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Design Analysis Cover Sheet

Complete only applicable items.

1.

QA: ~~L~~ N/A TL 11/9/95

2. DESIGN ANALYSIS TITLE Thermal Evaluation of the use of BWR MOX SNF in the Multi-Purpose Canister (MPC) with ACD Disposal Container (SCPB: N/A)			
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	Print Name	Signature	Date
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14. REMARKS

This is an approved SCOPING Design Analysis. The QAP 2-0 Activity Evaluation, "Studies Not Supported by the Office of Civilian Radioactive Waste Management", DI#: BB0000000-01717-2200-00035 REV 01, lists the procedural controls which are required. Therefore, this design analysis is *__NOT__ subject to the QAP 3-series procedures and does not require QAP 3-9 signatures. All information contained in this analysis is TBV and has received a technical review only.*

CRWMS/M&O

Design Analysis Revision Record

Complete only applicable items.

1.

TL 11/9/95

QA: ~~L~~ N/A

2. DESIGN ANALYSIS TITLE

Thermal Evaluation of the use of BWR MOX SNF in the Multi-Purpose Canister (MPC) with ACD Disposal Container (SCPB: N/A)

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Title: Thermal Evaluation of the use of BWR MOX SNF in the Multi-Purpose Canister (MPC) with ACD Disposal Container (SCPB: N/A)

Document Identifier: BBAB00000-01717-0200-00002 REV 00

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Date: November 13, 1995

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 40 BWR Multi-Purpose Canister (MPC) Waste Package (WP) design to show that the design is feasible for use in the MGDS environment when loaded with BWR MOX SNF.

2) Characterize the conceptual 24 BWR Multi-Purpose Canister (MPC) Waste Package (WP) design to show that the design is feasible for use in the MGDS environment when loaded with BWR MOX SNF.

The purpose of this analysis is to respond a concern that the long-term disposal thermal issues for the Multi-Purpose Canister (MPC) Subsystem Design, if used with SNF designed for a MOX fuel cycle, do not preclude MPC compatibility with the MGDS. The objective of this analysis is to provide thermal parameter information for the conceptual MPC design with disposal container which is loaded with BWR MOX SNF 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, to provide the required guidance to determining the major design issues for future design efforts, and to show that the BWR MOX SNF loaded MPC performance is similar to an MPC loaded with commercial BWR SNF. Future design efforts will focus on specific MPC vendor designs and BWR MOX SNF designs when they become available.

2. Quality Assurance

The QA program does not apply to this analysis. The information in this analysis concerning disposal long-term thermal parameters for the conceptual MPC WP loaded with BWR MOX SNF will be used as a guide as to the possible requirements which might be used in the MPC WP design. The performance of the MPC internals will affect the proper function of the waste package and the waste package has been identified as an MGDS Q-List item important to safety (Ref. 5.4, p. 5). However, this analysis is for the conceptual MPC design and a proposed BWR MOX SNF type and will not contribute to any MGDS designs. The work performed for this analysis is covered by reference 5.2, Studies Not Supported by the Office of Civilian Radioactive Waste Management and is part the WPDD QAP-2-0 Work Control evaluation documents. This QAP-2-0 evaluation determined such activities are not subject to Quality Assurance Requirements and Description (Ref. 5.3) requirements. Applicable procedural controls are listed in the evaluation.

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 PWR Effective Thermal Conductivity Analysis (Ref. 5.11) by using the same method for SNF thermal modeling and the results for the WP surface temperatures from the three-dimensional emplacement scale model. This method was also performed in references 5.40 and 5.41 for the MGDS design basis SNF. Thus, the BWR MPC 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; p. 26, ref. 5.39; and pp. 3-11, ref. 5.30) 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

4.1 Design Parameters

Tables 4.1-1 and 4.1-2 lists 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.

$$\mathit{Thermal\ Diffusivity}(ft^2/hr) = \frac{\mathit{Thermal\ Conductivity}(Btu/hr{\cdot}ft{\cdot}^\circ F)}{\mathit{Density}(lb/ft^3) \times \mathit{Specific\ Heat}(Btu/lb{\cdot}^\circ F)}$$

(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 lists 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 (kg/m^3)	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/m³)	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 (pp. 43 and 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/in³)	C71500 Density (kg/m³)	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 (EBDRD, 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, EBDRD, 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 EBDRD 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 EBDRD Requirements for Thermal Design

The criteria applicable to thermal analysis of waste package emplacement are equivalent to the applicable requirements in the EBDRD (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 EBDRD (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 EBDRD (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 assumptions identified in this section will require verification (or superseding assumptions) as the waste package design proceeds and should be treated as TBV items for preliminary design. For Pre-title II design (conceptual or preliminary) and documents not subject to 3-series QAPs, assumptions are identified and documented, but they are not subject to tracking in accordance with MGDS NLP-3-15.

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 EBDRD 3.7.G.2, p. 6-76, Ref. 5.7)
- Keep the emplacement drift wall temperature less than 200°C. (CDA EBDRD 3.7.G.2, p. 6-76, Ref. 5.7)
- Limit the TSw3 (basal vitrophyre) maximum temperature to less than 115°C. (CDA EBDRD 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 EBDRD 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 EBDRD 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 EBDRD 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 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). Also, in an effort to have all of the M&O analysts on the same "sheet of music", thermal loadings of 25 and 83 MTU/acre were recommended in a Systems Engineering interoffice correspondence (p. 2, Ref. 5.23). 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 MPC 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 5.30 (Table 2.6, pages 9 and 10) determined the thermal design basis BWR MOX 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 37,609 MWd/MTHM, and 3) assembly average initial plutonium mass loading of 5.334 kg. To complete the characterization of the BWR MOX SNF and in order to remain consistent with the analysis performed in references 5.40 and 5.41, the following data will be used to determine the BWR MOX SNF homogenized density and specific heat. The assumption is that the use of the following values also bounds the BWR MOX SNF designs in the same fashion for commercial BWR SNF. Thus, it is assumed that a GE-7 8x8 MOX SNF assembly with a uranium mass of 0.200 MTU/assembly and an active fuel length of 150 inches will adequately represent the BWR MOX SNF as a class of waste. This data is required in order to determine the homogenized density and specific heat of the thermal design basis BWR MOX SNF. Based upon data from pages 2A-21 and 2A-22 of reference 5.12, page 26 of reference 5.39, and page 4 of reference 5.30; 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 Section 7 and in Section 4.3.

4.3.5 The decay heat curve for the BWR MOX SNF thermal design basis is given in Table 2.10 on page 20 of reference 5.30. The data from reference 5.30 is assumed to accurately represent the BWR MOX SNF which may be received by the MGDS. Use of the data from reference 5.30 in this manner is consistent with the reasons for its creation. This assumption is used throughout Section 7. The data, however, is not presented in ANSYS format and has time steps which are too large for the analysis. Thus, the MATHCAD software was used to perform a curve fit of the data and to create a MATHCAD print file with the required ANSYS decay heat curve data. This MATHCAD print file was then translated by hand into an ANSYS readable file to be used by the analysis. It is further assumed that the curve fit representation of the data is a reasonable representation of the data presented in reference 5.30 and that the use of curve fit representation does not affect the results presented in this analysis. The basis for this assumption is engineering judgement and the curve fit deviation evaluation presented in Attachment I. This assumption is used throughout Section 7. The MATHCAD calculation file is presented in Attachment I which echoes the data used from reference 5.30 as input. The MATHCAD print file containing the ANSYS data is presented in Attachment II. The ANSYS readable file used in this analysis is presented in Attachment III. The decay heat curve is presented in Sections 6.0 and 7.4.

4.3.6 The material properties, i.e., effective thermal conductivities, developed for the B&W 15x15 PWR SNF in reference 5.11 may be conservatively applied to the GE-7 8x8 BWR MOX 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 5.11 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 5.11 data in a consistent manner. This assumption is used throughout Section 7.

4.3.7 The MPC 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 MOX 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 MOX SNF. The basis for this assumption is that BWR reactor cores are designed such that axial peaking larger than 1.40 are typically not allowed. 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 MPC conceptual design as presented on pages II.A.4-13, II.A.4-14, II.A.4-24, and II.A.4-25 of reference 5.8, Figures 4.2.1.2-1, 4.2.1.2-2, 4.2.2.2-1, and 4.2.2.2-2 are assumed to be the representative designs which specifies the geometry and materials of construction. The basis of this assumption is that the specified reference is the only MPC design available. This assumption is used throughout Section 7.

4.3.12 The waste package disposal container 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, 5.37, 5.42, and 5.43 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 MPC waste package is assumed to be evacuated and filled with helium gas. The basis for this assumption is that this process is considered in 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 MPC internals. This assumption is used throughout Section 7.

4.3.14 The gap between the MPC and the disposal container is assumed to be modeled conservatively if it is modeled as being void of material (i.e., a vacuum). The basis for this assumption is as follows: this space will most likely be evacuated and backfilled with helium gas for similar reasons as specified in assumption 4.3.13 for the MPC internals. However, since helium has a reasonably good thermal conductivity, assuming a vacuum will result in slightly higher internal temperatures. This is conservative for this analysis. This assumption is equivalent to assuming only radiative heat transfer between the MPC shell and the disposal container. 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: convective heat transfer will occur with the fill gas which is placed internal to the MPC, 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 convection 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 with disposal container will not have filler material placed in side of it. The basis for this assumption is that the consideration of filler material is beyond the scope of this analysis. Evaluation of effect 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 with disposal container 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 with disposal container 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 It is assumed for this analysis that waste package materials which are in contact that a perfect weld will be modeled. 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 Modeling the MPC container as "floating" in the disposal container such that the MPC package does not touch the disposal container at any point is assumed to provide conservative results for this analysis. The basis for this assumption is engineering judgement. The assumption is conservative with respect to MPC internal temperatures since the modeled geometry eliminates any conduction heat transfer and will limit the mode of heat transfer to only radiation between two surfaces. This assumption is used throughout Section 7.

4.3.21 Modeling the MPC basket as "floating" in the MPC container such that the SNF tubes do not touch the MPC corner guides or any other part of the MPC is assumed to provide conservative results for this analysis. The basis for this assumption is engineering judgement. This is conservative with respect to SNF temperatures since the modeled geometry will eliminate any conduction heat transfer, other than that of conduction through the helium fill gas, from the SNF basket to the MPC shell and limits the main heat transfer mode to that of radiative heat transfer. This configuration uses the manufacturing tolerances for the MPC container and creates a basket/shell gap. 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 MPC 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 less pressure in their designs. Use of one atmosphere is representative of the most likely 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 used in the MPC 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 MPC 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 MPC 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 MPC 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-boron 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 and the fact that the temperature dependent values of thermal conductivity and specific heat are specified well enough to cover the most of the anticipated temperatures the MPC 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 aluminum emissivity for the aluminum-boron material is assumed reasonable in the absence of data for aluminum-boron since, for the MPC, the aluminum-boron material is clad in stainless steel and has only a minor edge exposed for the outer most tubes only. Finally, the emissivity for aluminum is sufficiently low at 0.07 that a lower value will have very little impact upon the solution and 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 MPC 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.

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 value used for SNF density is 0.388242×10^4 kg/m^3. 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 meters) and the assembly length of 175.87 inches (4.467 meters) 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 used is: Density = 0.388242×10^4 kg/m^3. 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 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 (i.e., the added plutonium has a negligible effect upon the final value), therefore the homogenized specific heat is a simple mass weighted average (i.e., SNF $C_p = (C_p\ UO_2 \cdot \text{Mass}\ UO_2 + C_p\ \text{Zr2} \cdot \text{Mass Zr2})$ / 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 Zr2 = 104.24 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 X and XI is 284.01 J/kg·K and is in error. However, the error is judged to be small relative to the given set of assumptions and has no impact upon any of the results given the small amount of thermal energy mass strorage expected in the homogeneous SNF assembly. This assumption is used throughout Section 7.

4.3.30 The analysis for the 100 MTU/acre repository thermal loading is assumed to bound all thermal loadings which are less than 100 MTU/acre. Further, it is assumed the performing only the 100 MTU/acre case is sufficient to show that the BWR MOX SNF loaded MPC will have similar performance parameters as the MPC loaded with commercial BWR SNF. This assumption is based upon the analysis performed in references 5.40 and 5.41 which show that the 100 MTU/acre thermal loading produce the highest SNF temperatures inside the MPC waste package and engineering judgement. Therefore, only the 100 MTU/acre ANSYS cases are repeated for the BWR MOX SNF analysis. 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

5.1 Nuclear Systems I Thermal Hydraulic Fundamentals, Neil E. Todreas and Mujid S. Kazimi, Hemisphere Publishing Corporation, New York, N.Y., 1990.

5.2 Activity Evaluation: Studies Not Supported by the Office of Civilian Radioactive Waste Management, Document Identifier (DI) Number: BB0000000-01717-2200-00035 REV 01, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O), August 30, 1995.

5.3 Quality Assurance Requirements and Description (QARD), DOE/RW-0333P REV 5, October 31, 1995.

5.4 Yucca Mountain Site Characterization Project Q-List, YMP/90-55Q, REV 3, Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM), December 1994.

5.5 Engineered Barrier Design Requirements Document, YMP/CM-0024, Rev 0, ICN 1, Yucca Mountain Site Characterization Project, September 21, 1994.

5.6 Mined Geological Disposal System Requirements Document, DOE/RW-0404P, DI: B00000000-00811-1708-00002, REV 01, DCN 01, U.S. DOE OCRWM, May 1995.

5.7 Controlled Design Assumptions (CDA) Document, DI#: B00000000-01717-4600-00032 REV 01, CRWMS M&O, April 28, 1995.

5.8 Multi-Purpose Canister (MPC) Implementation Program Conceptual Design Phase Report, Volume II.A - MPC Conceptual Design Report, DI#: A20000000-00811-5705-00002 REV 00, September 30, 1994.

5.9 Waste Package Plan, YMP/90-62, Rev 1, Yucca Mountain Site Characterization Project March, 1993.

5.10 Waste Package Implementation Plan, YMP/92-11Q, Rev 1, Yucca Mountain Site Characterization Project, January, 1995.

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5.12 Characteristics of Potential Repository Wastes, DOE/RW-0184-R1; Volume 1, U.S. DOE OCRWM, July 1992

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5.40 Thermal Evaluation of the Conceptual 40 BWR Multi-Purpose Canister (MPC) with Advanced Conceptual Design (ACD) Disposal Container, DI#: BBABB0000-01717-0200-00003, REV 00, CRWMS M&O, DRAFT to be issued in 1995.

5.41 Thermal Evaluation of the Conceptual 24 BWR Multi-Purpose Canister (MPC) with Advanced Conceptual Design (ACD) Disposal Container, DI#: BBABA0000-01717-0200-00003, REV 00, CRWMS M&O, DRAFT to be issued in 1995.

5.42 MPC Disposal Container (12-PWR/24-BWR), DI: BBA000000-01717-2100-15018, R00B, CRWMS M&O, August, 1994.

5.43 Low TL/Humid MPC Disposal Container (12-PWR/24-BWR), DI: BBA000000-01717-2100-15074, R00A, CRWMS M&O, August, 1994.

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6. Use of Computer Software

The FEA analysis computer code used for this analysis is ANSYS V5.0A 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 (page 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 (page 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 MATHCAD V5.0+ and is classified as computational support software. MATHCAD V5.0+ 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. MATHCAD V5.0+ simply provides a frame work to automate a simple mathematical calculations which can easily be checked by hand or through alternate calculational methods. Based upon the data provided in assumption 4.3.5, MATHCAD V5.0+ performs a simple curve fit via an iterative least squares method. Once the proper equation coefficients for the curve fit of the data is obtained, MATHCAD V5.0+ summarizes the numeric differences between the input data and the curve fit data and writes an ASCII print file with the heat curve data versus ANSYS time steps. The ASCII print file was then translated by hand to an ANSYS readable file format. The MATHCAD V5.0+ calculation file, MATHCAD V5.0+ print file, and ANSYS data file are provided as Attachments I, II, and III. 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. MATHCAD V5.0+ was utilized for the purpose of computational support software as it was intended and it is appropriate for the use of generating a curve fit to supply data for an ANSYS SNF heat load file. The MATHCAD V5.0+ 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 MPC 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 them 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 an homogeneous SNF assembly. The effective conductivity was determined using a detailed third model of an intact SNF assembly as presented in reference 5.11. 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 in the Controlled Design Assumptions Document (CDA) (Key 019, p. 6-24, Ref. 5.7) and the MPC 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). However, for the BWR MOX SNF, only the 100 MTU/acre (High Thermal Loading #1) will be analyzed (see assumption 4.3.30). The intent of this analysis is to show that the BWR MOX SNF has a very similar performance profile to commercial BWR SNF which was analyzed in references 5.40 and 5.41.

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

AML MTU/acre	Initial APD kW/acre	Small Waste Package Spacing	Large Waste Package Spacing	Drift Spacing
100 (high #1)	113.7	9.2 m	16.2 m	22.5 m
83 (high #2)	94.4	11.1 m	19.5 m	22.5 m
25 (low #1)	28.4	18.5 m	32.3 m	45.0 m
25 (low #2)	28.4	12.3 m	21.6 m	67.5 m
25 (low #3)	28.4	9.2 m	16.2 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 commercial SNF design basis SNF for WP design is covered in reference 5.28. The design basis BWR MOX SNF which will be used to compare to commercial BWR SNF is presented in reference 5.30 and assumption 4.3.5.

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 40 BWR MPC, is a temperature of no more than 350°C at the SNF cladding. Several different design basis SNF types have been used in by the OCRWM to demonstrate compliance with requirements and to allow comparison with previous evaluations. Table 7.2-1 summarizes the commercial SNF types used as specified in references 5.40 and 5.41.

Table 7.2-1. Thermal Analysis Commercial SNF Design Bases

Organization	SNF Type	SNF Age	SNF Burnup	Initial Heat
MGDS (ref. 5.28)	PWR	10 years	48 GWd/MTU	850 watts
MGDS (ref. 5.28)	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 large 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 BWR MOX SNF defined in reference 5.30 has been used to in the ANSYS analysis. Any information concerning commercial BWR SNF was obtained directly from references 5.40 and 5.41. The time dependence of the design basis BWR MOX SNF is provided in Appendix III as provided by MATHCAD V5.0+ using the data provided in reference 5.30. MATHCAD V5.0+ uses the data provided in assumption 4.3.5, performs a curve fit for the input decay heat data to obtain the heat generation rate versus time. Then prints the decay heat data at the desired ANSYS time steps to an ASCII file. The data was then reformatted into a file suitable for direct use by ANSYS. The MATHCAD V5.0+ calculation file is provided as Attachment I, along with the MATHCAD V5.0+ print file as Attachment II, and the ANSYS readable file created from the MATHCAD V5.0+ print file as Attachment III.

7.3 2-D Waste Package Model Development

The general philosophy used to create an input file for each thermal loading case is outlined here for the reader's enjoyment. Since the there are only two major differences between individual cases, i.e., boundary condition and 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 outer barrier material and thickness data entered into the input decks. Now, specifically for the BWR MOX SNF analysis, the base high thermal load cased from references 5.40 and 5.41 were copied and the BWR MOX SNF decay heat curve data file was entered into the input decks instead of the commercial BWR SNF data file.

The basic lay out 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 MPC basket geometry parameters are reported in reference 5.8 in units of inches. 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. Long winded, 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 (B.C.'s) to the appropriate geometry components. Since this calculation is a transient, the loads and B.C.'s are applied at each time step. 7) Finally, selected positions in the SNF, basket, MPC shell, and disposal container 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 X and XI. 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 VIII and IX.

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 an design thesis.

The creation of an ANSYS model for the 40 and 24 BWR MPC 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 reference 5.8 (Section 4.2.2.2) for the 40 and 24 BWR MPC conceptual design and references 5.31, 5.35, 5.37, 5.42, and 5.43 for the disposal container (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 alloy 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. However, as explained in Sections 1, 7.1, and 7.4, only the 100 MTU/acre case will be analyzed for this analysis.

Since this model is part of a larger calculational scheme as indicated in references 5.11 and 5.13, a simple 2-D cross section of the MPC with waste package will be modeled (see assumption 4.3.7). A vertical plane a symmetry is easily identified and thus, the geometry modeled will be that of the right hand side of the MPC with disposal container. 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. Attachments VI (40 BWR MPC) and VII (24 BWR MPC) provide the mesh plots of the general lay out 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 assumption 4.3.22, 4.3.23, 4.3.24, 4.3.25, 4.3.26, and 4.3.27). The effective conductivity of the SNF assembly model area was developed in reference 5.11 and are provided as Attachment V. The additional properties were 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, 10, 13, 14, 15, 16, 17, 18, 19, 20, 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 carries 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 are from the data provided in reference 5.30 for design basis BWR MOX SNF. 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 MPC/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 requirement to create the 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 the high thermal load #1 scenario described in Section 7.1 for the BWR MOX SNF loaded into a 40 and 24 BWR MPC. 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 results of each ANSYS execution are provided as Attachments X and XI. 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

The results provided in this section for BWR MOX SNF 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. The results for commercial BWR SNF were copied directly from references 5.40 and 5.41.

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 relationship 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 pins 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 relationship 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 relation 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 relation that were used in the ANSYS model (see assumption 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. 5.11)
Basket emissivity	0.600 (Stainless 316L)
Basket cell width	152.4 mm (6.0 inches)
SNF array size (N)	8 pins
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 and 7.4-2 summarize the temperature data for the 40 BWR MOX SNF case analyzed and the 40 commercial BWR SNF case from page 42 of reference 5.40. 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.

Tables 7.4-3 and 7.4-4 summarize the temperature data for the 24 BWR MOX SNF case analyzed and the 24 commercial BWR SNF case from page 42 of reference 5.41. 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 of peak SNF temperatures for each case is presented graphically in Figures 7.4-1 and 7.4-2. Figure 7.4-1 compares the MOX and commercial SNF for the 40 BWR MPC design. Figure 7.4-2 compares the MOX and commercial SNF for the 24 BWR MPC design.

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 7.4-4, the BWR MOX SNF has a significantly lower initial heat load than the commercial BWR SNF for the first 60 years of emplacement which reduces the magnitude of the peak cladding temperatures and moves the peaks further out in time. However, the heat load for BWR MOX SNF is higher for long term emplacement, but the long term temperatures are not significantly above those for commercial BWR SNF.

Table 7.4-1. High Thermal Load #1; 40 BWR MOX MPC Waste Package Thermal Results

40 BWR MPC with Disposal Container
100 MTU/acre with 16.165 m WP Spacing
10 year old, 36.7 GWd/MTHM burnup MOX design basis SNF (WPD)

Time	Heat Load	Wooten-E Eff Cond		ANSYS FEM Temperature Results (Deg. C)						
(years)	(W/assy)	Pk Fuel	Pk Fuel	Basket	MPC Side	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	255.6	221	209	201	133	69	26	26	26	26
0.1	255.1	235	223	216	151	98	71	48	30	26
0.2	254.6	239	227	220	156	105	79	57	36	27
0.3	254.1	241	230	223	159	109	85	62	40	27
0.4	253.6	243	231	224	161	113	89	66	44	29
0.5	253.1	244	233	226	163	116	92	70	47	30
0.6	252.6	245	234	227	165	118	95	73	49	32
0.7	252.1	246	235	228	166	120	97	75	52	34
0.8	251.7	247	236	229	168	122	100	78	54	36
0.9	251.2	248	237	230	169	123	102	80	56	38
1	250.7	249	237	231	170	125	103	82	58	40
2	246	253	242	236	177	135	116	95	73	56
3	241.4	255	245	239	181	142	124	104	84	67
4	237	257	247	241	185	147	131	111	91	75
5	232.7	258	248	242	188	152	136	117	97	82
6	228.6	259	249	244	191	156	141	122	102	88
7	224.6	260	250	245	193	159	145	127	106	92
8	220.7	260	251	245	195	162	148	130	110	95
9	216.9	260	251	245	196	164	151	133	113	97
10	213.3	260	251	245	196	166	153	136	116	99
20	182.6	257	249	244	202	177	167	154	138	125
30	160	254	247	243	206	185	177	165	152	141
40	143.1	250	243	239	[illegible]	188	181	171	160	150
50	130.3	245	239	235	205	188	182	174	164	155
60	120.3	241	235	232	204	[illegible]	[illegible]	175	166	159
70	112.5	237	231	228	202	187	182	[illegible]	167	161
80	106.1	233	228	225	200	186	181	175	168	162
90	100.8	230	224	222	198	184	180	174	[illegible]	162
100	96.34	228	222	219	196	183	179	174	168	162
200	69.87	210	205	203	186	176	174	170	166	[illegible]
300	55.34	198	194	193	179	171	169	166	163	160
400	46.03	191	188	186	175	168	166	164	161	159
500	39.82	186	183	182	172	166	164	162	160	158
600	35.46	182	180	178	169	164	162	161	159	157
700	32.26	178	176	175	166	161	160	159	157	155
800	29.78	175	172	171	164	159	158	156	155	153
900	27.76	171	169	168	161	156	155	154	153	151
1000	26.04	169	166	165	158	154	153	152	151	149

Table 7.4-2. High Thermal Load #1; 40 BWR MPC WP Thermal Results (p. 42, Ref. 5.40)

40 BWR MPC with Disposal Container
100 MTU/acre with 16.165 m WP Spacing
10 year old, 49 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Wooten-E	Eff Cond	ANSYS FEM Temperature Results (Deg. C)						
(years)	(W/assy)	Pk Fuel	Pk Fuel	Basket	MPC Side	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	409.42	283	268	258	160	69	26	26	26	26
0.1	407.68	293	279	270	176	98	71	48	30	26
0.2	405.97	296	282	273	180	105	79	57	36	27
0.3	404.28	297	283	274	182	109	85	62	40	27
0.4	402.61	298	284	275	184	113	89	66	44	29
0.5	400.97	299	285	276	185	116	92	70	47	30
0.6	399.34	299	286	277	187	118	95	73	49	32
0.7	397.74	300	286	277	188	120	97	75	52	34
0.8	396.16	300	287	278	189	122	100	78	54	36
0.9	394.6	300	287	278	189	123	102	80	56	38
1	393.06	300	287	278	190	125	103	82	58	40
2	379.49	301	288	280	195	135	116	95	73	55
3	367.7	300	288	280	199	142	124	104	84	67
4	357.29	300	288	280	201	147	131	111	91	75
5	348.3	299	287	280	203	152	136	117	97	82
6	339.03	298	287	279	205	156	141	122	102	88
7	331	297	286	279	206	159	145	127	106	92
8	323.52	297	285	278	208	162	148	130	110	95
9	316.46	295	284	277	208	164	151	133	113	97
10	310.56	294	283	276	209	166	153	136	116	99
20	255.61	283	273	267	212	177	167	154	138	125
30	214.52	274	265	260	[illegible]	185	177	165	152	141
40	183.32	264	257	252	211	188	181	171	160	150
50	157.9	255	248	244	209	188	182	174	164	155
60	138.15	248	241	238	206	188	183	175	166	159
70	122.25	241	235	232	204	187	182	[illegible]	167	161
80	109.37	234	229	226	200	186	181	175	168	162
90	99.33	229	224	221	198	184	180	174	168	162
100	90.35	224	219	217	196	183	179	174	168	162
200	51.61	201	198	196	184	176	174	170	166	163
300	38.89	190	188	186	177	171	169	166	163	160
400	31.79	184	182	181	173	168	166	164	161	159
500	27.23	180	178	177	170	166	164	162	160	158
600	23.69	176	174	174	167	164	162	161	159	157
700	21.02	173	171	170	165	161	160	159	157	155
800	18.76	169	167	167	162	159	158	156	155	153
900	16.96	166	164	164	159	156	155	154	153	151
1000	15.49	163	161	161	157	154	153	152	151	149

Table 7.4-3. High Thermal Load #1; 24 BWR MOX MPC Waste Package Thermal Results

24 BWR MPC with Disposal Container
100 MTU/acre with 9.237 m WP Spacing
10 year old, 36.7 GWd/MTHM burnup MOX design basis SNF (WPD)

Time	Heat Load	Wooten-E Eff Cond		ANSYS FEM Temperature Results (Deg. C)						
(years)	(W/assy)	Pk Fuel	Pk Fuel	Basket	MPC Side	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpln
0	255.6	189	175	166	111	58	26	26	26	26
0.1	255.1	202	188	180	128	83	60	43	29	26
0.2	254.6	206	192	184	133	90	68	51	34	26
0.3	254.1	208	195	187	137	95	74	56	38	27
0.4	253.6	210	197	189	140	99	79	61	42	29
0.5	253.1	212	199	191	142	102	82	64	45	30
0.6	252.6	213	200	193	144	105	85	67	47	32
0.7	252.1	214	201	194	145	107	88	70	50	34
0.8	251.7	215	203	195	147	109	90	72	52	36
0.9	251.2	216	203	196	148	111	92	75	54	37
1	250.7	217	204	197	149	112	94	77	56	39
2	246	223	211	203	158	124	108	91	72	55
3	241.4	226	214	207	163	131	116	100	82	66
4	237	229	217	210	167	137	123	107	90	75
5	232.7	231	219	213	171	142	129	113	96	82
6	228.6	232	221	215	174	147	134	119	101	87
7	224.6	234	223	216	177	150	138	123	105	92
8	220.7	235	224	218	179	153	142	127	109	95
9	216.9	235	224	218	180	156	145	130	112	97
10	213.3	236	225	219	182	157	147	132	115	99
20	182.6	236	227	222	[illegible]	171	163	151	137	125
30	160	236	228	223	196	180	173	163	151	141
40	143.1	233	226	222	198	183	178	169	159	150
50	130.3	230	223	220	197	184	180	172	163	155
60	120.3	227	220	217	197	185	180	174	166	158
70	112.5	224	218	215	195	184	180	174	167	160
80	106.1	221	215	212	194	183	179	174	167	161
90	100.8	218	212	210	192	182	179	173	167	162
100	96.34	216	210	207	191	181	178	173	167	162
200	69.87	201	196	194	182	174	172	169	166	163
300	55.34	191	187	186	175	169	168	165	163	160
400	46.03	185	182	180	172	166	165	163	161	159
500	39.82	181	178	177	169	165	164	162	160	158
600	35.46	178	175	174	167	163	162	160	158	157
700	32.26	174	171	170	164	160	159	158	157	155
800	29.78	171	168	167	161	158	157	156	154	153
900	27.76	168	165	164	159	155	155	154	152	151
1000	26.04	165	163	162	157	153	153	152	150	149

Table 7.4-4. High Thermal Load #1; 24 BWR MPC WP Thermal Results (p. 42, Ref. 5.41)

24 BWR MPC with Disposal Container
100 MTU/acre with 9.237 m WP Spacing
10 year old, 49.0 GWd/MTU burnup design basis SNF (WPD)

Time	Heat Load	Wooten-E	Eff Cond		ANSYS FEM Temperature Results (Deg. C)					
(years)	(W/assy)	Pk Fuel	Pk Fuel	Basket	MPC Side	WP Side	Drift Wall	1m Rock	3m Rock	Df Midpt
0	409.42	243	225	214	135	58	26	26	26	26
0.1	407.68	252	235	225	149	83	60	43	29	26
0.2	405.97	255	238	228	154	90	68	51	34	26
0.3	404.28	257	240	230	157	95	74	56	38	27
0.4	402.61	258	242	231	159	99	79	61	42	29
0.5	400.97	259	243	232	161	102	82	64	45	30
0.6	399.34	260	244	233	162	105	85	67	47	32
0.7	397.74	260	244	234	163	107	88	70	50	34
0.8	396.16	261	245	235	165	109	90	72	52	36
0.9	394.6	261	245	235	166	111	92	75	54	37
1	393.06	262	246	236	167	112	94	77	56	39
2	379.49	264	249	239	173	124	108	91	72	55
3	367.7	264	250	241	177	131	116	100	82	66
4	357.29	265	251	242	181	137	123	107	90	75
5	348.3	265	251	243	184	142	129	113	96	82
6	339.03	265	252	243	186	147	134	119	101	87
7	331	265	252	244	188	150	138	123	105	92
8	323.52	265	252	244	190	153	142	127	109	95
9	316.46	264	251	244	191	156	145	130	112	97
10	310.56	264	251	243	192	157	147	132	115	99
20	255.61	257	246	240	198	171	163	151	137	125
30	214.52	252	242	237	201	180	173	163	151	141
40	183.32	245	237	232	201	183	178	169	159	150
50	157.9	238	231	227	200	184	180	172	163	155
60	138.15	232	225	222	198	185	180	174	166	158
70	122.25	227	221	217	196	184	180	174	167	160
80	109.37	222	216	213	194	183	179	174	167	161
90	99.33	218	212	209	192	182	179	173	167	162
100	90.35	214	208	206	190	181	178	173	167	162
200	51.61	194	191	189	180	174	172	169	166	163
300	38.89	185	182	181	174	169	168	165	163	160
400	31.79	180	177	176	170	166	165	163	161	159
500	27.23	176	174	173	168	165	164	162	160	158
600	23.69	173	171	170	165	163	162	160	158	157
700	21.02	169	168	167	163	160	159	158	157	155
800	18.76	166	164	164	160	158	157	156	154	153
900	16.96	163	161	161	158	155	155	154	152	151
1000	15.49	160	159	158	155	153	153	152	150	149

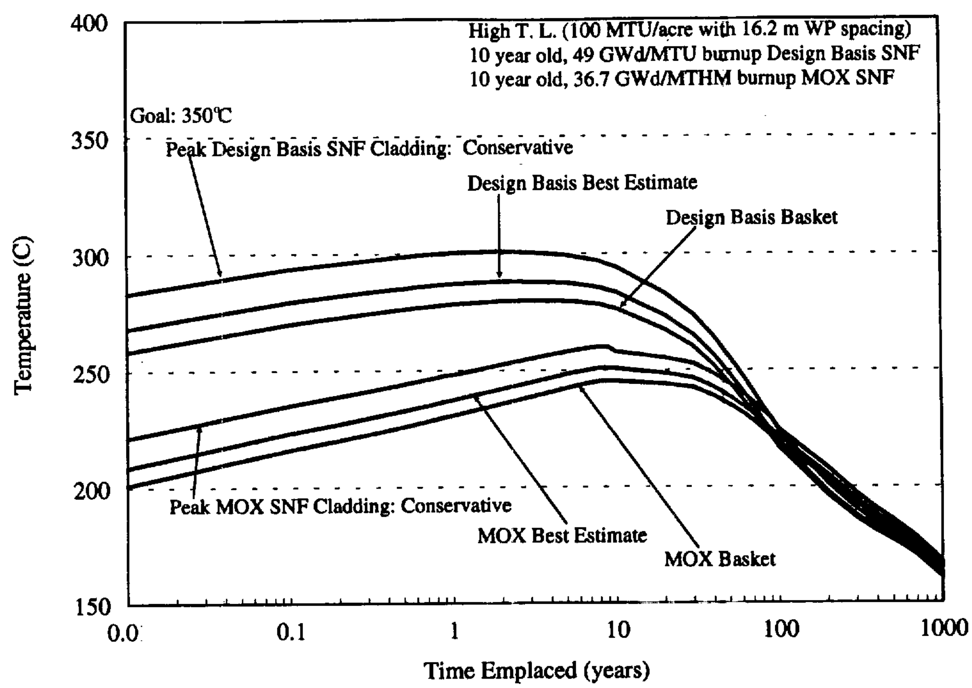

Figure 7.4-1. Summary of Peak SNF Temperatures; 40 BWR MPC

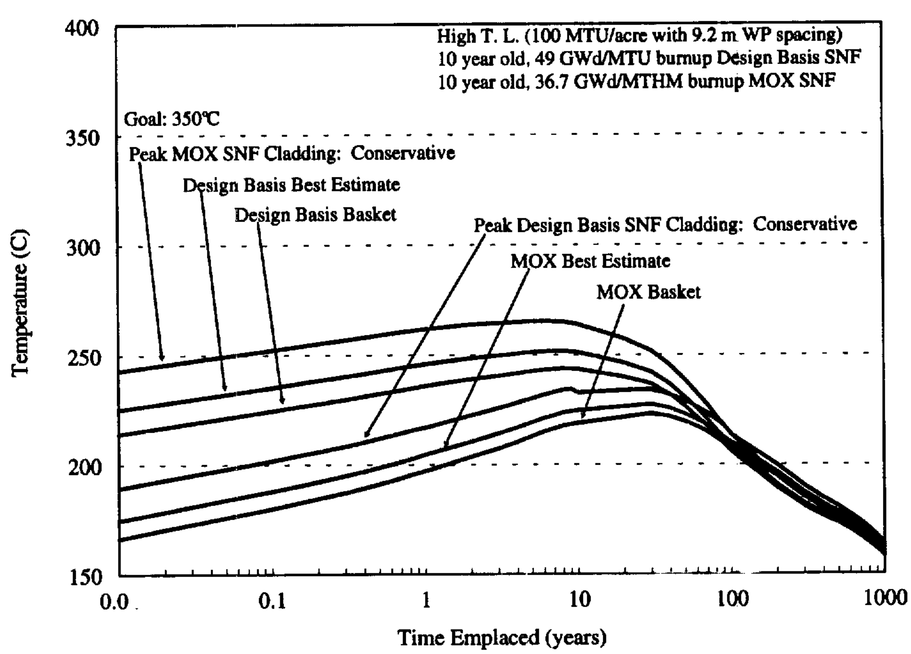

Figure 7.4-2. Summary of Peak SNF Temperatures; 24 BWR MPC

8. Conclusions

Table 8-1 summarizes the peak temperatures and the time of occurrence for each of the MOX BWR cases analyzed and presents the data from page 51 of each of the references 5.40 and 5.41. 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. BWR MPC MOX/Commercial SNF Thermal Analysis Results Summary

Thermal Load	Design Basis SNF	Peak Cladding				Peak Basket		MPC shell		WP Surface	
		Cons. Est.		Best Est.							
		°C	yrs	°C	yrs	°C	yrs	°C	yrs	°C	yrs
High # 1 40 BWR	MGDS	301	2	288	2	280	3	213	30	188	50
High #1 40 BWR	MOX	260	8	251	8	245	9	207	40	188	50
High #1 24 BWR	MGDS	265	8	252	8	244	8	201	40	185	60
High #1 24 BWR	MOX	236	30	228	30	223	30	198	40	185	60

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 MPC conceptual designs are not such that melting or rapid mechanical failure would occur. The MOX and commercial SNF thermal behavior are similar and therefore the thermal behavior of the MOX SNF at lower thermal loadings is expected to follow that of the commercial BWR SNF. Thus, the high thermal load #1 is a bounding case.

The results of the thermal evaluations indicate that the 40 or 24 BWR MPC with disposal container design loaded with MOX SNF 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. Further, the design conditions as very similar to that for commercial SNF and indicate that specific design changes to accommodate MOX SNF is not required. Thus, this MPC conceptual design may be used as a point of departure for analysis of designs put forth by the MPC manufacturers. However, two points should be noted: 1) more analysis is required to determine conditions for anticipated off-normal conditions, drift backfill, and for the MPC vendor specific designs and 2) this analysis relies on input data which is TBV. These items need to be addressed in any work which utilizes these results.

9. Attachments

The attachments included are summarized in Table 9-1.

Table 9-1. Attachments of Supporting Documentation for the BWR MOX MPC Analysis

Attachment Number	Title / Description	# of Pages
I	MATHCAD File Listing to Curve Fit BWR MOX SNF Assembly Heat Load (File name: bwrmox1.mcd)	5
II	MATHCAD Print File of BWR MOX SNF Versus ANSYS Time Steps (File name: bwrmox.prn)	2
III	ANSYS ready input created from MATHCAD Print File. (File name: bwrmox1.dat)	1
IV	Material Properties File for ANSYS; Data from Section 4.1. (File name: props01.dat)	3
V	Effective Thermal Conductivity File; Reference 5.11 (File name: pwr15e.parm)	3
VI	Model Mesh Plots: 40 BWR Geometry; 1) Full Mesh, 2) Full Mesh/No He, 3) Radiation Surfaces	3
VII	Model Mesh Plots: 24 BWR Geometry; 1) Full Mesh, 2) Full Mesh/No He, 3) Radiation Surfaces	3
VIII	Boundary Condition File for High Thermal Load #1; Reference 5.13 Large MPC (File name: c21x5a.parm used in Attachment X)	11
IX	Boundary Condition File for High Thermal Load #1; Reference 5.13 Small MPC (File name: c12x5a.parm used in Attachment XI)	11
X	ANSYS Output for the 100 MTU/acre Thermal Loading for the 40 BWR MPC WP Loaded with the BWR MOX SNF (File name: pu40mox.old.out)	240
XI	ANSYS Output for the 100 MTU/acre Thermal Loading for the 24 BWR MPC WP Loaded with the BWR MOX SNF (File name: pu24mox.old.out)	215

1) Read in data from reference 5.40 to obtain ANSYS time steps, file setup is as follows:

Column 1 = Time step in years; MGDS emplacement is t=0
Column 2 = W/Assembly for 10 year old/ 49 GWd/MTU BWR SNF (Not Used)
Column 3 = W/Assembly for 10 year old/ 48 GWd/MTU PWR SNF (Not Used)
Number of rows = nl

$$HL := READPRN(heatfile)$$

$nl := rows(HL)$ $\qquad nl = 101$

Set index range: $\qquad i := 1..nl$

2) Break matrix into respective vectors for processing (i.e., get vector of ANSYS time steps isolated for use in the curve fit tests) 10 Years is added to the time step vector T in order to perfom the curve fit on the BWR MOX data directly (i.e., T is time since MOX SNF discharge from the reactor as stated in reference 5.30) :

$$T := HL^{\langle 1 \rangle} + 10 \qquad BWR := HL^{\langle 2 \rangle} \qquad PWR := HL^{\langle 3 \rangle}$$

Echo the time steps to show that they are indeed the ANSYS time steps plus 10 years:

$i1 := 1..15 \quad i2 := 16..30 \quad i3 := 31..45 \quad i4 := 46..60$

$i5 := 61..75 \quad i6 := 76..90 \quad i7 := 91..nl$

T_{i1}	T_{i2}	T_{i3}	T_{i4}	T_{i5}	T_{i6}	T_{i7}
10	10.35	12	19.5	90	660	5010
10.01	10.4	12.5	20	95	710	5510
10.02	10.45	13	25	100	760	6010
10.03	10.5	13.5	30	105	810	6510
10.04	10.55	14	35	110	860	7010
10.05	10.6	14.5	40	160	910	7510
10.06	10.65	15	45	210	960	8010
10.07	10.7	15.5	50	260	1010	8510
10.08	10.75	16	55	310	1510	9010
10.09	10.8	16.5	60	360	2010	9510
10.1	10.85	17	65	410	2510	10010
10.15	10.9	17.5	70	460	3010	
10.2	10.95	18	75	510	3510	
10.25	11	18.5	80	560	4010	
10.3	11.5	19	85	610	4510	

3) Enter BWR Mox Data from Table 2.10, page 10 of reference 5.30:
The current analysis is interested in W/MOX Assembly after 10 years of cooling to 10,000 years after emplacement, therefore only the data for 10 to 10,000 years after discharge from the reactor will be curve fit.

Tb = the vector containing the base, or reference, time steps
BHG = the vector which contains the base, or reference, W/MOX Assembly
nbt = the number of data points from reference 5.30
bm = the index range counter

$nbt := 7$ $bm := 1..nbt$ $Tb_{bm} :=$ $BHG_{bm} :=$

Tb_{bm}	BHG_{bm}
10	255.390
30	181.767
100	99.4014
300	57.7384
1000	24.9049
3000	9.55479
10000	5.23460

4) Perform fuction fit to BWR MOX SNF data:

4.1) Define function equation form for curve fit:
The variables used are defined as follows:

F = Value of W/MOX assembly at time x after discharge
x = Time since discharge for desired W/MOX Assembly
aa = Curve fit coefficient 1
bb = Curve fit coefficient 2
cc = Curve fit coefficient 3
dd = Curve fit coefficient 4
ee = Curve fit coefficient 5
ff = Curve fit coefficient 6
gg = Curve fit coefficient 7
hh = Curve fit coefficient 8

$$F(x,aa,bb,cc,dd,ee,ff,gg,hh) := aa\cdot e^{\left(\frac{x}{bb}\right)} + cc\cdot e^{\left(\frac{x}{dd}\right)} + ee\cdot e^{\left(\frac{x}{ff}\right)} + gg\cdot x + hh$$

4.2) Define an initial guess for each equation coefficient in order to start:

$a := 179$ $\quad c := 90$ $\quad e := 40$ $\quad g := 0$

$b := -28$ $\quad d := -190$ $\quad f := -1500$ $\quad h := 5.2$

4.3) Define function to minimize:
Function is simply the sum of the squares of the difference between the data point and the curve fit function's estimate of the value of the data point; as per the least squares method (p. 612, Ref. 5.44).

$$SSE(a,b,c,d,e,f,g,h) := \sum_{n=1}^{nbt} \left(BHG_n - F\left(Tb_n,a,b,c,d,e,f,g,h\right)\right)^2$$

4.4) Set MATHCAD to perform least squares solution to obtain curve fit equation coefficients. Set value restrictions for selected coefficients, give MATHCAD the goal of obtaining a set of equation coefficients which sets the function SSE to as close to zero as possible, and assign the newly defined curve fit coefficients to variables for later use.

Given

$SSE(a,b,c,d,e,f,g,h) = 0$ $\quad b<0$ $\quad d<0$ $\quad f<0$ $\quad g<0$

$1 = 1$ $\quad 2 = 2$ $\quad 3 = 3$

$$\begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \end{bmatrix} := \mathrm{Minerr}(a,b,c,d,e,f,g,h)$$

4.5) List the new curve fit coefficient values as obtained from least squares method:

a = 179	c = 90	e = 40	g = 0
b = -28	d = -190	f = -1500	h = 5.2

5) Compare the curve fit function to the data points:

D = Curve fit function at each desired data point
res = Residual i.e., difference between curve fit function and data point
perc = Percent difference from data point value BHG
BHG = Data point value (Watts/MOX Assembly)
Tb = Time in years since discharge from the reactor

$$D_{bm} := F(Tb_{bm}, a, b, c, d, e, f, g, h)$$

$$res_{bm} := BHG_{bm} - D_{bm} \qquad perc_{bm} := 100 \cdot \frac{res_{bm}}{BHG_{bm}}$$

Tb_{bm}	D_{bm}	BHG_{bm}	res_{bm}	$perc_{bm}$
10	255.5613	255.39	-0.1713	-0.0671
30	182.5734	181.767	-0.8064	-0.4436
100	100.823	99.4014	-1.4216	-1.4301
300	56.5105	57.7384	1.2279	2.1267
1000	26.2028	24.9049	-1.2979	-5.2114
3000	10.6134	9.5548	-1.0586	-11.0796
10000	5.2509	5.2346	-0.0163	-0.3115

The curve fit values are slightly larger, with the exception of the 300 year data point, than the data points provided in reference 5.30. Thus, the curve fit is a slight conservative representation of the data. The data point at 300 years differs by only 2.1% and is therfore judged to be within an acceptable tolorance. Based on engineering judgement, the use of the curve fit function will not significantly affect the solutions performed by ANSYS.

6.0) Calculate the Watts/MOX Assembly for each ANSYS time step (with the added 10 years added to the value for cooling time), create the matrix A which has the ANSYS time step as the first column and the Watts/MOX Assembly as the second column, and write the newly created matrix out to a MATHCAD print file.

$$DD_i := F(T_i, a, b, c, d, e, f, g, h)$$

$$A^{<1>} := T \qquad A^{<2>} := DD$$

$$\mathrm{WRITEPRN(BWRMOX)} := A$$

10	255.6
10.01	255.5
10.02	255.5
10.03	255.4
10.04	255.4
10.05	255.3
10.06	255.3
10.07	255.2
10.08	255.2
10.09	255.1
10.1	255.1
10.15	254.8
10.2	254.6
10.25	254.3
10.3	254.1
10.35	253.8
10.4	253.6
10.45	253.4
10.5	253.1
10.55	252.9
10.6	252.6
10.65	252.4
10.7	252.1
10.75	251.9
10.8	251.7
10.85	251.4
10.9	251.2
10.95	250.9
11	250.7
11.5	248.3
12	246
12.5	243.7
13	241.4
13.5	239.2
14	237
14.5	234.8
15	232.7
15.5	230.6
16	228.6
16.5	226.6
17	224.6
17.5	222.6
18	220.7
18.5	218.8
19	216.9
19.5	215.1
20	213.3
25	196.7
30	182.6
35	170.4
40	160
45	150.9
50	143.1
55	136.2
60	130.3
65	125
70	120.3
75	116.2
80	112.5
85	109.1
90	106.1
95	103.3
100	100.8
105	98.49
110	96.34
160	80.52
210	69.87
260	61.76
310	55.34
360	50.2

410	46.03
460	42.63
510	39.82
560	37.46
610	35.46
660	33.75
710	32.26
760	30.95
810	29.78
860	28.72
910	27.76
960	26.87
1010	26.04
1510	19.85
2010	15.68
2510	12.7
3010	10.58
3510	9.053
4010	7.961
4510	7.178
5010	6.617
5510	6.216
6010	5.928
6510	5.721
7010	5.574
7510	5.468
8010	5.392
8510	5.337
9010	5.298
9510	5.271
1.001e+004	5.251

```
/COM, *******************************************************************
/COM, ** History of PWR MOX SNF Assembly Heat Generation Rates         **
/COM, ** Output Calculated by T. L. Lotz 4/1/95 for ORNL Report Data   **
/COM, **                                                               **
/COM, **    Executable File Name:    MATHCAD.EXE                       **
/COM, **    Output File Name:        bwrmox1.dat                       **
/COM, **    Execution Date:          04/01/95                          **
/COM, **    Start Age (years):       10.0                              **
/COM, **    Decay Period (years):    10000                             **
/COM, **    Enrichment (kg Pu):      5.334 kg Pu/Assembly              **
/COM, **    Burnup (MWd/MTHM):       37609                             **
/COM, **    Assembly Type:           BWR                               **
/COM, **    Pu Fract. (kg Pu/KG HM):0.0300                             **
/COM, **                                                               **
/COM, ** ASSY(#,1) is the SNF assembly heat in Watts.                  **
/COM, ** ASSY(#,0) is the time post emplacement in years.              **
/COM, *******************************************************************
ASSY( 1,1)=   255.60,   255.50,   255.50,   255.40,   255.40,   255.30,
ASSY( 7,1)=   255.30,   255.20,   255.20,   255.10,   255.10,   254.80,
ASSY(13,1)=   254.60,   254.30,   254.10,   253.80,   253.60,   253.40,
ASSY(19,1)=   253.10,   252.90,   252.60,   252.40,   252.10,   251.90,
ASSY(25,1)=   251.70,   251.40,   251.20,   250.90,   250.70,   248.30,
ASSY(31,1)=   246.00,   243.70,   241.40,   239.20,   237.00,   234.80,
ASSY(37,1)=   232.70,   230.60,   228.60,   226.60,   224.60,   222.60,
ASSY(43,1)=   220.70,   218.80,   216.90,   215.10,   213.30,   196.70,
ASSY(49,1)=   182.60,   170.40,   160.00,   150.90,   143.10,   136.20,
ASSY(55,1)=   130.30,   125.00,   120.30,   116.20,   112.50,   108.10,
ASSY(61,1)=   106.10,   103.30,   100.80,    98.49,    96.34,    80.52,
ASSY(67,1)=    69.87,    61.76,    55.34,    50.20,    46.03,    42.63,
ASSY(73,1)=    39.82,    37.46,    35.46,    33.75,    32.36,    30.95,
ASSY(79,1)=    29.78,    28.72,    27.76,    26.87,    26.04,    19.85,
ASSY(85,1)=    15.68,    12.70,    10.58,    9.053,    7.961,    7.178,
ASSY(91,1)=    6.617,    6.216,    5.928,    5.721,    5.574,    5.468,
ASSY(97,1)=    5.392,    5.337,    5.298,    5.271,    5.251,
ASSY( 1,0)= 0.000001,     0.01,     0.02,     0.03,     0.04,     0.05,
ASSY( 7,0)=     0.06,     0.07,     0.08,     0.09,     0.10,     0.15,
ASSY(13,0)=     0.20,     0.25,     0.30,     0.35,     0.40,     0.45,
ASSY(19,0)=     0.50,     0.55,     0.60,     0.65,     0.70,     0.75,
ASSY(25,0)=     0.80,     0.85,     0.90,     0.95,     1.00,     1.50,
ASSY(31,0)=     2.00,     2.50,     3.00,     3.50,     4.00,     4.50,
ASSY(37,0)=     5.00,     5.50,     6.00,     6.50,     7.00,     7.50,
ASSY(43,0)=     8.00,     8.50,     9.00,     9.50,    10.00,    15.00,
ASSY(49,0)=    20.00,    25.00,    30.00,    35.00,    40.00,    45.00,
ASSY(55,0)=    50.00,    55.00,    60.00,    65.00,    70.00,    75.00,
ASSY(61,0)=    80.00,    85.00,    90.00,    95.00,   100.00,   150.00,
ASSY(67,0)=   200.00,   250.00,   300.00,   350.00,   400.00,   450.00,
ASSY(73,0)=   500.00,   550.00,   600.00,   650.00,   700.00,   750.00,
ASSY(79,0)=   800.00,   850.00,   900.00,   950.00,  1000.00,  1500.00,
ASSY(85,0)=  2000.00,  2500.00,  3000.00,  3500.00,  4000.00,  4500.00,
ASSY(91,0)=  5000.00,  5500.00,  6000.00,  6500.00,  7000.00,  7500.00,
ASSY(97,0)=  8000.00,  8500.00,  9000.00,  9500.00, 10000.00,
ASSY( 0,1)=1.0
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/EOF
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/COM,     ****************************************************************
/COM,     **      ANSYS 5.0 MPC MATERIAL PROPERTY TABLES                **
/COM,     ****************************************************************
/COM,     **      Filename: props01.dat                                 **
/COM,     **      Compiled by R. Bahney III on 1-30-95                   **
/COM,     ****************************************************************
/COM,
/COM,     NUMBER  MATERIAL                DESCRIPTION
/COM,     1       Stainless Steel 316     Basket Structural Support
/COM,     2       Incaloy 825             Inner Container (resistant)
/COM,     3       A516 Mild Steel         Outer Container (allowance)
/COM,     4       UO2 Pellet              SNF Uranium Oxide Pellet
/COM,     5       Zircaloy 4              SNF Cladding
/COM,     6       Oxidation Layer         Stably Oxidized Zircaloy Surface
/COM,     7       Helium                  Canister Fill Gas
/COM,     8       Air                     Alternate Fill Gas
/COM,     9       Nitrogen                Alternate Fill Gas
/COM,     10      Argon                   Alternate Fill Gas
/COM,     11      Aluminum 6063           Thermal Conductor
/COM,     12      Copper                  Alternate Thermal Conductor
/COM,     13      Aluminum-Boron          Aluminum Boron Criticality Matl
/COM,
/COM,     ****************************************************************
/COM,     **      Density:        DENS    (kg/m^3)                      **
/COM,     **      Emissivity      EMIS                                  **
/COM,     **      Conductivity:   KXX     (W/m/K)                       **
/COM,     **      Specific Heat:  C       (J/kg/K)                      **
/COM,     ****************************************************************
/COM,
/COM,             Define densities for all materials except gases
MPTEMP
MPTEMP,   1, .00000E+00,
MPDATA,DENS, 1, 1, .80000E+04,
MPDATA,DENS, 2, 1, .81379E+04,
MPDATA,DENS, 3, 1, .81310E+04,
MPDATA,DENS, 4, 1, .10970E+05,
MPDATA,DENS, 5, 1, .65000E+04,
MPDATA,DENS, 6, 1, .65000E+04,
MPDATA,DENS,11, 1, .26900E+04,
MPDATA,DENS,12, 1, .89330E+04,
MPDATA,DENS,13, 1, .26930E+04,
/COM,
/COM,             Define emissivities for all materials except gases
MPDATA,EMIS, 1, 1, .60000E+00,
MPDATA,EMIS, 2, 1, .80000E+00,
MPDATA,EMIS, 3, 1, .80000E+00,
MPDATA,EMIS, 4, 1, .79000E+00,
MPDATA,EMIS, 5, 1, .80600E+00,
MPDATA,EMIS, 6, 1, .80600E+00,
MPDATA,EMIS,11, 1, .07000E+00,
MPDATA,EMIS,12, 1, .50000E+00,
MPDATA,EMIS,13, 1, .07000E+00,
/COM,
/COM,             Define specific heat for matl. 4, 5, 6, 7, 11, 14, 15
MPDATA,   C, 4, 1, .24700E+03,
MPDATA,   C, 5, 1, .33000E+03,
MPDATA,   C, 6, 1, .33000E+03,
MPDATA,   C, 7, 1, .51930E+04,
MPDATA,   C,11, 1, .90000E+03,
/COM,
/COM,             Define K and C for materials 1, 3
MPTEMP
MPTEMP,   1,  21.11,  37.78,  65.56,  93.33, 121.11, 148.89,
MPTEMP,   7, 176.67, 204.44, 232.22, 260.00, 287.78, 315.56,
MPTEMP,  13, 343.33, 371.11, 398.89, 426.67, 454.44, 482.22,
MPTEMP,  19, 510.00, 537.78, 565.56, 593.33, 621.11, 648.89,
MPTEMP,  25, 676.67, 704.44, 732.22, 760.00, 787.78, 815.56,
MPDATA, KXX, 1, 1,  13.33,  13.67,  14.19,  14.54,  15.06,  15.58,
MPDATA, KXX, 1, 7,  15.92,  16.44,  16.96,  17.31,  17.83,  18.17,
MPDATA, KXX, 1,13,  18.52,  19.04,  19.38,  19.90,  20.25,  20.77,
```

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MPDATA, KXX, 1,19,  21.11,  21.46,  21.98,  22.33,  22.67,  23.02,
MPDATA, KXX, 1,25,  23.54,  23.88,  24.23,  24.58,  24.92,  25.27,
MPDATA,   C, 1, 1, 481.68, 486.92, 498.09, 499.38, 509.98, 520.29,
MPDATA,   C, 1, 7, 521.07, 527.38, 536.92, 537.34, 543.02, 543.31,
MPDATA,   C, 1,13, 546.91, 552.14, 552.26, 557.22, 557.25, 565.11,
MPDATA,   C, 1,19, 565.01, 564.91, 572.35, 572.14, 574.92, 574.68,
MPDATA,   C, 1,25, 581.64, 581.30, 583.86, 586.36, 585.96, 588.39,
MPDATA, KXX, 3, 1,  40.84,  41.36,  41.88,  42.23,  42.23,  42.23,
MPDATA, KXX, 3, 7,  42.06,  41.88,  41.36,  41.02,  40.50,  39.98,
MPDATA, KXX, 3,13,  39.29,  38.77,  38.08,  37.56,  36.69,  36.17,
MPDATA, KXX, 3,19,  35.48,  34.61,  33.92,  33.23,  32.36,  31.50,
MPDATA, KXX, 3,25,  30.29,  28.90,  27.35,  26.48,  26.13,  26.13,
MPDATA,   C, 3, 1, 428.72, 444.95, 460.94, 476.87, 486.08, 495.66,
MPDATA,   C, 3, 7, 506.09, 517.07, 525.64, 536.99, 543.63, 550.62,
MPDATA,   C, 3,13, 562.21, 577.32, 589.10, 600.57, 611.35, 629.09,
MPDATA,   C, 3,19, 645.32, 665.12, 682.07, 694.52, 724.07, 761.95,
MPDATA,   C, 3,25, 806.31, 888.60,1095.04,1638.78, 808.68, 736.90,
/COM,
/COM,          Define K for material 2
MPTEMP
MPTEMP,   1,   93.33,  121.11,  148.89,  176.67,  204.44,  232.22,
MPTEMP,   7,  260.00,  287.78,  315.56,  343.33,  371.11,  398.89,
MPTEMP,  13,  426.67,  454.44,  482.22,  510.00,  537.78,  565.56,
MPTEMP,  19,  593.33,  621.11,  648.89,  676.67,  704.44,  732.22,
MPTEMP,  25,  760.00,  787.78,  815.56,
MPDATA, KXX, 2, 1,  12.29,  12.63,  13.15,  13.67,  14.02,  14.54,
MPDATA, KXX, 2, 7,  14.88,  15.40,  15.75,  16.10,  16.61,  16.96,
MPDATA, KXX, 2,13,  17.31,  17.65,  18.00,  18.52,  18.86,  19.21,
MPDATA, KXX, 2,19,  19.73,  20.08,  20.42,  20.94,  21.46,  21.98,
MPDATA, KXX, 2,25,  22.33,  23.02,  23.54,
/COM,
/COM,          Define C for material 2
MPTEMP
MPTEMP,   1,   93.33,  121.11,  148.89,  176.67,  204.44,  232.22,
MPTEMP,   7,  260.00,  287.78,  315.56,  343.33,  371.11,  398.89,
MPTEMP,  13,  426.67,  454.44,  482.22,  510.00,  537.78,
MPDATA,   C, 2, 1, 460.69, 477.42, 501.02, 504.65, 498.12, 520.45,
MPDATA,   C, 2, 7, 536.88, 559.85, 576.83, 576.21, 581.68, 598.20,
MPDATA,   C, 2,13, 619.58, 636.76, 654.20, 678.25, 696.29,
/COM,
/COM,          Define K for materials 4, 5, 6
MPTEMP
MPTEMP,   1,     0.0,    10.0,    20.0,    30.0,    40.0,    50.0,
MPTEMP,   7,    60.0,    70.0,    80.0,    90.0,   100.0,   110.0,
MPTEMP,  13,   120.0,   130.0,   140.0,   150.0,   160.0,   170.0,
MPTEMP,  19,   180.0,   190.0,   200.0,   210.0,   220.0,   230.0,
MPTEMP,  25,   240.0,   250.0,   260.0,   270.0,   280.0,   290.0,
MPTEMP,  31,   300.0,   310.0,   320.0,   330.0,   340.0,   350.0,
MPTEMP,  37,   360.0,   370.0,   380.0,   390.0,   400.0,   410.0,
MPTEMP,  43,   420.0,   430.0,   440.0,   450.0,   460.0,   470.0,
MPTEMP,  48,   480.0,   490.0,   500.0,
MPDATA, KXX, 4, 1,   8.72,   8.54,   8.36,   8.19,   8.03,   7.87,
MPDATA, KXX, 4, 7,   7.72,   7.58,   7.44,   7.31,   7.18,   7.05,
MPDATA, KXX, 4,13,   6.93,   6.82,   6.70,   6.60,   6.49,   6.39,
MPDATA, KXX, 4,19,   6.29,   6.19,   6.10,   6.01,   5.92,   5.84,
MPDATA, KXX, 4,25,   5.76,   5.68,   5.60,   5.52,   5.45,   5.38,
MPDATA, KXX, 4,31,   5.31,   5.24,   5.18,   5.11,   5.05,   4.99,
MPDATA, KXX, 4,37,   4.93,   4.87,   4.81,   4.76,   4.70,   4.65,
MPDATA, KXX, 4,43,   4.60,   4.55,   4.50,   4.45,   4.40,   4.35,
MPDATA, KXX, 4,48,   4.31,   4.27,   4.22,
MPDATA, KXX, 5, 1,  12.29,  12.44,  12.58,  12.72,  12.87,  13.01,
MPDATA, KXX, 5, 7,  13.15,  13.28,  13.42,  13.55,  13.69,  13.82,
MPDATA, KXX, 5,13,  13.95,  14.08,  14.21,  14.34,  14.46,  14.59,
MPDATA, KXX, 5,19,  14.72,  14.84,  14.96,  15.09,  15.21,  15.33,
MPDATA, KXX, 5,25,  15.45,  15.57,  15.69,  15.81,  15.93,  16.05,
MPDATA, KXX, 5,31,  16.17,  16.29,  16.40,  16.52,  16.64,  16.76,
MPDATA, KXX, 5,37,  16.88,  16.99,  17.11,  17.23,  17.35,  17.46,
MPDATA, KXX, 5,43,  17.58,  17.70,  17.82,  17.94,  18.06,  18.18,
MPDATA, KXX, 5,48,  18.30,  18.42,  18.54,
MPDATA, KXX, 6, 1,   1.94,   1.94,   1.94,   1.94,   1.94,   1.94,
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MPDATA, KXX, 6, 7,   1.94,   1.95,   1.95,   1.95,   1.95,   1.95,
MPDATA, KXX, 6,13,   1.95,   1.95,   1.96,   1.96,   1.96,   1.96,
MPDATA, KXX, 6,19,   1.96,   1.97,   1.97,   1.97,   1.97,   1.98,
MPDATA, KXX, 6,25,   1.98,   1.98,   1.98,   1.99,   1.99,   1.99,
MPDATA, KXX, 6,31,   2.00,   2.00,   2.00,   2.01,   2.01,   2.01,
MPDATA, KXX, 6,37,   2.02,   2.02,   2.02,   2.03,   2.03,   2.03,
MPDATA, KXX, 6,43,   2.04,   2.04,   2.04,   2.05,   2.05,   2.06,
MPDATA, KXX, 6,48,   2.06,   2.06,   2.07,
/COM,
/COM,          Define p, K, C for materials 7, 8, 9, -10
MPTEMP
MPTEMP,   1,  -13.15,    6.85,   26.85,   76.85,  126.85,  176.85,
MPTEMP,   7,  226.85,  276.85,  326.85,  376.85,  426.85,  476.85,
MPTEMP,  13,  526.85,  626.85,  726.85,
MPDATA,DENS, 7, 1, 0.1875, 0.1750, 0.1625, 0.1422, 0.1219, 0.1097,
MPDATA,DENS, 7, 7, 0.0975, 0.0906, 0.0836, 0.0767, 0.0697, 0.0662,
MPDATA,DENS, 7,13, 0.0627, 0.0558, 0.0488,
MPDATA, KXX, 7, 1, 0.1370, 0.1450, 0.1520, 0.1700, 0.1870, 0.2040,
MPDATA, KXX, 7, 7, 0.2200, 0.2360, 0.2520, 0.2640, 0.2780, 0.2910,
MPDATA, KXX, 7,13, 0.3040, 0.3300, 0.3540,
MPDATA,DENS, 8, 1, 1.3480, 1.2547, 1.1614, 0.9950, 0.8711, 0.7740,
MPDATA,DENS, 8, 7, 0.6964, 0.6329, 0.5804, 0.5356, 0.4975, 0.4643,
MPDATA,DENS, 8,13, 0.4354, 0.3868, 0.3482,
MPDATA, KXX, 8, 1, 0.0230, 0.0250, 0.0260, 0.0300, 0.0340, 0.0370,
MPDATA, KXX, 8, 7, 0.0410, 0.0440, 0.0470, 0.0500, 0.0520, 0.0550,
MPDATA, KXX, 8,13, 0.0570, 0.0620, 0.0670,
MPDATA,   C, 8, 1, 1006.2, 1006.6, 1007.0, 1009.0, 1014.0, 1021.0,
MPDATA,   C, 8, 7, 1030.0, 1040.0, 1051.0, 1063.0, 1075.0, 1087.0,
MPDATA,   C, 8,13, 1099.0, 1121.0, 1141.0,
MPDATA,DENS, 9, 1, 1.3037, 1.2135, 1.1233, 0.9625, 0.8425, 0.7485,
MPDATA,DENS, 9, 7, 0.6739, 0.6124, 0.5615, 0.5214, 0.4812, 0.4512,
MPDATA,DENS, 9,13, 0.4211, 0.3743, 0.3368,
MPDATA, KXX, 9, 1, 0.0230, 0.0240, 0.0260, 0.0290, 0.0330, 0.0360,
MPDATA, KXX, 9, 7, 0.0390, 0.0420, 0.0450, 0.0470, 0.0500, 0.0520,
MPDATA, KXX, 9,13, 0.0550, 0.0600, 0.0650,
MPDATA,   C, 9, 1, 1041.8, 1041.4, 1041.0, 1042.0, 1045.0, 1050.0,
MPDATA,   C, 9, 7, 1056.0, 1065.0, 1075.0, 1086.5, 1098.0, 1159.0,
MPDATA,   C, 9,13, 1220.0, 1146.0, 1167.0,
MPDATA, KXX,10, 1, 0.0170, 0.0170, 0.0180, 0.0210, 0.0230, 0.0250,
MPDATA, KXX,10, 7, 0.0270, 0.0280, 0.0300, 0.0320, 0.0340, 0.0360,
MPDATA, KXX,10,13, 0.0370, 0.0410, 0.0440,
/COM,
/COM,          Define K and C for material 12
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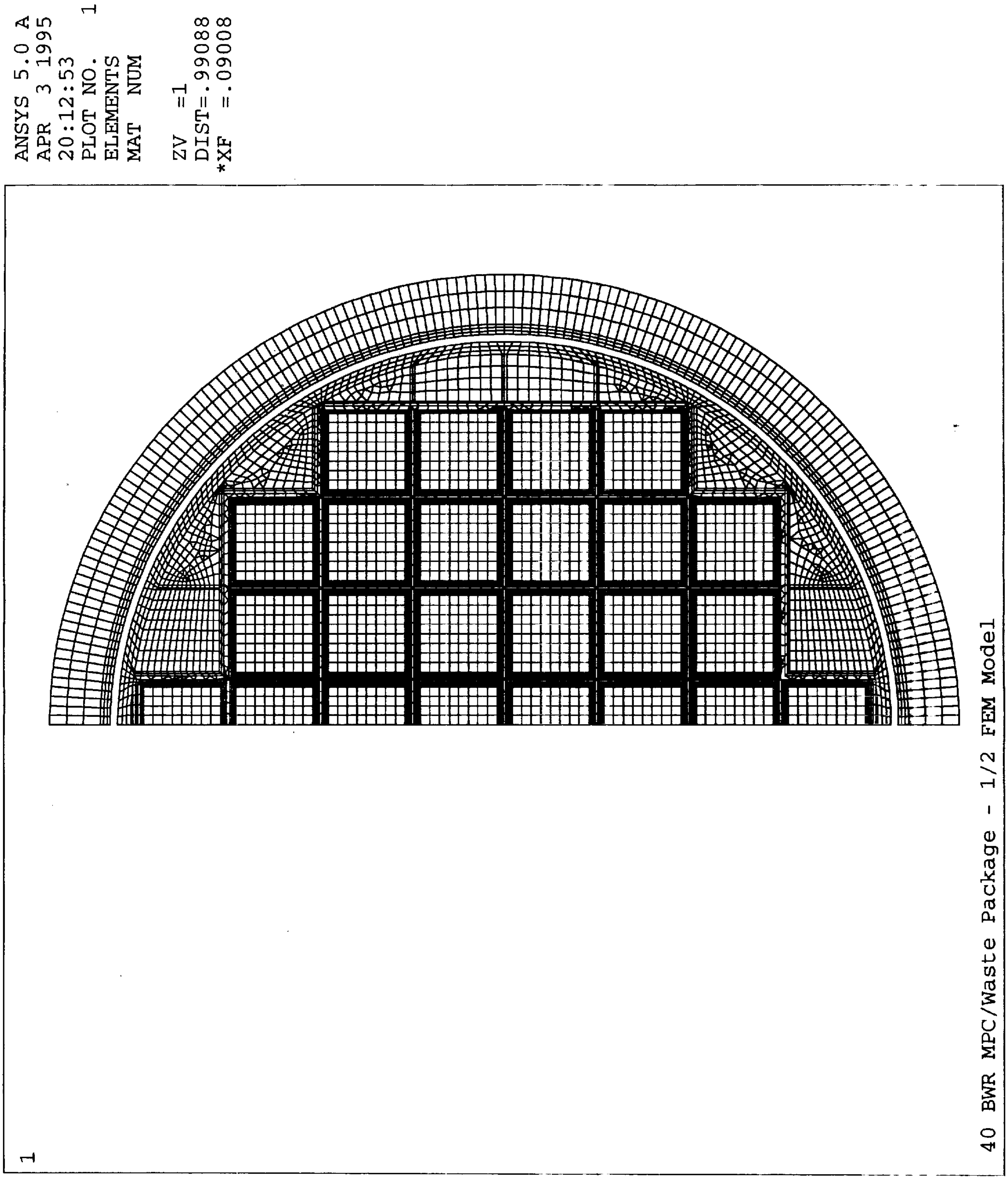
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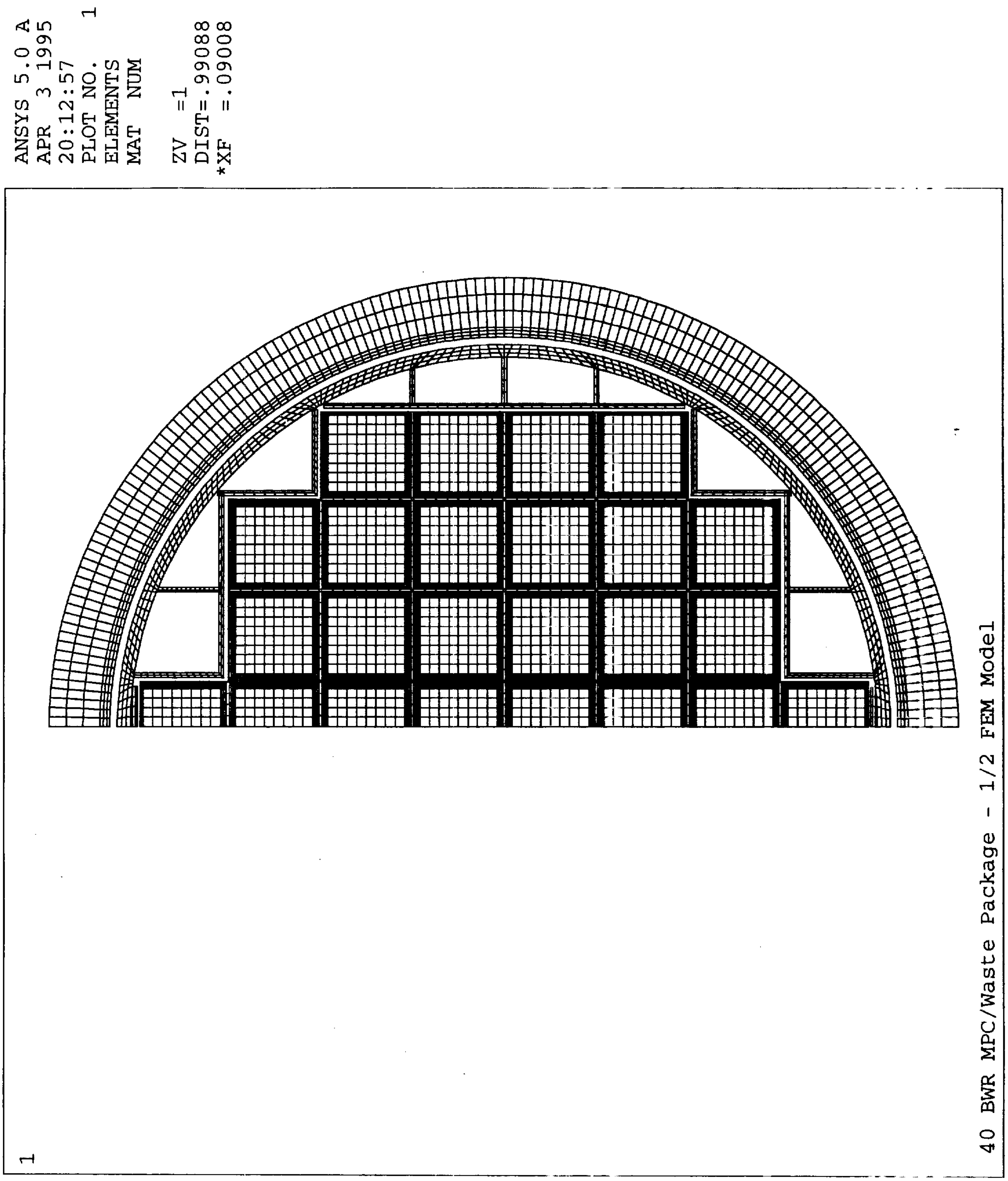
40 BWR MPC/Waste Package - 1/2 FEM Model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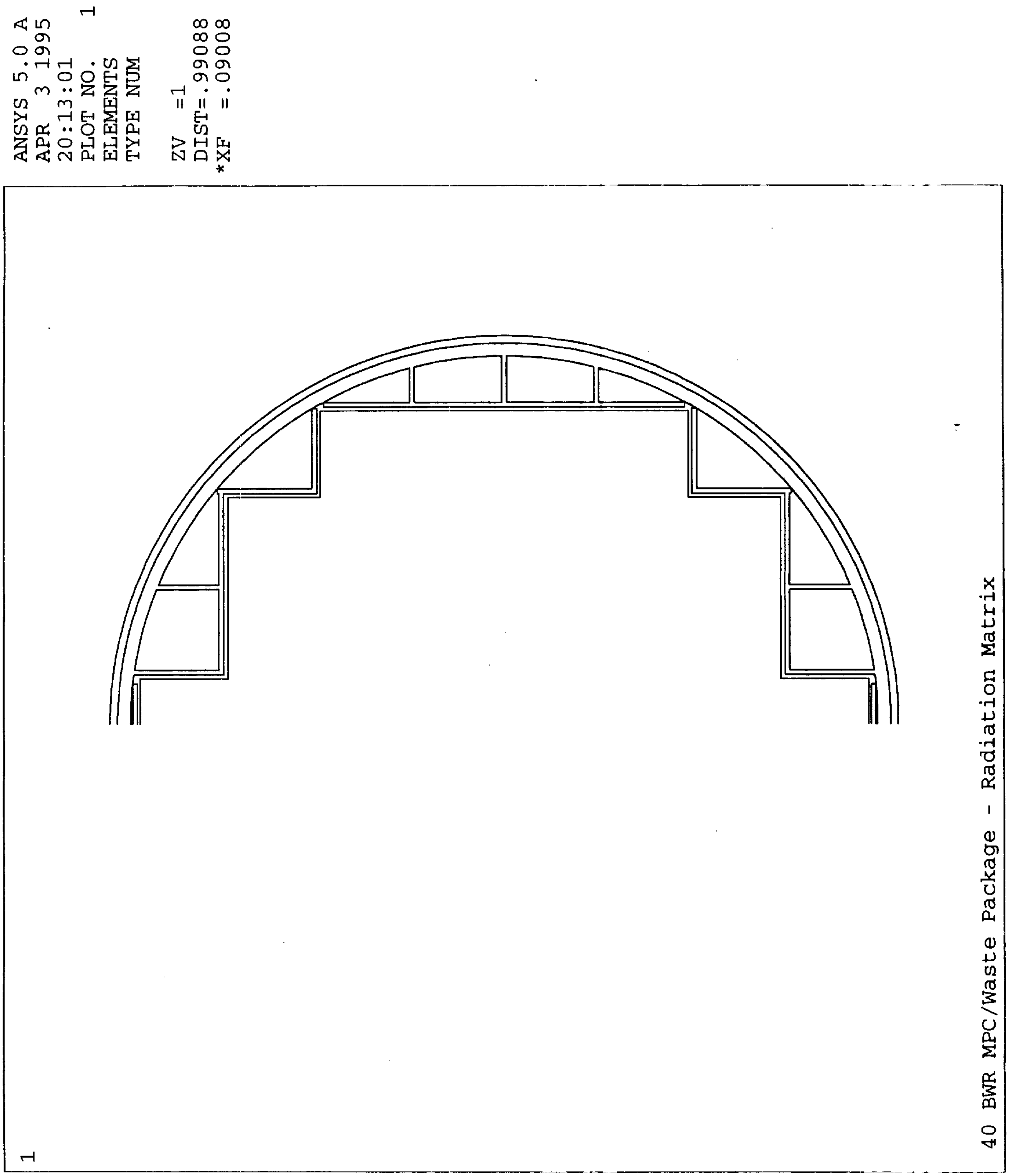
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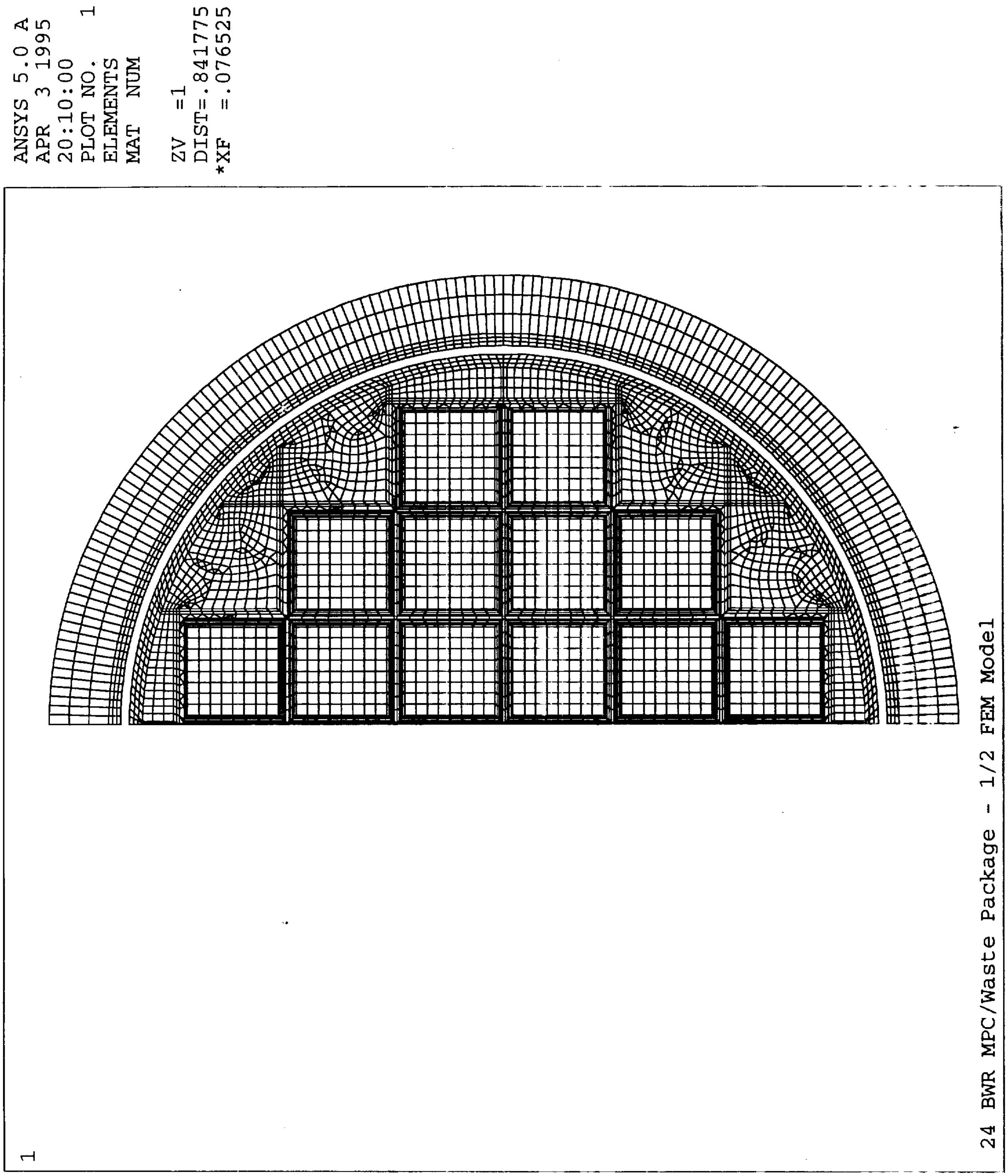
40 BWR MPC/Waste Package - Radiation Matrix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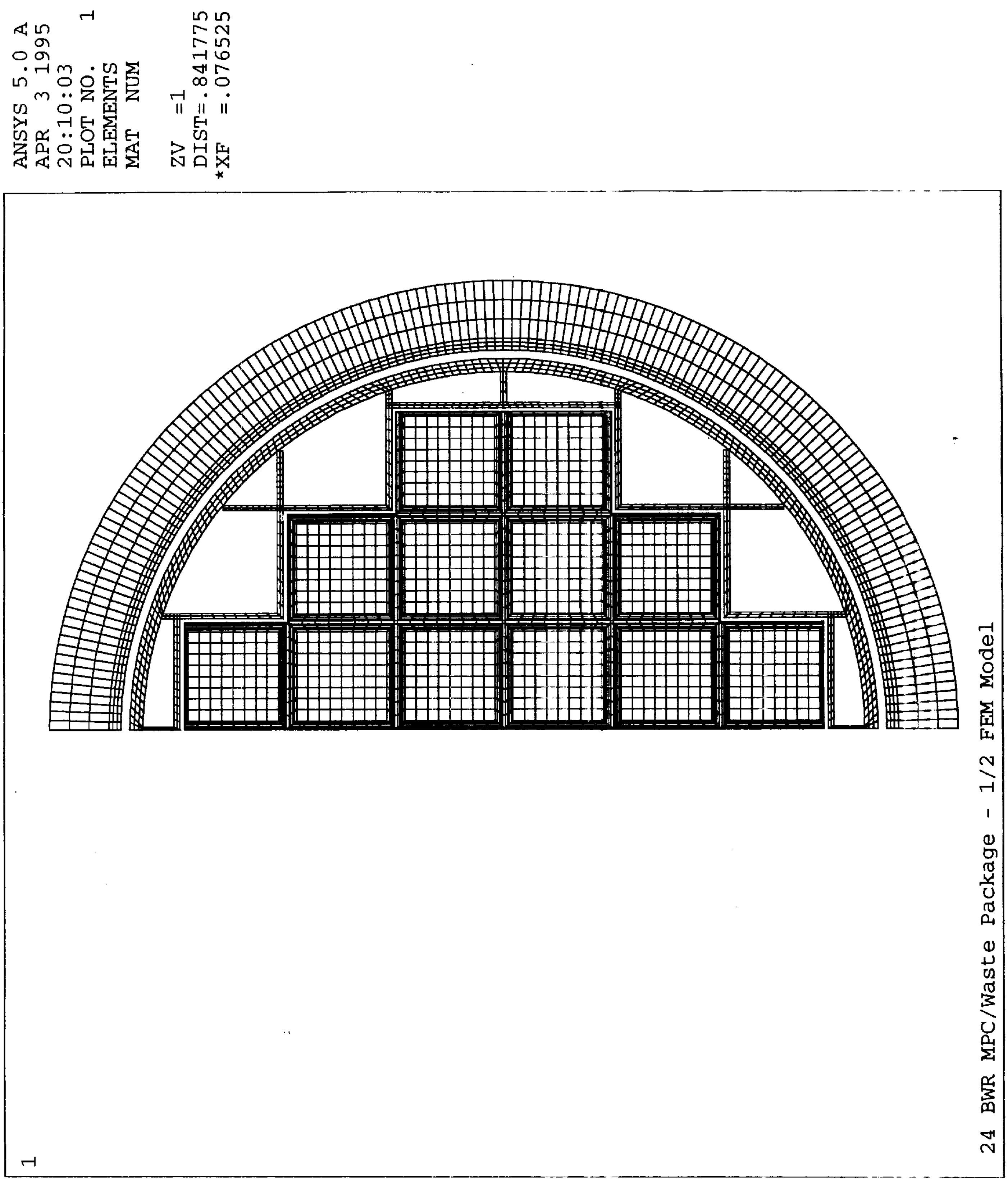
24 BWR MPC/Waste Package - 1/2 FEM Model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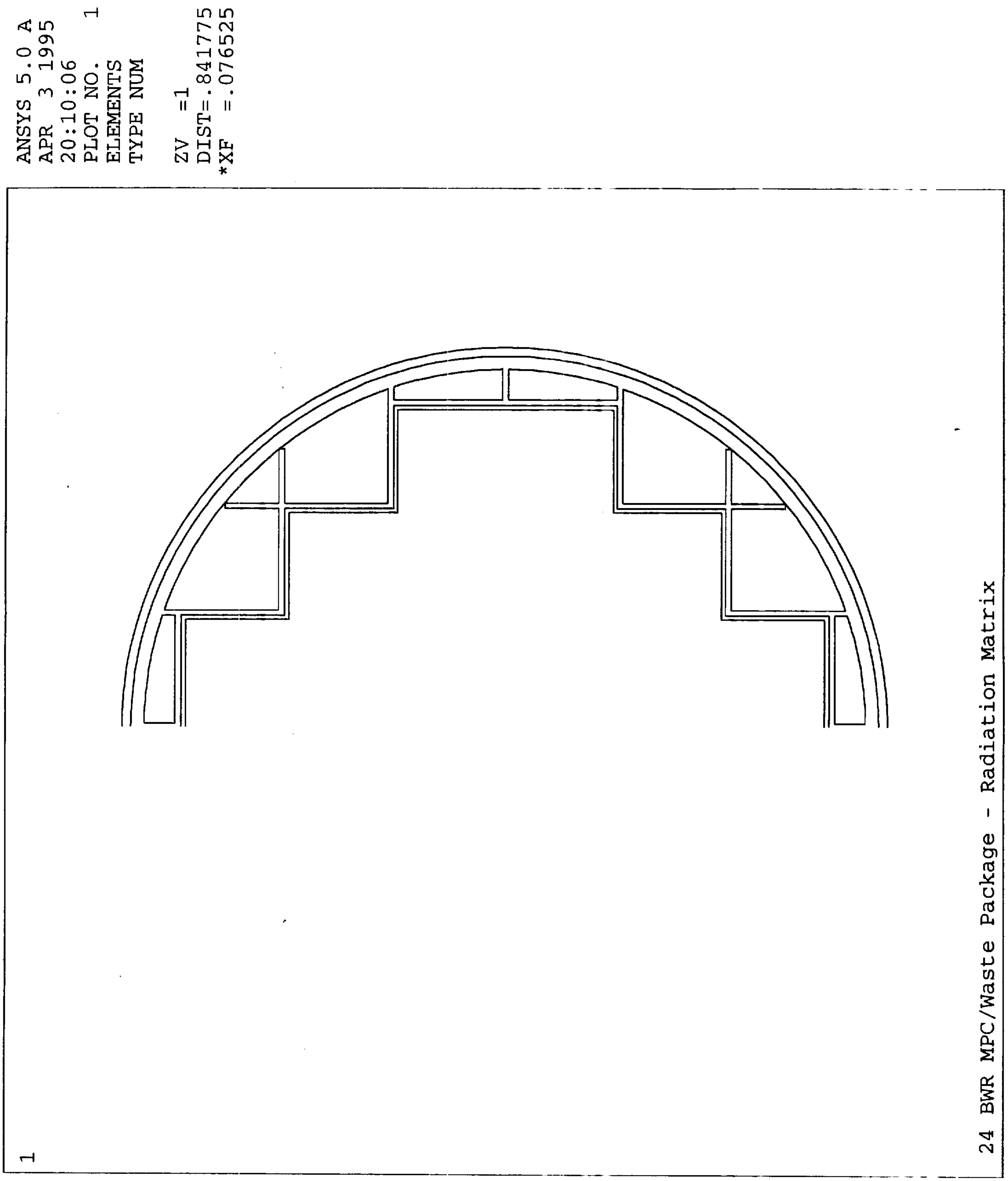
24 BWR MPC/Waste Package - 1/2 FEM Model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24 BWR MPC/Waste Package - Radiation Matrix

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