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	Printed Name	Signature	Date
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8. Checker	JOHN KEVIN MCCOY	<i>John Kevin McCoy</i>	3-15-96
9. Lead Design Engineer	CARL W. CHAGNON	<i>Carl W Chagnon</i>	3-15-96
10. QA Manager	Joe W. Willis	<i>Joe W Willis</i>	3-18-96
11. Department Manager	HUGH A. BENTON	<i>Hugh A. Benton</i>	3/19/96

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1. Purpose

This analysis is prepared by the Mined Geologic Disposal System (MGDS) Waste Package Development Department (WPDD) in response to a request received via a QAP-3-12 Design Input Data Request^(5.1) from Waste Acceptance, Storage & Transportation (WAST) Design (formerly MRS/MPC Design). The request is to provide:

5) Specific material requirements for the various MPC components (shell, basket, closure lids, shield plug, neutron absorber, and flux traps, if used).

The objective of this analysis is to provide the requested requirements. The purpose of this analysis is to provide a documented record of the basis for the requested requirements. The response is stated in Section 8 herein. The analysis is based upon requirements from an MGDS perspective.

2. Quality Assurance

The QA Program applies to this analysis. This analysis focuses on compatibility of certain Multi-Purpose Canister (MPC) design features that interface with the MGDS. These features could potentially affect the proper functioning of the MGDS waste package; the waste package has been identified as an MGDS Q-List item that is important to safety and waste isolation^(5.2). A QAP-2-3 evaluation has not been performed for the MGDS waste package. The waste package is on the Q-List by direct inclusion by the Department of Energy (DOE). This work is covered by Activity Evaluation *MPC Design Compatibility with the MGDS*^(5.3). This evaluation determined that such activities were subject to the *Quality Assurance Requirements and Description*^(5.4) requirements. Applicable procedural controls are listed in the Activity Evaluation.

3. Method

Information from the engineering literature is used to evaluate the performance of proposed MPC materials under expected conditions.

4. Design Inputs

4.1 Design Parameters

The preliminary selection of waste package materials was used in the analysis.^(5.21)

4.2 Criteria

The criteria for criticality control, structural integrity, compatibility, and prevention of environment-induced degradation for MPCs, based on criteria derived from the Mined

Geologic Disposal System Requirements Document (MGDS-RD)^(5.5), that apply to this analysis are the following:

Criticality Control: Section 3.2.2.6.A - "All systems for processing, transporting, handling, storing, retrieving, emplacing, and isolating radioactive waste shall be designed to ensure that a nuclear criticality accident is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system shall be designed for criticality safety under normal and accident conditions. The calculated effective multiplication factor 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."

Section 3.2.3.2.3.M - "The waste package design shall interface with the MPC design to ensure compliance with the nuclear criticality requirements specified in Section 3.2.2.6 of this MGDS-RD."

Section 3.2.3.2.3.S - "The MGDS shall have the capability to cut open an MPC, remove and replace SNF without damage to the SNF, and reseal the MPC for disposal."

Section 3.2.3.2.3.T - "The MGDS shall ensure that MPCs (as delivered to the MGDS) do not compromise the ability of the waste package to meet its requirements. This may require that MPCs be modified at the MGDS for the addition of filler material to contribute to criticality control, corrosion control, and heat transfer."

Section 3.7.3.3.B.3 - "The waste package design shall ensure loaded wastes are maintained subcritical in compliance with the nuclear criticality requirements specified in Section 3.2.2.6 of this MGDS-RD."

Structural Integrity: Section 3.2.3.2.3.Q - "The waste package container(s) shall protect the loaded MPCs from structural damage due to the loads induced in waste-handling operations, including retrieval."

Compatibility : Section 3.2.3.2.3.O - "The waste package design shall be coordinated with the MPC design to ensure structural, metallurgical, thermal, radiological, and dimensional compatibility."

Prevention of Degradation: Section 3.7.3.3.A - General. "Packages for SNF and HLW 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."

Section 3.7.3.3.B.1 - Integrity. "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."

4.3 Assumptions

This analysis focuses on the development of a menu of materials that can be utilized by WAST for MPC components which will be compatible with the waste package. Thus, the ultimate specification by WAST of materials from the menu of materials provided in Section 8 will resolve the MGDS concern that the function of the waste package will not be compromised. Information provided in the engineering literature was utilized to establish these bounding requirements for compatibility.

One additional assumption taken from Section 6.1 KEY ASSUMPTIONS of the Controlled Design Assumption Document^(5,6) (CDA) was used in this analysis:

4.3.1 "Criticality Control Period - The Criticality Control Period ends when trends indicate that the criticality risk will continue to decrease with time out to 1,000,000 years." from Key Assumption 039 of the CDA. (Section 7.2)

4.4 Codes and Standards

N/A

5. References

- 5.1 QAP-3-12 Design Input Data Request, N. L. Seagle, 11/13/93, to W. D. Schutt, an attachment to Interoffice Correspondence (IOC) CH.MRS.NLS.11/93.081, Stringer to Schutt, November 16, 1993, Civilian Radioactive Waste Management Systems (CRWMS) Management and Operating Contractor (M&O)
- 5.2 Yucca Mountain Site Characterization Project Q-List, YMP/90-55Q, REV 3, December 1994
- 5.3 Activity Evaluation, MPC Design Compatibility with the MGDS, Document Identifier Number (DI#) BB0000000-01717-2200-00003 REV 03, Sep. 5, 1995, CRWMS M&O

- 5.4 Quality Assurance Requirements and Description, DOE/RW-0333P, Rev. 05, Oct. 31, 1995, Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM)
- 5.5 Mined Geologic Disposal System Requirements Document, DI# B00000000-00811-1708-00002 REV 01 DCN 01, May 1995, DOE OCRWM
- 5.6 Controlled Design Assumption Document (CDA) (TBV-221-DD), DI# B00000000-01717-4600-00032 REV 02, December 19, 1995, CRWMS M&O
- 5.7 Multi-Purpose Canister (MPC) Implementation Program Conceptual Design Phase Report, Volume II.A-MPC Conceptual Design Report, DI# A20000000-00811-5705-00002 REV 00, September 1994, CRWMS M&O
- 5.8 Metals Handbook, Volume 3, Ninth Edition, pp. 6-7, 56-93 (American Society for Metals, Metals Park, Ohio 1980)
- 5.9 "Long-Term Criticality Control Issues for the MPC", DI# BB0000000-01717-0200-00008 REV 00, March 1996, CRWMS M&O
- 5.10 C. E. Makepeace, "Design and Analysis of Corrosion Experiments for Testing Materials Exposed to Gamma Radiation," Journal of Testing and Evaluation, Volume 2, No.3, pp. 202-209 (May 1974)
- 5.11 J. Draley and W. Ruther, "Corrosion of Aluminum," *Corrosion*, 12, 441t, 480t (1956)
- 5.12 J.K. Dawson and R.G. Sowden, "Chemical Aspects of Nuclear Reactors," Volume 2, Water-Cooled Reactors, p. 213, Butterworths, London (1963)
- 5.13 E. Cook, R. Horst, and W. Binger, "Corrosion of Commercially Pure Aluminum," *Corrosion*, 17, 25t (1961)
- 5.14 "Borated Stainless Steel Application in Spent-Fuel Storage Racks," Electric Power Research report, EPRI TR-100784, June 1992
- 5.15 Metals Handbook, Volume 13, Ninth Edition, p.83 and pp. 707-721 (ASM International, Metals Park, Ohio 1987)
- 5.16 C.A. Zimmerman, "Disassembly and Inspection of J-134 Vessel to Evaluate Vessel Integrity after Seventeen Years of Service," Exxon Nuclear Idaho, Company report, ENI-165, May 1981
- 5.17 "Report to Congress on the Potential Use of Lead in the Waste Packages for a Geologic Repository at Yucca Mountain, Nevada," DOE/RW-0254, December, 1989

- 5.18 "Thermal Analysis of Emplacement Drift Backfill," IOC LV.WP.RHB.09/95-309, R.H. Bahney III, to K.E. Suchsland and R.D. Memory, Sept. 15, 1995
- 5.19 Westerman, R.E., et al, "Potential Uses of Lead in Nuclear Waste Disposal," Battelle Pacific Northwest Laboratory Report, LM-337-9, May 1992
- 5.20 Dreyfus, D.A., Memorandum for the Secretary, "Information of National Environmental Policy Act requirements for the potential repository at Yucca Mountain, June 22, 1995, DOE OCRWM
- 5.21 "Preliminary Selection of Waste Package Materials (TBV-085-WPD)," DI# BBA000000-01717-5705-00007 REV 01, Nov. 3, 1995, CRWMS M&O

6. Use of Computer Software

N/A

7. Design Analysis

The analyses contained herein are partially based on unqualified data, including two reports that carry TBV's (References 5.6 and 5.21). However, the conclusions drawn are bounding in scope in that they provide a menu of acceptable materials that WAST can specify in its procurements that will not compromise the ability of the waste container to meet its containment requirement or other waste package components to perform their function. Therefore, the requirements stated in the conclusion are bounding conservative requirements that will not require further confirmation.

The Controlled Design Assumptions Document^(5.6) and the report on the Preliminary Selection of Waste Package Materials^(5.21) each carry a TBV. However, a TBV will not be assigned to this analysis based on the rationale that the conclusions derived by this analysis are conservative bounding requirements that will not require further confirmation.

7.1 MPC Shell and Closure Lids

The primary function of the MPC shell is to confine radionuclides throughout the storage period, during transfer operations involved in transportation, and during handling at the repository.

No performance has been allocated to the MPC shell as a disposal containment barrier. This is due to the difficulty in assuring compliance of the canister to the containment requirement after a lengthy storage period. Thus, the basic strategy for waste containment at the MGDS is to rely on the disposal container as the containment barrier.

The canister, from the criteria in Section 4.2 - Compatibility and Prevention of Degradation,

must be compatible with the containment barriers, and not compromise their performance (MGDS 3.7.3.3 A and 3.7.3.3 B.1). This is satisfied by utilization of a metallic corrosion-resistant canister material such as austenitic low carbon stainless steel or stabilized stainless steel.^(5.7 p.II. A. 4-4) These materials are chemically close^(5.8) to that currently considered for the reference inner container, Alloy 825.^(5.21) Other corrosion resistant alloys such as Alloy 825 or other high-nickel alloys are also acceptable. Thus, galvanic or other interactions are unlikely. Similarly, the closure lid of the same grades of austenitic stainless steel as the shell will also be compatible with the container.

7.2 SNF Basket: Neutron Absorber

The MGDS-RD specifies the criticality control requirements for disposal.^(5.5) These are given in Section 4.2. One approach involves the use of supplemental neutron absorbing material. Another approach utilizing alternative neutron absorbing materials appears likely to meet the criticality control requirements, such as putting control rods of highly corrosion-resistant material in the guide tubes in those spent nuclear fuel (SNF) assemblies that can accommodate them. These rods can be inserted either at the reactor sites during initial loading of the MPCs or at the MGDS. Filler material to displace moderator could also be put into the MPCs at the MGDS. These alternative approaches are not discussed any further in this document.

If meeting these requirements depends on supplemental neutron absorbing material such as boron, the boron carrier material should essentially remain intact for the period of isolation (Key Assumption 020). Loss of neutron absorber capability due to degradation of the absorber host material could increase the potential for criticality. Compensation must be made for any such absorber loss and resulting increase in reactivity.

It is assumed in the Design Analysis on Long-Term Criticality Control Issues for the MPC that the neutron absorber will need to be finely dispersed in a long-term performance material for criticality control in the expected repository conditions.^(5.9) There are two reasons why a fine dispersion is required: neutronic performance, and removal concern with long-term degradation of the carrier material. The first one is to minimize neutron streaming pathways which would reduce the effectiveness of the neutron absorber. The latter is to ensure that localized corrosion will not remove the neutron absorber from a large section of the material. Thus, the fine dispersion will ensure that the loss of the neutron absorber is no greater than the proportional loss of carrier material.

Consideration of boron dispersed in aluminum for the MPC SNF basket stems from the beneficial effects of aluminum (Al) and boron (B) in enhancing the thermal conductivity and neutron attenuation, respectively. One material, commercially known as "Alboron" and manufactured by Eagle-Picher Industries, Inc., is an alloy of 1100 aluminum alloy and enriched ¹⁰B. Another material is Boral, a composite of aluminum and boron carbide.

As discussed above, boron finely dispersed throughout the carrier alloy, whether aluminum or austenitic stainless steel, will initially provide the necessary level of criticality control.

However, for stainless steel, weight and thickness may require the use of enriched boron due to limitations on the boron loading.^(5.14) Thus, the significantly increased expense of using enriched ^{10}B may need to be evaluated.

Aluminum-boron, as Boral, has been chosen as a criticality control material for pressurized water reactor fuel for the first buy of the MPC. However, aluminum is known to corrode when contacted by water. An evaluation of the open literature^(5.10) indicates that the formation of $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ (gibbsite) is favored at room temperature in irradiated saturated moist air where NO_x (NO , NO_2) and HNO_3 generated in the gas phase are concentrated in thin layers of water on the surface of aluminum. At higher temperatures, boehmite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) will form. Corrosion without a radiation field will occur over a range of pH values from 4.5 to 7 at a rate of about 1.0 to 10 $\mu\text{m}/\text{yr}$.^(5.11,5.12) Large amounts of nitric acid, if generated as a result of radiolysis, will cause the rapid dissolution of aluminum, due to general corrosion, at rates in excess of 3 mm/yr.^(5.13) Furthermore, localized attack such as pitting corrosion may occur as a result of condensation of NO_x on the aluminum surface. The MPC is to be vacuum dried and filled with helium, so water vapor and nitrogen initially are intended to be present only in trace amounts. Therefore, until there should be a breach of the disposal containment barriers and water enters, there will be negligible nitric acid formation. However, if a breach has occurred and water has entered and contacted the aluminum, the aluminum sheath and matrix will be attacked and boron leaching will occur. Thus, under these conditions, aluminum-boron cannot be depended upon over the very long time period ($> 10,000$ years) required for criticality control (Key Assumption 039).

The criteria from Section 4.2 dealing with compatibility of the waste package and MPC designs requires the consideration of material compatibility and galvanic reactions. Galvanic corrosion occurs when a metal or alloy is electrically coupled to another metal in the same electrolyte. The more active metal becomes anodic, and the more noble metal becomes cathodic in the couple, resulting in an enhanced corrosion of the more active member of the couple. An examination of the galvanic series^(5.15) indicates that aluminum and its alloys would corrode preferentially when coupled with either austenitic Type 316L stainless steel or nickel-rich Alloy 825, since the former material will be anodic. On the other hand, Type 316L stainless steel and the austenitic nickel-based alloys are adjacent to each other and are therefore compatible with each other from a galvanic perspective.

In light of the above explanations, aluminum-boron once contacted by water does not possess sufficient corrosion resistance to permit its use as the carrier for the neutron absorbing material. However, it is quite acceptable to use an aluminum alloy as a component of the SNF basket to provide criticality control during storage, transportation, and pre-closure operations, and to enhance overall thermal conductivity when decay heat is high.

Stainless steel has been utilized by the chemical industry for a variety of applications under aggressive environments. Thus, it is expected that the use of austenitic stainless steel with a finely dispersed boron-containing phase will ensure that the boron will be present over a longer period of time. A recent Electric Power Research Institute report evaluated the use of

stainless steel-boron in spent fuel storage racks.^(5.14) The conditions experienced by the storage racks are not too different in neutron fluence and temperature from those expected in a breached waste package that is contacted by water. The report indicated, based on mechanical and other tests, that the use of borated stainless steel was both practical and cost-effective. The only long-term exposure information comes from experience at the Idaho Chemical Processing Plant. Analysis of a Type 304L stainless steel tank after 17 years of acid service indicated that only minor grain edge attack had occurred and that no measurable loss of boron occurred.^(5.16) Thus, the potential of criticality due to the failure of the basket material will be moved out in time and leads to a reduced probability of occurrence. While austenitic stainless steel is still not ideal as a carrier for neutron absorber, it is better than aluminum-based material, based on the data cited above.

Zirconium-hafnium alloys are being considered for use as long-term criticality control materials.^(5.9) Zirconium has been long used in reactor applications, mostly as cladding for fuel rods as Zircaloy-2 or Zircaloy-4 alloys, due to its excellent corrosion resistance in hot water and steam and its low thermal-neutron cross section. Corrosion resistance results from the formation of a dense, tenacious oxide on the surface of the metal. Corrosion rates are generally on the order of a few microns a year at elevated temperature, with negligible rates at or below the normal boiling point.^(5.15) Corrosion rates in ambient or boiling sea water are also negligible. Zirconium alloys are also resistant to crevice and pitting corrosion and stress corrosion cracking. Under some conditions, zirconium alloys are attacked by ferric chloride solutions. Hafnium and zirconium-hafnium alloys also possess excellent corrosion resistance in hot water and steam. Hafnium occurs naturally in zirconium ores in quantities ranging from 1.5 to 4.0 weight percent. Zirconium alloys, such as Alloy 702, contain this range of hafnium. Hafnium is used in naval reactors as control rod material due to its corrosion resistance and high thermal-neutron cross section.

The long-term material testing program will evaluate and recommend a criticality control material for disposal. Materials, such as stainless steel-boron, copper-boron, aluminum-boron, hafnium, zirconium-hafnium alloy, boron carbide, as well as oxides of hafnium and gadolinium, will be tested. Scoping studies just completed at Lawrence Livermore National Laboratory (LLNL) indicated that aluminum-boron, and to some extent copper-boron reacted as a result of the short-term exposure to oxidizing, low pH, chloride solutions. Stainless steel-boron, zirconium-hafnium, and the ceramic materials did not appreciably react under these conditions.

In summary, if supplemental neutron absorbing material is required to meet the criticality control requirements cited in the MGDS-RD under aqueous conditions, i.e., water contacting the material, aluminum-boron is unsatisfactory for the reasons stated earlier in this analysis. Austenitic stainless steel with a finely dispersed boron-containing phase and zirconium-hafnium alloys are considered acceptable by the MGDS based on current knowledge, but would need to be tested to verify their long-term performance under expected repository conditions. Such a test program is currently being initiated, but will not produce any conclusive results for several years.

7.3 SNF Basket: Structural

The function of the structural component of the SNF basket is to provide separation of the SNF assemblies and to ensure that they remain in their original positions without interference as emplaced, during the period of waste isolation. This is consistent with the criteria for structural integrity provided in Section 4.2. The basket material should maintain structural integrity, and enhance conduction of heat away from the waste form. Furthermore, it must be compatible with the basket criticality control material and waste form, from the criteria of compatibility in Section 4.2. If the basket also acts as a flux trap, then the basket must maintain its geometry to contribute to criticality control, from the criteria for criticality control from Section 4.2.

These requirements can most effectively be met by using corrosion-resistant materials such as low-carbon austenitic stainless steel or stabilized austenitic stainless steel. High-nickel alloys may also be considered to ensure maintenance of integrity should the containment barriers be breached. These materials are chemically similar to the current reference container material, Alloy 825,^(5,21) such that they will be compatible and not compromise the ability of the container to meet its containment function.

The use of carbon steel or other metals or alloys, which are not long-term performance materials, as basket structural materials is not precluded. These materials may be used if they are compatible with the shell and other internals and do not compromise the function of the waste package to meet the containment requirements. However, credit may not be taken for their presence to support long-term criticality control.^(5,9) If coatings or sheathings are utilized, they must be compatible with the MPC components and must not compromise containment.

7.4 Shield Plug

The function of the shield plug is to reduce the radiation dose. The plug material should be effective in shielding both gamma and neutron radiation. The shield plug has no specific function relative to containment, but it must be compatible with MPC and waste package materials and not compromise their functions. Depleted uranium sheathed with stainless steel is anticipated for the MPC shield plug^(5,7 p. II. A. 4-4). Of the possible alternative materials, only carbon steel was considered. These materials would not compromise the ability of the barriers and other waste package components to perform their long-term functions. The MGDS finds these materials acceptable, imposing no other requirement except the exclusion of lead, due to the potential for embrittlement by lead of the MPC and waste package components and the potential for impacting the licensing process. However, the use of a removable shield plug containing lead is not excluded.

The shield plug will be exposed to high temperatures (up to 200°C).^(5,7) At these temperatures, it is possible that lead will embrittle the sheathing of the shield plug,^(5,17) and the embrittled sheathing may fail. The phenomenon, called solid-metal embrittlement, is caused

by attack of the grain boundary substrate. Lead can mobilize at temperatures exceeding three-fourths of its absolute melting point, about 175°C. Stress can accelerate embrittlement and cause complete penetration of the metal within days or months. Short-term experiments have shown that iron-base materials are embrittled (grain-boundary attack) by lead in short-term experiments at temperatures as low as 160°C.^(5.17) Evidence for embrittlement of stainless steels is inconclusive. Recent experiments by Westerman et al^(5.19) evaluated the reduction of ductility for carbon steel and Alloy 825 utilizing a slow-strain rate approach. These tests were conducted for one to four days in molten lead. Specimens were fully annealed prior to the test. No embrittlement was found as a result of these short-term tests. However, no testing was conducted on welded samples or samples that contained residual stresses. In addition, stainless steel was not evaluated in the tests. Expected maximum temperatures (up to 200°C) for the shield plug^(5.18) are close enough to the melting point of lead (327°C), so the lead would be expected to creep out, contact, and potentially embrittle the MPC shell and other waste package components. In addition, if backfill of the emplacement drifts is required, the shield plug temperatures could reach 270°C.^(5.18)

Stainless steel, as well as carbon steel, sheathing is compatible with the container material and would not compromise its ability to meet the containment requirement. Uranium melts at a high temperature (1132°C) and hence should not react with stainless or carbon steel or creep at expected storage temperatures. Note that under some conditions, the Nuclear Regulatory Commission has required that uranium be coated to prevent eutectic reactions. However, the presence of uranium could reduce the corrosion rate of spent nuclear fuel, since it introduces uranium cations into solution which retards the UO₂ dissolution process.

One other concern has been raised regarding the use of lead in the repository. This concern is whether it will meet the requirements of the Resource Conservation and Recovery Act (RCRA) regarding the land disposal of hazardous materials controlled under 40 CFR Part 261. Since the State of Nevada is an agreement state, which permits it to act for the Environmental Protection Agency on matters relating to RCRA permitting in the state, it is possible that the permitting process could be protracted. This could be possible even though the lead itself is not a waste. To avoid this issue, Dr. Dreyfus in a recent memo stated that "The Office of Civilian Radioactive Waste Management will accept only spent nuclear fuel and high-level radioactive wastes that do not include components regulated as hazardous wastes under the Resource Conservation and Recovery Act."^(5.20)

8. Conclusions

The following material requirements, which do not compromise the ability of the container to meet its containment requirement or other waste package components to perform their function, apply to the MPC for long-term performance at the MGDS. These are bounding requirements, since they include those materials that are compatible with the waste package components, that will not require further confirmation.

MPC Shell and Closure Lids: Low carbon austenitic stainless steel or stabilized austenitic stainless steel.

SNF Basket - Neutron Absorber: Austenitic stainless steel with a finely dispersed boron-containing phase and zirconium-hafnium alloys are the currently recommended materials. Austenitic stainless steel is still not an ideal carrier for neutron absorbing material, but it is superior to aluminum-based material. The expected long-term performance of stainless steel and zirconium-hafnium alloys will be supported by corrosion testing being initiated at LLNL. Aluminum boron is not acceptable as a long-term criticality control material if water is expected to be present. However, it can be utilized during the storage, transportation and pre-closure operational periods. In addition, the supplemental criticality control requirements can be achieved by adding moderator-displacing filler materials, or inserting disposable control rods made of corrosion-resistant materials.

SNF Basket, Including Flux Trap or Other Structure - Structural: Low carbon austenitic stainless steel or stabilized austenitic stainless steel, or high nickel alloy, for disposal criticality control credit; or carbon steel or other metals and alloys which are not long-term performance materials for which no credit may be taken for criticality control.

Shield Plug: Depleted uranium, sheathed in a compatible material such as stainless or carbon steel. Lead is not allowed in the waste package. Other high density materials may be used without sheathing if compatible with the basket and shell materials.

9. Attachments

N/A