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Design Analysis Cover Sheet

Complete only applicable items.

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14. REMARKS

This document has one TBV numberr controlled in accordance with NLP-3-15:TBV-213-WPD.

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Design Analysis Revision Record

Complete only applicable items.

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2. DESIGN ANALYSIS TITLE	
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Table of Contents:

1. Purpose

This analysis is prepared by the Mined Geologic Disposal System (MGDS) Waste Package Development Department (WPDD) as specified in the Waste Package Implementation Plan (pp. 4-8, 4-11, 4-24, 5-1, and 5-13; Ref. 5.10) and Waste Package Plan (pp. 3-15, 3-17, and 3-24; Ref. 5.9). The design data request addressed herein is:

1) Characterize the conceptual 24 boiling water reactor (BWR) uncanistered fuel (UCF) waste package (WP) to show that the design is feasible for use in the MGDS environment.

The purpose of this analysis is to respond to a concern that the long-term disposal thermal issues for the UCF waste package do not preclude UCF waste package compatibility with the MGDS. The objective of this analysis is to provide thermal parameter information for the conceptual UCF WP design under nominal MGDS repository conditions. The results are intended to show that the design has a reasonable chance to meet the MGDS design requirements for normal MGDS operation and to provide the required guidance to determining the major design issues for future design efforts. Future design efforts will focus on UCF design changes as further design and operations information becomes available.

2. Quality Assurance

The Quality Assurance (QA) program does apply to this analysis. The information in this analysis concerning disposal long-term thermal parameters for the conceptual UCF WP will be used as a guide as to the possible requirements which might be used in the final UCF WP design. The performance of the UCF internals will affect the proper function of the waste package and the waste package has been identified as a MGDS Q-List item important to safety (p. 5, Ref. 5.4). The waste package is on the Q-List by direct inclusion by DOE without conducting a QAP-2-3 evaluation. The work performed for this analysis is covered by reference 5.2, Perform Criticality, Thermal, Structural, and Shielding Analysis, which is part of the WPDD QAP-2-0 Work Control evaluation documents. This QAP-2-0 evaluation determined such activities are subject to Quality Assurance Requirements and Description (QARD) (Ref. 5.3) requirements. Applicable procedural controls are listed in the evaluation.

All design inputs which are identified in this document are for pre-Title II (conceptual or preliminary) designs; some or all of these design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. For design documents subject to the QARD requirements, unqualified design inputs must be considered as TBV (to be verified) items subject to tracking, in accordance with applicable procedures. The design inputs identified and documented in Section 4 have been assigned the single tracking number TBV-213-WPD, to meet tracking requirements.

3. Method

The analytical method to be employed is Finite Element Analysis (FEA). The analysis will build upon the Emplacement Scale Thermal Evaluations (Ref. 5.13) and the thermal conductivity analysis used in reference 5.40, by using the same method for SNF thermal modeling and the results for the WP surface temperatures from the three-dimensional emplacement scale model. Thus, the BWR UCF internals will be modeled with the spent nuclear fuel (SNF) approximated by a homogeneous material property region based upon the GE-7 BWR-5 fuel assembly data (pp. 2A-21, 2A-22, Ref. 5.12 and p. 26, Ref. 5.39) and the SNF effective thermal conductivity calculations (Ref. 5.11). Peak SNF cladding temperatures will also be determined using the Wooton-Epstein Correlation (Ref. 5.14) for comparison purposes. The calculation shall be performed as a transient analysis to evaluate the first 1000 years of proposed repository operation.

4. Design Inputs

All design inputs are for pre-Title II designs; some or all of these design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. The design inputs identified and documented in Section 4 have been assigned the single tracking number TBV-213-WPD, to meet tracking requirements in accordance with applicable procedures.

4.1 Design Parameters

Tables 4.1-1 and 4.1-2 list the material and thermal properties of density, emissivity, thermal conductivity, and specific heat of stainless steel 316 (see assumption 4.3.23). The density of 316 stainless steel provided in Table 4.1-1 was taken from Table 17 of the Metals Handbook (p. 423, Ref. 5.18). The emissivity provided in Table 4.1-1 was taken from Table 4.3.2 of Marks' Handbook (p. 4-68, Ref. 5.17) and is about average for heated stainless steel 316.

Table 4.1-1. Material Properties of Stainless Steel 316 (Refs. 5.17 and 5.18)

	Density	Emissivity
Stainless Steel 316	8000.0 kg/m^3	0.60

Table 4.1-2 lists the thermal properties of stainless steel 316. Values for thermal conductivity and thermal diffusivity of stainless steel 316 (Cr-Ni-Mo) were taken from Table I-4.0, Appendix I of the 1986 ASME Boiler and Pressure Vessel Code (p. 97, Ref. 5.15) and are converted here to conductivity and specific heat in SI units. The conversion of thermal diffusivity (defined in equation 4.1-1 below) to specific heat requires the density listed in Table 4.1-1.

$$\textit{Thermal Diffusivity}(ft^2/hr) = \frac{\textit{Thermal Conductivity}(Btu/hr\,ft\cdot{}^\circ F)}{\textit{Density}(lb/ft^3) \times \textit{Specific Heat}(Btu/lb\cdot{}^\circ F)} \qquad \text{(Equation 4.1-1)}$$

Table 4.1-2. Thermal Properties of Stainless Steel 316 (Ref. 5.15)

Temperature		Thermal Conductivity (Btu/hr·ft·°F)	Thermal Diffusivity (ft^2/hr)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
°F	°C				
70	21.11	7.7	0.134	13.33	481.68
100	37.78	7.9	0.136	13.67	486.92
150	65.56	8.2	0.138	14.19	498.09
200	93.33	8.4	0.141	14.54	499.38
250	121.11	8.7	0.143	15.06	509.98
300	148.89	9.0	0.145	15.58	520.29
350	176.67	9.2	0.148	15.92	521.07
400	204.44	9.5	0.151	16.44	527.38
450	232.22	9.8	0.153	16.96	536.92
500	260.00	10.0	0.156	17.31	537.34
550	287.78	10.3	0.159	17.83	543.02
600	315.56	10.5	0.162	18.17	543.31
650	343.33	10.7	0.164	18.52	546.91
700	371.11	11.0	0.167	19.04	552.14
750	398.89	11.2	0.170	19.38	552.26
800	426.67	11.5	0.173	19.90	557.22
850	454.44	11.7	0.176	20.25	557.25
900	482.22	12.0	0.178	20.77	565.11
950	510.00	12.2	0.181	21.11	565.01
1000	537.78	12.4	0.184	21.46	564.91
1050	565.56	12.7	0.186	21.98	572.35
1100	593.33	12.9	0.189	22.33	572.14
1150	621.11	13.1	0.191	22.67	574.92
1200	648.89	13.3	0.194	23.02	574.68
1250	676.67	13.6	0.196	23.54	581.64
1300	704.44	13.8	0.199	23.88	581.30
1350	732.22	14.0	0.201	24.23	583.86
1400	760.00	14.2	0.203	24.58	586.36
1450	787.78	14.4	0.206	24.92	585.96
1500	815.56	14.6	0.208	25.27	588.39

Table 4.1-3. Thermal Properties of A 516 Carbon Steel (Ref. 5.15)

Temperature		Thermal Conductivity (Btu/hr·ft·°F)	Thermal Diffusivity (ft^2/hr)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
°F	°C				
70	21.11	23.6	0.454	40.84	428.72
100	37.78	23.9	0.443	41.36	444.95
150	65.56	24.2	0.433	41.88	460.94
200	93.33	24.4	0.422	42.23	476.87
250	121.11	24.4	0.414	42.23	486.08
300	148.89	24.4	0.406	42.23	495.66
350	176.67	24.3	0.396	42.06	506.09
400	204.44	24.2	0.386	41.88	517.07
450	232.22	23.9	0.375	41.36	525.64
500	260.00	23.7	0.364	41.02	536.99
550	287.78	23.4	0.355	40.50	543.63
600	315.56	23.1	0.346	39.98	550.62
650	343.33	22.7	0.333	39.29	562.21
700	371.11	22.4	0.320	38.77	577.32
750	398.89	22.0	0.308	38.08	589.10
800	426.67	21.7	0.298	37.56	600.57
850	454.44	21.2	0.286	36.69	611.35
900	482.22	20.9	0.274	36.17	629.09
950	510.00	20.5	0.262	35.48	645.12
1000	537.78	20.0	0.248	34.61	665.12
1050	565.56	19.6	0.237	33.92	682.07
1100	593.33	19.2	0.228	33.23	694.52
1150	621.11	18.7	0.213	32.36	724.07
1200	648.89	18.2	0.197	31.50	761.95
1250	676.67	17.5	0.179	30.29	806.31
1300	704.44	16.7	0.155	28.90	888.60
1350	732.22	15.8	0.119	27.35	1095.04
1400	760.00	15.3	0.077	26.48	1638.78
1450	787.78	15.1	0.154	26.13	808.68
1500	815.56	15.1	0.169	26.13	736.90

Table 4.1-3 lists the thermal properties of A 516 carbon steel (see assumption 4.3.24). Values for thermal conductivity and thermal diffusivity of A 516 (C-Mn-Si) were taken from Table I-4.0, Appendix I of the 1986 ASME Boiler and Pressure Vessel Code (p. 97, Ref. 5.15) and are converted here to conductivity and specific heat in SI units. The conversion of thermal diffusivity (defined in equation 4.1-1) to specific heat requires the density listed in Table 4.1-4.

Table 4.1-4 lists the density and emissivity of A 516 carbon steel. The density of A 516 (C-Mn-Si) was taken from Table A.1 of a standard heat transfer text (p. 670, Ref. 5.16) and the emissivity (average for smooth oxidized iron) was taken from Table 4.3.2 of Marks' Handbook (p. 4-68, Ref. 5.17).

Table 4.1-4. Material Properties of A 516 Carbon Steel (Refs. 5.16 and 5.17)

	Density	Emissivity
A 516 Carbon Steel	8131.0 kg/m^3	0.80

Tables 4.1-5 and 4.1-6 list the material and thermal properties of density, emissivity, thermal conductivity, and specific heat of Alloy 825 (see assumption 4.3.25). The density of Alloy 825 (Ni-Fe-Cr-Mo-Cu) provided in Table 4.1-5 was taken from the product specifications published by the manufacturer; Huntington Alloys (p. 31, Ref. 5.19). The emissivity of Alloy 825 (Ni-Fe-Cr-Mo-Cu) provided in Table 4.1-5 was taken from the LLNL report on the Thermal Performance of a Buried Nuclear Waste Storage Container Storing a Hybrid Mix of PWR and BWR Spent Fuel Rods (p. 15, Ref. 5.20).

Table 4.1-5. Material Properties of Alloy 825 (Refs. 5.19 and 5.20)

	Density	Emissivity
Alloy 825	8137.9 kg/m^3	0.80

Table 4.1-6 lists the thermal properties of Alloy 825. Values for thermal conductivity and thermal diffusivity of Alloy 825 (Ni-Fe-Cr-Mo-Cu) were taken from Table I-4.0, Appendix I of the 1986 ASME Boiler and Pressure Vessel Code (p. 97, Ref. 5.15) and are converted here to conductivity and specific heat in SI units. The conversion of thermal diffusivity (defined in equation 4.1-1) to specific heat requires the density listed in Table 4.1-5.

Table 4.1-6. Thermal Properties of Alloy 825 (Ref. 5.15)

Temperature		Thermal Conductivity (Btu/hr·ft·°F)	Thermal Diffusivity (ft²/hr)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
°F	°C				
200	93.33	7.1	0.127	12.29	460.69
250	121.11	7.3	0.126	12.63	477.42
300	148.89	7.6	0.125	13.15	501.02
350	176.67	7.9	0.129	13.67	504.65
400	204.44	8.1	0.134	14.02	498.12
450	232.22	8.4	0.133	14.54	520.45
500	260.00	8.6	0.132	14.88	536.88
550	287.78	8.9	0.131	15.40	559.85
600	315.56	9.1	0.130	15.75	576.83
650	343.33	9.3	0.133	16.10	576.21
700	371.11	9.6	0.136	16.61	581.68
750	398.89	9.8	0.135	16.96	598.20
800	426.67	10.0	0.133	17.31	619.58
850	454.44	10.2	0.132	17.65	636.76
900	482.22	10.4	0.131	18.00	654.20
950	510.00	10.7	0.130	18.52	678.25
1000	537.78	10.9	0.129	18.86	696.29
1050	565.56	11.1	[redacted]	19.21	[redacted]
1100	593.33	11.4	[redacted]	19.73	[redacted]
1150	621.11	11.6	[redacted]	20.08	[redacted]
1200	648.89	11.8	[redacted]	20.42	[redacted]
1250	676.67	12.1	[redacted]	20.94	[redacted]
1300	704.44	12.4	[redacted]	21.46	[redacted]
1350	732.22	12.7	[redacted]	21.98	[redacted]
1400	760.00	12.9	[redacted]	22.33	[redacted]
1450	787.78	13.3	[redacted]	23.02	[redacted]
1500	815.56	13.6	[redacted]	23.54	[redacted]

Table 4.1-7 lists the thermal properties of helium (see assumption 4.3.22). Values for thermal conductivity and thermal diffusivity of helium were taken from Table A.4, Appendix A of a standard heat transfer text (p. 683, Ref. 5.16). Indicated values were linearly interpolated from the data supplied in the reference.

Table 4.1-7. Thermal Properties of Helium (Ref. 5.16)

Temperature		Helium Density at 1 atm. (kg/m³)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
K	°C			
260	-13.15	0.1875	0.137	5193.0
280	6.85	0.1750*	0.145	5193.0
300	26.85	0.1625	0.152	5193.0
350	76.85	0.1422*	0.170	5193.0
400	126.85	0.1219	0.187	5193.0
450	176.85	0.1097*	0.204	5193.0
500	226.85	0.0975	0.220	5193.0
550	276.85	0.0906*	0.236*	5193.0
600	326.85	0.0836*	0.252	5193.0
650	376.85	0.0767*	0.264	5193.0
700	426.85	0.0697	0.278	5193.0
750	476.85	0.0662*	0.291	5193.0
800	526.85	0.0627*	0.304	5193.0
900	626.85	0.0558*	0.330	5193.0
1000	726.85	0.0488	0.354	5193.0

* Values marked with an * were linearly interpolated from the table because values were not given.

Table 4.1-8 lists the thermal properties of aluminum-boron alloy (see assumption 4.3.26). Values for thermal conductivity and thermal diffusivity for aluminum-boron alloy were taken from Table 3 of a report by Properties Research Laboratory on the thermal conductivity of aluminum-boron alloy (p. 4, Ref. 5.21). The emissivity of aluminum-boron alloy is assumed to be equivalent to that of a rough plate of aluminum (see assumption 4.3.26). The emissivity of a rough plate of aluminum at 26°C is 0.07 as reported in Table 4.3.2 of Marks' Handbook (p. 4-68, Ref. 5.17).

Table 4.1-8. Thermal Properties of Aluminum-Boron Alloy (Ref. 5.21)

Temperature		Al-B Alloy Density (kg/m^3)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
K	°C			
296.15	23.0	[redacted]	182.56	868.0
323.15	50.0	2693.0	190.17	903.0
373.15	100.0	[redacted]	199.22	946.0
423.15	150.0	[redacted]	202.91	976.0
473.15	200.0	[redacted]	203.72	998.0

Table 4.1-9 lists the thermal properties of C71500 70/30 copper-nickel alloy (see assumption 4.3.27). Values for thermal conductivity for C71500 70/30 copper-nickel alloy were taken from Tables 2-46 and 2-48 of a report issued by Yucca Mountain Site Characterization Project which provided basic design data (p. 44, Ref. 5.22). The density and specific heat of C71500 70/30 copper-nickel alloy were taken from Table 2-46 of the same report (p. 43, Ref. 5.22).

Table 4.1-9. Thermal Properties of C71500 70/30 Copper-Nickel Alloy (Ref. 5.22)

Temperature		C71500 Density (lb/in^3)	C71500 Density (kg/m^3)	Thermal Conductivity (Btu/ hr·ft ·°F)	Thermal Conductivity (W/m·K)	Specific Heat (Btu/ lb·°F)	Specific Heat (J/kg·K)
°F	°C						
68.0	20	0.323	8940.64	17.0	29.42	0.09	376.79
212.0	100	[redacted]	[redacted]	16.9	29.25	[redacted]	[redacted]
392.0	200	[redacted]	[redacted]	19.7	34.09	[redacted]	[redacted]
572.0	300	[redacted]	[redacted]	22.3	38.59	[redacted]	[redacted]
752.0	400	[redacted]	[redacted]	24.9	43.09	[redacted]	[redacted]
832.0	500	[redacted]	[redacted]	27.8	48.11	[redacted]	[redacted]
1112.0	600	[redacted]	[redacted]	30.7	53.13	[redacted]	[redacted]
1292.0	700	[redacted]	[redacted]	33.6	58.15	[redacted]	[redacted]

4.2 Criteria

The design of the engineered barrier segment (EBS) will depend on thermal analyses of the repository host rock and near-field. Criteria that relate to the thermal analysis of the EBS are derived from the applicable requirements and planning documents. Upper-level systems requirements are provided in the Mined Geologic Disposal System Requirements Document (MGDS-RD) (Ref. 5.6). The requirements flow down to the Engineered Barrier Design Requirements Document (EB-DRD, Ref. 5.5) as specific requirements for engineered barrier segment design. The Waste Package Implementation Plan (WPIP) (Ref. 5.10) also provides criteria and goals for the thermal design of the EBS. The criteria applicable to thermal analysis of waste package emplacement are equivalent to the applicable requirements, interface requirements, and criteria cited in the MGDS-RD, EB-DRD, WPIP and all requirements which apply to thermal analysis are listed in this section for completeness.

4.2.1 MGDS-RD Requirements for Thermal Design

The criteria applicable to thermal analysis of waste package emplacement which appear in the MGDS-RD (pp. 29, 44, 107; Ref. 5.6) but do not appear in the EB-DRD are listed here:

"3.1.5 Major Considerations and Assumptions

...

M. It is assumed that loaded MPCs emplaced for disposal will have a maximum thermal output of 14.2 kilowatts. Accommodation of this condition will require management of the waste delivery schedule or storage of loaded MPCs with a higher thermal output until the thermal output has decreased to 14.2 kilowatts. This 14.2 kilowatts is equivalent to the thermal output of 21 PWR assemblies with 40 GWd/MTU burnup and 3.75% initial enrichment 10 years after discharge from a reactor. (Twenty-one assemblies represents the capacity of one of several potential MPC configurations.)"

"3.2.3.2.3 MGDS-Transportation Interface Requirements

...

J. The MGDS shall provide an emplacement environment (e.g., waste package design, underground facility design, emplacement mode or orientation, spacing between waste packages, etc.) for the MPC with disposal container, such that an emplaced waste package with thermal output of 14.2 kW will not result in an MPC surface temperature higher than 225°C <TBR> [Ref 2.4.2.C][RW-0199][10 CFR 60.135(a)(2)][Derived by 3.2.1.1.H]

The MPC Design is responsible for maintaining the peak SNF cladding temperature below the maximum temperature designated for disposal. To meet this requirement, the peak cladding temperature in a loaded MPC with a thermal output of 14.2 kW may not exceed 350°C when subjected to an MPC external wall temperature of 225°C."

"3.7.3.3 Waste Package Requirements

...

B.2. Waste packages shall be emplaced in an environment (e.g., waste package design, underground facility design, emplacement mode or orientation, spacing between waste packages, etc.), such that SNF cladding temperatures in an emplaced waste package do not exceed 350°C <TBR>. [10 CFR 60.135(a)(2)][Derived by CRD 3.2.1.1.H]"

4.2.2 EB-DRD Requirements for Thermal Design

The criteria applicable to thermal analysis of waste package emplacement are equivalent to the applicable requirements in the EB-DRD (pp. 3-10, 3-14, 3-21, 3-23, 3-25, 3-26, 3-47, 3-49, 3-50, 3-53, and 3-54; Ref. 5.5) and are listed here:

"3.1.5 MAJOR CONSIDERATIONS AND ASSUMPTIONS

...

B. The assumption used in developing this EB-DRD is that the extent of blending (i.e., the mixing in waste packages of SNF and/or HLW of different thermal outputs) required is limited to that which can be accommodated by the WA process.

Thermal loading studies will determine the extent of blending that must occur. Limited blending can be accomplished at the MRS through the WA process. If significant blending is required, this could have a major impact on the MRS and/or MGDS design and operations, and will be the subject of system studies. If these studies show that changes in system design requirements are necessary, the RDs will be revised."

"3.2.2 RADIOLOGICAL PROTECTION

3.2.2.1 GENERAL REQUIREMENTS

...

C. The Engineered Barrier Segment, together with the Repository Segment, shall provide adequate shielding from radioactive components and high ambient temperatures. [Derived]"

"3.2.3.3 ENGINEERED BARRIER SEGMENT - REPOSITORY SEGMENT INTERFACE REQUIREMENTS

...

A.8. The Repository Segment will accommodate the emplacement concept (TBD) selected during ACD. [Derived]

...

b. The Repository Segment design will prevent free-liquid-phase water from contacting the waste package during the period from package insertion until repository closure. [Derived]

c. The Repository Segment layout will be designed so that a combination of characteristics will assist in keeping liquid water from contacting the waste packages for the first 300 to 1000 (TBV) years after closure. [Derived]

d. The Repository Segment layout will also ensure that the design limit temperatures (TBD) for waste forms are not exceeded. [Derived]

...

A.10 If the design requires the waste form to be transferred for any purpose (such as from shipping casks to waste packages), the Repository Segment is responsible for the following:

...

b. Repository Segment options at the surface handling facility will be designed so that cladding failure from mechanical abrasion or deformation considering thermally-induced effects will result in less than five percent (TBV) cladding strain. [Derived]

...

A.17 The underground facility will be designed so that the performance objectives will be met taking into account the predicted thermal and thermo-mechanical response of the host rock, and surrounding strata, and ground water system. [MGDS-RD 3.7.3.4.C][10 CFR 60.133(i)]"

"3.2.3.4 ENGINEERED BARRIER SEGMENT - WASTE ACCEPTANCE INTERFACE REQUIREMENTS

...

A. WA will provide standard HLW meeting the following criteria:

...

1.e. Total heat generation rate: Up to 1500 watts per canister (TBV) at the year of shipment.

1.f. Waste temperature: Will not have exceeded 400°C (TBV) during transit to ensure the glass transition temperature was not exceeded. [MGDS-RD 3.2.3.2.2.B.1]

...

C. WA will provide standard SNF meeting the following criteria:

...

1.b. Cross-section: 6 inches x 6 inches or less for BWR and 9 inches x 9 inches or less for PWR (TBV). [MGDS-RD 3.2.3.2.2.A.1][10 CFR 961.11, App. E, B.1]

...

1.d. Cooling: The minimum cooling time for fuel is five (5) years. [MGDS-RD 3.2.3.2.2.A.1][10 CFR 961.11, App. E, B.3]

...

1.f. Consolidated Fuel Rods: Fuel which has been disassembled and stored with the fuel rods in a consolidated manner shall be classified as Nonstandard Fuel Class NS-5. [MGDS-RD 3.2.3.2.2.A.1][10 CFR 961.11, App E., B.5]

...

2. Temperature will not have exceeded 350°C (TBV) during storage under inert gas. [Derived]"

"3.7 ENGINEERED BARRIER SEGMENT MAJOR COMPONENT CHARACTERISTICS/REQUIREMENTS

The major components of the Engineered Barrier Segment are the waste packages, the underground facility, any backfill placed in the emplacement drifts, and any emplacement hardware provided to support and protect the emplaced waste package. (The underground facility portion of the Engineered Barrier Segment and the associated requirements allocated to the EB-DRD by the MGDS-RD are identified as interfaces with the Repository Segment in Section 3.2.3.3.) These major components shall be capable of contributing to the assigned function, Isolate Waste (1.4.3), by containing waste in the waste package during the containment period of 300 to 1,000 years (TBR), and then by limiting the release of radionuclides during the post-containment period.
[MGDS-RD 3.7.3.1.A, B] [CRD 3.7.4.1.1]

...

G. To limit the predicted thermal and thermo-mechanical response of the host rock and surrounding strata, and groundwater system, the Engineered Barrier Segment configuration and loading shall:

1. Limit borehole wall temperature (if a borehole is used) to 275°C (TBV)

2. Limit the maximum temperature 1 meter into the rock to 200°C (TBV)

3. Limit the TSw3 (vitrophyre tuff) maximum temperature to 115°C (TBV)

4. Limit the maximum ground surface temperature change in the vicinity of the repository to 6°C (TBV)

5. Limit the emplacement drift maximum temperature to 100°C (TBV)

6. Limit the access drift maximum temperature to 50°C (TBV)

[MGDS-RD 3.7.3.4.C] [10 CFR 60.133(i)]"

"3.7.1 WASTE PACKAGE SUBSYSTEM REQUIREMENTS

...

B. The design of waste packages shall include, but not 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.
[MGDS-RD 3.7.3.3.B] [10 CFR 60.135(a)(2)]"

"3.7.1.3 INTERNAL STRUCTURE REQUIREMENTS

...

G. The internal structure shall maintain functionality under the thermal and chemical conditions generated by the waste form.
[Derived]"

"3.7.2 BACKFILL REQUIREMENTS

...

C. The transfer of heat from the waste package to the geologic setting by the backfill material shall not have an adverse effect on the long term performance of the WP.
[Derived]

...

F. The chemical and mechanical stability of the backfill when subjected to the maximum thermal environment anticipated in the repository shall not have an adverse effect on the long term performance of the waste package. [Derived]"

4.2.3 WPIP Criterion for Thermal Design

The impetus to perform thermal evaluations of the waste package and near-field is provided by the Waste Package Implementation Plan (WPIP, Ref. 5.10). Design goals and the activities supporting these goals are listed in the WPIP. The source of the design goals is, for the most part, the Engineered Barrier Design Requirements Document and for the remainder the design goals were selected based upon engineering judgement. Design goals related to thermal analysis are listed in Section 2.4 of the WPIP (p. 2-4; Ref. 5.10) and provide basic thermal criteria for the design of the EBS:

"2.4 DESIGN GOALS

...
- Center line fuel pin temperature limit of (to be determined (TBD)) °C
- Rock wall temperature limit of (TBD) °C
- Thermal loading of the repository (TBD)

...
The maximum temperature of the glass waste forms must be maintained below limits established for them. This limit is about 500°C (to be verified) for West Valley Defense High-Level Waste glass. The YMP and the glass producers have the responsibility to maintain the peak temperature below the transition temperature.

...
- Meet temperature limits for components
- Provide for a range of thermal loads
- Provide capability to adjust repository thermal loading after emplacement"

Activities to support the design goals related to thermal analysis are indicated in Sections 3.4, 4.5, and 5.1 of the WPIP (pp. 3-2, 4-31, and 5-1; Ref. 5.10):

"3.4 PERFORMANCE ALLOCATION

... Thermal analyses will be performed to determine the temperature profiles across the drifts for drift emplacement. Limited thermal analyses will also be performed for the borehole emplacement modes, assuming various package sizes and thermal loadings. These analyses will permit the re-evaluation of the goals given in the SCP for performance measures. ..."

"4.5 ENVIRONMENTAL INFORMATION NEEDS

...

4.5.2 Hydrologic Properties

Determine hydrologic (and thermal) properties of the WP environment in order to:

- Develop comprehensive model of the thermal and hydrologic behavior of the waste package environment as a function of overall repository thermal loading and rock properties, including two phase fluid flow.

- Use the model to forecast the near field temperature and fluid flow; these near field parameters will be used by the M&O Waste Package Development, M&O PA, and LLNL to calculate/forecast the WP temperatures (surface and centerline) and the distribution of corrosion rates and package lifetimes (as input to the models determined by the chemical and mineralogical properties investigation described above)."

"5.1 WP/EBS DESIGN ACTIVITIES

...

2. Thermal Evaluation (time dependent)
   - 2.1. Internal
     - 2.1.1. SNF and HLW
     - 2.1.2. WP basket
     - 2.1.3. WP internal barrier(s)
     - 2.1.4. WP body
     - 2.1.5. Closure
   - 2.2. External, EBS and near field
   - 2.3. Receipt rate and thermal variability"

4.2.4 Thermal Goals for EBS Design

Based on assumption 4.3.1, the requirements of Section 3.7.G of the EB-DRD (Ref. 5.5), and the design goals of the WPIP (Ref. 5.10), the following thermal criteria are established for the design of the EBS:

- Keep the rock mass temperature at 1 meter from a vertical borehole less than 200°C.

- Keep the emplacement drift wall temperature less than 200°C.

- Limit the TSw3 (basal vitrophyre) maximum temperature to less than 115°C.

- Limit the maximum ground surface temperature change in the vicinity of the repository to less than 2°C.

- Limit the emplacement drift maximum temperature for borehole emplacement to less than 100°C.

- Limit the access drift wall rock maximum temperature to less than 50°C during preclosure.

- Limit the CHn maximum temperature to less than 115°C.

- Limit the PTn (Upper Paint Brush non-welded) maximum temperature to less than 115°C.

- Limit the SNF cladding maximum temperature to less than 350°C.

- Limit the high-level waste glass maximum temperature to less than 500°C.

- The structural strength of any material component of the waste package shall not be compromised by temperature/environment of the EBS environment.

- Maximize the time the waste package container stays above boiling consistent with the thermal strategy developed.

The above thermal criteria are in addition to those previously quoted from the EB-DRD (Ref. 5.5).

4.2.5 Thermal Goals/Criterion Addressed by this Analysis

Based on assumption 4.3.1, the requirements listed in the previous sections, and the design goals of the WPIP (Ref. 5.10), the following thermal criteria are to be addressed by this analysis:

- Limit the SNF cladding maximum temperature to less than 350°C.

- The structural strength of any material component of the Waste Package shall not be compromised by temperature/environment of the EBS environment.

4.3 Assumptions

All design inputs are for pre-Title II designs; some or all of these design inputs will require subsequent qualification (or superseding inputs) as the waste package design proceeds. The design inputs identified and documented in Section 4 have been assigned the single tracking number TBV-213-WPD, to meet tracking requirements in accordance with applicable procedures.

4.3.1 The following thermal criteria are assumed to apply to the design of the Engineered Barrier Segment. These criteria are consistent with current program decisions in the Controlled Design Assumption Document (CDA, Ref. 5.7). The criteria are originally based on a reevaluation of the Site Characterization Plan (SCP) thermal goals (Table 3, p. 22, Ref. 5.33). Each thermal criterion is listed here followed by its CDA or SCP reference. This assumption is used in Section 4.2. As specified in Section 4.2.5, only the 350°C SNF cladding temperature and the material structural strength criteria are used directly for this analysis. These two criteria are used throughout Section 7. However, the other listed items are used in reference 5.13 and were used to generated the waste package surface boundary condition used for this analysis. They are listed here in the interests of consistency.

- Keep the rock mass temperature at 1 meter from a vertical borehole less than 200°C. (CDA EB-DRD 3.7.G.2, p. 6-76, Ref. 5.7)
- Keep the emplacement drift wall temperature less than 200°C. (CDA EB-DRD 3.7.G.2, p. 6-76, Ref. 5.7)
- Limit the TSw3 (basal vitrophyre) maximum temperature to less than 115°C. (CDA EB-DRD 3.7.G.3, p. 6-77, Ref. 5.7)
- Limit the maximum ground surface temperature change in the vicinity of the repository to less than 2°C. (CDA EB-DRD 3.7.G.4, p. 6-78, Ref. 5.7)
- Limit the emplacement drift maximum temperature for borehole emplacement to less than 100°C. (CDA EB-DRD 3.7.G.5, p. 6-79, Ref. 5.7)
- Limit the access drift wall rock maximum temperature to less than 50°C during preclosure. (CDA EB-DRD 3.7.G.6, p. 6-80, Ref. 5.7)
- Limit the CHn maximum temperature to less than 115°C. (CDA DCSS 025, p. 6-155, Ref. 5.7)
- Limit the PTn (Upper Paint Brush non-welded) maximum temperature to less than 115°C. (CDA DCSS 031, p. 6-160, Ref. 5.7)

- Limit the SNF cladding maximum temperature to less than 350°C. (CDA DCWP 001, p. 6-165, Ref. 5.7)

- Limit the high-level waste glass maximum temperature to less than 500°C. (CDA DCWP 002, p. 6-166, Ref. 5.7)

- The structural strength of any material component of the waste package shall not be compromised by temperature/environment of the EBS environment. (derived from p. 2-4, Ref. 5.10, and EB-DRD 3.7.1.3.E, p. 3-53, Ref. 5.5)

- Maximize the time the waste package container stays above boiling consistent with the thermal strategy developed. (Table 3, p. 23, Ref. 5.33)

4.3.2 Two primary high thermal loadings (100 MTU/acre and 83 MTU/acre) and a couple variations of a low thermal loading (25 MTU/acre) will be considered in this analysis. These values are consistent with the range of thermal loadings (20 - 100 MTU/acre) given in the CDA (Key 019, p. 6-24, Ref. 5.7). Systems Engineering (p. 2, Ref. 5.23) recommended thermal loadings of 25 and 83 MTU/acre be used for MGDS design analysis in order for the MGDS to present a consistent design. A thermal loading of 100 MTU/acre represents the likely maximum possible without violating thermal goals according to the FY 93 Thermal Loading System Study (p. 10-2, Ref. 5.24) and is a bounding case for this analysis. This assumption is used in Section 7.1.

4.3.3 The waste package will be emplaced in-drift in a horizontal mode. This is consistent with large waste packages such as the UCF with disposal container and is a current program decision (CDA Key 011, p. 6-18, Ref. 5.7). This assumption is used throughout Section 7.

4.3.4 Reference 5.40 (pp. 22, 35) determined the thermal design basis BWR SNF for the MGDS waste package to have the following characteristics: 1) an age (or cooling time) of 10 years at the time of emplacement, 2) a burn up of 49,000 MWd/MTU, and 3) average assembly uranium enrichment of 3.74%. To complete the characterization of the BWR SNF, it is assumed that a GE-7 8x8 SNF assembly with a uranium mass of 0.200 MTU/assembly and an active fuel length of 150 inches will adequately represent the BWR SNF as a class of waste. This data is required in order to determine the decay heat curve of the MGDS thermal design basis BWR SNF. Based upon data from pages 2A-21 and 2A-22 of reference 5.12 and page 26 of reference 5.39, 0.200 MTU/assembly and an active fuel length of 150 inches was selected to conservatively bound the BWR assembly types given the wide variety of uranium loading configurations. This assumption is used throughout Sections 6 and 7.

4.3.5 The decay heat curve for the MGDS thermal design basis was generated with the use of the PHIA V00B code with data input from Attachment 2 of reference 5.30. The data from reference 5.30 is assumed to accurately represent the SNF currently in storage throughout the United States. Use of the data from reference 5.30 is consistent with the reasons for its creation. This assumption is used throughout Section 7. The PHIA V00B code is presented in Attachment I and the data used from reference 5.30 as input to the PHIA V00B code is presented in Attachment II. The decay heat curve is presented in Sections 6 and 7.4.

4.3.6 The material properties, i.e., effective thermal conductivities, used for the B&W 15x15 PWR SNF in reference 5.40 may be conservatively applied to the GE-7 8x8 BWR SNF for this analysis. The basis for this assumption is that the dominant mode of heat transfer from SNF to the basket is radiation. The BWR bundle has larger view factors to the waste package basket for the center rods of an assembly than the PWR counterpart. Thus, it is expected that the BWR SNF assembly will dissipate heat more efficiently than the PWR SNF assembly. Therefore, using the PWR effective conductivity material properties for the BWR SNF assembly is expected to over-predict the BWR SNF cladding temperatures. Also, the use of data from reference 5.40 requires that the heat generation be homogenous in the modeled SNF region. Heat generation in SNF regions must be applied in this fashion to use the reference 5.40 data in a consistent manner. This assumption is used throughout Section 7.

4.3.7 The UCF with disposal container model assumes that a two-dimensional finite element model of a cross section at the midsection of the waste package will be representative of the hottest portion of the waste package. Inherent in this assumption is that axial heat transfer does not significantly affect the solution (i.e., the flow of heat in the radial direction is assumed to dominate the solution). The basis for this assumption is that the metal thermal conductivities and heat generation distributions are such that axial heat transfer is very small or negligible. This was shown by the analysis in reference 5.13 which modeled the waste package in three dimensions. This assumption is used throughout Section 7.

4.3.8 For the cross section model of the waste package, an axial power peaking factor of 1.40 is applied to the BWR SNF heat generation rate. This factor is based upon the data in Appendix E of reference 5.34 and is assumed to bound the range of axial power peaking factors for BWR SNF. The basis for this assumption is that BWR reactor cores are designed such that axial peaking larger than 1.40 are not desirable for the full duration of a reactor operating cycle for both licensing and economic reasons. This assumption is used throughout Section 7.

4.3.9 The average waste package surface temperatures (time dependent), as defined in reference 5.13 for each thermal load case, will be applied as the boundary conditions for the detailed waste package analysis (normal conditions). The detailed waste package model will examine the design basis SNF rather than the average SNF which will result in slightly higher near field temperatures. This effect, however, will be assumed to have a small impact upon the SNF cladding temperatures calculated and will be neglected. The basis for this assumption is engineering judgement. This assumption is used throughout Section 7.

4.3.10 The effects of drift backfilling will not be considered for the repository base case analysis. Backfill material has not been defined to date and will not be considered to be within the scope of this analysis. Backfill effects on the waste package design will be addressed in a different analysis. This assumption is used throughout Section 7.

4.3.11 The UCF conceptual design SNF basket and internal structure as presented in references 5.31, 5.35, and 5.37 is assumed to be the representative design which specifies the geometry and materials of construction. The basis of this assumption is that the specified references are the only UCF design documents available. This assumption is used throughout Section 7.

4.3.12 The UCF disposal container shell material composition, geometry, and dimensions are assumed to be those specified in reference 5.31. This data is also presented as Waste Package Development sketches which are identified as specified in references 5.35 and 5.37, and are based upon reference 5.31. This assumption is consistent with CDA KEY 042, page 6-37 of reference 5.7. This assumption is used throughout Section 7.

4.3.13 The UCF waste package is assumed to be evacuated and backfilled with helium gas. The basis for this assumption is that this process is considered on pages II.A.3-20, II.A.3-53, and II.A.4-2 of reference 5.8 as a method to meet the internal humidity requirement for the Multi-Purpose Canister (MPC) internals. The UCF is assumed to use the same evacuation / backfilling operation as the MPC in order to provide a consistent MGDS EBS concept. This assumption is used throughout Section 7.

4.3.14 Part length tube guides shall not be included in the ANSYS model and will be conservative with respect to internal temperature estimations. The basis of this assumption is that the part length tube guides are an additional conduction path from the SNF tubes to the waste package shell. Elimination of this conduction path forces more heat to be dissipated by conduction through the helium gap or by radiative heat transfer which is less efficient than conduction through an Alloy 825 tube guide. This assumption is used throughout Section 7.

4.3.15 Modeling only conduction and radiative heat transfer is assumed to provide conservative results for this analysis. The basis for this assumption is as follows: the fill gas placed internally to the UCF WP will allow a convective heat transfer path to exist; however, the natural convective heat transfer will have a small or negligible contribution to the total heat transfer (see reference 5.16 for a discussion on natural convective heat transfer). Thus, the problem may be modeled with only the dominant heat transfer modes with a negligible or conservative impact upon the results. This assumption is used throughout Section 7.

4.3.16 It is assumed for this analysis that the waste package will not have filler material placed inside of it. The basis for this assumption is that the consideration of filler material is beyond the scope of this analysis. The affect of filler materials will be evaluated with additional analysis at a later time. This assumption is used throughout Section 7..

4.3.17 It is assumed for this analysis that the waste package will not be individually fitted with radiation shielding. This is consistent with the CDA; KEY 031, page 6-32, of reference 5.7. This assumption is used throughout Section 7.

4.3.18 It is assumed for this analysis that the waste package will not contain consolidated SNF rods, but will only contain intact SNF assemblies. See KEY 008 on page 6-15 of reference 5.7 for the justification of this assumption. This assumption is used throughout Section 7.

4.3.19 A perfect weld will be modeled for any waste package materials which are in contact. It is assumed for this analysis that this modeling practice has a negligible impact upon the results of the analysis. This means that a contact thermal resistance will not be modeled between touching materials. This assumption is intended to make the modeling of the problem simpler and is judged to have a negligible impact upon the results of this analysis and any non-conservative impact will be more than offset by the conservatism in the other assumptions used for this analysis. The basis for this assumption is engineering judgement. This assumption is used throughout Section 7.

4.3.20 The UCF waste package internal components and the waste package shell are assumed to be integrally connected. The basis for this assumption is that the current design philosophy is to weld corner guides directly to the inner shell of the waste package as indicated in references 5.35 and 5.37. Thus, the UCF waste package design will not have a third shell like the MPC design (Ref. 5.8). This assumption is used throughout Section 7.

4.3.21 Modeling the UCF basket tubes as touching the aluminum thermal shunts and Alloy 825 corner guides is assumed to have a minor impact upon the results. The basis for this assumption is engineering judgement given the conservative values of thermal conductivity used for the aluminum thermal shunts (see assumption 4.3.26), the temperature drops between the MPC basket and corner guides (Ref. 5.40), and the conservative assumptions used in this analysis. The model was created to be consistent with the dimensions provided in references 5.31, 5.35, and 5.37, however, as the design evolves tolerances will be established such that some gaps will be created. Based upon the analysis documented in reference 5.40 for the MPC waste package which models small gaps that will be larger than those for the UCF WP, internal temperatures will be 10°C to 15°C higher. However, the use of aluminum-boron thermal conductivities will mitigate the affects of this assumption. Reference 5.22, page 50, provides a value of thermal conductivity at 68°F (20°C) for aluminum alloy 6063 of 201 W/m·K. This compares to the value of aluminum-boron at 23°C of 182.6 W/m·K (Table 4.1-8). This indicates that the use of the aluminum-boron thermal conductivities invokes roughly a 10% reduction in thermal conductivity for aluminum 6063. Thus, these two modeling conventions roughly balance each other such that the effect on the results of the calculation is judged to be small. This assumption is used throughout Section 7.

4.3.22 The properties of helium at atmospheric pressure are assumed to be representative of the conditions which helium in the UCF will experience. This assumption is based upon the fact that a one atmosphere fill pressure is representative of industry standard for storage casks. Page 10 of reference 5.36 provides the highest pressure which storage casks are filled as approximately 1.5 atmosphere; also most industry vendors use substantially lower pressure in their designs. Use of one atmosphere is representative of the most likely pressure to be used. This assumption is used in Section 4.1 and throughout Section 7.

4.3.23 Use of the material properties for stainless steel 316 provided in Tables 4.1-1 and 4.1-2 is assumed to adequately represent any stainless steel or borated stainless steel (316 B6A) materials used in the UCF waste package for this analysis. Particularly the use of a constant value for the density and emissivity is assumed to be adequate for this analysis. The basis for this assumption is engineering judgement and the fact that the temperature dependent values of thermal conductivity and specific heat are specified well enough to cover the anticipated temperatures the UCF is expected to experience. Also, the values for density and emissivity change only slightly over the expected range of temperatures. Thus, using a single value will not affect the results of the analysis. This assumption is used in Section 4.1 and throughout Section 7.

4.3.24 Use of the material properties for A 516 carbon steel provided in Tables 4.1-3 and 4.1-4 is assumed to adequately represent A 516 carbon steel for this analysis. Particularly the use of a constant value for the density and emissivity is assumed to be adequate for this analysis. The basis for this assumption is engineering judgement and the fact that the temperature dependent values of thermal conductivity and specific heat are specified well enough to cover the anticipated temperatures the UCF is expected to experience. Also, the values for density and emissivity change only slightly over the expected range of temperatures. Thus, using a single value will not affect the results of the analysis. This assumption is used in Section 4.1 and throughout Section 7.

4.3.25 Use of the material properties for Alloy 825 provided in Tables 4.1-5 and 4.1-6 is assumed to adequately represent Alloy 825 for this analysis. Particularly the use of a constant value for the density and emissivity is assumed to be adequate for this analysis. The basis for this assumption is engineering judgement and the fact that the temperature dependent values of thermal conductivity and specific heat are specified well enough to cover the anticipated temperatures the UCF is expected to experience. Also, the values for density and emissivity change only slightly over the expected range of temperatures. Thus, using a single value will not affect the results of the analysis. This assumption is used in Section 4.1 and throughout Section 7.

4.3.26 Use of the material properties for aluminum-boron provided in Table 4.1-8 and Section 4.1 is assumed to adequately represent aluminum for this analysis. Particularly, the use of a constant value for the density and the use of the constant value of aluminum emissivity is assumed to be adequate for this analysis. The basis for this assumption is engineering judgement, the fact that non-metallic additions to metal materials will reduce the capability of the metal to conduct heat (i.e., reduce its thermal conductivity), and the fact that the temperature dependent values of thermal conductivity and specific heat are specified well enough to cover most of the anticipated temperatures the UCF is expected to experience. ANSYS does not extrapolate beyond the given tabulated values, rather it uses the last value available in the table. Thus, since thermal conductivity and specific heat generally increase with increasing temperature, ANSYS will use a conservative value if the aluminum-boron material experiences temperatures above 200°C. Also, the values for density and emissivity change only slightly over the expected range of temperatures. Thus, using a single value will not affect the results of the analysis. The use of a single value for aluminum emissivity is assumed reasonable since the emissivity for aluminum is sufficiently low at 0.07 that a lower value will have very little impact upon the solution. The results of the analysis will be conservative if the value for aluminum-boron is indeed larger. This assumption is used in Section 4.1 and throughout Section 7.

4.3.27 Use of the material properties for C71500 70/30 copper-nickel alloy provided in Table 4.1-9 is assumed to adequately represent C71500 70/30 copper-nickel alloy for this analysis. Particularly the use of a constant value for the density and specific heat is assumed to be adequate for this analysis. The basis for this assumption is engineering judgement and the fact that the temperature dependent values for thermal conductivity are specified well enough to cover the anticipated temperatures the UCF is expected to experience. Also, the value for density changes only slightly over the expected range of temperatures. Thus, using a single value will not affect the results of the analysis. ANSYS does not extrapolate beyond the given tabulated values, rather it uses the last value available in the table. Thus, since specific heat generally increases with increasing temperature, ANSYS will use a conservative value for specific heat by using the C71500 70/30 copper-nickel alloy specific heat at 20°C. This assumption is used in Section 4.1 and throughout Section 7.

4.3.28 The use of single, homogenized SNF material density used in conjunction with assumption 4.3.6 is assumed reasonable and adequate. The basis for this assumption is engineering judgement. The density value was determined using the BWR assembly mass from Table 5.1.1.2.1-1 on page 26 of reference 5.39 of 730 lbs (331.126 kg) and dividing by the BWR assembly volume which provides an average density in kg/m^3 (density = mass / volume). The BWR volume was determined using the overall assembly width of 5.44 inches (0.138 m) and the assembly length of 175.87 inches (4.467 m) from page 2A-21 of reference 5.12. The volume calculation is then simply that of the assembly width squared multiplied by the assembly length (volume = width x width x length). The SNF density calculated is: density = 3882.42 kg/m^3. The value used in each of the ANSYS input decks provided in Attachments XII through XVI is 3960.0 kg/m^3 and is in error. However, the error is judged to be small relative to the given set of assumptions and will have no impact upon any of the results given the small amount of thermal energy mass storage expected in the homogeneous SNF assembly. This assumption is used throughout Section 7.

4.3.29 The use of single, homogenized SNF material specific heat used in conjunction with assumption 4.3.6 is assumed reasonable and adequate. The basis for this assumption is engineering judgement. The specific value was determined using: 1) the BWR assembly and uranium mass from Table 5.1.1.2.1-1 on page 26 of reference 5.39 of 730 lbs (331.126 kg) and 200 kg, respectively, and 2) the specific heat of uranium oxide of 247 J/kg·K (100°C) and Zirc2 of 330.0 J/kg·K (400°C) from Tables 8-1 and 8-2 on page 296 of reference 5.1. The assembly is assumed to be comprised only of uranium oxide and Zirc2; therefore, the homogenized specific heat is a simple mass weighted average (i.e., SNF C_p = (C_p UO_2·mass UO_2 + C_p Zirc2·mass Zr2) / mass of assembly). The mass of UO_2 is determined from the mass of uranium (i.e., mass UO_2 = mass U·(Atomic wt U + 2·Atomic wt of O^{16}) / Atomic wt of U = 226.886 kg). The mass of Zirc2 is then simply the difference between the total assembly mass and the UO_2 mass (mass Zirc2 = 104.240 kg). The SNF specific heat value is then calculated to be: SNF C_p = 273.129 J/kg·K. The value used in each of the ANSYS input decks provided in Attachments XII through XVI is 274.0 J/kg·K and is in error. However, the error is judged to be small relative to the given set of assumptions and will have no impact upon any of the results given the small amount of thermal energy mass storage expected in the homogeneous SNF assembly. This assumption is used throughout Section 7.

4.4 Codes and Standards

Not Applicable. Thermal design of the waste package is not controlled by codes and standards. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Ref. 5.15) has been used only as a source of material properties.

5. References

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5.4 Yucca Mountain Site Characterization Project Q-List, YMP/90-55Q, REV 3, Yucca Mountain Site Characterization Project.

5.5 Engineered Barrier Design Requirements Document, YMP/CM-0024, REV 0, ICN 1, Yucca Mountain Site Characterization Project.

5.6 Mined Geological Disposal System Requirements Document, DOE/RW-0404P, DI Number: B00000000-00811-1708-00002 REV 01, DCN 01, U.S. DOE OCRWM.

5.7 Controlled Design Assumptions Document, DI Number: B00000000-01717-4600-00032 REV 01, CRWMS M&O.

5.8 Multi-Purpose Canister (MPC) Implementation Program Conceptual Design Phase Report, Volume II.A - MPC Conceptual Design Report, DI Number: A20000000-00811-5705-00002 REV 00, CRWMS M&O.

5.9 Waste Package Plan, YMP/90-62, REV 1, Yucca Mountain Site Characterization Project.

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5.18 Metals Handbook, 8th Edition, Volume 1, Properties and Selection of Metals, American Society for Metals, 1961.

5.19 Manufacturer's Product Specification for Incoloy Alloy 825, Published by Huntington Alloys, 1992.

5.20 Thermal Performance of a Buried Nuclear Waste Storage Container Storing a Hybrid Mix of PWR and BWR Spent Nuclear Fuel Rods, G. Johnson, Lawrence Livermore National Laboratory (LLNL), UCID-21414, Revision 1, 1991.

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5.22 "Engineered Materials Characterization Report for the Yucca Mountain Site Characterization Project, Volume 2: Design Data", REV 0, SCP8.3.5.9, Attachment 2 of M&O Correspondence Number: LV.MG.JAB.12/94-299, December 22, 1994, CRWMS M&O.

5.23 "Correction to Thermal Calculation Memo", S. F. Saterlie, Interoffice Correspondence LV.SEA.SFS.1/95-003, January 17, 1995, CRWMS M&O.

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5.25 Verification and Validation Final Report for ANSYS 5.0A, DI Number: B00000000-01717-2006-30003 REV 00, CRWMS M&O.

5.26 Life Cycle Plan for ANSYS 5.0A CSCI B00000000-01717-1200-30003, DI Number: B00000000-01717-2007-30003 REV 00, CRWMS M&O.

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5.31 "Waste Package Designs", Thomas L. Lotz for Thomas W. Doering to Carl W. Chagnon, Interoffice Correspondence LV.WP.TLL.04/94.135, April 11, 1995, CRWMS M&O.

5.32 Evaluation of Thermo-Hydrological Performance in Support of the Thermal Loading Systems Study, T. A. Buscheck, J. J. Nitao, et al, UCRL-JC-115352, LLNL, February 1994.

5.33 Site Characterization Plan Thermal Goals Reevaluation, DI Number: B00000000-01717-5705-00005, REV 00, CRWMS M&O.

5.34 Station Nuclear Engineering Manual, GE Mechanical & Nuclear Engineering Training, General Electric Co., NEDO-24810 / 80NED032, September 1980.

5.35 Waste Package Tube Design (24-BWR), DI Number: BBA000000-01717-2100-15029 R00B, CRWMS M&O.

5.36 Analysis of Degradation Due to Water and Gases in MPC, DI Number: BB0000000-01717-0200-00005 REV 01, CRWMS M&O.

5.37 Low TL/Humid Waste Package Tube Design (24-BWR), DI Number: BBA000000-01717-2100-15041 R00A, CRWMS M&O.

5.38 Final Design Package, BR-100 Ton Rail/Barge Spent Fuel Shipping Cask, No. 51-1203400-01, B&W Fuel Company, November 1991.

5.39 Multi-Purpose Canister (MPC) Subsystem Design Procurement Specification, DI Number: DBG000000-01717-6300-00001 REV 04, CRWMS M&O.

5.40 Thermal Evaluation of the Conceptual 24 BWR Multi-Purpose Canister (MPC) with Advanced Conceptual Design (ACD) Disposal Container, DI Number: BBABA0000-01717-0200-00003 REV 00, CRWMS M&O.

6. Use of Computer Software

The FEA analysis computer code used for this analysis is ANSYS version (V) 5.0A which is identified with the Computer System Configuration Identifier (CSCI) B00000000-1717-1200-30003. ANSYS is a commercially available finite element thermal and mechanical analysis code and is appropriate for the thermal analysis of waste packages, waste package emplacements, and waste package environments. The analyses using the ANSYS software were executed on a Hewlett-Packard 9000 Series 735 workstation. The software qualification of the ANSYS software, including problems of the type analyzed in this report, is summarized in the ANSYS V5.0A Verification and Validation Final Report (p. 1, Ref. 5.25). The ANSYS evaluations performed for this design are fully within the range of the validation performed for the ANSYS V5.0A code. Access to and use of the code for the analysis granted and performed in accordance with the ANSYS V5.0A Life Cycle Plan (p. 1, Ref. 5.26) and the QAP-SI series procedures. Inputs and outputs to the ANSYS software are included as attachments as described in the following design analysis.

The ANSYS SNF heat load file was generated with the computer code PHIA version (V) 00B and is classified as computational support software. PHIA V00B is not a controlled computer code and has not been qualified under the QAP-SI series of M&O procedures. PHIA requires the data provided in assumptions 4.3.4 and 4.3.5 as inputs. Based upon the data provided in assumption 4.3.4, PHIA performs a table look up using the data set of assumption 4.3.5. Once the proper sub-set of data is obtained, PHIA then will interpolate data points in order to generate an ANSYS usable data file. The PHIA code listing, input database file, and ANSYS data file are provided as Attachments I, II, and III. The PHIA code is simply an automation of a simple data manipulation which can easily be checked by hand. The data is provided in this analysis for the purpose of performing hand calculation checks. The data manipulation has been checked by hand, and will be used in this analysis on that basis. The PHIA code was utilized for the purpose of computational support software as it was intended and it is appropriate for the use of generating a ANSYS SNF heat load file. The PHIA software was executed on an IBM PC compatible.

The Wooton-Epstein correlation calculation was performed with the computer code Lotus 1-2-3 for Windows Version 1.1 and is classified as computational support software. Lotus 1-2-3 for Windows Version 1.1 is not a controlled computer code and has not been qualified under the QAP-SI series of M&O procedures and will not be qualified under the M&O procedures. Lotus 1-2-3 for Windows Version 1.1 simply provides a frame work to automate a simple calculation which can easily be checked by hand. The input data and a description of the calculation performed is provided in Section 7.4 for the purpose of performing hand calculation checks. The calculation has been checked by hand and will be used in this analysis on that basis. Lotus 1-2-3 for Windows Version 1.1 was utilized for the purpose of computational support software as it was intended and it is appropriate for the use of generating peak cladding temperatures as specified in Section 7.4. Lotus 1-2-3 for Windows Version 1.1 was executed on an IBM PC compatible.

The presentation graphics provided in Section 7.4 was generated with the computer code Harvard Graphics Version 2.0 and is classified as computational support software. Harvard Graphics Version 2.0 was executed on a IBM PC compatible. Harvard Graphics Version 2.0 is not a controlled computer code and has not been qualified under the QAP-SI series of M&O procedures and will not be qualified under the M&O procedures. Harvard Graphics Version 2.0 simply provides a frame work to create a graphical representation of data. No calculation or modification beyond cut and paste operations with tabular ANSYS or Lotus 1-2-3 output was performed in Harvard Graphics.

7. Design Analysis

7.1 Background

As part of an engineered barrier system for the containment of radionuclides, the UCF waste package (WP) must be shown to comply with all regulations and requirements that govern the conditions of the emplaced SNF and the near-field rock at the repository horizon. Temperatures in the WP and near-field host rock are key to radionuclide containment, as they directly affect oxidation rates of the metal barriers, metal and fuel cladding structural integrity, and the ability of the rock to impede particle movement.

Maximum allowable temperatures are based on material performance criteria and are specified as design goals for the WP/EBS design. For SNF, the Commercial Spent Fuel Management Program (p. xii, Ref. 5.27) at Pacific Northwest Laboratory recommended a 380°C temperature limit for the SNF cladding to prevent creep rupture failure. A more conservative value of 350°C has been selected (CDA DCWP 001, p. 6-165, Ref. 5.7) to account for uncertainties in source characteristics as well as heat transfer calculations. To limit the predicted thermal and thermo-mechanical response of the host rock and surrounding strata, maximum temperatures of 200°C for TSw2 (at the emplacement drift wall) and 115°C in the TSw3 (vitrophyre tuff) layer have been specified. Specific characteristics and requirements for the engineered barrier system are listed in the Yucca Mountain Site Characterization Project Engineered Barrier Design Requirements Document (Ref. 5.5) and are discussed in Section 4.2.

The method for WP thermal evaluations involves a three-model approach to determine the time-dependent WP thermal behavior. As presented in reference 5.13, a three-dimensional (3-D) transient finite element model of the WP emplacement provides the WP surface temperature history for use as a boundary condition. The WP boundary condition is then applied to a detailed two-dimensional (2-D) WP model; it is this 2-D model which is analyzed in this report. Resulting SNF basket wall temperature predictions from the WP model provide the boundary for an estimation of peak SNF cladding temperatures. Cladding temperatures are predicted in the WP model using an effective conductivity defined to represent a homogeneous SNF assembly. The effective conductivity was determined using a detailed third model of an intact SNF assembly, the data files for the effective thermal conductivities are provided in reference 5.40. Cladding temperatures are also conservatively estimated using an empirical correlation from reference 5.14.

The thermal environment of the WP in the repository will change with time and is affected by the heat produced in the WP. Therefore, the WP thermal evaluation must be a transient analysis that takes into account the time varying heat load of the WP. This can be contrasted to a SNF storage cask analysis where the thermal environment is assumed constant and is provided by regulations.

To determine the effect of the WP on repository near-field temperatures, a 3-D emplacement model was evaluated for a range of thermal loadings. The analysis is described in detail in the supporting emplacement thermal model design analysis (Ref. 5.13). A parametric set of thermal loading cases, summarized in Table 7.1-1, is required because the thermal loading for the repository has been specified as a range (CDA Key 019, p. 6-24, Ref. 5.7) and the UCF WP must be shown to meet requirements over that range. Representative "high" and "low" thermal loadings of 100 MTU/acre (24.7 kg U/m^2), 83 MTU/acre (20.5 kg U/m^2), and 25 MTU/acre (6.2 kg U/m^2) were selected (see assumption 4.3.2) to be consistent with the CDA and the Thermal Loading Systems Study (Ref. 5.24), and drift spacings in multiples of 22.5 m (see ref. 5.13) were selected to be consistent with the Repository/WP Initial Summary Report (Ref. 5.29).

Table 7.1-1. Small Waste Package Thermal Loading Scenarios
(From Table 7.5-2 of Reference 5.13)

Areal Mass Loading (AML) MTU/acre	Initial Areal Power Density (APD) kW/acre	Waste Package Spacing	Drift Spacing
100 (high #1)	113.7	9.2 m	22.5 m
83 (high #2)	94.4	11.1 m	22.5 m
25 (low #1)	28.4	18.5 m	45.0 m
25 (low #2)	28.4	12.3 m	67.5 m
25 (low #3)	28.4	9.2 m	90.0 m

The low thermal loading drift spacings described in Table 7.1-1 represent the utilization of even multiples of the high thermal loading drift spacing (every other drift, every third, etc.). Low thermal loading #1 achieves the longest reasonable WP spacing and results in the lowest near-field temperatures; low thermal loading #2 has a WP spacing similar to that for the high thermal loading; and low thermal loading #3 has a short WP spacing and represents the "localized disturbance" concept for low loadings. The "localized disturbance" concept depends on high temperature gradients (due to the closely spaced WPs) to drive local water in the rock away from the emplacement drifts. The analysis performed in reference 5.13 was performed to determine the rock wall temperatures for these conditions and whether the rock temperature goals were met. The WP surface temperatures from that analysis can be used as a boundary condition to determine the WP internal and SNF cladding temperatures.

7.2 Design Basis Fuel

To capture a majority of the SNF, the WP must be designed and evaluated to accommodate the bounding or limiting case of fresh SNF which has a thermal output much higher than average. Thus, a design basis SNF can be determined which can be considered the hottest SNF that could be loaded and emplaced in that waste package. The detailed waste package/EBS evaluation would then represent the hottest waste package in a repository at a given thermal loading (with otherwise average SNF). While all of the waste packages (hot and cold) will collectively influence repository temperatures (average SNF characteristics), every waste package must meet thermal goals (design basis SNF characteristics). The methodology and selection of design basis SNF for WP design is covered in reference 5.40.

Given that higher capacity waste packages are more likely to exceed thermal goals than smaller ones in the same repository thermal environment, the choice of a design basis SNF is important because it could limit the number of assemblies that can be loaded in one WP without exceeding thermal goals for disposal. The limiting thermal goal for waste packages, such as the 24 BWR UCF, is either a temperature of no more than 350°C at the SNF cladding or the drift wall temperature limit of 200°C. Several different design basis SNF types have been used by the OCRWM to demonstrate compliance with requirements and to allow comparison with previous evaluations. Table 7.2-1 summarizes the SNF types used. The heat loads for the assembly areas were interpolated from the database of spent fuel characteristics (Ref. 5.30) for each of the assumed design basis SNF types using the PHIA V00B code (see Attachment I).

Table 7.2-1. Thermal Analysis SNF Design Bases

Organization	SNF Type	SNF Age	SNF Burnup	Initial Heat
MGDS (Ref. 5.40)	PWR	10 years	48 GWd/MTU	850 watts
MGDS (Ref. 5.40)	BWR	10 years	49 GWd/MTU	409 watts
MPC (Ref. 5.39)	PWR	20 years	40 GWd/MTU	547 watts
MPC (Ref. 5.39)	BWR	20 years	40 GWd/MTU	265 watts
MPC Historic (Ref. 5.8)	PWR	10 years	40 GWd/MTU	718 watts

Design basis SNF will impact the timing of peak temperatures as well as the magnitude of the peak. The repository host rock temperatures will peak between 10 to 500 years depending on the thermal loading but will be largely independent of the individual waste package design. The waste package itself will experience its peak temperature before the rock temperature peaks. The peak temperature and its timing will depend on the design basis SNF and the basket/container design. In previous analyses of the small waste package (p. 6-108, Ref. 5.29), higher conductivity SNF baskets were seen to lower and delay the peak temperatures experienced. The choice of the design basis SNF is of key importance. Younger SNF types produce high peak temperatures within the first year which then drop off quickly. Older SNF (at the same initial APD, but not AML) produces lower and later peaks with more stable and higher long-term temperatures.

In the following evaluation, only the MGDS design basis BWR SNF type has been used to illustrate the cladding temperatures which the UCF waste package will produce when placed in the MGDS. The time dependence of the design basis BWR SNF heat load is provided in Appendix III as provided by the PHIA code using the data provided in Attachment 2 of reference 5.30. The PHIA code uses the data provided in assumption 4.3.4 and 4.3.5, sorts through the SNF decay heat data to obtain the correct heat generation rate versus time for the given SNF parameters, then interpolates as required to obtain the desired ANSYS time step intervals. The data is then written to an output file suitable for direct use by ANSYS. The PHIA code is provided as Attachment I, along with the input file from reference 5.30 as Attachment II, and the output file from PHIA as Attachment III.

7.3 2-D Waste Package Model Development

The general philosophy used for this analysis is to create a separate input file for each thermal loading case. Since the there are only two major differences between individual cases, i.e., boundary condition and WP outer barrier for high and low thermal load, a base deck (High Thermal Load #1 Case) was created with the basic modeling information. The base deck was then copied for each ANSYS case. Each individual file then had the appropriate boundary condition file from reference 5.13 entered into the input decks. Finally, the Low Thermal Load cases then had the appropriate WP outer barrier material and thickness data entered into the input decks.

The basic layout of each deck follows the following pattern: 1) Comment header used to define problem modeled, additional files read by the input deck, and what information is contained in the data files used in the input deck. 2) Define model parameters and dimensions which are used repeatedly. This includes all material properties, reading of boundary condition files, reading of body load files, etc. The ANSYS input decks make use of defined variables which are then used to perform simple calculations concerning units conversions and geometric positions. Many of the UCF basket geometry parameters are reported in references 5.35 and 5.37 in units of millimeters. These values were entered into the ANSYS input decks along with the units conversion to meters, assigned a variable name, and the variable name was then used through out the remainder of the input deck to determine the geometry of the basket and the disposal container. Also, units of years are used in the file defining SNF heat loads. The years are converted to seconds for this analysis. The variables are clearly identified and defined via comments included in the ANSYS input deck. 3) Define element types which will be used to perform the solution. 4) Define the model geometry and mesh structure. The approach used is to define all components by first defining the basic key points, then lines, then areas and finally the mesh. A time consuming approach to input development, but it is easily followed and repeated. 5) Define all radiation surfaces and create radiation mesh matrix. The ANSYS AUX12 utility is used to generate all of the required view factors between radiation elements. 6) Apply the body loads and boundary conditions to the appropriate geometry components. Since this calculation is a transient, the loads and boundary conditions are applied at each time step. 7) Finally, selected positions in the SNF, basket, and disposal container shell were selected to have temperatures for each time step of the transient echoed to the output file for examination.

Each ANSYS input deck is provided as part of the ANSYS output files in Attachments XII, XIII, XIV, XV, and XVI. Heat and material input files are provided as Attachments III, IV, V and the boundary condition files for each thermal loading case is provided in Attachments VII through XI.

The development of any ANSYS model involves the following specific steps:

1) Identify the geometry to be modeled.
2) Identify the material properties which will be required.
3) Identify the assumptions used to model the real geometry and materials.
4) Identify the body loads (i.e., heat generation rates in specific materials).
5) Identify the boundary conditions/surface loads (i.e., surfaces with known or given temperatures).
6) Specify the problem as steady state or transient. If transient specify the time frame which is to be considered.
7) Execute the model generated to obtain solutions for the given conditions.
8) Analyze the results to form a conclusion or support a design thesis.

The creation of an ANSYS model for the 24 BWR UCF waste package conceptual design followed the listed steps. Discussion of some of these steps will be combined for convenience.

1) Identify the geometry to be modeled.
2) Identify the material properties which will be required.

The geometry and the material composition of each component is specified in references 5.31, 5.35, and 5.37 for the 24 BWR UCF waste package conceptual design (see assumptions 4.3.11 and 4.3.12). Notice that the high thermal load and low thermal load waste packages have different outer barrier thicknesses and material compositions. The high thermal loading disposal container is 0.020 meter thick Alloy 825 with an outer barrier of 0.100 meter thick A 516 carbon steel. The low thermal loading disposal container is 0.020 meter thick Alloy 825 with an outer barrier of 0.050 meter thick C71500 copper-nickel alloy.

Since this model is part of a larger calculational scheme as indicated in reference 5.13, a simple 2-D cross section of the UCF waste package will be modeled (see assumption 4.3.7). A vertical plane of symmetry is easily identified and thus, the geometry modeled will be that of the right hand side of the UCF waste package. The geometry is not modeled with quarter symmetry since the boundary condition, as specified in reference 5.13, indicates a vertical surface temperature distribution and requires half symmetry. Attachment VI provides mesh plots of the general layout of the waste package internals.

Material properties to be used for each component of the design are specified in Section 4.1 along with the references from which they were obtained. The ANSYS file containing this material property data is provided as Attachment IV (see assumptions 4.3.22, 4.3.23, 4.3.24, 4.3.25, 4.3.26, and 4.3.27). The effective thermal conductivity of the SNF assembly model areas is listed in reference 5.40 and is provided as Attachment V. The additional properties was developed in Section 4.3 (see assumptions 4.3.6, 4.3.28, and 4.3.29) and entered into the input deck. Attachment IV also includes material properties which were not used in this analysis (i.e., those identified as material ID's 4, 5, 6, 8, 9, 10, 11, and 12 were not used).

3) Identify the assumptions used to model the real geometry and materials.

All assumptions used for this ANSYS model are listed in Section 4.3. These assumptions provide all of the required insight for a competent ANSYS user as to why the ANSYS geometry and material selections were entered into the ANSYS input decks in the given fashion (including assumptions 4.3.3, 4.3.10, 4.3.13, 4.3.14, 4.3.15, 4.3.16, 4.3.17, 4.3.18, 4.3.19, 4.3.20, 4.3.21).

4) Identify the body loads (i.e., heat generation rates in specific materials).
5) Identify the boundary conditions/surface loads (i.e., surfaces with known or given temperatures).
6) Specify the problem as steady state or transient. If transient specify the time frame which is to be considered.
7) Execute the model generated to obtain solutions for the given conditions.

The material which generates the heat load is the SNF and is modeled as a solid material placed in the interior of each tube. The heat load is dependant upon the design basis SNF selected and is discussed in Section 7.2. Briefly, the heat loads for the SNF areas were interpolated from the data provided in reference 5.30 for the assumed MGDS design basis SNF types. The heat load will decrease logarithmically with time as the fission products decay and therefore was created as a function of time. The heat loads were applied volumetrically and were multiplied by an axial heat peaking factor of 1.40 to approximate the axial center of the WP with a 2-D model (see assumption 4.3.8). A SNF assembly is much hotter at the mid-length than at the ends, and it is conservative to assume the 2-D waste package model represents the hottest cross-section of the UCF waste package.

As indicated in section 7.1, this analysis is part of a three part calculation method. As such the boundary conditions are provided by the calculations performed in reference 5.13. The boundary conditions for each repository thermal loading scenario was applied to the waste package surface as a temperature condition to create five ANSYS decks (see assumption 4.3.9). The boundary conditions are time dependent, the SNF heat generation rate is also time dependent, and therefore the problem is a transient. The boundary conditions and heat loads were applied and solved out to 1000 years for each of the five thermal loading scenarios described in Section 7.1 and for the BWR MGDS design basis SNF type described in Table 7.2-1. The transient time of 1000 years was performed to be consistent with the analysis performed in reference 5.13.

8) Analyze the results to form a conclusion or support an design thesis.

The outputs of each ANSYS execution are provided as Attachments XII through XVI. Discussion and summary of the ANSYS results are provided in Section 7.4 and conclusions are provided in Section 8.0. Notice that selected data was requested in the input deck and echoed into the output file for ease of use. This data is summarized in Section 7.4.

7.4 2-D Waste Package Analysis Results

All of the results provided in this section were derived from the ANSYS V5.0A executions. These models are presented in the ANSYS output files summarized in Section 9.0 and provided as attachments to this report. All of the assumptions concerning geometry, material composition, boundary conditions, and other inputs are provided in Section 4.3.

To check the above SNF model preliminary results, the Wooton-Epstein correlation (reference 5.14) was applied for each of the cases. This empirically derived correlation was shown to be conservative in Section 3.6.2 of the BR-100 Spent Fuel Shipping Cask report (reference 5.38). The Wooton-Epstein correlation is described by Equation 7-1.

$$q''=\sigma\frac{C_1}{\frac{1}{\epsilon_{cl}}+\frac{1}{\epsilon_{ba}}-1}(T_{cl}^4-T_{ba}^4)+C_2(T_{cl}-T_{ba})^{\frac{4}{3}}$$

(Equation 7-1)

Where:

q"	= heat flux from SNF based on the basket inner surface heat transfer area (Btu/hr·ft^2)
C_1	= constant depending on the spent fuel rod array size,
	= $4N/(N+1)^2$ for odd N
	= 4/(N+2) for even N
C_2	= regression constant = 0.118
N	= number of fuel rods in a single row of a square spent fuel assembly
T_{cl}	= cladding surface temperature (absolute scale, °R)
T_{ba}	= basket surface temperature (absolute scale, °R)
ε_{cl}	= cladding surface emissivity
ε_{ba}	= basket surface emissivity
σ	= Stefan-Boltzmann constant (Btu/hr·ft^2·°R^4)

The correlation has two terms; one representing radiation heat transfer, and one representing gaseous convection in an array of heat producing rods. Because the cladding temperature occurs in both terms, the correlation must be solved iteratively. A complete description of the correlation development is given in the Wooton-Epstein paper (reference 5.14). For this analysis, the same material properties and conditions were assumed with the Wooton-Epstein correlation that were used in the ANSYS model (see assumptions 4.3.4, 4.3.5, 4.3.6, 4.3.8, 4.3.16, 4.3.18, and 4.3.23):

Stefan-Boltzmann constant	1.714×10^{-9} (Btu/hr·ft^2·°R^4)
Cladding emissivity	0.806 (0.002 inch oxidation layer, Ref. 5.40)
Basket emissivity	0.600 (Stainless Steel 316L)
Basket cell width	152.4 mm (6.0 inches)
SNF array size (N)	8 rods
Assembly active length	3810 mm (150.0 inches)
Axial peaking factor	1.40

The conservative peak cladding temperatures were calculated with the Wooton-Epstein correlation, the above values for required parameters, and the ANSYS calculated peak basket temperatures.

Tables 7.4-1 through 7.4-5 summarize the temperature data for each of the cases analyzed. Both "conservative" estimates of peak cladding temperatures using the Wooton-Epstein correlation, and "best estimate" predictions using the effective conductivity method are presented in the table. Peak cladding temperatures using effective conductivity are calculated directly in the ANSYS program, and Wooton-Epstein calculations for each time step in the ANSYS analysis were also performed for comparison.

The thermal history for each case is presented graphically in Figures 7.4-1 and 7.4-3 through 7.4-6. Figure 7.4-2 graphically presents the temperature profile from the center of the waste package to the drift wall at the time of peak cladding temperature for the 83 MTU/acre thermal loading case. The highest peak conservative estimate for SNF cladding temperature was 242°C which can be compared to the thermal goal of 350°C. The results show that a greater WP spacing results in lower near-field temperatures.

Peak temperatures inside the waste package occur between the time of emplacement and the time of peak drift wall temperatures. At emplacement the SNF heat load is at its highest, but the drift is still cool, and by the time of peak drift temperatures, the heat load has decayed so that internal temperature drops are lower. As indicated in Tables 7.4-1 through 7.4-5, the time of peak temperatures varies depending on thermal loading, WP spacing, and the time-dependent WP decay heat (SNF type). For most design basis SNF types, peak WP internal temperatures will occur in less than 10 years after emplacement even though waste package surface temperatures do not peak for 10 years or more. The timing and magnitude of the peak cladding temperatures experienced is very dependant upon the SNF basket design, the design basis SNF and the thermal loading conditions. By 100 years, however, the temperature drop across the WP (from center to edge using the effective thermal conductivity model) has dropped to less than 25°C.

While 83 MTU/acre (Figures 7.4-1 and 7.4-2) is considered a more likely scenario for a high thermal loading, a higher thermal loading of 100 MTU/acre (Figure 7.4-3) was also evaluated to bound the WP internal temperatures for the full range of possible thermal loadings. The combination of short WP spacing and high thermal loading resulted in the highest temperature of all of the cases. SNF cladding temperatures peaked at 225°C (242°C for Wooton-Epstein correlation) and average repository horizon temperatures remained above 150°C past 1000 years. Calculations at LLNL (Ref. 5.32) have shown that above boiling conditions will persist for thousands of years at AMLs in this range, however, some thermal goals are close to upper limits.

Figure 7.4-4 displays the thermal history of the 24 BWR UCF waste package at 25 MTU/acre (6.2 kgU/m^2) with the long WP spacing (low thermal loading #1) for the MGDS design basis SNF. Peak internal temperatures are lowest of all the cases due to the long WP spacing.

Figure 7.4-5 displays the thermal history of the 24 BWR UCF waste package for low thermal loading #2 and for the MGDS design basis SNF. Because the WP spacing is similar to that for high thermal loading #2, similar temperatures are predicted for the first few years of emplacement. However, as thermal loading effects emerge, all of the low thermal loading results converge.

Figure 7.4-6 displays the thermal history of the 24 BWR UCF waste package for low thermal loading #3 and for the MGDS design basis SNF. The highest internal temperature for all cases occurred where the MGDS design basis SNF is used and the shortest WP spacing (16.2 m) defines the thermal loading. The peak temperatures occur before drift-to-drift effects emerge such that WP spacing drives the near-field temperatures and high thermal loading #1 and low thermal loading #3 have nearly the same peak cladding temperature.

Table 7.4-1. High Thermal Load #1; 24 BWR UCF Waste Package Thermal Results

24 BWR UCF WP (all temperatures in deg. C)
100 MTU/acre with 9.237 m WP Spacing
10 year old, 49.0 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Peak SNF Temp.		ANSYS FEM Temperature Results (Deg. C)						
(years)	(W/assy)	Wooten-E	Eff Cond	Basket	MPC Side	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	189	160	153		58	26	26	26	26
0.1	407.68	207	180	174		83	60	43	29	26
0.2	405.97	212	186	180		90	68	51	34	26
0.3	404.28	216	190	184		95	74	56	38	27
0.4	402.61	218	192	186		99	79	61	42	29
0.5	400.97	220	195	189		102	82	64	45	30
0.6	399.34	221	196	191		105	85	67	47	32
0.7	397.74	223	198	192		107	88	70	50	34
0.8	396.16	224	199	194		109	90	72	52	36
0.9	394.6	225	201	195		111	92	75	54	37
1	393.06	226	202	196		112	94	77	56	39
2	379.49	231	209	203		124	108	91	72	55
3	367.7	234	213	207		131	116	100	82	66
4	357.29	236	216	210		137	123	107	90	75
5	348.3	238	218	213		142	129	113	96	82
6	339.03	240	220	215		147	134	119	101	87
7	331	241	222	217		150	138	123	105	92
8	323.52	241	223	218		153	142	127	109	95
9	316.46	241	223	219		156	145	130	112	97
10	310.56	[illegible]	224	219		157	147	132	115	99
20	255.61	240	225	221		171	163	151	137	125
30	214.52	238	225	222		180	173	163	151	141
40	183.32	233	222	219		183	178	169	159	150
50	157.9	228	218	215		184	180	172	163	155
60	138.15	223	214	212		[illegible]	[illegible]	174	166	158
70	122.25	218	210	208		184	180	[illegible]	167	160
80	109.37	214	206	204		183	179	174	167	161
90	99.33	210	203	201		182	179	173	[illegible]	162
100	90.35	207	200	199		181	178	173	167	162
200	51.61	190	186	185		174	172	169	166	[illegible]
300	38.89	181	178	177		169	168	165	163	160
400	31.79	176	174	173		166	165	163	161	159
500	27.23	173	171	170		165	164	162	160	158
600	23.69	170	168	168		163	162	160	158	157
700	21.02	167	165	165		160	159	158	157	155
800	18.76	164	162	162		158	157	156	154	153
900	16.96	161	159	159		155	155	154	152	151
1000	15.49	159	157	157		153	153	152	150	149

Table 7.4-2. High Thermal Load #2; 24 BWR UCF Waste Package Thermal Results

24 BWR UCF WP (all temperatures in deg. C)
83 MTU/acre with 11.129 m WP Spacing
10 year old, 49 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Peak SNF Temp.		ANSYS FEM Temperature Results (Deg. C)					
(years)	(W/assy)	Wooten-E	Eff Cond	Basket	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	189	159	153	57	26	26	26	26
0.1	407.68	205	178	171	79	57	41	29	26
0.2	405.97	209	182	176	85	64	48	33	26
0.3	404.28	212	185	179	89	68	53	37	27
0.4	402.61	213	187	181	92	72	56	39	28
0.5	400.97	215	189	183	95	75	59	42	30
0.6	399.34	216	191	185	97	78	62	44	31
0.7	397.74	217	192	186	99	80	64	46	33
0.8	396.16	218	193	187	100	82	66	48	34
0.9	394.6	219	194	188	102	83	68	50	36
1	393.06	219	195	189	103	85	69	52	37
2	379.49	224	201	195	113	97	82	65	50
3	367.7	226	204	198	120	105	91	75	60
4	357.29	228	206	201	125	111	97	82	68
5	348.3	229	208	203	130	116	102	87	75
6	339.03	229	209	204	133	120	107	92	80
7	331	230	210	205	136	124	111	96	84
8	323.52	230	211	206	139	127	114	99	88
9	316.46	230	211	206	141	130	117	102	91
10	310.56	230	[illegible]	207	143	132	119	105	94
20	255.61	224	208	204	152	143	133	120	109
30	214.52	218	204	201	157	150	141	131	122
40	183.32	212	199	197	159	153	145	137	129
50	157.9	206	195	192	[illegible]	154	148	140	133
60	138.15	200	190	188	159	[illegible]	149	142	136
70	122.25	195	186	184	159	155	[illegible]	143	138
80	109.37	191	182	180	158	154	149	143	139
90	99.33	187	179	177	157	153	149	[illegible]	139
100	90.35	184	176	175	156	152	148	143	139
200	51.61	167	162	161	150	148	146	143	[illegible]
300	38.89	159	155	155	146	145	143	140	138
400	31.79	155	152	151	144	143	141	139	137
500	27.23	152	149	148	142	141	140	138	137
600	23.69	149	146	146	140	139	138	137	135
700	21.02	146	144	143	139	138	136	135	134
800	18.76	144	142	141	137	136	135	134	133
900	16.96	142	140	139	136	135	134	133	132
1000	15.49	140	138	138	134	134	133	132	131

Table 7.4-3. Low Thermal Load #1; 24 BWR UCF Waste Package Thermal Results

24 BWR UCF WP (all temperatures are in deg. C)
25 MTU/acre with 18.475 m WP Spacing
10 year old, 49 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Peak SNF Temp.		ANSYS FEM Temperature Results (Deg. C)					
(years)	(W/assy)	Wooten-E	Eff Cond	Basket	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	188	159	152	57	26	26	26	26
0.1	407.68	201	173	167	75	51	39	28	26
0.2	405.97	204	176	170	78	56	43	32	26
0.3	404.28	205	178	172	81	59	46	34	26
0.4	402.61	206	179	173	82	61	48	36	26
0.5	400.97	206	180	174	84	63	50	37	26
0.6	399.34	207	180	174	85	64	52	39	26
0.7	397.74	207	181	175	86	65	53	40	26
0.8	396.16	208	181	175	87	66	54	41	26
0.9	394.6	208	182	176	88	67	55	42	26
1	393.06	[illegible]	182	176	88	68	56	43	26
2	379.49	208	183	[illegible]	93	74	62	49	28
3	367.7	207	182	176	95	77	65	52	30
4	357.29	205	181	176	97	79	68	55	32
5	348.3	204	180	175	98	81	70	57	34
6	339.03	202	179	174	99	82	71	59	36
7	331	201	178	172	99	83	72	60	38
8	323.52	199	177	171	100	84	73	61	39
9	316.46	197	175	170	100	85	74	62	41
10	310.56	196	174	169	100	85	75	63	42
20	255.61	182	162	158	[illegible]	88	80	70	52
30	214.52	169	151	148	99	[illegible]	81	73	58
40	183.32	158	142	139	97	88	[illegible]	74	61
50	157.9	149	134	131	95	86	81	75	63
60	138.15	141	127	125	93	85	80	[illegible]	64
70	122.25	134	122	120	91	84	80	75	65
80	109.37	129	117	115	89	83	79	74	66
90	99.33	124	113	112	88	82	78	74	66
100	90.35	120	110	108	87	81	78	74	67
200	51.61	101	94	93	81	77	75	73	[illegible]
300	38.89	94	88	87	78	75	73	71	68
400	31.79	89	85	84	76	74	72	71	68
500	27.23	86	82	82	75	73	72	70	68
600	23.69	84	80	80	74	72	71	69	67
700	21.02	82	78	78	73	71	70	69	67
800	18.76	80	77	76	72	70	69	68	66
900	16.96	78	75	75	71	69	68	68	66
1000	15.49	77	74	74	70	69	68	67	65

Table 7.4-4. Low Thermal Load #2; 24 BWR UCF Waste Package Thermal Results

24 BWR UCF WP (all temperatures are in deg. C)
25 MTU/acre with 12.317 m WP Spacing
10 year old, 49 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Peak SNF Temp.		ANSYS FEM Temperature Results (Deg. C)					
(years)	(W/assy)	Wooten-E	Eff Cond	Basket	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	188	159	152	57	26	26	26	26
0.1	407.68	204	176	170	78	55	40	29	26
0.2	405.97	207	180	174	83	62	47	33	26
0.3	404.28	210	183	177	87	66	51	36	26
0.4	402.61	211	185	179	90	69	54	38	26
0.5	400.97	212	186	180	92	72	57	41	26
0.6	399.34	213	188	182	94	74	59	43	26
0.7	397.74	214	189	183	95	76	61	44	26
0.8	396.16	215	189	183	97	78	62	46	26
0.9	394.6	215	190	184	98	79	64	47	26
1	393.06	216	191	185	99	80	65	48	26
2	379.49	218	194	188	106	89	75	57	26
3	367.7	[redacted]	[redacted]	189	110	94	80	63	27
4	357.29	218	195	[redacted]	113	97	83	67	28
5	348.3	217	195	189	115	100	86	69	29
6	339.03	216	194	188	116	101	88	72	30
7	331	214	193	188	117	103	89	73	31
8	323.52	213	192	187	118	104	90	75	33
9	316.46	211	190	185	118	104	91	76	34
10	310.56	210	189	184	[redacted]	104	92	77	35
20	255.61	194	176	172	116	[redacted]	94	82	46
30	214.52	181	164	160	113	103	[redacted]	[redacted]	52
40	183.32	168	153	150	109	100	92	83	56
50	157.9	158	144	141	105	97	91	82	59
60	138.15	149	136	134	102	95	89	81	61
70	122.25	142	130	128	100	93	88	81	62
80	109.37	136	125	123	97	91	86	80	63
90	99.33	131	120	118	95	90	85	79	64
100	90.35	126	116	115	94	88	84	79	64
200	51.61	105	98	97	85	81	79	75	67
300	38.89	97	91	91	81	78	76	74	67
400	31.79	92	87	87	79	76	75	73	[redacted]
500	27.23	89	85	84	77	75	74	72	67
600	23.69	86	82	82	76	74	73	71	67
700	21.02	83	80	80	74	73	72	70	66
800	18.76	81	78	78	73	72	71	69	66
900	16.96	80	77	76	72	71	70	69	65
1000	15.49	78	75	75	71	70	69	68	65

Table 7.4-5. Low Thermal Load #3; 24 BWR UCF Waste Package Thermal Results

24 BWR UCF WP (all temperatures are in deg. C)
25 MTU/acre with 9.237 m WP Spacing
10 year old, 49 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Peak SNF Temp.		ANSYS FEM Temperature Results (Deg. C)					
(years)	(W/assy)	Wooten-E	Eff Cond	Basket	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	189	159	153	58	26	26	26	26
0.1	407.68	207	180	174	83	60	43	29	26
0.2	405.97	212	186	180	90	69	51	34	26
0.3	404.28	215	189	183	95	74	56	38	26
0.4	402.61	218	192	186	98	79	61	41	26
0.5	400.97	220	194	188	101	82	64	44	26
0.6	399.34	221	196	190	104	85	67	47	26
0.7	397.74	222	198	192	106	88	70	49	26
0.8	396.16	223	199	193	108	90	72	51	26
0.9	394.6	224	200	194	110	92	74	53	26
1	393.06	225	201	195	111	94	76	55	26
2	379.49	229	206	201	121	105	88	67	26
3	367.7	230	208	203	126	111	94	73	26
4	357.29	230	209	204	129	115	98	78	26
5	348.3	230	209	[illegible]	132	118	101	81	27
6	339.03	229	209	204	133	120	104	84	27
7	331	228	208	203	135	122	106	86	28
8	323.52	228	208	203	136	124	108	88	29
9	316.46	226	207	202	136	124	109	90	29
10	310.56	225	206	201	[illegible]	125	110	91	30
20	255.61	210	193	189	135	125	[illegible]	96	39
30	214.52	195	179	176	130	121	110	[illegible]	46
40	183.32	182	167	164	124	117	107	95	51
50	157.9	170	157	154	119	112	103	93	55
60	138.15	160	148	145	115	108	100	91	57
70	122.25	152	141	138	111	105	98	89	59
80	109.37	145	134	132	107	101	95	87	60
90	99.33	139	129	127	104	99	93	86	61
100	90.35	134	125	123	102	97	92	85	62
200	51.61	110	103	102	90	87	83	79	65
300	38.89	101	95	95	85	82	80	76	66
400	31.79	95	91	90	82	80	78	75	66
500	27.23	92	88	87	80	78	76	74	[illegible]
600	23.69	88	85	84	78	76	75	73	66
700	21.02	86	82	82	77	75	74	72	66
800	18.76	83	80	80	75	74	72	71	65
900	16.96	81	79	78	74	73	71	70	65
1000	15.49	80	77	77	73	72	71	69	64

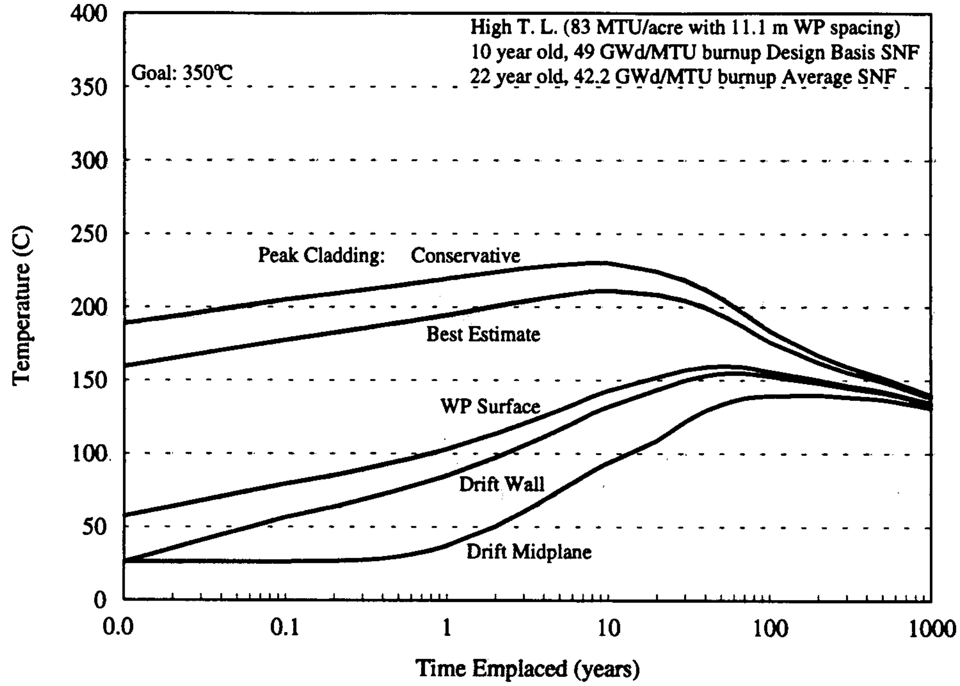

Figure 7.4-1. 24 BWR UCF Temperatures, High Thermal Load #2 (83 MTU/Acre)

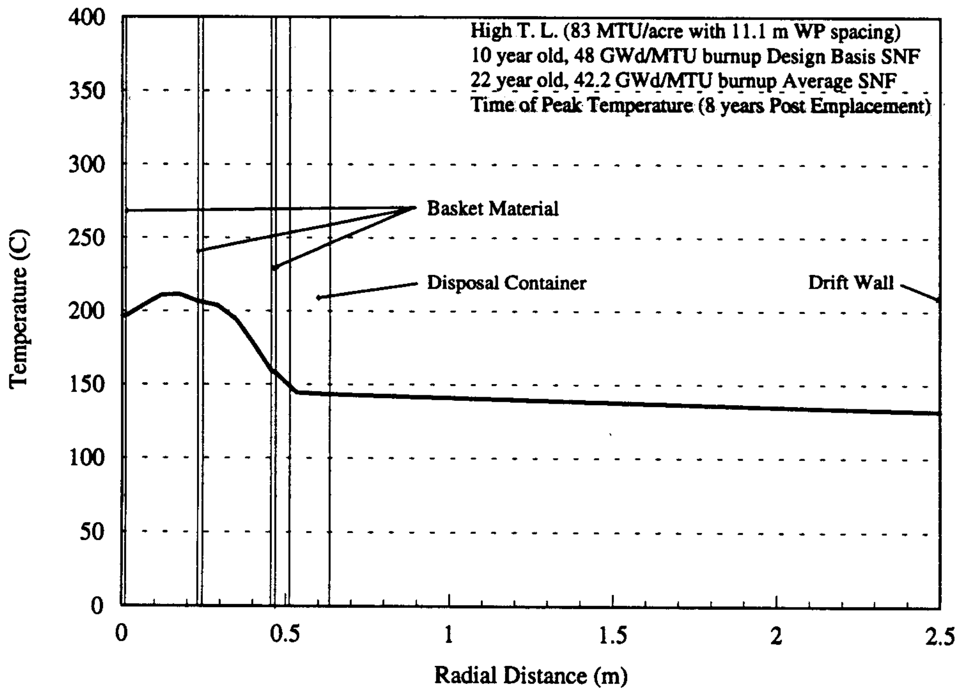

Figure 7.4-2. Temperature Profile, 24 BWR UCF

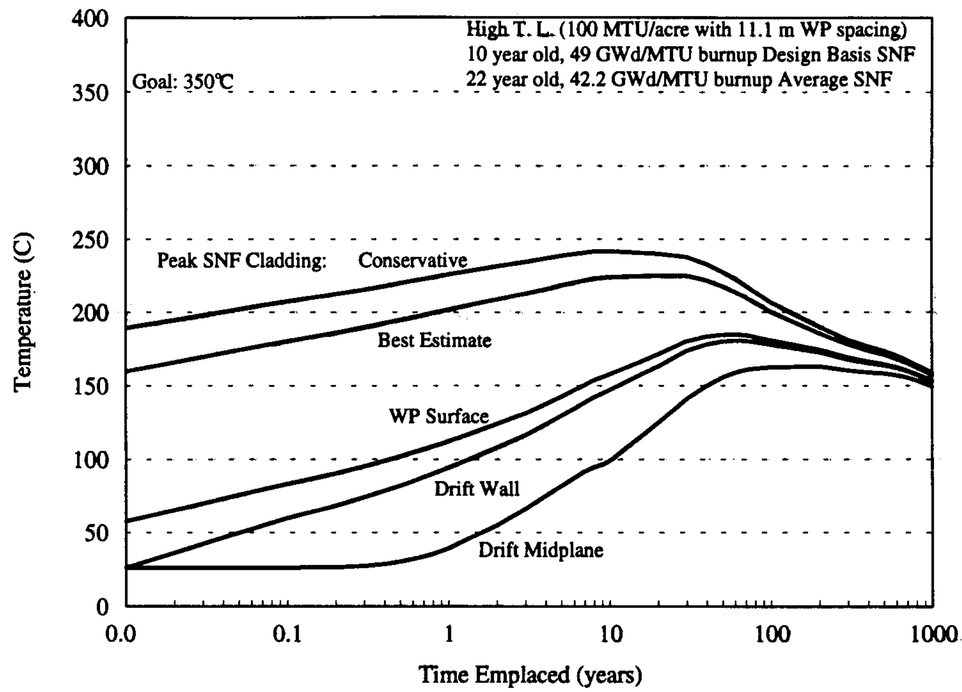

Figure 7.4-3. 24 BWR UCF Temperatures, High Thermal Load #1 (100 MTU/Acre)

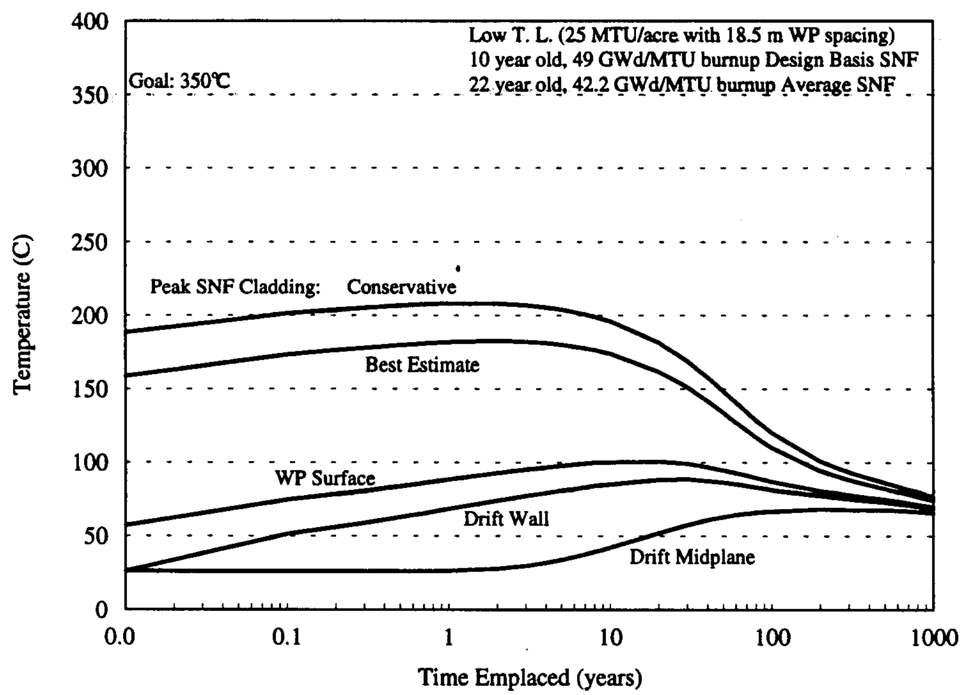

Figure 7.4-4. 24 BWR UCF Temperatures, Low Thermal Load #1 (25 MTU/Acre 18.5 m)

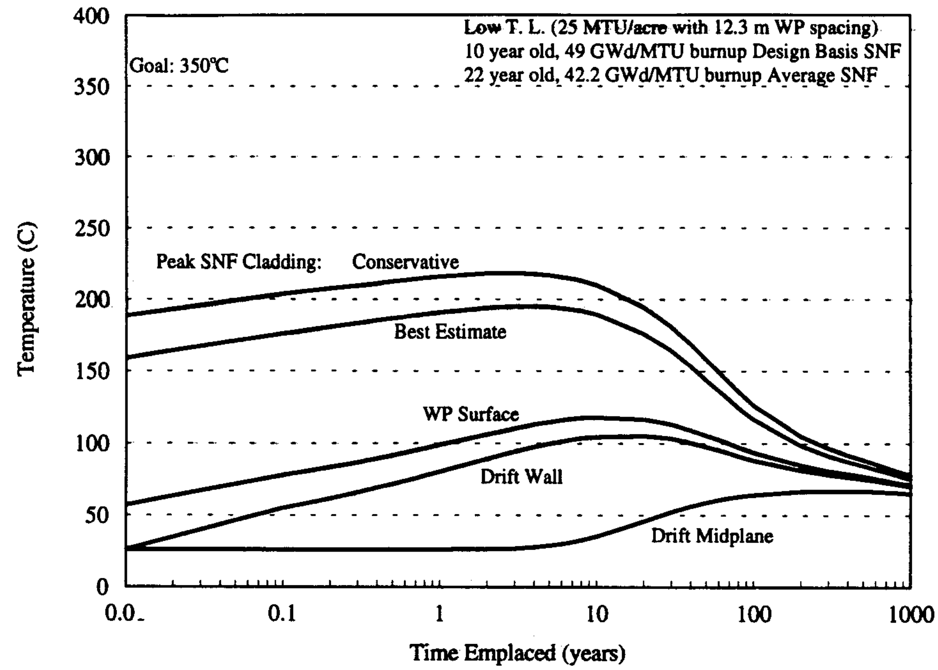

Figure 7.4-5. 24 BWR UCF Temperatures, Low Thermal Load #2 (25 MTU/Acre 12.3 m)

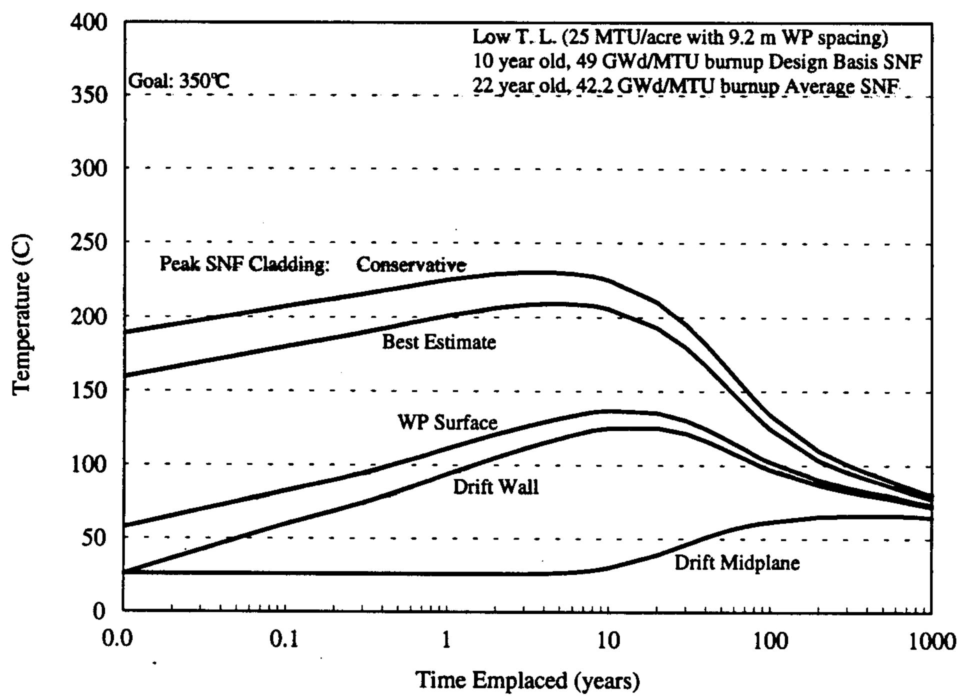

Figure 7.4-6. 24 BWR UCF Temperatures, Low Thermal Load #3 (25 MTU/Acre 9.2 m)

8. Conclusions

Table 8-1 summarizes the peak temperatures and the time of occurrence for each of the cases analyzed. The thermal loading scenarios indicated in Table 8-1 are defined in Table 7.1-1, and the design basis SNF descriptions are provided in Table 7.2-1. Both "conservative" estimates of peak cladding temperatures using the Wooton-Epstein correlation and "best estimate" predictions using the effective conductivity method are presented in the table. Peak cladding temperatures using effective conductivity are calculated directly in the ANSYS program, and Wooton-Epstein calculations for each time step in the ANSYS analysis were also performed for comparison.

Table 8-1. 24 BWR UCF Thermal Analysis Results Summary

Thermal Load	Design Basis SNF	Peak Cladding				Peak Basket		WP Surface	
		Cons. Est.		Best Est.					
		°C	yrs	°C	yrs	°C	yrs	°C	yrs
High #1	MGDS	242	10	225	20	222	30	184	60
High #2	MGDS	230	8	211	10	207	10	160	50
Low #1	MGDS	208	1	183	2	177	2	101	20
Low #2	MGDS	218	3	195	3	190	4	118	10
Low #3	MGDS	230	4	209	5	204	4	137	10

The repository thermal loading has not been specified by the MGDS program and will not be finally established for years. Therefore, the thermal evaluation of the 24 BWR UCF WP conceptual design with respect to the repository has considered a number of thermal loading scenarios. For each repository thermal loading scenario, a 3-D repository emplacement (Ref. 5.13) and 2-D waste package evaluation were performed. As indicted by the data provided in Table 8-1, the peak SNF cladding temperatures remain below 350°C and the temperatures for the materials used in the UCF WP conceptual designs are not such that melting or rapid mechanical failure would occur.

The results of the thermal evaluations indicate that the 24 BWR UCF WP conceptual design can satisfy the thermal limitations (i.e., goals) specified in Section 4.2.5 during normal expected conditions for disposal in the MGDS and therefore has a reasonable chance to meet the MGDS requirements for permanent disposal. Thus, the UCF WP conceptual design may be used as a point of departure for analysis of design changes put forth by the UCF WP designers. However, two points should be noted: 1) more analysis is required to determine conditions for anticipated off-normal conditions and drift backfill; and 2) this analysis relies on unqualified design inputs. These items need to be considered by any work which uses these results.

9. Attachments

The attachments included are summarized in Table 9-1.

Table 9-1. Attachments of Supporting Documentation for the 24 BWR UCF MGDS Analysis

Attachment Number	Title / Description	# of Pages
I	PHIA code listing (File name: phia00b.cpp date: 2/15/95)	4
II	PHIA code database input; reference 5.30 (File name: heatdat.dat date: 8/8/95)	6
III	PHIA code output; ANSYS ready input. (File name: bwr1049.dat date: 3/7/95)	1
IV	Material properties file for ANSYS; data from Section 4.1. (File name: props01.dat date: 3/7/95)	3
V	Effective thermal conductivity file; reference 5.40 (File name: pwr15e.parm date: 3/7/95)	3
VI	Model mesh plots geometry; 1) full mesh, 2) full mesh/no He, 3) radiation surfaces (File name: ansysplots.doc date: 8/4/95)	3
VII	Boundary condition file for high thermal load #1; reference 5.13 (File name: c12x5a.parm used in Attachment XII date: 3/31/95)	11
VIII	Boundary condition file for high thermal load #2; reference 5.13 (File name: c12b5a.parm used in Attachment XIII date: 3/7/95)	11
IX	Boundary condition file for low thermal load #1; reference 5.13 (File name: c12w5a.parm used in Attachment XIV date: 3/7/95)	11
X	Boundary condition file for low thermal load #2; reference 5.13 (File name: c12j5a.parm used in Attachment XV date: 3/7/95)	11
XI	Boundary condition file for low thermal load #3; reference 5.13 (File name: c12h5a.parm used in Attachment XVI date: 3/7/95)	11
XII	ANSYS output for the 100 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24x.old.out; WP spacing: 9.2 m; drift spacing: 22.5 m date: 6/27/95)	193
XIII	ANSYS output for the 83 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24b.old.out; WP spacing: 11.1 m; drift spacing: 22.5 m date: 6/27/95)	198
XIV	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24w.old.out; WP spacing: 18.5 m; drift spacing: 45.0 m date: 6/29/95)	246
XV	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24j.old.out; WP spacing: 12.3 m; drift spacing: 67.5 m date: 6/28/95)	248
XVI	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24h.old.out; WP spacing: 9.2 m; drift spacing: 90.0 m date: 6/27/95)	227

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Attachment Number	Title / Description	# of Pages
I	PHIA code listing (File name: phia00b.cpp date: 2/15/95)	4
II	PHIA code database input; reference 5.30 (File name: heatdat.dat date: 8/8/95)	6
III	PHIA code output; ANSYS ready input. (File name: bwr1049.dat date: 3/7/95)	1
IV	Material properties file for ANSYS; data from Section 4.1. (File name: props01.dat date: 3/7/95)	3
V	Effective thermal conductivity file; reference 5.40 (File name: pwr15e.parm date: 3/7/95)	3
VI	Model mesh plots geometry; 1) full mesh, 2) full mesh/no He, 3) radiation surfaces (File name: ansysplots.doc date: 8/4/95)	3
VII	Boundary condition file for high thermal load #1; reference 5.13 (File name: c12x5a.parm used in Attachment XII date: 3/31/95)	11
VIII	Boundary condition file for high thermal load #2; reference 5.13 (File name: c12b5a.parm used in Attachment XIII date: 3/7/95)	11
IX	Boundary condition file for low thermal load #1; reference 5.13 (File name: c12w5a.parm used in Attachment XIV date: 3/7/95)	11
X	Boundary condition file for low thermal load #2; reference 5.13 (File name: c12j5a.parm used in Attachment XV date: 3/7/95)	11
XI	Boundary condition file for low thermal load #3; reference 5.13 (File name: c12h5a.parm used in Attachment XVI date: 3/7/95)	11
XII	ANSYS output for the 100 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24x.old.out; WP spacing: 9.2 m; drift spacing: 22.5 m date: 6/27/95)	193
XIII	ANSYS output for the 83 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24b.old.out; WP spacing: 11.1 m; drift spacing: 22.5 m date: 6/27/95)	198
XIV	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24w.old.out; WP spacing: 18.5 m; drift spacing: 45.0 m date: 6/29/95)	246
XV	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24j.old.out; WP spacing: 12.3 m; drift spacing: 67.5 m date: 6/28/95)	248
XVI	ANSYS output for the 25 MTU/acre thermal loading for the 24 BWR UCF WP (File name: ucf24h.old.out; WP spacing: 9.2 m; drift spacing: 90.0 m date: 6/27/95)	227