the functional requirements with adequate margins, cost can be a useful discriminating factor.

In calculating cost comparisons, the barrier materials thicknesses used were the same as those used for lifetime calculations. Several different material vendors were contacted but formal price quotes could not be obtained due to a lack of well defined certification requirements. However, informal estimates were available for all of the materials of interest.

Ref. 5.77 provides mass for each of the barrier materials for the thicknesses being used. These are listed below.

Carbon steel, 100 mm = 22,782 kg
Alloy C-22, 20 mm = 4,345 kg
Alloy C-22, 55 mm = 12,574 kg
Ti Grade 16, 20 mm = 2,256 kg

Material costs:
Carbon steel, $0.4/lb
Alloy C-22, $8.50/lb
Ti Grade 16, $12.64/lb
Above cost figures include costs related to material certification.

Using the above weights and the costs of the materials, the cost of CAM-CRM package (for 21 PWR uncanistered fuel) including fabrication costs was calculated to be $398,725 and that for the two CRM package $686,846. These cost figures are preliminary and are being used here only to show approximate differences between the two design options being evaluated. Formal estimates of costs are expected to be available at a later date.

Recommendation: It is clear from the above discussions, that the two CRM design is far superior to the CAM-CRM option based on corrosion performance. However, in view of the fabrication problems associated with welding titanium, the CAM-CRM option is recommended for use for TSPA-VA. It is to be noted that this option meets the current lifetime requirements of 3000 years for 99.9% of waste packages with a margin of more than two orders of magnitude. It is also recommended that the two CRM option be pursued further because of its potential for excellent performance. A development program for remote welding of titanium should be pursued and a successful demonstration of remote welding of titanium should lead to a reevaluation of the selection of containment barrier materials for repository license application.

7.4 *Section not used*

7.5 *Section not used*

7.6 Fuel basket tubes for SNF waste forms

7.6.1 Candidate materials

Much of the early work on materials selection considered only the containment barriers, and serious consideration of fuel baskets is a relatively recent development, so this component was not treated in previous reports on materials selection.

As is discussed in Section 7.1, the fuel basket tubes are intended primarily to help in conducting heat from the fuel to the containment barriers. The fuel basket tubes also contribute to preventing criticality by displacing moderator, whether they are in their original condition or have been converted to corrosion products. The tubes also contribute to maintaining structural integrity by supporting loads due to handling, emplacement, and (if necessary) retrieval.

Candidate materials were taken to be the same as those for the corrosion allowance barrier for SNF waste forms: ASTM A 27 Grade 70-40, ASTM A 387 Grade 22, ASTM A 516 Grade 55, ASTM A 516 Grade 70, ASTM B 127, and ASTM B 171 C71500. Since this component is intended primarily to conduct heat from the fuel to the containment barriers, its importance decreases as the output of decay heat decreases, and the more expensive corrosion resistant materials are not needed.

7.6.2 Constraints

Plans for fabrication are that the fuel basket tubes are to be made of wrought material. Of the candidate materials, ASTM A 27 is a specification for steel castings (Ref. 5.11), so this analysis will not consider that material further. Some common names for the remaining candidate materials are given in Section 7.3.1.1.2.

7.6.3 Selection criteria and ratings

The functions of this component are discussed in Section 7.1, along with the criteria that will be used to determine the effectiveness of the materials in performing the functions. The following discussion justifies the choices of weighting factors that are listed in Table 7.1-1.

As is discussed in Section 7.1, this component must be able to sustain mechanical loads due to handling, emplacement, and, if necessary, retrieval, but these loads are not especially large, so a light weighting factor (10) is applied to mechanical performance. This component is not intended to provide corrosion resistance, so a zero weighting factor is assigned to both chemical performance and predictability of performance. The tubes are in contact with both the waste form and the fuel basket plates. If the tubes cause degradation of the waste form, release rates could be increased, and if they cause degradation of the plates, criticality control could be compromised, so a moderately large weighting factor (20) is applied to compatibility with other materials. The material will be formed into tubes and the tubes will be welded together, so a moderately large weighting factor (20) is applied to fabricability. Long-term performance is not required of the tubes, so expensive corrosion resistant materials are not needed. In addition, the tubes have a significant mass, a large weighting factor (25) is applied to cost. Since predictions of chemical performance are not important, previous experience is assigned a zero weighting factor. The tubes provide an important path for conducting heat from the fuel to the containment barriers, so a large weighting factor (25) is applied to thermal performance. Although the component and its corrosion products will serve to displace moderator, this component is not designed to provide a neutron-absorbing function, so no weighting is applied to neutronic performance. For reference, these weighting factors are also given in Table 7.1-1.

7.6.3.1 Mechanical performance

Weighting factor = 10

As in Section 7.3.1.1.3.1, mechanical performance score is the sum of scores for strength and ductility, and the definitions of strength and ductility are the same as those used in that section. Justification for this choice of properties is given in Section 7.3.1.1.3.1. In general, higher strength and higher ductility are preferable.

Strength:

Rating	Characteristics
5	Yield strength > 250 MPa
4	250 MPa ≥ Yield strength > 200 MPa
3	200 MPa ≥ Yield strength > 150 MPa
2	150 MPa ≥ Yield strength > 100 MPa
1	100 MPa ≥ Yield strength > 50 MPa
0	50 MPa ≥ Yield strength

Material	Yield strength, MPa	Rating	Reference
ASTM A 387 Grade 22	207	4	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	207	4	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	262	5	Ref. 5.14, Table 2.
ASTM B 127	193	3	See text below.
ASTM B 171 C71500	124	2	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

Ductility:

Rating	Characteristics
5	Elongation > 25%
4	25% ≥ Elongation > 20%
3	20% ≥ Elongation > 15%
2	15% ≥ Elongation > 10%
1	10% ≥ Elongation > 5%

0	5% ≥ Elongation

Material	Elongation, %	Rating	Reference
ASTM A 387 Grade 22	18	3	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	27	5	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	21	4	Ref. 5.14, Table 2.
ASTM B 127	35	5	See text below.
ASTM B 171 C71500	30	5	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

7.6.3.2 Chemical performance

Weighting factor = 0

7.6.3.3 Predictability of performance

Weighting factor = 0

7.6.3.4 Compatibility with other materials

Weighting factor = 20

Scores for compatibility with other materials were taken to be the sum of scores for compatibility with the fuel basket plates and for compatibility with the waste form.

Compatibility with the fuel basket plates:

The function of preventing criticality is allocated primarily to the fuel basket plates, and corrosion of that component could lead to loss of neutron absorbing material or settling of neutron absorbing material to the bottom of the waste package, where it would be less effective in controlling criticality. The fuel basket tubes and plates are in close contact, so, if the containment barriers are breached, there is the possibility for galvanic corrosion of one component or the other. Compatibility of the fuel basket tubes is defined as their providing galvanic protection for the fuel basket plates. The effectiveness of galvanic protection has been determined according to the galvanic series (Ref. 5.31, p. 235, Fig. 1). As is discussed in Section 7.3.1.1.3.4, the strategy in materials selection is that, regardless of the environment, the fuel basket tubes should corrode sacrificially and protect the plates.

Rating	Characteristics
14	Expected to provide galvanic protection: Entire galvanic potential range for the material of the fuel basket tubes is below the range for any candidate material for the fuel basket plates.
7	May or may not provide galvanic protection: Galvanic potential range for the material of the fuel basket tubes overlaps the range for some candidate material(s) for the fuel basket plates but does not extend above the top of the range for any candidate material for the fuel basket plates.
0	Not expected to provide galvanic protection: Galvanic potential range for the material of the fuel basket tubes extends above the top of the range for some candidate material for the fuel basket plates.

Material	Rating	Reference
ASTM A 387 Grade 22	14	See text below.
ASTM A 516 Grade 55	14	See text below.
ASTM A 516 Grade 70	14	See text below.
ASTM B 127	7	See text below.
ASTM B 171 C71500	14	See text below.

According to Ref. 5.31, p. 235, Fig. 1, the maximum galvanic potential for low-carbon steel and low-alloy steel in seawater are about −570 mV versus a saturated calomel electrode (SCE). These materials are comparable to ASTM A 387 Grade 22 and ASTM A 516 Grades 55 and 70. Similarly, 70-30 copper nickel (ASTM B 171 C71500) has a maximum galvanic potential of about −170 mV SCE, and nickel-copper alloy 400 (ASTM B 127) has a maximum galvanic potential of about −20 mV SCE.

The candidate materials for the fuel basket plates are based on stainless steels, particularly, types 304 and 316. Because of the benign nature of the base case for the near-field environment, these materials are expected to be in the passive state, and the ranges of passive potentials are considered here. The lower end of the galvanic potential range for these may be as low as −100 mV SCE (for both type 304 and type 316), and the upper end may be as low as −30 mV SCE (for type 304). From the data given here and in the previous paragraph, it is seen that ASTM B 127 may or may not provide galvanic protection, but all of the other materials are expected to provide galvanic protection.

Compatibility with waste form:

Rating	Characteristics
6	No evidence of degradation of waste form by material or its products of corrosion.
0	Evidence of degradation of waste form by material or its products of corrosion.

Material	Rating	Reference
ASTM A 387 Grade 22	6	See Section 7.3.1.1.3.4.
ASTM A 516 Grade 55	6	See Section 7.3.1.1.3.4.
ASTM A 516 Grade 70	6	See Section 7.3.1.1.3.4.
ASTM B 127	6	See Section 7.3.1.1.3.4.
ASTM B 171 C71500	6	See Section 7.3.1.1.3.4.

7.6.3.5 Fabricability

Weighting factor = 20

Scores for fabricability were taken to be the sum of scores for formability and weldability. Since this component does not have a containment function, all welding can be completed before the waste form is placed in the package. As a result, the full range of nondestructive evaluation methods are available for inspection, and inspectability will not have a significant effect on materials selection.

Formability:

Rating	Characteristics
10	Forms easily.
5	Forms with slight difficulty.
0	Forms with great difficulty.

Material	Rating	Reference
ASTM A 387 Grade 22	10	See Section 7.3.1.1.3.5.
ASTM A 516 Grade 55	10	See Section 7.3.1.1.3.5.
ASTM A 516 Grade 70	10	See Section 7.3.1.1.3.5.
ASTM B 127	5	See Section 7.3.1.1.3.5.
ASTM B 171 C71500	5	See Section 7.3.1.1.3.5.

Weldability:

Rating	Characteristics
10	Welds easily.
5	Welds with slight difficulty.
0	Welds with great difficulty.

Material	Rating	Reference
ASTM A 387 Grade 22	10	See Section 7.3.1.1.3.5.
ASTM A 516 Grade 55	10	See Section 7.3.1.1.3.5.
ASTM A 516 Grade 70	10	See Section 7.3.1.1.3.5.
ASTM B 127	10	See Section 7.3.1.1.3.5.
ASTM B 171 C71500	10	See Section 7.3.1.1.3.5.

7.6.3.6 Cost

Weighting factor = 25

As in Section 7.3.1.1.3.6, "cost" is defined as the price per kilogram of raw material. Details of price estimates may vary from one material to another.

Rating	Characteristics
25	Cost < $2/kg
20	$2/kg ≤ Cost < $4/kg
15	$4/kg ≤ Cost < $6/kg
10	$6/kg ≤ Cost < $8/kg
5	$8/kg ≤ Cost < $10/kg
0	$10/kg ≤ Cost

Material	Cost, $/kg	Rating	Reference
ASTM A 387 Grade 22	0.95	25	See Section 7.3.1.1.3.6.
ASTM A 516 Grade 55	0.79	25	See Section 7.3.1.1.3.6.
ASTM A 516 Grade 70	0.79	25	See Section 7.3.1.1.3.6.
ASTM B 127	9.92	5	See Section 7.3.1.1.3.6.
ASTM B 171 C71500	7.17	10	See Section 7.3.1.1.3.6.

7.6.3.7 Previous experience with the material

Weighting factor = 0

7.6.3.8 Thermal performance

Weighting factor = 25

Thermal performance was taken to be dependent on the thermal conductivity. For convenience, and because waste package internal temperatures are time-dependent, room temperature thermal conductivities are used.

Rating	Characteristics
25	Thermal conductivity > 50 W/m·K
20	50 W/m·K ≥ Thermal conductivity > 40 W/m·K
15	40 W/m·K ≥ Thermal conductivity > 30 W/m·K
10	30 W/m·K ≥ Thermal conductivity > 20 W/m·K
5	20 W/m·K ≥ Thermal conductivity > 10 W/m·K
0	10 W/m·K ≥ Thermal conductivity

Material	Conductivity, W/m·K	Rating	Reference
ASTM A 387 Grade 22	36.1	15	See text below.
ASTM A 516 Grade 55	51.7	25	See text below.
ASTM A 516 Grade 70	51.7	25	See text below.
ASTM B 127	21.8	10	See text below.
ASTM B 171 C71500	29	10	See text below.

The thermal conductivity of ASTM A 387 Grade 22 was taken from Ref. 5.39, vol. 2, p. 40, Table 2-36, which gives properties for 2 1/4 Cr - 1 Mo steel. The value for 70°F was used. The reference did not specify which definition of the British thermal unit (BTU) was used. In interpreting the reference, the unit was taken to be a thermochemical BTU.

The thermal conductivities of ASTM A 516 Grade 55 and 70 were taken from Ref. 5.39, vol. 2, p. 37, Table 2-28, which gives properties for American Iron and Steel Institute 1020 carbon steel. Because of the similarity of composition between the two grades, the same conductivity was used for both. The value given here is for 20°C; it was obtained by interpolating linearly between values for 0°C and 100°C.

The thermal conductivity of ASTM B 127 was taken from Ref. 5.39, vol. 2, p. 43, Table 2-44, which gives properties for alloy 400. The value for 70°F was used.

The thermal conductivity of ASTM B 171 C71500 was taken from Ref. 5.39, vol. 2, p. 43, Table 2-46, which gives properties for C71500. The value is for 68°F = 20°C.

7.6.3.9 Neutronic performance

Weighting factor = 0

7.6.4 Summary

Results from Sections 7.6.3.1 through 7.6.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria treated in Section 7.6.3.1, Mechanical performance, through Section 7.4.3.9, Neutronic performance, respectively. The column "Total" gives the total score for the material.

Table 7.6.4-1. Ratings of materials for fuel basket tubes for SNF waste forms

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
ASTM A 387 Grade 22	7	0	0	20	20	25	0	15	0	87
ASTM A 516 Grade 55	9	0	0	20	20	25	0	25	0	99
ASTM A 516 Grade 70	9	0	0	20	20	25	0	25	0	99
ASTM B 127	8	0	0	13	15	5	0	10	0	51
ASTM B 171 C71500	7	0	0	20	15	10	0	10	0	62

ASTM A 516 Grade 55 and ASTM A 516 Grade 70 tie for the highest score. Either of these materials could be used; a choice between them will require additional engineering analysis. Although the scores for ASTM B 127 and ASTM B 171 C71500 are well below those for the other materials, inspection of the ratings for each material has not revealed any single rating that is so low that the material should be disqualified on the basis of that single rating.

7.7 Fuel basket plates for SNF waste forms

7.7.1 Candidate materials

Much of the early work on materials selection considered only the containment barriers, and serious consideration of fuel baskets is a relatively recent development, so this component was not treated in previous reports on materials selection.

Candidate materials included ASTM A 887 Type 304B3 Grade A, ASTM A 887 Type 304B4 Grade A, ASTM A 887 Type 304B5 Grade A, ASTM A 887 Type 304B6 Grade A, Neutronit A976 with 1.6% boron, and Neutronit A978 with 1.6% boron. A variety of additional materials were considered in a recent corrosion test (Ref. 5.21). The materials (Ref. 5.21, Table 2) may be classified as follows: aluminum-matrix composites, copper-matrix composites, austenitic stainless steel without boron, austenitic stainless steels with boron, zirconium hafnium alloys, and nonmetallic materials (ceramics or minerals).

Neutronit A976 and A978 are grades of plate produced by Böhler Bleche GmbH of Mürzzuschlag, Austria. The various types of ASTM A 887 Grade A are apparently produced only by Carpenter Technology Corporation of Reading, PA.

7.7.2 Constraints

Of the groups of materials discussed in Ref. 5.21, only the austenitic stainless steels with boron are acceptable for fabrication of fuel basket plates. Aluminum-matrix composites and copper-matrix composites have unacceptably high corrosion rates (Ref. 5.21, Abstract). In particular, Boral is subject to hydrogen gas production, deformation, and delamination (Ref. 5.64, p. 3-1). Austenitic stainless steel without boron was a control material and was not intended for fabrication of basket plates. Zirconium hafnium alloys are unacceptable because of the high cost and limited availability of hafnium. The nonmetallic materials are brittle and would not provide acceptable mechanical performance.

7.7.3 Selection criteria and ratings

The functions of this component are discussed in Section 7.1, along with the criteria that will be used to determine the effectiveness of the materials in performing the functions. The following discussion justifies the choices of weighting factors that are listed in Table 7.1-1.

As is discussed in Section 7.1, this component must be able to sustain mechanical loads due to handling, emplacement, and, if necessary, retrieval, but these loads are not especially large, so a moderate weighting factor (10) is applied to mechanical performance. Corrosion behavior is important in keeping the neutron absorbers in place and effective, so a large weighting factor (20) is applied to chemical performance. The material should provide criticality control in a variety of environments, so a moderate weighting factor (10) is given to predictability of performance. The material should not degrade other components, but its function of controlling criticality is primarily of importance long after emplacement. Criticality control will not be significant unless moderator (water) is present in the package, and for that to happen, the containment barriers must already have failed, so compatibility requires only that the basket plates not degrade the waste form. Accordingly, a moderate weighting factor (10) is applied to compatibility with other materials. These components are simple slotted plates, so fabricability is not important. A zero weighting factor is applied to fabricability. The fuel basket plates provide a substantial fraction of the cost of the disposal container, so a moderate weighting factor (10) is applied to cost. Previous experience is helpful in providing assurance that material behavior is well understood, but, as in the treatment of the containment barriers, it only provides a backup for evaluations of chemical performance and predictability of performance, so a light weighting factor (5) is applied to previous experience. The fuel basket plates provide an important path for conducting heat from the fuel to the containment barriers; a moderately large weighting factor (15) is applied to thermal performance. The most important function of the fuel basket plates is to absorb neutrons, so a large weighting factor (20) is applied to neutronic performance. For reference, these weighting factors are also given in Table 7.1-1.

7.7.3.1 Mechanical performance

Weighting factor = 10

As in Section 7.6.3.1, mechanical performance score is the sum of scores for strength and ductility, and the definitions of strength and ductility are the same as those used in that section. Justification for this choice of properties is given in Section 7.3.1.1.3.1. In general, higher strength and higher ductility are preferable. Values given below are minima.

Strength:

Rating	Characteristics
5	Yield strength > 250 MPa
4	250 MPa ≥ Yield strength > 200 MPa
3	200 MPa ≥ Yield strength > 150 MPa
2	150 MPa ≥ Yield strength > 100 MPa
1	100 MPa ≥ Yield strength > 50 MPa
0	50 MPa ≥ Yield strength

Material	Yield Strength, MPa	Rating	Reference
ASTM A 887 Type 304B3 Grade A	207	4	Ref. 5.15, Table 2.
ASTM A 887 Type 304B4 Grade A	207	4	Ref. 5.15, Table 2.
ASTM A 887 Type 304B5 Grade A	207	4	Ref. 5.15, Table 2.
ASTM A 887 Type 304B6 Grade A	207	4	Ref. 5.15, Table 2.
Neutronit A976	300	5	Ref. 5.56, p. 16 of attachment.
Neutronit A978	300	5	Ref. 5.56, p. 16 of attachment.

Ductility:

Rating	Characteristics
5	Elongation > 25%
4	25% ≥ Elongation > 20%
3	20% ≥ Elongation > 15%
2	15% ≥ Elongation > 10%
1	10% ≥ Elongation > 5%
0	5% ≥ Elongation

Material	Elongation, %	Rating	Reference
ASTM A 887 Type 304B3 Grade A	31	5	Ref. 5.15, Table 2.
ASTM A 887 Type 304B4 Grade A	27	5	Ref. 5.15, Table 2.
ASTM A 887 Type 304B5 Grade A	24	4	Ref. 5.15, Table 2.
ASTM A 887 Type 304B6 Grade A	20	3	Ref. 5.15, Table 2.
Neutronit A976	10	1	Ref. 5.56, p. 16 of attachment.
Neutronit A978	10	1	Ref. 5.56, p. 16 of attachment.

For consistency with the treatment of other materials, the mechanical properties above are specification minima. However, the specifications cited above are from different sources, so the values may represent different levels of conservatism.

7.7.3.2 Chemical performance

Weighting factor = 20

For conditions that are relevant to repository conditions, less information on corrosion of the candidate materials is available for this component than for the others. The following information on corrosion performance is noted: Van Konynenburg and Curtis (Ref. 5.21) exposed samples of Böhler A976 SD (Neutronit A976), Neutrosorb Plus (ASTM A 887 Grade A, type not specified) base metal, and Neutrosorb Plus (ASTM A 887 Grade A, type not specified) welded metal to an aqueous mixture of formic acid, sodium formate, sodium oxalate, nitric acid, sodium chloride and hydrogen peroxide in a short term corrosion test. They observed corrosion rates of 41 µm/yr for corrosion of the Neutronit A976, 60 µm/yr for the ASTM A 887 Grade A base metal, and 880 µm/yr, with pitting, for the ASTM A 887 Grade A welded metal (Ref. 5.21, Table 3). Ref. 5.64 also reports on several corrosion tests. These include corrosion rate in 65% nitric acid (Ref. 5.64, Table 3-15 and Table 3-19), intergranular corrosion tests in 6% copper sulfate plus 6% sulfuric acid (Ref. 5.64, Table 3-16), tests in 2000 ppm H_3BO_3(Ref. 5.64, Table 3-17), 5% sodium chloride spray and 5% ferric chloride (Ref. 5.64, Table 3-18), and ferric sulfate plus sulfuric acid (Ref. 5.64, Table 3-19). However, the results reported in Ref. 5.64 were not intended to address repository conditions.

A significant difference between the candidate materials for this component and those for other components is that the compositions of candidate materials for this component are much more tightly clustered. Because of this and because limited corrosion data are available, chemical performance is therefore evaluated by invoking analogous materials of similar composition but without boron.

Rating	Characteristics
20	Composition without boron is based on material that is more corrosion resistant than ASTM A 240 Type 316.
13	Composition without boron is based on material that is comparable to ASTM A 240 Type 316.
7	Composition without boron is based on material that is comparable to ASTM A 240 Type 304.
0	Composition without boron is based on material that is less corrosion resistant than ASTM A 240 Type 304.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	7	See text below.
ASTM A 887 Type 304B4 Grade A	7	See text below.
ASTM A 887 Type 304B5 Grade A	7	See text below.
ASTM A 887 Type 304B6 Grade A	7	See text below.
Neutronit A976	7	See text below.
Neutronit A978	13	See text below.

For the ASTM alloys, compositions can be compared between Ref. 5.15, Table 1 and Ref. 5.12, Table 1. The composition limits for carbon, manganese, phosphorus, sulfur, silicon, chromium, and nitrogen are identical for ASTM A 887 Types 304B3 through 304B6 and ASTM A 240 Type 304. The range of allowable nickel contents is higher for ASTM A 887 Types 304B3 through 304B6 than for ASTM A 240 Type 304. This is taken as evidence that the composition without boron of ASTM A 887 Types 304B3 through 304B6 is based on that of ASTM A 240 Type 304.

For the Neutronit alloys, the manufacturer's information provides average values for some elements and maxima for others. For Neutronit A976, the specified values for carbon, chromium, and nickel are all within the specification limits of Ref. 5.15, Table 1. The limit on carbon is more stringent than that of ASTM A 887, and a limit on cobalt is added. This is taken as evidence that the composition without boron of Neutronit A976 is similar to that of the alloys specified in ASTM A 887. Those alloys in turn have already been shown to be based on ASTM A 240 Type 304, so the composition without boron of Neutronit A976 is based on that of ASTM A 240 Type 304.

For Neutronit A978, the specified values for carbon, nickel, and molybdenum are all within the specification limits of Ref. 5.12, Table 1 for ASTM A 240 Type 316. The limit on carbon is more stringent than that of Ref. 5.12, Table 1, and a limit on cobalt is added. The average chromium content is slightly above the range specified in Ref. 5.12, Table 1. This is taken as evidence that the composition without boron of Neutronit A978 is similar to that of ASTM A 240 Type 316.

7.7.3.3 Predictability of performance

Weighting factor = 10

As in Section 7.3.1.3.3, scores for predictability of performance were taken to be the sum of scores for performance in bounding environments and availability of corrosion data. The rating scales of Section 7.3.1.3.3 were also adopted, but fewer points are assigned because of the smaller weighting factor.

Performance in bounding environments:

Rating	Characteristics
8	Severe loss of performance, relative to the base case, in none of the three bounding environments of Ref. 5.28, p. 18.
5	Severe loss of performance, relative to the base case, in one of the three bounding environments.
3	Severe loss of performance, relative to the base case, in two of the three bounding environments.
0	Severe loss of performance, relative to the base case, in all of the three bounding environments.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	5	See text below.
ASTM A 887 Type 304B4 Grade A	5	See text below.
ASTM A 887 Type 304B5 Grade A	5	See text below.
ASTM A 887 Type 304B6 Grade A	5	See text below.
Neutronit A976	5	See text below.
Neutronit A978	5	See text below.

Since there is little corrosion information available on these materials, predicting which environments will cause severe degradation of performance is difficult. In general, it is expected that increased boron content will result in increased corrosion rates (Ref. 5.64, p. 3-22). However, these results appear to bear more on the amount by which performance is degraded rather than on the existence of such an effect.

One approach is to consider the composition of the boron-free stainless steels on which the materials are based. As is discussed in Section 7.7.3.2, the ASTM alloys and Neutronit A976 are based on ASTM A 240 Type 304, and Neutronit A978 is based on ASTM A 240 Type 316.

Ref. 5.31, pp. 557-558 discusses the resistance of stainless steels to acid solutions. Some of the acids discussed (such as nitric acid) do not attack stainless steels. In contrast, hydrochloric acid does attack them. In view of this information, it is judged that these materials may suffer a severe loss of performance in the acidic bounding environment.

Ref. 5.31, p. 559 states that "Stainless steels are highly resistant to most neutral or alkaline non-halide salts," but notes that "Halogen salts are more corrosive to stainless steels because of the ability of the halide ions to penetrate the passive film and cause pitting." However, the bounding environments described in Section 7.3.1.1.3.2 will have chloride concentrations of only 143 mg/L to 714 mg/L. In view of this information, it is judged that these materials will probably not suffer a severe loss of performance in the neutral and alkaline bounding environments.

Availability of corrosion data:

Rating	Characteristics
2	Large amounts of corrosion data available.
1	Limited amounts of corrosion data available.
0	No corrosion data available.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	1	See text below.
ASTM A 887 Type 304B4 Grade A	1	See text below.
ASTM A 887 Type 304B5 Grade A	1	See text below.
ASTM A 887 Type 304B6 Grade A	1	See text below.
Neutronit A976	1	See text below.
Neutronit A978	1	See text below.

As is discussed in Section 7.7.3.7 below, these materials have been used only in a limited variety of applications. Accordingly, little information on corrosion of these materials is available. Ref. 5.56, p. 20 of attachment states that for the Neutronit alloys, "Corrosion resistance has proven satisfactory under the conditions encountered in practice." The reference makes several other qualitative statements about corrosion performance but does not provide corrosion rates. Information on corrosion of the ASTM alloys was not found. However, estimates of the corrosion rates could be made from data for stainless steels without boron, so it is judged that limited amounts of corrosion data are available for all six materials.

7.7.3.4 Compatibility with other materials

Weighting factor = 10

The function of preventing criticality is not significant unless the containment barriers fail and large amounts of liquid water enter the degraded waste package. Therefore, before the fuel basket plates begin to provide this function, the remaining components will be severely degraded and will not be providing significant functionality. As a result, this component need only be compatible with the waste form.

Rating	Characteristics
10	No evidence of degradation of waste form by candidate material or its products of corrosion.
0	Evidence of degradation of waste form by candidate material or its products of corrosion.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	10	See text below.
ASTM A 887 Type 304B4 Grade A	10	See text below.
ASTM A 887 Type 304B5 Grade A	10	See text below.
ASTM A 887 Type 304B6 Grade A	10	See text below.
Neutronit A976	10	See text below.
Neutronit A978	10	See text below.

Stainless steels are used in proximity with nuclear fuel assemblies. This is taken as evidence the stainless steels will not degrade the waste form.

7.7.3.5 Fabricability

Weighting factor = 0

7.7.3.6 Cost

Weighting factor = 10

As in Section 7.3.1.3.6, "cost" is defined as the price per kilogram of raw material. Details of price estimates may vary from one material to another.

Rating	Characteristics
10	Cost < \$6/kg
8	\$6/kg ≤Cost < \$12/kg
6	\$12/kg ≤Cost < \$18/kg
4	\$18/kg ≤Cost < \$24/kg
2	\$24/kg ≤Cost < \$30/kg
0	\$30/kg ≤Cost

Material	Cost, \$/kg	Rating	Reference
ASTM A 887 Type 304B3 Grade A	22.05	4	See text below.
ASTM A 887 Type 304B4 Grade A	24.25	2	See text below.
ASTM A 887 Type 304B5 Grade A	26.46	2	See text below.
ASTM A 887 Type 304B6 Grade A	28.66	2	See text below.
Neutronit A976	24.00	2	See text below.
Neutronit A978	27.00	2	See text below.

Costs for the ASTM alloys are the "balanced costs" as estimated by W. Wallin in Ref. 5.57. Costs for the Neutronit alloys are as specified in Ref. 5.58. Note that Ref. 5.58 contains a typographical error; the specification for boron content should read "≤ 1.6% AND ≥ 0.6%," not "≥ 1.6% AND ≥ 0.6%."

7.7.3.7 Previous experience with the material

Weighting factor = 5

As in Section 7.3.1.3.7, scores for previous experience with the material were taken to be the sum of scores for existence of ASTM standards and variety of applications.

Existence of ASTM standards:

Rating	Characteristics
1	ASTM standard exists for material.
0	No ASTM standard exists for material.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	1	Ref. 5.15.
ASTM A 887 Type 304B4 Grade A	1	Ref. 5.15.
ASTM A 887 Type 304B5 Grade A	1	Ref. 5.15.
ASTM A 887 Type 304B6 Grade A	1	Ref. 5.15.
Neutronit A976	0	See text below.
Neutronit A978	0	See text below.

Ref. 5.56, p. 15 of attachment makes mention of ASTM A 887, but does not state that either of the Neutronit alloys is produced to this specification.

Variety of applications:

Rating	Characteristics
4	Material or similar materials are used in a wide variety of applications.
2	Material or similar materials are used in a limited variety of applications.
0	Material or similar materials are used in an extremely limited variety of applications.

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	0	See text below.
ASTM A 887 Type 304B4 Grade A	0	See text below.
ASTM A 887 Type 304B5 Grade A	0	See text below.
ASTM A 887 Type 304B6 Grade A	0	See text below.
Neutronit A976	2	See text below.
Neutronit A978	2	See text below.

Ref. 5.56, p. 7 of attachment mentions "compact storage racks" and "transportation baskets" as applications for the Neutronit alloys. The Neutronit alloys are evidently in commercial production and use; "more than 2000 tons" (presumably metric tons) have been produced (Ref. 5.59, p. 14 of attachment). This information is taken as evidence that these materials are used in a limited variety of applications. In contrast, no evidence has been found that the ASTM A 887 Grade A materials have actually been used in commercial applications. This information is taken as evidence that these materials are used in an extremely limited variety of applications.

7.7.3.8 Thermal performance

Weighting factor = 15

As in Section 7.6.3.8, ratings for thermal performance were based on room temperature thermal conductivities.

Rating	Characteristics
15	Thermal conductivity > 50 W/m·K
12	50 W/m·K ≥ Thermal conductivity > 40 W/m·K
9	40 W/m·K ≥ Thermal conductivity > 30 W/m·K
6	30 W/m·K ≥ Thermal conductivity > 20 W/m·K
3	20 W/m·K ≥ Thermal conductivity > 10 W/m·K
0	10 W/m·K ≥ Thermal conductivity

Material	Rating	Reference
ASTM A 887 Type 304B3 Grade A	3	See text below.
ASTM A 887 Type 304B4 Grade A	3	See text below.
ASTM A 887 Type 304B5 Grade A	3	See text below.
ASTM A 887 Type 304B6 Grade A	3	See text below.
Neutronit A976	3	See text below.
Neutronit A978	3	See text below.

Thermal conductivities for these materials are difficult to find. Ref. 5.56, p. 18 of attachment gives a thermal conductivity of 10.3 W/m·K at 20°C for the Neutronit alloys. No distinction is made between the two alloys, so their thermal conductivities are presumably similar.

Thermal conductivities were not found for the ASTM alloys. On the basis of the composition of the matrix, these may have a slightly higher thermal conductivity than Neutronit A978. As is discussed above, the ASTM alloys and Neutronit A976 have compositions that are based on ASTM A 240 Type 304, whereas Neutronit A978 has a composition that is based on ASTM A 240 Type 316. For comparison, Ref. 5.60, p. 671 gives thermal conductivities of 14.9 W/m·K for American Iron and Steel Institute Type 304 and 13.4 W/m·K for American Iron and Steel Institute Type 316, both at 300 K. These two alloys are similar to ASTM A 240 Type 304 and ASTM A 240 Type 316, respectively. The addition of borides appears to reduce the thermal conductivity. This information on thermal conductivity is taken as evidence that all six candidate materials have thermal conductivities of less than or equal to 20 W/m·K but greater than 10 W/m·K.

7.7.3.9 Neutronic performance

Weighting factor = 20

For all of the candidate materials, boron is the element that contributes most heavily to neutron absorption. Accordingly, the neutronic performance is rated by the amount of boron in the alloy.

In oral discussions, it has been claimed that ASTM A 887 Grade A materials have a finer microstructure than ASTM A 887 Grade B materials, and that the finer microstructure results in more effective neutron absorption. The reasoning behind the claim is that if the boron is agglomerated into a few large chunks, there will be spaces between the chunks where neutrons can stream through. Inspection of photomicrographs (Ref. 5.64, pp. 3-12 and 3-13) shows that there is indeed a difference is the fineness of the microstructure. However, the basket plates have substantial thickness. For the PWR disposal container, the plates are 7 mm thick (Ref. 5.89) and for the BWR disposal container, the plates are 10 mm thick (Ref. 5.86). In view of these thicknesses, it appears that the finer microstructure of the ASTM A 887 Grade A material does not provide a significant advantage in neutronic performance.

Rating	Characteristics
20	Boron content > 1.5%
16	1.5% ≥ Boron content > 1.2%
12	1.2% ≥ Boron content > 0.9%
8	0.9% ≥ Boron content > 0.6%
4	0.6% ≥ Boron content > 0.3%
0	0.3% ≥ Boron content

Material	Boron, %	Rating	Reference
ASTM A 887 Type 304B3 Grade A	0.87	8	See text below.
ASTM A 887 Type 304B4 Grade A	1.12	12	See text below.
ASTM A 887 Type 304B5 Grade A	1.37	16	See text below.
ASTM A 887 Type 304B6 Grade A	1.62	20	See text below.
Neutronit A976	1.6	20	See text below.
Neutronit A978	1.6	20	See text below.

For the ASTM alloys, the boron content is the arithmetic mean of the maximum and minimum of the boron content for that type, as indicated in the specification (Ref. 5.15, Table 1). For the Neutronit alloys, the boron content is according to customer specifications (Ref. 5.56, p. 15 of attachment), and a boron content of 1.6% is specified in Section 7.7.1.

7.7.4 Summary

Results from Sections 7.7.3.1 through 7.7.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria treated in Section 7.7.3.1, Mechanical performance, through Section 7.7.3.9, Neutronic performance, respectively. The column "Total" gives the total score for the material. The abbreviation "Gr." denotes "Grade."

Table 7.7.4-1. Ratings of materials for fuel basket plates for SNF waste forms

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
ASTM A 887 Type 304B3 Gr. A	9	7	6	10	0	4	1	3	8	48
ASTM A 887 Type 304B4 Gr. A	9	7	6	10	0	2	1	3	12	50
ASTM A 887 Type 304B5 Gr. A	8	7	6	10	0	2	1	3	16	53
ASTM A 887 Type 304B6 Gr. A	7	7	6	10	0	2	1	3	20	56
Neutronit A976	6	7	6	10	0	2	2	3	20	56
Neutronit A978	6	13	6	10	0	2	2	3	20	62

In the table above, it is seen that Neutronit A978 received the highest rating. This material is recommended for future design work. Inspection of the ratings for each material has not revealed any single rating that is so low that the material should be disqualified without further consideration.

7.8 Waste container fill gas for SNF waste forms

7.8.1 Candidate materials

Candidate materials include vacuum plus a variety of common gases: helium, carbon dioxide, nitrogen, oxygen, argon, dry air, and environmental air. Classification of vacuum as a gas is arbitrary and serves only to indicate that evacuating the containers is a possibility.

7.8.2 Constraints

To avoid questions of compromising the underground facility, the fill gas should not be explosive or chemically reactive (Ref. 5.25, sec. 3.7.1.D). This constraint clearly excludes oxygen.

7.8.3 Selection criteria and ratings

The functions of this component are discussed in Section 7.1, along with the criteria that will be used to determine the effectiveness of the materials in performing the functions. The following discussion justifies the choices of weighting factors that are listed in Table 7.1-1.

The fill gas provides no mechanical or chemical resistance, so zero weighting factors are given to mechanical performance, chemical performance, and predictability of performance. The fill gas should not degrade other components of the waste package, so a large weighting factor (60) is applied to compatibility with other materials. The gas is not fabricated, so a zero weighting factor is given to fabricability. Controlling cost is desirable, but fill gas is an inexpensive part of the waste package (as is shown in Section 7.8.3.6), so a small weighting factor (15) is applied to cost. Previous experience with a gas will not provide significant advantages, so a zero weighting factor is given to this. The fill gas is a significant conductor of heat from the fuel to the basket, so a moderate weighting factor (25) is applied to thermal performance. The gas is not intended to provide neutron absorption, so a zero weighting factor is given to neutronic performance. For reference, these weighting factors are also given in Table 7.1-1.

7.8.3.1 Mechanical performance

Weighting factor = 0

7.8.3.2 Chemical performance

Weighting factor = 0

7.8.3.3 Predictability of performance

Weighting factor = 0

7.8.3.4 Compatibility with other materials

Weighting factor = 60

Rating	Characteristics
60	Completely inert.
45	Causes negligible damage to waste package under expected conditions.
30	May cause damage to waste package if radiolysis is significant.
15	Can cause damage to waste package under expected conditions.
0	Chemically reactive.

Material	Rating	Reference
Vacuum	60	See text below.
Helium	45	See text below.
Carbon dioxide	30	See text below.
Nitrogen	30	See text below.
Argon	45	See text below.
Dry air	15	See text below.
Environmental air	15	See text below.

Justifications for the ratings are as follows. Vacuum is chemically inert. Helium and argon are noble gases, and noble gases are essentially chemically inert, so they will cause negligible damage to the waste package. Radiolysis of carbon dioxide might conceivably liberate oxygen, which could oxidize fuel with failed cladding. For packages filled with nitrogen, radiolysis of nitrogen and water from waterlogged fuel might produce sufficient quantities of nitric acid for condensation of corrodents to take place. Carbon dioxide and nitrogen may thus cause damage if radiolysis is significant. Because of their nitrogen content, dry air and environmental air have the same disadvantages as nitrogen, plus the disadvantage that oxygen in the air could oxidize fuel with failed cladding. Dry air and environmental air can thus cause damage under expected conditions.

7.8.3.5 Fabricability

Weighting factor = 0

7.8.3.6 Cost

Weighting factor = 15

Rating	Characteristics
15	Free, no effort required to ensure presence of gas.
10	Material is free, but effort is required to ensure presence of gas.
5	Gas must be purchased, but cost is reasonable.
0	Cost of gas is prohibitive.

Material	Rating	Reference
Vacuum	10	See text below.
Helium	5	See text below.
Carbon dioxide	5	See text below.
Nitrogen	5	See text below.
Argon	5	See text below.
Dry air	10	See text below.
Environmental air	15	See text below..

Justifications for ratings are as follows. Vacuum is free, but effort must be made to assure that the waste package has been evacuated. Rough cost estimates for helium, carbon dioxide, nitrogen, and argon with minimum purity of 99.995% were received by telephone from Air Liquide of Las Vegas, Nevada on June 26, 1996. All four gases are available locally at a price of "about $100 a bottle." This estimate is taken as evidence that the cost of the gases is reasonable. Dry air is free, but the air must be dried and effort is necessary to assure that the waste package is filled with dry air. Environmental air is free and will be present without extra effort when the waste package is sealed.

7.8.3.7 Previous experience with the material

Weighting factor = 0

7.8.3.8 Thermal performance

Weighting factor = 25

The criterion for thermal performance of the fill gas is taken to be its thermal conductivity at 600 K and 101 kPa. Thermal conductivity of the gas is most important at high temperature because of the thermal goal of limiting fuel cladding temperature (Ref. 5.26, DCWP 001). The following tables specify the grading scale and show the ratings of the materials against that scale.

Rating	Characteristics
25	≥ 0.20 W/m·K
20	≥ 0.16 W/m·K, < 0.20 W/m·K
15	≥ 0.12 W/m·K, < 0.16 W/m·K
10	≥ 0.08 W/m·K, < 0.12 W/m·K
5	≥ 0.04 W/m·K, < 0.08 W/m·K
0	< 0.04 W/m·K

Material	Thermal conductivity, W/m·K	Rating	Reference
Vacuum	0	0	See text below.
Helium	0.2524	25	Ref. 5.61, p. 6-251.
Carbon dioxide	0.0416	5	Ref. 5.61, p. 6-251.
Nitrogen	0.0440	5	Ref. 5.61, p. 6-251.
Argon	0.0306	0	Ref. 5.61, p. 6-251.
Dry air	0.0457	5	Ref. 5.61, p. 6-251.
Environmental air	0.0457 to 0.0471	5	See text below.

A vacuum does not conduct heat.

Ref. 5.61, p. 6-251 gives the values specified for dry air and water (vapor), respectively. Since environmental air is a mixture of dry air and water vapor, the thermal conductivity of environmental air is expected to be between these two values.

7.8.3.9 Neutronic performance

Weighting factor = 0

7.8.4 Summary

Results from Sections 7.8.3.1 through 7.8.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria treated in Section 7.8.3.1, Mechanical performance, through Section 7.6.3.9, Neutronic performance, respectively. The column "Total" gives the total score for the material.

Table 7.8.4-1. Ratings of materials for waste container fill gas for SNF waste forms

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
Vacuum	0	0	0	60	0	10	0	0	0	70
Helium	0	0	0	45	0	5	0	25	0	75
Carbon dioxide	0	0	0	30	0	5	0	5	0	40
Nitrogen	0	0	0	30	0	5	0	5	0	40
Argon	0	0	0	45	0	5	0	0	0	50
Dry air	0	0	0	15	0	10	0	5	0	30
Environmental air	0	0	0	15	0	15	0	5	0	35

In the table above, it is seen that helium received the highest rating. This material is recommended for future design work. Inspection of the ratings for each material reveals that dry air and environmental air have such poor compatibility with the waste form that they may be unacceptable on this basis alone.

7.9 Basket guides

7.9.1 Candidate materials

Much of the early work on materials selection considered only the containment barriers, and serious consideration of fuel baskets and basket guides is a relatively recent development, so this component was not treated in previous reports on materials selection.

As is discussed in Section 7.1, the basket guides are intended primarily to hold the basket in place by supporting loads due to handling, emplacement, and (if necessary) retrieval. The guides also help in conducting heat from the basket to the containment barriers.

Candidate materials were taken to be the same as those for the corrosion allowance barrier for SNF waste forms.

7.9.2 Constraints

Inspection of drawings (Ref. 5.87 and Ref. 5.88) indicates that the basket guides are to be made by forming from plate and welding. Since ASTM A 27 is a specification for steel castings (Ref. 5.11), this analysis will not consider that material further. Some common names for the remaining candidate materials are given in Section 7.3.1.1.1.

7.9.3 Selection criteria and ratings

The functions of this component are discussed in Section 7.1, along with the criteria that will be used to determine the effectiveness of the materials in performing the functions. The following discussion justifies the choices of weighting factors that are listed in Table 7.1-1.

Perhaps the most important function of the basket guides is to hold the fuel basket in place during loading, handling, emplacement, and, if necessary, retrieval. As a result, mechanical performance is assigned a moderately large weighting factor (25). However, this component is not intended to provide corrosion resistance; performance of its functions is expected to be complete before the containment barriers fail and the component is exposed to corrodents. As a result, chemical performance has a zero weighting factor. Predictability of performance is likewise not of interest and is also assigned a zero weighting factor. The material is in contact with the fuel basket plates and the inner barrier. To avoid compromising long-term criticality control, the basket guides must not degrade the basket plates, so a moderate weighting factor (20) is applied to compatibility with other materials. The material will be formed and welded into various shapes, so a moderate weighting factor (20) is applied to fabricability. These components need not provide long-term performance after failure of the containment barrier, so a moderate weighting factor (20) is applied to cost. Chemical performance of the material is of no interest, so previous experience is not needed to provide assurance that chemical performance is understood. A zero weighting factor is applied to previous experience. The basket guides provide an important path for conducting heat toward the shell, but the path length is short, so a moderately small weighting factor (15) is applied to thermal performance. This component is not intended to provide a neutron-absorbing function, so no weighting is applied to neutronic performance. For reference, these weighting factors are also given in Table 7.1-1.

7.9.3.1 Mechanical performance

Weighting factor = 25

As in Section 7.3.1.3.1, mechanical performance score is the sum of scores for strength and ductility, and the definitions of strength and ductility are the same as those used in that section. Justification for this choice of properties is given in Section 7.3.1.3.1. In general, higher strength and higher ductility are preferable.

Strength:

Rating	Characteristics
13	Yield strength > 250 MPa
10	250 MPa ≥ Yield strength > 200 MPa
8	200 MPa ≥ Yield strength > 150 MPa
5	150 MPa ≥ Yield strength > 100 MPa
3	100 MPa ≥ Yield strength > 50 MPa
0	50 MPa ≥ Yield strength

Material	Yield strength, MPa	Rating	Reference
ASTM A 387 Grade 22	207	10	Ref. 5.13, Table 2.
ASTM.A 516 Grade 55	207	10	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	262	13	Ref. 5.14, Table 2.
ASTM B 127	193	8	See text below.
ASTM B 171 C71500	124	5	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

Ductility:

Rating	Characteristics
12	Elongation > 25%
10	25% ≥ Elongation > 20%
7	20% ≥ Elongation > 15%
5	15% ≥ Elongation > 10%
2	10% ≥ Elongation > 5%
0	5% ≥ Elongation

Material	Elongation, %	Rating	Reference
ASTM A 387 Grade 22	18	7	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	27	12	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	21	10	Ref. 5.14, Table 2.
ASTM B 127	35	12	See text below.
ASTM B 171 C71500	30	12	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

7.9.3.2 Chemical performance

Weighting factor = 0

7.9.3.3 Predictability of performance

Weighting factor = 0

7.9.3.4 Compatibility with other materials

Weighting factor = 20

Scores for compatibility with other materials were taken to be the sum of scores for compatibility with the fuel basket plates and for compatibility with the waste form.

Compatibility with the fuel basket plates:

The function of preventing criticality is allocated primarily to the fuel basket plates, and corrosion of that component could lead to loss of neutron absorbing material or settling of neutron absorbing material to the bottom of the waste package, where it would be less effective in controlling criticality. The basket guides and the basket plates are in close contact, so, if the containment barriers are breached, there is the possibility for galvanic corrosion of one component or the other. Compatibility of the basket guides is defined as their providing galvanic protection for the fuel basket plates. The effectiveness of galvanic protection has been determined according to the galvanic series (Ref. 5.31, p. 235, Fig. 1). As is discussed in Section 7.3.1.1.3.4, the strategy in materials selection is that, regardless of the environment, the basket guides should corrode sacrificially and protect the fuel basket plates.

Rating	Characteristics
13	Expected to provide galvanic protection: Entire galvanic potential range for the basket guide material is below the range for any candidate material for the fuel basket plates.
6	May or may not provide galvanic protection: Galvanic potential range for the basket guide material overlaps the range for some candidate material(s) for the fuel basket plates but does not extend above the top of the range for any candidate material for the fuel basket plates.
0	Not expected to provide galvanic protection: Galvanic potential range for the basket guide material extends above the top of the range for some material for the fuel basket plates.

Material	Rating	Reference
ASTM A 387 Grade 22	13	See Section 7.6.3.4.
ASTM A 516 Grade 55	13	See Section 7.6.3.4.
ASTM A 516 Grade 70	13	See Section 7.6.3.4.
ASTM B 127	0	See Section 7.6.3.4.
ASTM B 171 C71500	13	See Section 7.6.3.4.

Compatibility with waste form:

Rating	Characteristics
7	No evidence of degradation of waste form by candidate material or its products of corrosion.
0	Evidence of degradation of waste form by candidate material or its products of corrosion.

Material	Rating	Reference
ASTM A 387 Grade 22	7	See Section 7.3.1.1.3.4.
ASTM A 516 Grade 55	7	See Section 7.3.1.1.3.4.
ASTM A 516 Grade 70	7	See Section 7.3.1.1.3.4.
ASTM B 127	7	See Section 7.3.1.1.3.4.
ASTM B 171 C71500	7	See Section 7.3.1.1.3.4.

7.9.3.5 Fabricability

Weighting factor = 20

As in Section 7.6.3.5, scores for fabricability were taken to be the sum of scores for formability and weldability. Formability and weldability depend only on the nature of the material being fabricated, so scores for fabricability are identical to those given in Section 7.6.3.5. These values have been copied to the table in Section 7.9.4.

7.9.3.6 Cost

Weighting factor = 20

Raw material costs do not depend on the nature of the component, so costs per kilogram are the same as those given in Section 7.6.3.6. For this component, the weighting factor for cost is 0.8 times that for the fuel basket tubes, so the ratings from Section 7.6.3.6 have been multiplied by 0.8 and the results recorded in the table in Section 7.9.4.

7.9.3.7 Previous experience with the material

Weighting factor = 0

7.9.3.8 Thermal performance

Weighting factor = 15

Thermal conductivity does not depend on the nature of the component, so thermal conductivities are the same as those given in Section 7.6.3.8. For this component, the weighting factor for cost is 0.6 times that for the fuel basket tubes, so the ratings from Section 7.6.3.8 have been multiplied by 0.6 and the results recorded in the table in Section 7.9.4.

7.9.3.9 Neutronic performance

Weighting factor = 0

7.9.4 Summary

Results from Sections 7.9.3.1 through 7.9.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria treated in Section 7.9.3.1, Mechanical performance, through Section 7.9.3.9, Neutronic performance, respectively. The column "Total" gives the total score for the material.

Table 7.9.4-1. Ratings of materials for basket guides for SNF waste forms

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
ASTM A 387 Grade 22	17	0	0	20	20	20	0	9	0	86
ASTM A 516 Grade 55	22	0	0	20	20	20	0	15	0	97
ASTM A 516 Grade 70	23	0	0	20	20	20	0	15	0	98
ASTM B 127	20	0	0	7	15	4	0	6	0	52
ASTM B 171 C71500	17	0	0	20	15	8	0	6	0	66

ASTM A 516 Grade 70 received the highest score, but it received only one point more than ASTM A 516 Grade 55. Moreover, the difference in scoring results from the unevenness of the grading scales in Section 7.9.3.1. As a result, difference in scores is considered insignificant. Either of these materials could be used; a choice between them will require additional engineering analysis. Inspection of the ratings for each material has not revealed any single rating that is so low that the material should be disqualified without further consideration.

7.10 Canister guide for HLW glass

7.10.1 Candidate materials

Much of the early work on materials selection considered only the containment barriers, and serious consideration of a canister guide is a relatively recent development, so this component was not treated in previous reports on materials selection.

As is discussed in Section 7.1, the canister guide is intended primarily to hold the canisters in place by supporting loads due to handling, emplacement, and (if necessary) retrieval.

Candidate materials were taken to be the same as those for the basket guides for SNF waste forms.

7.10.2 Constraints

There are no plans to produce the canister guide by casting. Since ASTM A 27 is a specification for steel castings (Ref. 5.11), this analysis will not consider that material further. Some common names for the remaining candidate materials are given in Section 7.3.1.2.

7.10.3 Selection criteria and ratings

The functions of this component are discussed in Section 7.1, along with the criteria that will be used to determine the effectiveness of the materials in performing the functions. The following discussion justifies the choices of weighting factors that are listed in Table 7.1-1.

One of the functions of this component is to provide resistance to handling, emplacement, and (if necessary) retrieval loads. As a result, mechanical performance is assigned a large weighting factor (40). However, this component is not intended to provide corrosion resistance; performance of its functions is expected to be complete before the containment barriers fail and the component is exposed to corrodents. As a result, chemical performance has a zero weighting factor. Predictability of performance is likewise not of interest and is also assigned a zero weighting factor. The material is near the waste glass, and the guide must not degrade the waste form, so a moderate weighting factor (20) is applied to compatibility with other materials. The material will be formed and welded into various shapes, so a moderate weighting factor (20) is applied to fabricability. These components perform their function early in the life of the waste package, so they need not provide long-term performance after failure of the containment barrier. Accordingly, a moderate weighting factor (20) is applied to cost. Chemical performance of the material is of no interest, so previous experience is not needed to provide assurance that chemical performance is understood. A zero weighting factor is applied to previous experience. Since the canister guide supports the canisters only at the end, they do not provide a significant path for conducting heat to the containment barriers, and a zero weighting factor is applied to thermal performance. This component is not intended to provide a neutron-absorbing function, so no weighting is applied to neutronic performance. For reference, these weighting factors are also given in Table 7.1-1.

7.10.3.1 Mechanical performance

Weighting factor = 40

As in Section 7.7.3.1, the mechanical performance score is the sum of scores for strength and ductility, and the definitions of strength and ductility are the same as those used in that section. Justification for this choice of properties is given in Section 7.3.1.1.3.1. In general, higher strength and higher ductility are preferable.

Strength:

Rating	Characteristics
20	Yield strength > 250 MPa
16	250 MPa ≥ Yield strength > 200 MPa
12	200 MPa ≥ Yield strength > 150 MPa
8	150 MPa ≥ Yield strength > 100 MPa
4	100 MPa ≥ Yield strength > 50 MPa
0	50 MPa ≥ Yield strength

Material	Yield strength, MPa	Rating	Reference
ASTM A 387 Grade 22	207	16	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	207	16	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	262	20	Ref. 5.14, Table 2.
ASTM B 127	193	12	See text below.
ASTM B 171 C71500	124	8	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

Ductility:

Rating	Characteristics
20	Elongation > 25%
16	25% ≥ Elongation > 20%
12	20% ≥ Elongation > 15%
8	15% ≥ Elongation > 10%
4	10% ≥ Elongation > 5%
0	5% ≥ Elongation

Material	Elongation, %	Rating	Reference
ASTM A 387 Grade 22	18	12	Ref. 5.13, Table 2.
ASTM A 516 Grade 55	27	20	Ref. 5.14, Table 2.
ASTM A 516 Grade 70	21	16	Ref. 5.14, Table 2.
ASTM B 127	35	20	See text below.
ASTM B 171 C71500	30	20	Ref. 5.17, Table 3.

For ASTM B 127, the value for hot-rolled plate, annealed, was taken from Ref. 5.16, Table 3.

7.10.3.2 Chemical performance

Weighting factor = 0

7.10.3.3 Predictability of performance

Weighting factor = 0

7.10.3.4 Compatibility with other materials

Weighting factor = 20
Until the waste container has failed, water cannot enter and chemical interactions between the canister guide and containment barriers is not expected. As a result, compatibility concerns

extend only to compatibility with waste form.

Rating	Characteristics
20	No evidence of degradation of waste form by candidate material or its products of corrosion.
0	Evidence of degradation of waste form by candidate material or its products of corrosion.

Material	Rating	Reference
ASTM A 387 Grade 22	0	See text below.
ASTM A 516 Grade 55	0	See text below.
ASTM A 516 Grade 70	0	See text below.
ASTM B 127	20	See text below.
ASTM B 171 C71500	20	See text below.

7.10.3.5 Fabricability

Weighting factor = 20

As in Section 7.7.3.5, scores for fabricability were taken to be the sum of scores for formability and weldability. Formability and weldability depend only on the nature of the material being fabricated, so scores for fabricability are identical to those given in Section 7.6.3.5 and then cited in Section 7.7.3.5. These values have been copied to the table in Section 7.10.4.

7.10.3.6 Cost

Weighting factor = 20

Raw material costs do not depend on the nature of the component, so scores for cost are identical to those given in Section 7.9.3.6. These values have been copied to the table in Section 7.10.4.

7.10.3.7 Previous experience with the material

Weighting factor = 0

7.10.3.8 Thermal performance

Weighting factor = 0

7.10.3.9 Neutronic performance

Weighting factor = 0

7.10.4 Summary

Results from Sections 7.10.3.1 through 7.10.3.9 are summarized in the following table. The columns "Mech" through "Neut" give the total score for each of the nine criteria treated in Section 7.10.3.1, Mechanical performance, through Section 7.10.3.9, Neutronic performance, respectively. The column "Total" gives the total score for the material.

Table 7.10.4-1. Summary of ratings for canister guide for HLW glass

Material	Rating									
	Mech	Chem	Pred	Comp	Fab	Cost	Exp	Thrm	Neut	Total
ASTM A 387 Grade 22	28	0	0	0	20	20	0	0	0	68
ASTM A 516 Grade 55	36	0	0	0	20	20	0	0	0	76
ASTM A 516 Grade 70	36	0	0	0	20	20	0	0	0	76
ASTM B 127	32	0	0	20	15	4	0	0	0	71
ASTM B 171 C71500	28	0	0	20	15	8	0	0	0	71

ASTM A 516 Grade 55 and ASTM A 516 Grade 70 tie for the highest score. Either of these materials could be used; a choice between them will require additional engineering analysis. Inspection of the ratings for each material has not revealed any single rating that is so low that the material should be disqualified without further consideration.

8. Conclusions

All design inputs which are identified in this document are for preliminary design and shall be treated as unqualified data; these design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. This document will not directly support any construction, fabrication or procurement activity and therefore does not require TBV (to be verified) tracking. However, use of any data from this analysis for input into documents supporting procurement, fabrication, or construction is required to be controlled as TBV in accordance with the appropriate procedures.

The requirements of EB-DRD 3.2.6.1.A are addressed to the extent that the selection criteria favor strong, ductile materials and materials that will corrode slowly in the near-field environment, as far as it is understood.

The requirements of EB-DRD 3.2.6.2.2 are addressed to the extent that all of the selected materials are non-combustible and heat-resistant.

The requirements of EB-DRD 3.3.1.A are addressed to the extent that several candidate materials have been considered for each component and several design options were evalauted.

The requirements of EB-DRD 3.3.1.I were considered to the extent that cost was included as on of the selection criterion for many of the components.

For spent fuel waste forms, the requirements of EB-DRD 3.7.1.A and EB-DRD 3.7.1.2.G are addressed to the extent that chemical interactions between waste package components (including the waste form) do not compromise the function of the waste package. For high-level waste glass, additional analysis will be needed to determine whether the materials selection will compromise the function of the waste package to control dissolution of waste.

The requirements of EB-DRD 3.7.1.B are addressed to the extent that oxidation/reduction reactions, corrosion, thermal effects, mechanical strength, and synergistic interactions have been considered.

The requirements of EB-DRD 3.7.1.C are addressed to the extent that none of the selected materials is explosive, pyrophoric, or chemically reactive.

The requirements of EB-DRD 3.7.1.D are addressed to the extent that none of the selected materials is liquid.

The requirements of EB-DRD 3.7.1.G were considered to the extent that currently available technology for fabrication is discussed under the fabricability criterion.

The requirements of EB-DRD 3.7.1.1, EB-DRD 3.7.1.2.B, and EB-DRD 3.7.1.2.D are addressed to the extent that the selection criteria were used to favor strong, ductile materials and materials that will corrode slowly in the near-field environment, as far as it is understood. Such materials are expected to provide a long containment lifetime.

The requirements of EB-DRD 3.7.1.2.A and EB-DRD 3.7.1.2.F are addressed to the extent that the selection criteria are used to favor materials that are strong and ductile. Such materials will contribute to containment, limiting dispersal, sustaining routine loads, and maintain lifting and handling capabilities.

The requirements of EB-DRD 3.7.1.3.A are addressed to the extent that, in selection of materials for components that will have a criticality control function, the selection criteria are used to favor materials that are effective neutron absorbers and that will provide long-term corrosion resistance.

The requirements of EB-DRD 3.7.1.3.D are addressed to the extent that the selection criteria are used to favor materials for the internal structure that are strong and ductile.

The requirements EB-DRD 3.7.1.3.E and EB-DRD 3.7.1.3.F are addressed to the extent that galvanic interactions between the internal structure and the containment barriers will not damage the containment barriers.

The requirements of EB-DRD 3.7.1.3.G are addressed to the extent that, for components with heat transfer functions, the selection criteria were used to favor materials with high thermal conductivity.

The work presented here has not been subjected to peer review. During later stages of design, such a review may be helpful in developing consensus and showing reasonable assurance that the performance objectives will be met.

The following table summarizes the materials recommended for use in future design work according to the information presented in the previous sections. Additional testing will be needed to qualify many of the inputs that contribute to the materials selection given in the table.

Component	Material
Dual-barrier design - Option 1 Corrosion allowance barrier Corrosion resistant barrier	 Carbon steel, ASTM A 516 Grade 55 or 70 Alloy C-22, ASTM B 575
Fuel basket tubes	Carbon steel (ASTM A 516 Grade 55 or 70)
Fuel basket plates	Neutronit A 978

Waste container fill gas	Helium
Basket guides	Carbon steel (ASTM A 516 Grade 55 or 70)
Canister guide for HLW (with codisposed DOE SNF) -- optional	Carbon steel (ASTM A 516 Grade 55 or 70)

Where a choice is indicated (ASTM A 516 Grade 55 or 70), either of these materials could be used; a choice between them will require additional engineering analysis.

9. Attachments

Not applicable.