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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
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9. Remarks

The electronic media (e.g. CD) must be attached to this calculation.

Revision History

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1. PURPOSE

The purpose of this calculation is to determine the thermal response of the 44-boiling water reactor (BWR) waste package (WP) to the hypothetical regulatory fire accident. The objective is to calculate the temperature response of the waste package materials to the hypothetical short-term fire defined in 10 CFR 71, Section 73(c)(4), Reference 1. The scope of the calculation includes evaluation of the accident with the waste package above ground, at the Yucca Mountain surface facility. The scope of this calculation is limited to the two-dimensional waste package temperature calculations to support the waste package design.

The information provided by the sketches attached to this calculation is that for the potential design of the type of WP considered in this calculation.

In addition to the nominal design configuration thermal load case, the effects of varying the BWR thermal load are determined.

The associated activity is the development of engineering evaluations to support the Licensing Application (LA) design activities. This document is developed using work planning document *Technical Work Plan for: Waste Package Design Description for LA* (Reference 26).

This calculation is performed in accordance with AP-3.12Q, Rev. 0, ICN 3, BSCN 1, *Calculations* (Reference 28).

2. METHOD

The solution method employs finite element analysis (FEA). A two-dimensional (2-D) finite element representation of a 44-BWR WP was developed and solved using the thermal analysis capabilities of ANSYS Version 5.4 (described in Section 4.1).

Calculation cases have been defined to determine effects on the thermal response of the waste package resulting from variations in parameters of importance. Variations include the presence/absence of gaps in the WP (between the inner and outer shell, between the plates and tubes, and between the plates and guides), and the volumetric heat generation rates. The FEA analysis investigated the thermal response of BWR spent nuclear fuel (SNF) using representative effective conductivities with and without a channel. These calculations are performed based on exposure of the waste package to the hypothetical fire conditions for a period of 30 minutes, followed by cooldown.

The control of electronic management of information was performed in accordance with the planned method specified in the technical work plan (Ref. 26).

3. ASSUMPTIONS

The following assumptions were used in developing the WP representation and obtaining the thermal solutions.

3.1 SYSTEM DESCRIPTION DOCUMENT (SDD) ASSUMPTIONS

3.1.1 It is assumed in this calculation that the WP is exposed to the fire conditions for transport packages as defined in 10 CFR 71, Section 73(c)(4). The rationale for this assumption is that it is based on Section 1.2.2.1.11 of Reference 8, which requires that the waste package/disposal container be designed to withstand the same fire criteria as applied to transport packages. This assumption is used in Section 5.1. This assumption does not require verification.

3.2 GENERAL ASSUMPTIONS

3.2.1 It is assumed that a 2-D finite element representation of the WP cross section midway along the longitudinal axis will conservatively represent the WP. Inherent to this assumption is that the axial heat transfer does not significantly affect the solution (i.e., the flow of the heat in the radial direction is assumed to dominate the solution since the radial direction represents the path of least thermal resistance). The rationale for this assumption is that the metal thermal conductivity and heat generation distributions are such that axial heat transfer is very small or negligible at the midsection. This assumption is used in Section 5.5. This assumption does not require verification.

3.2.2 It is assumed that the mode of heat transfer between the WP outer surface and the surroundings, or environment, is by radiation only, except for the fire condition during which free convection heat transfer heating of the WP shell is included. The rationale for this assumption is that it maximizes the calculated peak temperature in the WP, which is conservative. This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.3 The calculations are performed assuming a 180-degree segment of the WP cross-section. The rationale for this assumption is the following. The geometry of the cross section is symmetrical about the cutting planes of the representation. Therefore, the heat generation paths will also be symmetrical, resulting in no heat conduction across the cutting planes. The radiative heat transfer across these cutting planes is assumed to be negligible relative to the radiative heat transfer in the rest of the cross section. This assumption is used in Sections 5.4.2 and 5.5. This assumption does not require verification.

3.2.4 The WP inner shell and basket components (corner guides, fuel basket F-plates and G-plates (thermal shunts), and the fuel basket A-plates and B-plates) of the 44-BWR WP (Attachment I), that separate the BWR SNF, are assumed to be integrally connected. The rationale for this assumption is that the connections between the inner shell and the basket guides are achieved by welding (p. 18, Ref. 2), and most of the divider plates will be in direct contact with the WP placed horizontally. This assumption is used in Section 5.5. This assumption does not require verification.

3.2.5 For the analysis configuration where gaps are assumed to be present in the 44-BWR WP, the WP inner shell is assumed to be centered in the WP outer shell with a uniform radial gap of 4 mm. The rationale for this assumption comes from p. 16, Ref. 2. The loose fit cylinder-within-a-cylinder construction requires that the surfaces of the inner reinforcement cylinder and outer barrier be machined. Loose fit is defined as a 0 - 4 mm gap between the cylinders (p. 16, Ref. 2). This assumption is used in Section 5.5. This assumption does not require verification.

3.2.6 For the analysis configuration where gaps are assumed to be present in the 44-BWR WP, gaps of 2 mm are assumed to exist between plates and tubes, tubes and guides, and plates and guides in the basket. The rationale for this assumption is that this reflects reasonable manufacturing and assembly tolerances of the basket components. This assumption is used in Section 5.5. This assumption does not require verification.

3.2.7 For the analysis configuration where no gaps are assumed to be present in the 44-BWR WP, it is assumed that perfect contact exists between the WP inner and outer shells, and between the basket components. The rationale for this assumption is that with no gap, the thermal resistance is minimized, thereby maximizing the heat flow to the BWR SNF with heating of the shell by the fire. No credit is taken for contact thermal resistance at the component interfaces. This assumption is used in Section 5.5. This assumption does not require verification.

3.2.8 It is assumed that a small change in basket width has a negligible impact on the effective thermal conductivities. Thus, the effective thermal conductivities established in pp. 147-148, Ref. 3 for a 0.1524-m basket width (p. 15, Ref. 3) remain applicable to this calculation, which uses a 0.1553-m basket width (Attachment I). The rationale for using the Reference 3 effective thermal conductivities is that the effective thermal conductivities are primarily a function of wall temperature, heat generation rate, and fill gas. This assumption is used in Section 5.3.8.

3.2.9 Natural convection heat transfer within the WP is neglected. The rationale for this conservative assumption is that the dimensions of the cavities within the waste package are such that natural convection is not significant compared to the other modes of heat transfer (conduction and radiation). This assumption is used in Section 5.5. This assumption does not require verification.

3.2.10 For the analysis configuration where gaps are assumed to be present in the 44-BWR WP, air is assumed to fill the gap between the inner and outer shells of the WP. The rationale for this assumption is that there are no special requirements of fill gas between the inner and outer shells during the WP closure welding process (Ref. 4). This assumption is used in Section

5.3.7. This assumption does not require verification.

3.2.11 The 44-BWR WP, inside the inner shell, is assumed to be evacuated and filled with helium gas. The rationale for this assumption is that helium as a fill gas for WP designs is a design basis recommendation (p. 9, Ref. 5). This assumption is used in Section 5.3.6. This assumption does not require verification.

3.2.12 The properties of helium at atmospheric pressure are assumed to be representative of the conditions that this gas will experience within the WP. The rationale for this assumption is the fact that approximately a one-atmosphere fill pressure is the design basis for uncanistered spent nuclear fuel (UCF) waste packages (p. 33, Ref. 8). Even though the internal pressure of the WP will increase due to the temperature rise, the thermal conductivity of most gases is pressure independent (p. 255, Ref. 7). Thus using the thermal conductivity at one atmosphere is reasonable. This assumption is used in Section 5.3.6. This assumption does not require verification.

3.2.13 This calculation utilizes the BWR SNF effective thermal conductivities (with and without channel) from pp. 147-148, Ref. 3. The rationale for this assumption is that these are the recommended bounding BWR effective thermal conductivity values to be used with finite element methods which explicitly model the SNF assembly as a homogeneous heat source. This assumption is used throughout the calculation.

3.2.14 The spent nuclear fuel within the 44-BWR fuel basket tubes is assumed to be a homogeneous uniform-property heat-generating volume. The rationale for this assumption is that this is consistent with the effective thermal conductivities calculated in Ref. 3, that will be used in this calculation. This assumption is used in Section 5.2.2 and 5.5.

3.2.15 The 44-BWR WP is assumed to be loaded with 44 identical heat-output fuel assemblies. The rationale for this assumption is that, since the waste stream is not finalized, and the loading of assemblies is still being determined, assuming a uniform heat-output loading will provide a reasonable average thermal response of the WP to the fire accident. This assumption is used in Section 5.4.1. This assumption does not require verification.

3.2.16 The maximum heat rate within a 44-BWR WP is 11.8 kW. The rationale for this value is that it is the design basis maximum thermal output for UCF WPs (p. 17, Ref. 8). This assumption is used in Sections 5.1 and 5.4.1. This assumption does not require verification.

3.2.17 An axial power peaking factor (APF) of 1.4 is assumed for the BWR SNF. The rationale for this assumption is that the value of 1.4 conservatively bounds the APF values given for the BWR SNF on page 47, Ref. 6, thereby providing the rationale for this assumption. This assumption is used in Sections 5.1 and 5.4.1.

3.2.18 The heat load of the 44-BWR WP is assumed constant with time throughout the fire accident transient. The rationale for this assumption is that the heat load will not decay significantly during the relatively short period of time for the fire accident. (A determination of the sensitivity of the calculated peak temperatures to the WP heat load is included in the evaluation.) This assumption is used in Section 5.1. This assumption does not require verification.

3.2.19 The fire accident is assumed to occur during preparations for WP emplacement. The rationale for this assumption is that this gives the maximum heat load for the WP. This assumption is used in Section 5.1. This assumption does not require verification.

3.2.20 A temperature of 38°C is assumed for the WP surroundings during pre- and post-fire conditions. The rationale for this assumption is that it is consistent with the requirements for fire-exposure testing of transport casks exposed to the sun as given in Section 73(b) of 10 CFR 71, Ref. 1, which specifies a maximum of 38°C. This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.21 A uniform temperature of 800°C for the WP surroundings, i.e., flame, is assumed for the fire condition. The rationale for this assumption is that it is consistent with the definition of the short-term fire for transport packages per Section 73(c)(4) of 10 CFR 71, Ref. 1. This assumption is used in Section 5.1 and 5.4.2. This assumption does not require verification.

3.2.22 The fire exposure duration is 30 minutes. The rationale for this value is the requirement from Section 73(c)(4) of 10 CFR 71, Ref. 1. This assumption is used in Section 5.1. This assumption does not require verification.

3.2.23 For purposes of calculating the effective emissivity for the radiative energy exchange between the WP outer surface and the surroundings, the outer surface is assumed characterized as an ideal gray surface. The rationale for this assumption is that it simplifies the calculation by considering the surface absorptivity equal to the surface emissivity, and maximizes the calculated rate of heating of the WP during the fire for the case where a value of 1.0 is used for emissivity, which is conservative. This assumption is used in Section 5.4.2. (Note that the assumption does not apply to the solar energy incident on the WP outer surface.) This assumption does not require verification.

3.2.24 A value of 1.0 for the emissivity of the WP surroundings for the pre- and post-fire conditions is assumed. The rationale for this assumption is that this conservatively maximizes the calculated radiative energy incident on the WP outer surface, and maximizes the WP temperatures calculated for both the pre-fire condition and the post-fire cooldown. This assumption is used in Section 5.1. This assumption does not require verification.

3.2.25 A value of 1.0 for the emissivity of the flame for the fire condition is assumed. The rationale for this assumption is that this conservatively maximizes heating of the WP and exceeds the minimum value of 0.9 specified in Section 73(c)(4) of 10 CFR 71, Ref. 1. This assumption is used in Section 5.1. This assumption does not require verification.

3.2.26 A value of 0.87 for the emissivity of the WP outer surface (Alloy 22) is assumed for both the pre- and post-fire conditions. The rationale for this assumption is that it is based on the data given on p. 10-297, Ref. 9 for nickel-chrome alloy. This assumption is used in Section 5.1 and 5.3.3. This assumption does not require verification.

3.2.27 A value of 1.0 for emissivity of the WP outer surface for the fire condition is assumed. The rationale for this assumption is that it conservatively maximizes heating of the WP and exceeds the minimum value of 0.8 specified in Section 73(c)(4) of 10 CFR 71, Ref. 1. This assumption is used in Section 5.1. This assumption does not require verification.

3.2.28 A constant rate of solar energy incident on the outer surface of the WP equal to 400 cal/cm^2 per 12-hour period is assumed. The rationale for this assumption is that it is consistent with the definition of the short-term fire for transport packages per Section 71(c)(1) of 10 CFR 71, Ref. 1, for the energy incident on the curved surface of a transport cask. The rate of solar energy incidence is maintained constant with time during all phases of the accident, i.e., from pre-fire through post-fire cooling. This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.29 The solar absorptivity of the WP outer surface is assumed to be 1.0. The rationale for this assumption is that it conservatively maximizes the calculated solar heat flux into the WP surface and maximizes the WP temperatures. The solar absorptivity is maintained constant during all phases of the accident. This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.30 The gas that flows around the waste package during the fire accident (pre-fire conditions through post-fire conditions) is assumed to be air. The rationale for this assumption is that the heat transfer properties of the gases around the waste package do not change significantly during the fire (Section 8.3, Ref. 7). The main component (79%) of air, gaseous nitrogen, reacts negligibly during the fire, and the other component, oxygen, reacts primarily to carbon dioxide. This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.31 Free-convection heat transfer at the WP outer surface is taken into account only during heating of the WP by the fire, and is assumed to vary based on the correlation for air at normal temperatures and atmospheric pressure per the equation 1.312 ($\Delta T^{1/3}$) $W/m^2 \cdot K$, ΔT in degrees-K (equivalent to the equation 0.19 $\Delta T^{1/3}$ $Btu/hr \cdot ft^2 \cdot F$, ΔT in degrees-F, from p. 4-88 of Reference 10). The rationale for this assumption is that the equation gives conservatively high values of the heat transfer coefficient for temperatures greater than normal room temperature, maximizing heat flow to the WP shell during the fire. Use of the equation is conservative at temperatures exceeding room temperatures because the free convection heat transfer coefficient decreases with increasing temperature of the gas due to the change in gas properties with temperature. (The free convection film coefficient increases with increasing Grashof number, which varies directly with the coefficient of thermal expansion and inversely with the square of the kinematic viscosity of the gas. Since the coefficient of thermal expansion varies inversely with the absolute temperature of the gas and the kinematic viscosity increases with temperature, the Grashof number therefore decreases with increasing temperature. Consequently, both the Grashof number and the heat transfer coefficient decrease with increasing temperature, so that use of the correlation is conservative in this case.) This assumption is used in Sections 5.1 and 5.4.2. This assumption does not require verification.

3.2.32 The emissivity of stainless steel 316 is assumed to be 0.62. The rationale for this assumption is consistency with the range of emissivity for this material (0.57 to 0.66) given on p. 4-68, Ref. 10. This assumption is used in Section 5.3.2. This assumption does not require verification.

3.2.33 The emissivity of A516 carbon steel is assumed to be 0.80. The rationale for this assumption is consistency with the range of emissivity for this material (0.78 to 0.82) given on p. 4-68, Ref. 10. This assumption is used in Section 5.3.1. This assumption does not require verification.

3.2.34 The emissivity of boron stainless steel (Neutronit A978) is assumed to be equal to that of stainless steel 316. The emissivity of stainless steel 316 is taken to be 0.62. The rationale for this assumption is consistency with the range of emissivity for this material (0.57 to 0.66) given on p. 4-68, Ref. 10. This assumption is used in Section 5.3.5. This assumption does not require verification.

3.2.35 The emissivity of aluminum alloy 6061 is assumed to be 0.07. The rationale for this assumption is consistency with the range of emissivity for rough aluminum plate (0.055 to 0.07) given on p. 4-68, Ref. 10. This assumption is used in Section 5.3.4. This assumption does not require verification.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE APPROVED FOR QUALITY ASSURANCE (QA) WORK

The FEA computer code used for this calculation is ANSYS Version (V) 5.4 (hereafter called 'ANSYS') (Reference 11), which is identified with the Software Tracking Number 10027-5.4L2-00. ANSYS is a commercially available finite element code and is appropriate for performing thermal analysis of WPs, WP emplacements, and WP environments as utilized in this calculation. ANSYS was operated on a Hewlett-Packard 9000/C200 workstation designated as 'gr0' (Tag #2002611431) in Lynchburg, Virginia. ANSYS V5.4L2 is the same software as the ANSYS V5.4 obtained from the ANSYS distributor. The evaluations performed in this calculation are fully within the range of validation for the ANSYS V5.4 code used. The software was obtained from Configuration Management and is appropriate for its intended use. Inputs to the ANSYS software and its outputs are included as attachments and are described in this document.

4.2 SOFTWARE ROUTINES

None used.

4.3 MODELS

None used.

5. CALCULATION

When converting values from English to metric units, the added digits of significance are an artifact of the conversion process and do not reflect actual precision of the value as expressed in metric.

Note that although the ASME designations are used to identify the materials involved in the calculation (Table 5-3), the Unified Numbering System (UNS) designations also provided in Table 5-3 serve as a link to ASTM references.

5.1 SCENARIO

This calculation determines the thermal response of the 44-BWR WP to the hypothetical fire accident. A set of runs are included to demonstrate sensitivity of the BWR peak cladding temperature to various configurations and variations in selected parameters. The objective is to calculate the temperature response of the BWR cladding to the hypothetical short-term fire defined in 10 CFR 71, Section 73(c)(4), Reference 1 (Assumption 3.1.1).

The conditions defined for the fire accident in Section 73(c)(4) of 10 CFR 71 are as follows:

> The waste package shall be considered totally immersed in flame of temperature equal to at least 800 °C, for a period of 30 minutes.
>
> The effective value of emissivity for gases in the flame shall be at least 0.9.
>
> The waste package outer surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the flame temperature specified, or 0.8, whichever is greater. Heat input from hot gases to the waste package will include the free-convection heat transfer mode in addition to thermal radiation (Assumption 3.2.2).
>
> No credit shall be taken for artificial cooling of the waste package after termination of exposure to the flame.

For transport package testing, Section 73(b) of 10 CFR 71, Reference 1 specifies a maximum temperature of +38°C for the temperature of ambient air before and after the specified 30-minute duration of the fire (Assumption 3.2.22). Section 71(c)(1) of 10 CFR 71, for normal conditions of transport, lists the total solar energy incident on the curved surface of a transport cask over a 12-hour period as 400 cal/cm^2.

Based on the above requirements, the fire accident evaluated with the WP at the surface facility (Assumption 3.2.19) is described as follows:

> The waste package is at the surface, loaded, sealed, and in a horizontal position. The WP is at steady thermal conditions with radiation heat transfer to the surroundings balancing the sum

of volumetric heat generation rates in the waste canisters and uniform solar radiation incident on the WP outer surface.

The waste package outer surface is instantaneously subjected to the thermal conditions specified for the regulatory fire as described above, producing uniform, rapid heating by both radiation and free convection heat transfer modes. Exposure of the WP to the fire is terminated after 30 minutes.

After termination of the fire, the surrounding air and surfaces return instantly to the temperature conditions existing prior to the accident. No credit is taken for free convection cooling after the fire. Cooling of the WP occurs by radiation to the immediate surroundings only.

The calculations for the fire accident proceed as follows:

(1) Base case FEA representations and a set of input variables for calculating the WP thermal response to the fire are first defined. Effective thermal conductivities for BWR SNF both with and without a channel are evaluated in separate base cases. The base case WP configuration includes gaps in the WP (between the inner and outer shell, between the plates and tubes, and between the plates and guides). In this configuration, the pre-fire temperatures in the WP will be maximized. However, the effects of the fire on the temperatures inside the WP will be minimized due to the lower thermal resistance effects of the gaps.

(2) The effects of the gaps in the WP will evaluated in the next set of cases. All of the gaps inside of the WP (including the inner/outer shell gap) will be eliminated. In this configuration, the pre-fire temperatures in the WP will be reduced. However, the effects of the fire on the temperatures inside the WP will be increased due to the elimination of the gaps which have a high thermal resistance.

(3) The sensitivity of calculated BWR peak cladding temperature to an increase in the BWR SNF thermal load will be evaluated in these cases. The BWR SNF thermal load is increased by a factor of 1.2.

Table 5-1 summarized the heat loads and boundary conditions used in the calculations.

Table 5-1. 44-BWR Waste Package Evaluation

Item	Accident Condition Initial/Fire/Post-Fire	Description
BWR SNF Thermal Load (Total kW)	11.8 (constant with time, Assumption 3.2.1.8)	Design value (Assumption 3.2.16).
Axial Peaking Factor	1.4	Design value (Assumption 3.2.17).
Temperature of Surroundings	38°C/ 800°C/ 38°C	Initial and post-fire value of 38°C is from Section 73(b) of 10 CFR 71 (Assumption 3.2.20). For the fire condition, the value of 800°C is from Section 73(c)(4) of 10 CFR 71 (Assumption 3.2.21).
Emissivity of Surroundings	1.0 / 1.0 / 1.0	Initial and post-fire values of 1.0 are used since the surroundings emit radiation at the ambient temperature (i.e., temperature of surroundings) (Assumption 3.2.24). For the fire condition, the value of 1.0 is conservative relative to the minimum value of 0.9 specified for the flame in Section 73(c)(4) of 10 CFR 71 (Assumption 3.2.25).
Emissivity of WP Outer Surface	0.87 / 1.0 / 0.87	Initial and post-fire values of 0.87 are used based on the value stated in Section 5.3.3 (Assumption 3.2.26). For the fire condition, a value of 1.0 is selected, which is greater than the minimum value of 0.8 specified for the outer surface when exposed to the flame per Section 73(c)(4) of 10 CFR 71 (Assumption 3.2.27).
Solar Energy Absorption Rate	400 cal/cm^2 per 12 hours (constant with time)	The rate of 400cal/cm^2 per 12-hour period is based on the value stated in Section 71 of 10 CFR 71 for energy incident on the curved surface of a transport cask (Assumption 3.2.28). Setting the absorption rate equal to the rate of incidence is equivalent to value of 1.0 for solar absorptivity, which is conservative (Assumption 3.2.29).
Free Convection Film Coefficient	$1.312(\Delta T^{1/3})$ w/m$^2\cdot$K	Free convection relationship for horizontal cylinder in air (Assumption 3.2.30 and 3.2.31)

Table 5-2 lists the 44-BWR WP configuration cases evaluated.

Table 5-2. 44-BWR Waste Package Fire Accident Evaluation Cases

Item	BWR SNF Fuel Representation	WP Configuration	BWR Thermal Load	Description
Case 1	With Channel	With Gaps	Max. Design	Base configurations
Case 2	No Channel	With Gaps	Max. Design	
Case 3	With Channel	No Gaps	Max. Design	Eliminating gaps should increase fire accident effects
Case 4	No Channel	No Gaps	Max. Design	
Case 5	With Channel	No Gaps	1.2 x Max. Design	Evaluate sensitivity of BWR peak cladding temperature to increased thermal load
Case 6	No Channel	No Gaps	1.2 x Max. Design	

5.2 WASTE PACKAGE PROPERTIES

5.2.1 44-BWR Waste Package

The waste package cross-section studied in this calculation consists of the inner and outer barriers, basket, and forty-four BWR SNF assemblies. Dimensional information for the WP inner and outer barriers, and basket are shown in Attachment I. Table 5-3 lists the WP materials and their ASME and UNS designations.

Table 5-3. WP Materials Used and Their ASME and UNS Designation

Item	Material Used	ASME and UNS Designation
WP Outer Shell	Alloy 22	SB-575 N06022
WP Inner Shell	Stainless Steel 316NG	SA-240 S31600
Basket Cornerguides and Sideguides	A516 Grade 70 Carbon Steel	SA-516 K02700
Basket Tubes	A516 Grade 70 Carbon Steel	SA-516 K02700
Basket Neutron Absorber Plates	Stainless Steel With Boron	Neutronit A 978
Basket Thermal Shunt Plates	Aluminum Alloy 6061	SB-209 A96061
WP Internal Fill Gas	Helium	N/A (Not Applicable)
Gas Between WP Inner and Outer Shell	Air	N/A

5.2.2 BWR Spent Nuclear Fuel

The uncanistered BWR SNF is modeled as a uniform homogeneous volume (Assumption 3.2.14) inside each of the tubes in the WP basket. The active BWR fuel length is 3.81 m (p. 2A-21, Ref. 16). The inside cell width of each of the basket tubes is 0.1553 m (Attachment I). This gives the following volumes for SNF heat load distribution.

Homogeneous Active Volume per SNF, $V_F = (\text{cell width})^2(\text{active fuel length})$

$$V_F = (0.1553)^2(3.81) = 0.09189 \text{ m}^3$$

WP Total Homogeneous SNF Volume, $V_{FT} = (44 \text{ assemblies})(0.09189) = 4.043 \text{ m}^3$

5.3 THERMAL PROPERTIES

5.3.1 A516 Carbon Steel

Table 5-4 lists the density and emissivity of A516 carbon steel. The density of A516 (C-Mn-Si) is from p. 9 of Ref. 17. The emissivity (average for smooth oxidized iron) is from Table 4.3.2 on page 4-68, Ref. 10 (Assumption 3.2.33).

Table 5-5 lists the thermal conductivity and specific heat of A516 carbon steel. Values for thermal conductivity and thermal diffusivity of A516 were taken from Table TCD, Section II , Ref. 18, and converted here to conductivity and specific heat in SI units (Syst^vsme International d'Unit^vss). The conversion of thermal diffusivity (defined in Equation 5.1) to specific heat requires the density listed in Table 5-4.

$$Specific\ Heat\ (Btu/lb\cdot{}^{o}F) = \frac{Thermal\ Conductivity\ (Btu/hr\cdot ft\cdot{}^{o}F)}{Density\ (lb/ft^3)\times Thermal\ Diffusivity\ (ft^2/hr)} \quad \text{[Equation 5.1]}$$

Table 5-4. Density and Emissivity of A516 Carbon Steel

	Density (kg/m^3)	Emissivity
A516 Carbon Steel	7850	0.80

Table 5-5. Thermal Conductivity and Specific Heat of A516 Carbon Steel

Temperature		Thermal Conductivity	Thermal Diffusivity	Thermal Conductivity	Specific Heat
(°F)	(°C)	(Btu/hr·ft·F)	(ft^2/hr)	(W/m·K)	(J/kg·K)
70	21.11	23.6	0.454	40.85	444.11
100	37.78	23.9	0.443	41.36	460.92
150	65.56	24.2	0.433	41.88	477.49
200	93.33	24.4	0.422	42.23	493.98
250	121.11	24.4	0.414	42.23	503.53
300	148.89	24.4	0.406	42.23	513.45
350	176.67	24.3	0.396	42.06	524.26
400	204.44	24.2	0.386	41.88	535.63
450	232.22	23.9	0.375	41.36	544.50
500	260.00	23.7	0.364	41.02	556.26
550	287.78	23.4	0.355	40.50	563.15
600	315.56	23.1	0.346	39.98	570.39
650	343.33	22.7	0.333	39.29	582.39
700	371.11	22.4	0.320	38.77	598.04
750	398.89	22.0	0.308	38.08	610.25
800	426.67	21.7	0.298	37.56	622.12
850	454.44	21.2	0.286	36.69	633.29
900	482.22	20.9	0.274	36.17	651.67
950	510.00	20.5	0.262	35.48	668.48
1000	537.78	20.0	0.248	34.61	688.99
1050	565.56	19.6	0.237	33.92	706.55
1100	593.33	19.2	0.228	33.23	719.45
1150	621.11	18.7	0.213	32.36	750.06
1200	648.89	18.2	0.197	31.50	789.29
1250	676.67	17.5	0.179	30.29	835.25
1300	704.44	16.7	0.155	28.90	920.49
1350	732.22	15.8	0.119	27.35	1134.34
1400	760.00	15.3	0.077	26.48	1697.60
1450	787.78	15.1	0.154	26.13	837.70
1500	815.56	15.1	0.169	26.13	763.35

5.3.2 Stainless Steel 316NG

Material properties of stainless steel 316 are used for stainless steel 316NG. 316NG, which is 316 with tightened control on carbon and nitrogen content, has the same mechanical and physical properties as 316 (see p. 931, Ref. 27 and Table 1, p. 315, Ref. 18). Table 5-6 lists the density and emissivity of stainless steel 316NG. The density is taken from Table X1, p. 7, Ref. 19. The emissivity is taken from Table 4.3.2, p. 4-68, Ref. 10 and is approximately the average of the range of values for heated stainless steel 316 (Assumption 3.2.32).

Table 5-7 lists the thermal conductivity and specific heat of stainless steel 316NG. Values for thermal conductivity and thermal diffusivity were taken from Table TCD, Section II, p. 606 of Ref. 18, converted here to conductivity and specific heat in SI units. The conversion of thermal diffusivity (defined in Equation 5.1) to specific heat requires the density listed in Table 5-6. Stainless steel 316 is listed in Ref. 18 by its chemical composition (16Cr-12Ni-2Mo).

Table 5-6. Density and Emissivity of Stainless Steel 316NG

	Density (kg/m^3)	Emissivity
Stainless Steel 316	7980	0.62

Table 5-7. Thermal Conductivity and Specific Heat of Stainless Steel 316NG

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	482.93
100	37.78	7.9	0.136	13.67	488.19
150	65.56	8.2	0.138	14.19	499.38
200	93.33	8.4	0.141	14.54	500.68
250	121.11	8.7	0.143	15.06	511.31
300	148.89	9.0	0.145	15.58	521.64
350	176.67	9.2	0.148	15.92	522.43
400	204.44	9.5	0.151	16.44	528.75
450	232.22	9.8	0.153	16.96	538.31
500	260.00	10.0	0.156	17.31	538.74
550	287.78	10.3	0.159	17.83	544.43
600	315.56	10.5	0.162	18.17	544.72
650	343.33	10.7	0.164	18.52	548.33
700	371.11	11.0	0.167	19.04	553.58
750	398.89	11.2	0.170	19.38	553.69
800	426.67	11.5	0.173	19.90	558.67
850	454.44	11.7	0.176	20.25	558.69
900	482.22	12.0	0.178	20.77	566.58
950	510.00	12.2	0.181	21.11	566.48
1000	537.78	12.4	0.184	21.46	566.38
1050	565.56	12.7	0.186	21.98	573.84
1100	593.33	12.9	0.189	22.33	573.63
1150	621.11	13.1	0.191	22.67	576.42
1200	648.89	13.3	0.194	23.02	576.17
1250	676.67	13.6	0.196	23.54	583.15
1300	704.44	13.8	0.199	23.88	582.81

1350	732.22	14.0	0.201	24.23	585.37
1400	760.00	14.2	0.203	24.58	587.89
1450	787.78	14.4	0.206	24.92	587.48
1500	815.56	14.6	0.208	25.27	589.92

5.3.3 Alloy 22

Table 5-8 lists the density and emissivity of Alloy 22. The density of Alloy 22 is taken from p. 2, Ref. 20. The emissivity of Alloy 22 is taken from p. 10-297, Ref. 9, for nickel-chromium alloy (Assumption 3.2.26).

Table 5-9 lists the thermal conductivity and specific heat of Alloy 22 taken from p. 13, Ref. 21.

Table 5-8. Density and Emissivity of Alloy 22

	Density (kg/m^3)	Emissivity
Alloy 22	8690	0.87

Table 5-9. Thermal Conductivity and Specific Heat of Alloy 22

Temperature (°C)	Thermal Conductivity (W/m·K)	Temperature (°C)	Specific Heat (J/kg·K)
48	10.1	52	414
100	11.1	100	423
200	13.4	200	444
300	15.5	300	460
400	17.5	400	476
500	19.5	500	485
600	21.3	600	514

5.3.4 Aluminum Alloy 6061

Table 5-10 lists the density and emissivity of aluminum alloy 6061. The density is taken from Table NF-2, Section II, p. 619 of Ref. 18, and the emissivity is taken from p. 4-68, Ref. 10 (Assumption 3.2.35). Table 5-11 lists the thermal conductivity and specific heat of aluminum alloy 6061. Values for thermal conductivity and diffusivity are taken from Table TCD, Section II, p. 612 of Ref. 18. The conversion of thermal diffusivity to specific heat is defined in Equation 5-1.

Table 5-10. Density and Emissivity of Aluminum Alloy 6061

	Density (kg/m^3)	Emissivity
Aluminum Alloy 6061	2713	0.07

Table 5-11. Thermal Conductivity and Specific Heat of Aluminum Alloy 6061

Temperature		Thermal Diffusivity	Thermal Diffusivity	Thermal Conductivity	Thermal Conductivity	Specific Heat
(°F)	(°C)	(ft²/hr)	(m²/s)	(Btu/hr·ft·°F)	(W/m·K)	(J/kg·K)
70	21.11	2.66	0.0000686	96.1	166.32	893
100	37.78	2.66	0.0000686	96.9	167.71	901
150	65.56	2.65	0.0000684	98.0	169.61	914
200	93.33	2.65	0.0000684	99.0	171.34	924
250	121.11	2.64	0.0000681	99.8	172.73	935
300	148.89	2.63	0.0000679	100.6	174.11	946
350	176.67	2.62	0.0000676	101.3	175.32	956
400	204.44	2.62	0.0000676	101.9	176.36	962

5.3.5 Neutronit A978

Table 5-12 lists the density and emissivity of boron stainless steel Neutronit A978. Table 5-13 lists the thermal conductivity and specific heat of boron stainless steel Neutronit A978. The density, specific heat, and thermal conductivity are taken from Reference 22, and the emissivity is taken from p. 4-68, Ref. 10 (Assumption 3.2.34).

Table 5-12. Density and Emissivity of Boron Stainless Steel Neutronit A978

	Density (kg/m³)	Emissivity
Neutronit A 978	7760	0.62

Table 5-13. Thermal Conductivity and Specific Heat of Boron Stainless Steel Neutronit A978

Temperature (°C)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
20	10.3	500
130	11.7	N/A
260	13.4	

5.3.6 Helium

The WP is assumed to be evacuated and filled with helium (Assumption 3.2.11). Table 5-14 lists the density of helium used for WP fill gas. The value for the density of helium was taken at a temperature of 27°C at one-atmosphere pressure (Assumption 3.2.12). Table 5-15 lists the thermal conductivity and specific heat of helium. All helium properties are taken from p. 19.71, Ref. 23.

Table 5-14. Density of Helium

	Density (kg/m³)
Helium (1 atm, 300K)	0.1626

Table 5-15. Thermal Conductivity and Specific Heat of Helium

Temperature		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(Btu/hr·ft·°F)	(W/m·K)	(Btu/lbm·°F)	(J/kg·K)
0	-17.78	0.08064	0.1396	1.2412	5196.7
20	-6.67	0.08304	0.1437	1.2412	5196.7
40	4.44	0.08542	0.1478	1.2412	5196.7
60	15.56	0.08776	0.1519	1.2412	5196.7
80	26.67	0.09008	0.1559	1.2411	5196.2
100	37.78	0.09238	0.1599	1.2411	5196.2
120	48.89	0.09465	0.1638	1.2411	5196.2
140	60.00	0.09690	0.1677	1.2411	5196.2
160	71.11	0.09912	0.1715	1.2411	5196.2
180	82.22	0.10133	0.1754	1.2411	5196.2
200	93.33	0.10351	0.1791	1.2411	5196.2
240	115.56	0.10783	0.1866	1.2411	5196.2
280	137.78	0.11207	0.1940	1.2411	5196.2
320	160.00	0.11624	0.2012	1.2411	5196.2
360	182.22	0.12036	0.2083	1.2411	5196.2
400	204.44	0.12441	0.2153	1.2411	5196.2
440	226.67	0.12841	0.2222	1.2411	5196.2
480	248.89	0.13236	0.2291	1.2411	5196.2
520	271.11	0.13626	0.2358	1.2411	5196.2
560	293.33	0.14011	0.2425	1.2411	5196.2
600	315.56	0.14392	0.2491	1.2411	5196.2
640	337.78	0.14768	0.2556	1.2412	5196.7
680	360.00	0.15141	0.2621	1.2412	5196.7
720	382.22	0.15509	0.2684	1.2412	5196.7
760	404.44	0.15874	0.2747	1.2412	5196.7
800	426.67	0.16236	0.2810	1.2412	5196.7

5.3.7 Air

For the analysis configuration where gaps are assumed to be present in the 44-BWR WP, air is assumed to fill the gap between the inner and outer shells of the WP (Assumption 3.2.10). Table 5-16 lists the density of air at a temperature of 27°C at one-atmosphere pressure. Table 5-17 lists the thermal conductivity and specific heat of air. All air properties are taken from p. 19.77, Ref. 23.

Table 5-16. Density of Air

	Density (kg/m³)
Air (1 atm, 300K)	1.1774

Table 5-17. Thermal Conductivity and Specific Heat of Air

Temperature		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(Btu/hr·ft·°F)	(W/m·K)	(Btu/lbm·°F)	(J/kg·K)
0	-17.78	0.01326	0.0229	0.2402	1005.7
20	-6.67	0.01372	0.0237	0.2402	1005.7
40	4.44	0.01419	0.0246	0.2403	1006.1
60	15.56	0.01465	0.0254	0.2403	1006.1
80	26.67	0.01510	0.0261	0.2404	1006.5
100	37.78	0.01554	0.0269	0.2405	1006.9
120	48.89	0.01599	0.0277	0.2407	1007.8
140	60.00	0.01642	0.0284	0.2408	1008.2
160	71.11	0.01685	0.0292	0.2410	1009.0
180	82.22	0.01728	0.0299	0.2412	1009.9
200	93.33	0.01771	0.0307	0.2414	1010.7
240	115.56	0.01854	0.0321	0.2420	1013.2
280	137.78	0.01937	0.0335	0.2426	1015.7
320	160.00	0.02019	0.0349	0.2433	1018.6
360	182.22	0.02099	0.0363	0.2442	1022.4
400	204.44	0.02180	0.0377	0.2451	1026.2
440	226.67	0.02260	0.0391	0.2460	1030.0
480	248.89	0.02339	0.0405	0.2471	1034.6
520	271.11	0.02418	0.0418	0.2482	1039.2
560	293.33	0.02496	0.0432	0.2493	1043.8
600	315.56	0.02575	0.0446	0.2505	1048.8
640	337.78	0.02653	0.0459	0.2517	1053.8
680	360.00	0.02731	0.0473	0.2530	1059.3
720	382.22	0.02808	0.0486	0.2543	1064.7
760	404.44	0.02885	0.0499	0.2555	1069.7
800	426.67	0.02962	0.0513	0.2568	1075.2

5.3.8 BWR Spent Nuclear Fuel

Table 5-18 lists values of density and specific heat for the homogeneous BWR represented in ANSYS. The density was calculated using the maximum BWR fuel assembly mass of 328.4 kg (p. 31, Ref. 25) and the homogeneous active volume per SNF ($V_F = 0.09189$ m^3) from Section 5.2.2. The specific heat was taken from p. 31, Ref. 25. Table 5-19 shows the bounding BWR effective thermal conductivities (p. 147-148, Ref. 3) for representing the BWR SNF assembly as a homogeneous heat source (Assumption 3.2.8) with a helium fill gas. The effective thermal conductivities for BWR SNF both with and without a channel are listed in Table 5-19.

Table 5-18. Density and Specific Heat of Homogeneous BWR SNF

	Density (kg/m^3)	Specific Heat (J/kg·K)
Homogeneous BWR SNF	3574	273

Table 5-19. Effective Thermal Conductivity of Homogeneous BWR SNF in Helium

Temperature (°C)	Effective Thermal Conductivity (W/m·K)	
	With Channel	No Channel
25	0.290	0.296
50	0.317	0.327
100	0.379	0.400
150	0.455	0.489
200	0.542	0.595
250	0.643	0.717
300	0.755	0.855
350	0.881	1.009
400	1.019	1.178

5.4 WASTE PACKAGE HEAT OUTPUT AND BOUNDARY CONDITIONS

5.4.1 BWR SNF Heat Output

The WP heat generation rate is calculated in a manner consistent with the effective thermal conductivities methodology developed in Ref. 3 and used in this calculation. The WP is loaded with 44 identical heat-output fuel assemblies (Assumption 3.2.15). The volumetric heat generation of the BWR SNF in the WP is calculated using the maximum design basis value for the 44-BWR WP of 11.8 kW (Assumption 3.2.16), and the total homogeneous SNF volume ($V_{FT} = 4.043\ m^3$) from Section 5.2.2.

$$\text{Volumetric Heat Rate} = (11{,}800\ \text{watts})/(4.043\ m^3) = 2918.6\ W/m^3$$

Applying an axial power peaking factor of 1.4 (Assumption 3.2.17), the volumetric heat generation rate used in the analysis model representation becomes:

$$\text{Volumetric Heat Rate With Peaking Factor} = 4086\ W/m^3$$

5.4.2 Waste Package Boundary Conditions

A 2-D, 180-degree, finite element representation of the WP cross-section is used in the calculations (Assumption 3.2.3). As illustrated in Figure 5-1, boundary conditions at the outer surface of the WP include the following:

(1) The temperature of the surroundings is set at one of two values, corresponding to the normal ambient or fire condition (Assumptions 3.2.20 and 3.2.21), and

(2) a constant heat flux is imposed at the outer surface of the WP corresponding to the absorption rate of incident solar radiation (Assumptions 3.2.28 and 3.2.29).

The modes of heat transfer between the outer shell and the immediate surroundings at the surface facility include radiation and free convection (Assumptions 3.2.2 and 3.2.31). However, convection effects are taken into account only during heating of the WP by the fire. No credit is taken for convection heat transfer for the normal, i.e., pre-fire, or the post-fire cooldown conditions.

Per Section 5.1, the total solar energy incident on the curved surface of a transport cask over a 12-hour period is 400 cal/cm^2 (Assumption 3.2.28). Using a conservative value of 1.0 for the solar absorptivity at the WP outer surface (Assumption 3.2.29), the average rate of absorption of this energy is calculated as follows:

$$q''_{solar} = (400\ \text{cal/cm}^2)\ /\ 12\text{hr}$$

$$= (400\ /\ 12)\ (\text{cal/cm}^2\cdot\text{hr})(4.184\ \text{J/cal})(100\ \text{cm /m})^2\ (\text{hr/3600sec})$$

$$= 387\ \text{J/m}^2\cdot\text{sec}\ \ (\text{or } 387\ \text{W/m}^2).$$

The heat flux due to solar irradiation is maintained constant during the transient, from initial condition through the post-fire cooldown.

The boundary condition involves a peripherally uniform ambient temperature of the surroundings. Consequently, the heat transfer may be considered similar to the general case of heat exchange between gray, parallel plane surfaces (Assumption 3.2.23). The heat flow at surface 1 with parallel surfaces at temperatures T_1 and T_2, is

$$q_r = \sigma\ \varepsilon_{eff}\ A\ (T_1^4 - T_2^4).$$

In this equation, σ is the Stefan-Boltzman constant, equal to 5.67E-8 W/m$^2\cdot$K^4 (p. 4-66, Ref. 10) and the expression for the effective emissivity, ε_{eff}, is (p. 4-71, Ref. 10)

$$\varepsilon_{eff} \cong [(1/\varepsilon_1) + (1/\varepsilon_2) - 1]^{-1}$$

where ε_1 and ε_2 are the emissivities of surfaces 1 and 2, respectively.

Considering that the view factor, F, is unity for parallel planes, this equation is equivalently,

$$q_r = (\sigma)\ (\varepsilon_{eff})\ (A)\ (T_1^2 + T_2^2)\ (T_1 + T_2)\ (T_1 - T_2)$$

$$= [(\sigma)\ (\varepsilon_{eff})\ (T_1^2 + T_2^2)\ (T_1 + T_2)]\ (A)\ (T_1 - T_2)$$

$$= (h_r)\ (A)\ (T_1 - T_2)$$

where the effective coefficient for radiation heat transfer, h_r, is $[(\sigma)\ (\varepsilon_{eff})\ (T_1^2 + T_2^2)\ (T_1 + T_2)]$.

For air at room temperature and atmospheric pressure, the average value of the convection heat transfer coefficient, h_c, for flow around horizontal cylinders is correlated by the equation (p. 4-88, Ref. 10) (Assumptions 3.2.30 and 3.2.31).

$$h_c = 0.19\,(\Delta T)^{1/3}\ \text{Btu/hr}\cdot\text{ft}^2\cdot\text{F, with } \Delta T \text{ in degrees Fahrenheit, for } D^3\Delta T>100\ \text{ft}^3\cdot\text{F},$$

$$= 1.312\,(\Delta T)^{1/3}\ \text{W/m}^2\cdot\text{K, with } \Delta T \text{ in degrees Kelvin or Celsius.}$$

The free convection heat transfer coefficient decreases with increasing temperature of the gas due to the change in gas properties with temperature. The above expression for the coefficient is therefore conservative for use during WP heating because of higher temperatures associated with the fire.

The radiation heat transfer on the WP outer surface may be combined with convection heat transfer and characterized as an effective heat transfer coefficient, h_{eff}.

The combined flow of heat via radiation and convection to the surroundings is then

$$q = q_r + q_c,$$

$$q = (h_r + h_c)\,(A)\,(T_1 - T_2)$$

where q_r and q_c are the heat transfer rates for radiation and convection, respectively.

Attachment III includes tables listing the effective values of heat transfer coefficient used in the calculations for the various cases evaluated.

5.5 FINITE ELEMENT DEVELOPMENT

This section briefly describes the ANSYS Version 5.4 input file format used to develop the ANSYS cases. Each ANSYS Version 5.4 input deck is provided as part of the ANSYS output files on the CD associated with this document. A separate input file is created for each case.

The following simplifying Assumptions were used in the development of the finite element representation: Assumptions 3.2.1, 3.2.3 to 3.2.7, 3.2.9 and 3.2.14.

The basic layout of an ANSYS input file includes the following seven steps:

1. Introduce and identify the problem represented, additional files read by the input deck, and what information is contained in the data files used in the input deck.

2. Define the parameters and dimensions that are used repeatedly in the case.

3. Define the element types that are needed to represent the geometry to perform the calculation.

4. Define the representative geometry and mesh structure.

5. Define all radiation surfaces and create the radiation mesh matrix.

6. Apply the internal heat loads (volumetrically) and the boundary conditions to the appropriate components. Heat loads and boundary conditions are applied at each time step.

7. Select the node sets associated with the various materials and/or components of interest and echo their maximum temperatures for each time step of the transient to the output file.

Table 5-2 lists the cases evaluated in this calculation. In all of these cases the thickness of the basket plates and guides, fuel basket tubes, and inner and outer shells were maintained in the analysis model representation consistent with Attachment I. For Cases 1 and 2, which include gaps in the WP configuration, as illustrated in Figure 5-2, the diameters of the inner and outer shells were adjusted to accommodate the presence of the gaps. For Cases 3 to 6, which had no gaps in the WP configuration, as illustrated in Figure 5-3, the diameters of the inner and outer shells in the analysis model were consistent with Attachment I since they did not need to be adjusted to accommodate the presence of the gaps.

In each of these cases the applicable finite element representation of the 44-BWR WP is as depicted in Figure 5-1.

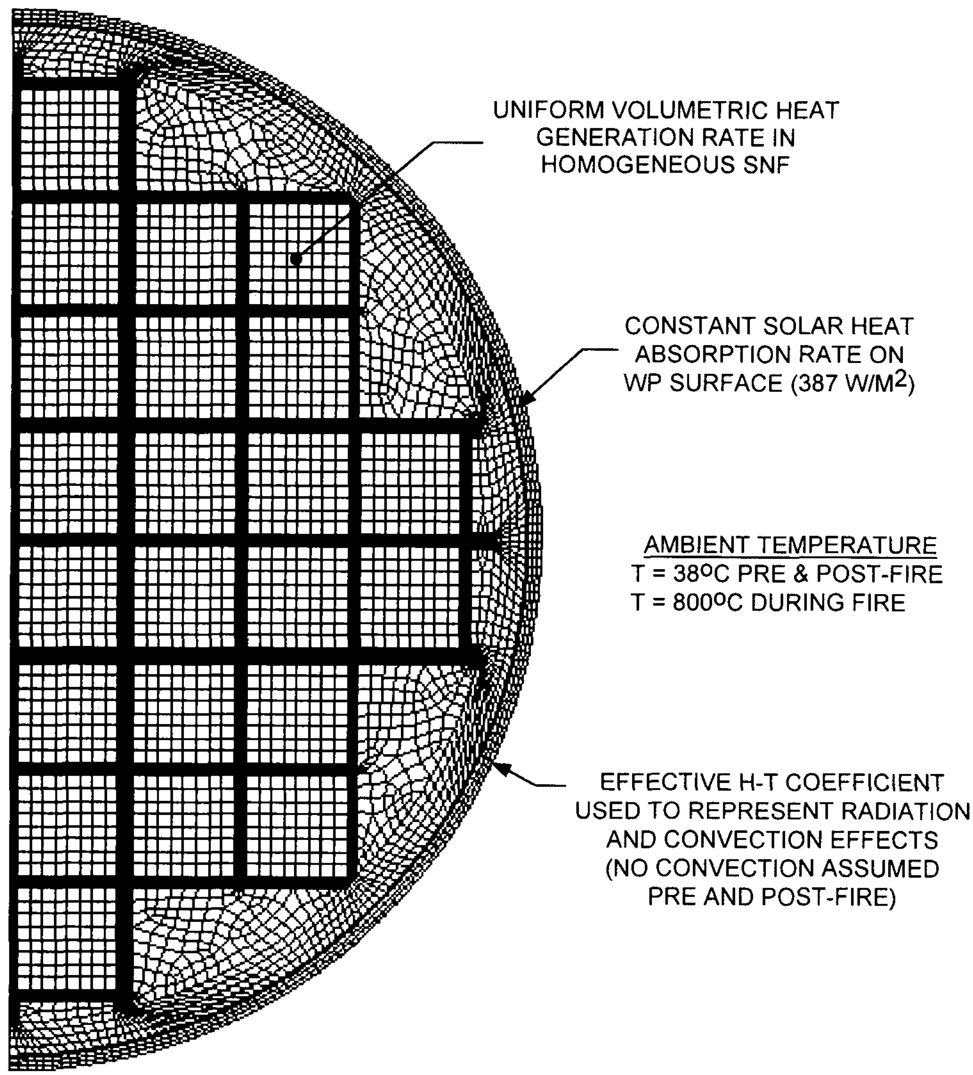

Figure 5-1. 44-BWR WP Finite Element Representation Showing Boundary Conditions

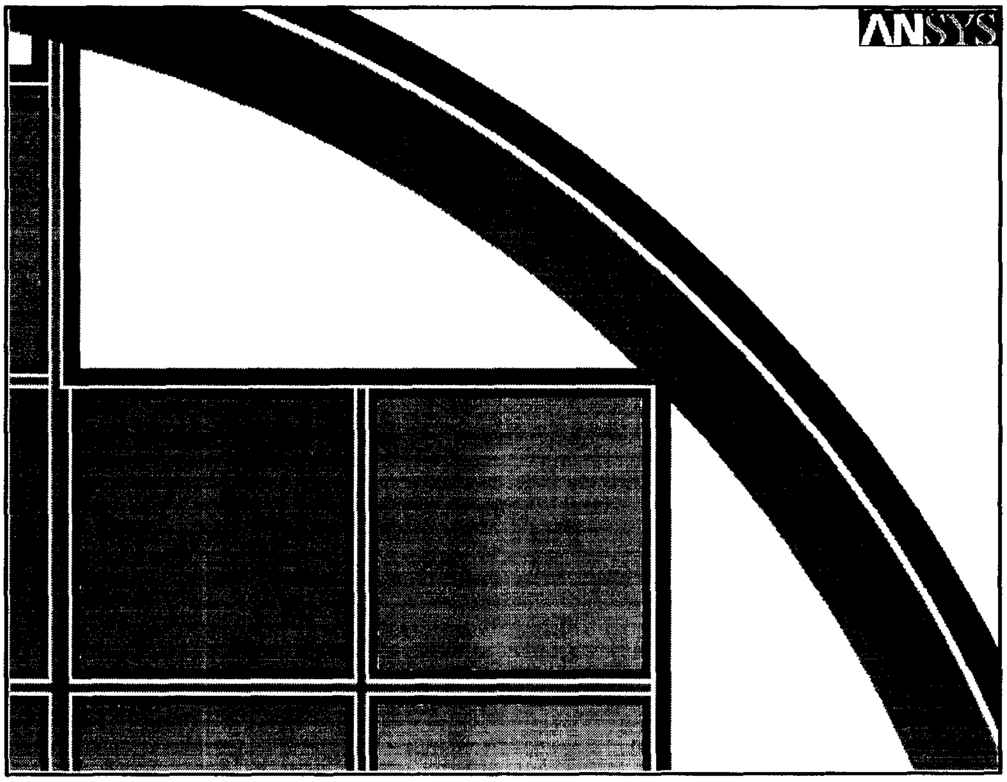

Figure 5-2. Illustration of 44-BWR WP Configuration With Gaps

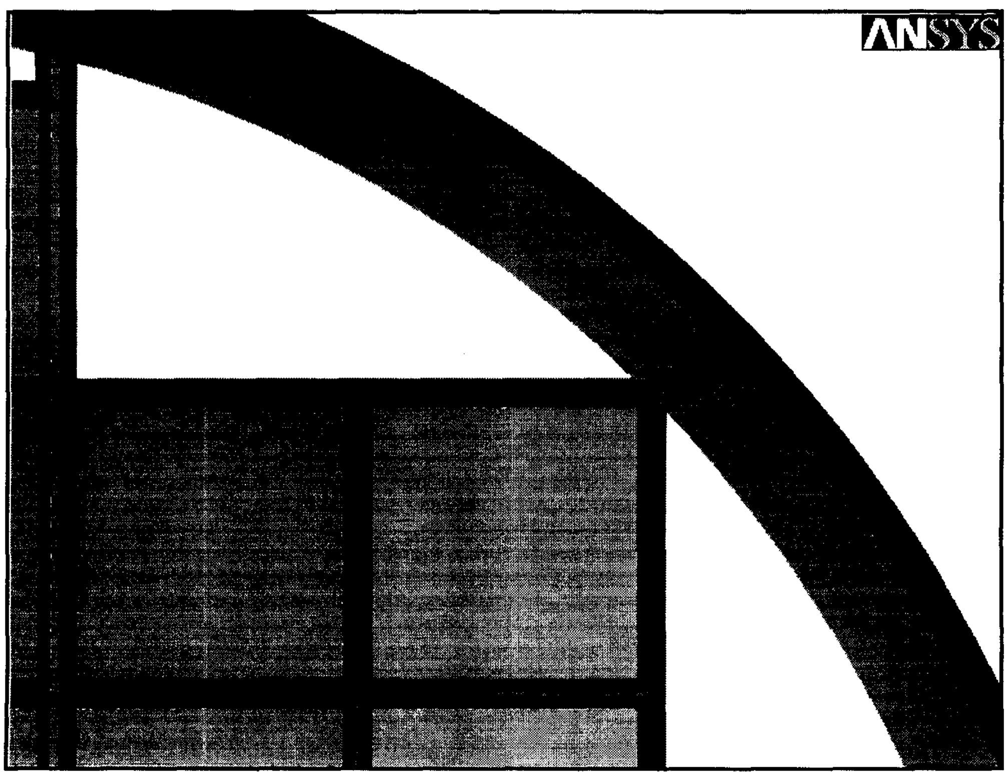

Figure 5-3. Illustration of 44-BWR WP Configuration Without Gaps

6. RESULTS

The results provided in this section are extracted from the ANSYS V5.4 output files (the files are stored on the compact disk (CD) provided with this document).

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

The six cases analyzed in this calculation are listed in Table 5-2.

6.1 CASES 1 & 2: WP WITH GAPS, MAX. DESIGN THERMAL LOAD

The first two cases evaluate the effects of the BWR fuel properties in a 44-BWR WP with assumed gaps between the inner and outer shell, and plates and tubes, tubes and guides and plates and guides in the basket. Case 1 uses BWR effective thermal conductivities representative of BWR fuel with a channel; Case 2 uses BWR effective thermal conductivities representative of BWR fuel without a channel.

Table 6-1 lists the peak temperature in each of the WP components before ($t = 0$ hr), during ($t > 0$ to 0.5 hr) and after ($t > 0.5$ hr) the hypothetical fire accident for the Case 1 configuration. Although the peak temperature (701°C) of the WP outer shell was reached at the end of the 30-minute fire, the peak cladding temperature (338°C) was not reached until approximately 10.5 hours after the fire. This was due to the assumed gaps in the WP configuration. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-1.

Table 6-2 lists the peak temperature in each of the WP components before, during and after the hypothetical fire accident for the Case 2 configuration. The small effect of the difference in effective thermal conductivities of the BWR fuel with and without a channel is evident in the results. The calculated highest fuel cladding temperature for this case is within 2°C of that calculated for Case 1. The calculated highest temperature for all other WP components are within 1°C. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-2.

Figure 6-1 shows the peak BWR cladding temperature locations in the finite element representation that correspond to the temperature values given in Tables 6-1 and 6-2. Figure 6-2 shows the BWR fuel cladding peak temperature time history for Cases 1 and 2 from the information in Tables 6-1 and 6-2. The peak temperature location changes with time as indicated in Tables 6-1 and 6-2. Figure 6-3 shows the WP outer shell peak temperature time history for Cases 1 and 2.

The assumed gaps in the WP for this configuration significantly insulated the BWR fuel from the effects of the fire. The peak BWR fuel cladding temperature increased less than a 40°C, while the WP outer surface increased about 400°C.

Table 6-1. Case 1 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (^oC)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	300.2	294.8	294.7	286.2	214.9	294.8
0.08	1	300.2	294.8	294.7	286.2	218.2	449.8
0.17	1	300.2	294.8	294.7	286.2	246.1	592.8
0.25	1	300.2	294.8	294.7	286.2	279.0	657.1
0.33	1	300.2	294.8	294.7	286.2	312.7	683.7
0.42	1	300.2	294.8	294.7	286.2	343.9	695.0
0.50	1	300.2	313.4	311.4	300.1	374.8	**700.8**
0.58	1	300.2	334.7	332.8	319.3	**385.3**	551.9
0.67	9	306.2	344.2	342.7	329.5	384.9	465.7
0.75	9	316.6	347.3	346.1	334.1	381.7	413.2
0.83	9	323.1	**347.4**	**346.4**	335.9	376.9	378.3
0.92	9	327.1	345.9	345.1	**336.1**	371.5	371.3
1.00	9	329.3	343.6	343.0	335.2	366.0	365.4
1.08	9	330.3	341.9	340.4	333.8	360.6	359.6
1.17	9	330.4	339.9	337.5	331.9	355.2	354.5
1.25	9	329.9	337.5	334.6	329.9	350.0	349.4
1.33	9	328.9	335.0	331.7	327.7	345.0	344.6
1.42	9	327.7	332.4	328.9	325.5	340.3	340.1
1.50	9	326.2	329.8	326.1	323.2	335.9	335.7
2.00	8	317.5	315.7	312.1	310.6	314.6	315.6
2.50	6	314.2	306.9	306.1	302.6	301.9	306.8
3.00	5	313.6	305.5	305.2	301.4	292.0	305.5
3.50	4	312.5	306.4	306.2	304.2	285.2	306.4
4.00	2	313.5	309.0	308.8	307.9	279.6	309.0
4.50	2	317.0	312.5	312.4	311.2	274.9	312.5
5.00	2	320.3	315.9	315.8	314.2	270.9	315.9
5.50	2	323.4	319.1	318.9	316.8	267.4	319.1
6.00	2	326.2	321.9	321.8	319.0	264.3	321.9
7.00	1	330.9	326.6	326.5	322.2	259.2	326.6
8.00	1	334.3	330.0	329.9	324.3	255.1	330.0
9.00	1	336.6	332.2	332.1	325.4	251.8	332.2
10.00	1	337.8	333.4	333.3	325.7	249.0	333.4
11.00	1	**338.3**	333.8	333.8	325.5	246.7	333.8
12.00	1	338.2	333.7	333.7	325.0	244.6	333.7
13.00	1	337.8	333.2	333.2	324.1	242.9	333.2
14.00	1	337.0	332.4	332.4	323.1	241.3	332.4
15.00	1	336.1	331.4	331.4	321.9	239.8	331.4
16.00	1	335.0	330.3	330.3	320.7	238.5	330.3
17.00	1	333.8	329.1	329.1	319.4	237.3	329.1
18.00	1	332.6	327.9	327.8	318.2	236.2	327.9
19.00	1	331.4	326.6	326.6	316.9	235.2	326.6
20.00	1	330.2	325.4	325.3	315.6	234.3	325.4

Table 6-2. Case 2 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (^{o}C)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	298.5	294.0	293.9	285.6	214.8	294.0
0.08	1	298.5	294.0	293.9	285.6	218.2	449.8
0.17	1	298.5	294.0	293.9	285.6	246.1	592.8
0.25	1	298.5	294.0	293.9	285.6	279.0	657.1
0.33	1	298.5	294.0	293.9	285.6	312.7	683.7
0.42	1	298.5	294.0	293.9	285.6	343.9	695.0
0.50	1	298.5	313.4	311.4	300.0	374.8	**700.8**
0.58	1	298.5	334.6	332.7	319.2	**385.3**	551.9
0.67	9	305.8	344.2	342.6	329.3	384.9	465.7
0.75	9	316.1	347.2	346.0	333.9	381.7	413.2
0.83	9	322.6	**347.2**	**346.3**	335.7	376.8	378.2
0.92	9	326.6	345.6	344.9	**335.8**	371.4	371.2
1.00	9	328.8	343.3	342.7	334.9	366.0	365.3
1.08	9	329.8	341.6	340.1	333.5	360.5	359.5
1.17	9	329.9	339.6	337.2	331.6	355.1	354.4
1.25	9	329.4	337.2	334.3	329.6	349.9	349.3
1.33	9	328.5	334.7	331.4	327.4	344.9	344.5
1.42	9	327.2	332.1	328.6	325.1	340.2	339.9
1.50	9	325.8	329.5	325.8	322.9	335.7	335.5
2.00	8	317.0	315.4	311.8	310.3	314.4	315.4
2.50	6	313.7	306.7	306.1	302.3	301.8	306.7
3.00	5	312.7	305.5	305.1	301.1	291.8	305.5
3.50	4	311.4	306.2	306.0	303.6	285.1	306.2
4.00	3	312.4	308.5	308.3	307.3	279.5	308.5
4.50	2	315.8	311.9	311.7	310.7	274.8	311.9
5.00	2	319.2	315.4	315.2	313.8	270.8	315.3
5.50	2	322.3	318.6	318.4	316.4	267.3	318.6
6.00	2	325.1	321.4	321.3	318.6	264.3	321.4
7.00	1	329.8	326.2	326.1	321.9	259.2	326.2
8.00	1	333.1	329.5	329.4	323.9	255.2	329.5
9.00	1	335.2	331.6	331.5	324.9	251.8	331.6
10.00	1	336.4	332.7	332.7	325.2	249.1	332.7
11.00	1	**336.8**	333.1	333.1	325.0	246.7	333.1
12.00	1	336.7	333.0	332.9	324.4	244.7	333.0
13.00	1	336.1	332.4	332.4	323.5	242.9	332.4
14.00	1	335.3	331.6	331.6	322.5	241.3	331.6
15.00	1	334.3	330.6	330.5	321.3	239.9	330.6
16.00	1	333.2	329.4	329.4	320.0	238.6	329.4
17.00	1	332.0	328.2	328.2	318.7	237.4	328.2
18.00	1	330.8	327.0	326.9	317.5	236.3	327.0
19.00	1	329.5	325.7	325.6	316.2	235.3	325.7
20.00	1	328.3	324.4	324.4	314.9	234.3	324.4

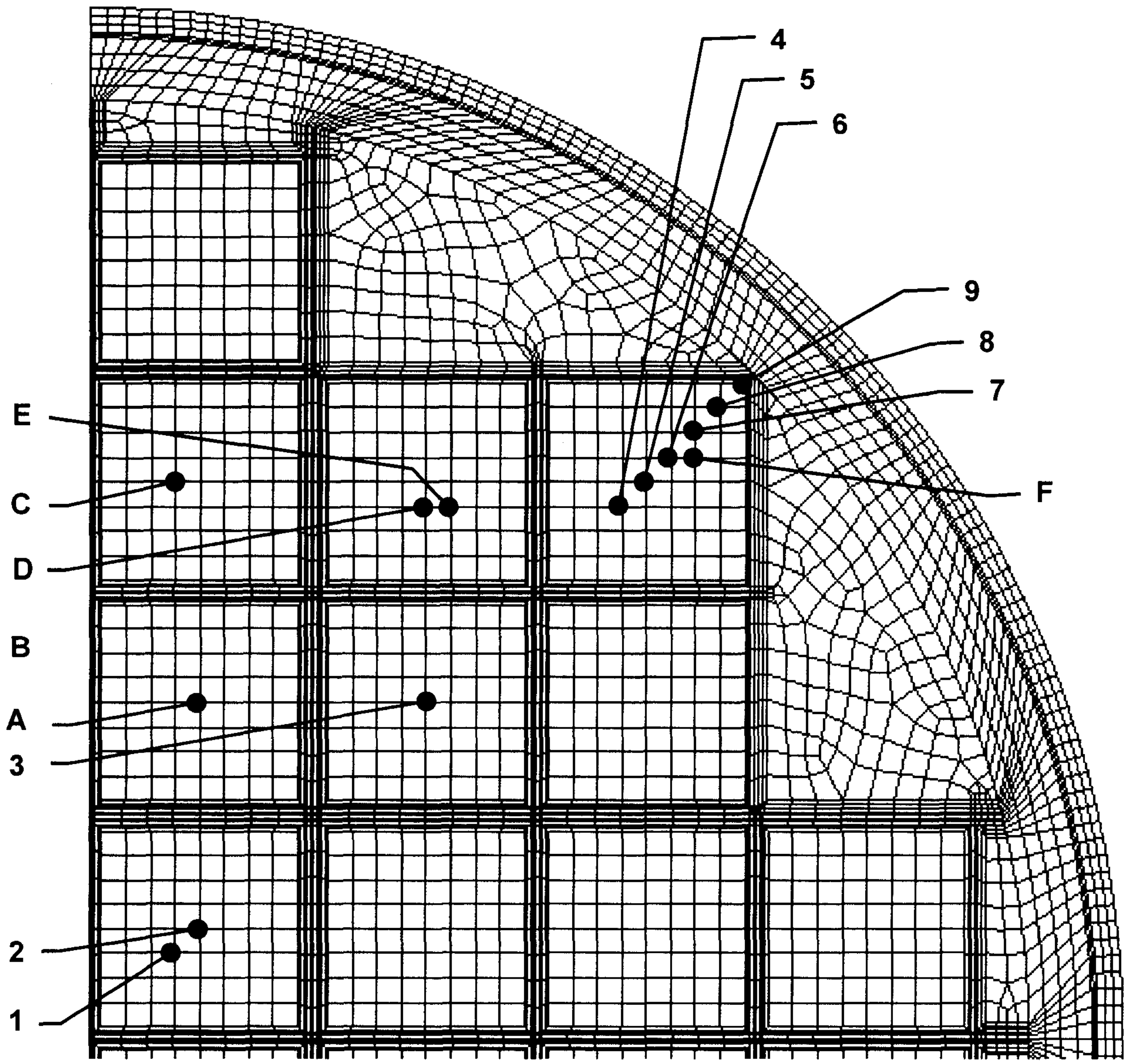

Figure 6-1. BWR Cladding Peak Temperature Locations

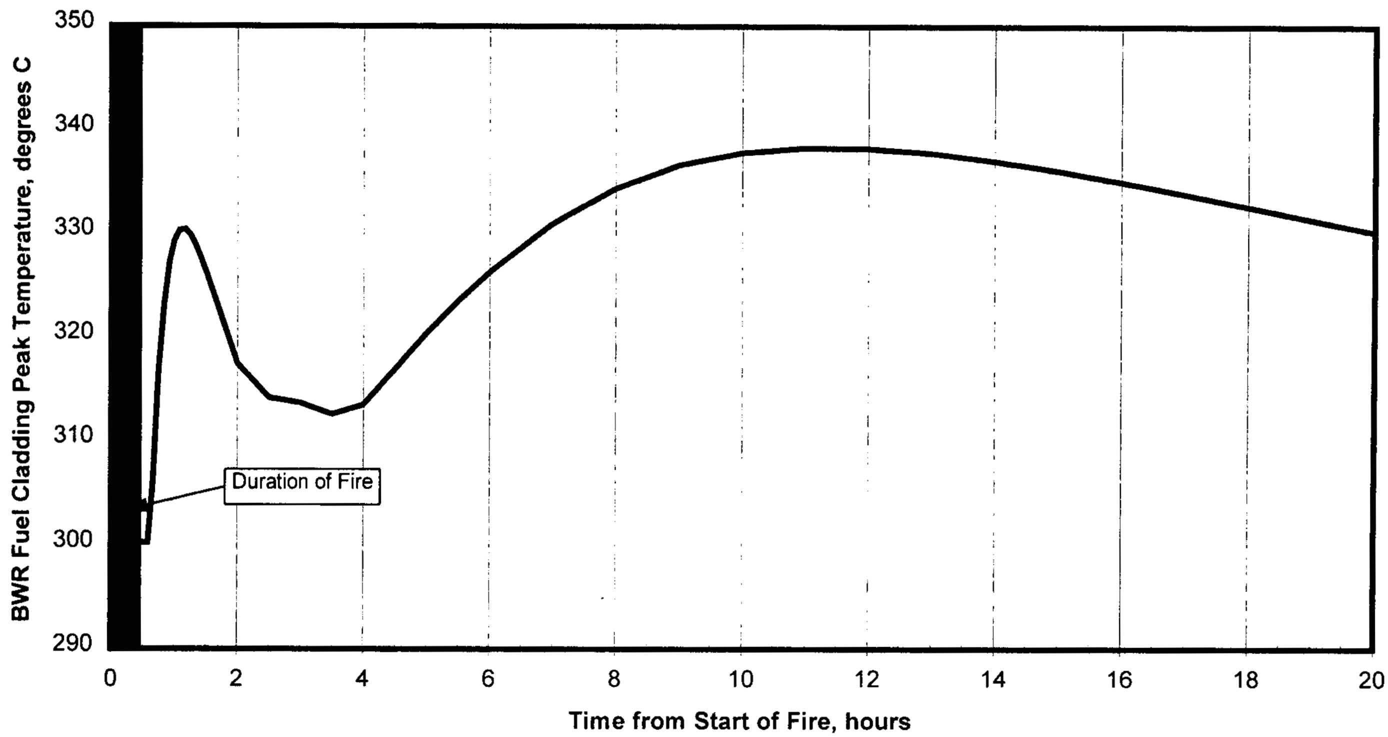

Figure 6-2. Temperature Time History of BWR Fuel Cladding for Cases 1 & 2

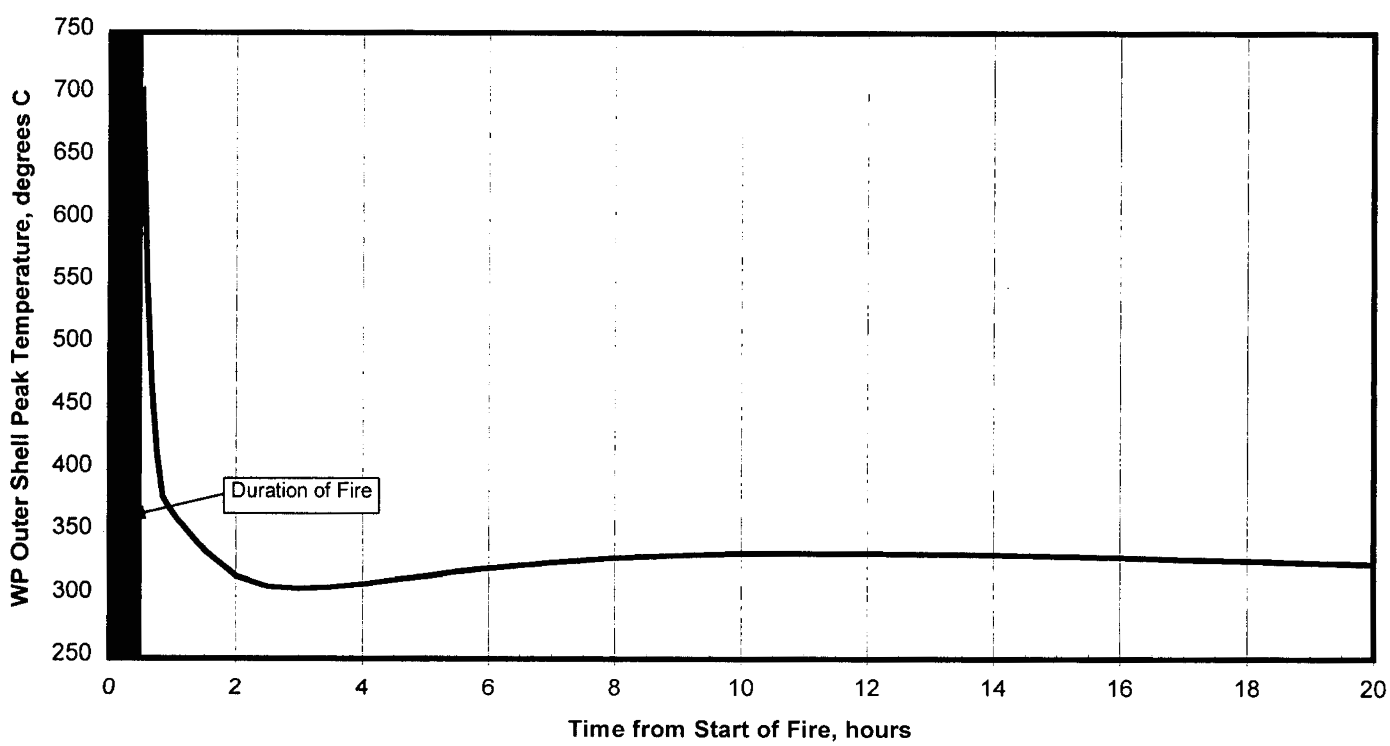

Figure 6-3. Temperature Time History of WP Outer Shell for Cases 1 & 2

6.2 CASES 3 & 4: WP WITHOUT GAPS, MAX. DESIGN THERMAL LOAD

The second two cases evaluate the effects of the BWR fuel properties in a 44-BWR WP with no gaps assumed in the WP and basket configuration. Case 3 uses BWR effective thermal conductivities representative of BWR fuel with a channel; Case 4 uses BWR effective thermal conductivities representative of BWR fuel without a channel.

Table 6-3 lists the peak temperature in each of the WP components before (t = 0 hr), during (t > 0 to 0.5 hr) and after (t > 0.5 hr) the hypothetical fire accident for the Case 3 configuration. Although the peak temperature (585°C) of the WP outer shell was reached at the end of the 30-minute fire, the peak cladding temperature (430°C) was reached about 5 minutes after the fire. This was due to the high thermal conductivity of the WP configuration with no gaps. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-3.

Table 6-4 lists the peak temperature in each of the WP components before, during and after the hypothetical fire accident for the Case 4 configuration. The small effect of the difference in effective thermal conductivities of the BWR fuel with and without a channel is evident in the results. The calculated highest fuel cladding temperature for this case is within 1°C of that calculated for Case 3. The calculated highest temperature for all other WP components are also within 1°C. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-4.

Figure 6-1 shows the peak BWR cladding temperature locations in the finite element representation that correspond to the temperature values given in Tables 6-3 and 6-4. Figure 6-4 shows the BWR fuel cladding peak temperature time history for Cases 3 and 4 from the information in Tables 6-3 and 6-4. The peak temperature location changes with time as indicated in Tables 6-3 and 6-4. Figure 6-5 shows the WP outer shell peak temperature time history for Cases 3 and 4.

The lack of gaps in the WP for this configuration significantly increased effects of the fire on the BWR fuel cladding. The peak BWR fuel cladding temperature increased 179°C, while the WP outer surface increased about 390°C. The temperature increase in the BWR fuel was much higher than that calculated in Cases 1 and 2 with gaps assumed in the WP configuration; the temperature increase in the WP outer shell was similar to that in Cases 1 and 2. However, in Cases 3 and 4 with no gaps, the pre-fire peak temperatures of the BWR fuel cladding and WP outer shell were approximately 49°C and 97°C lower, respectively.

Table 6-3. Case 3 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (°C)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	251.4	244.4	244.4	237.7	173.8	198.2
0.08	1	251.4	244.4	244.4	237.7	271.2	349.9
0.17	1	251.4	244.4	244.4	237.7	342.8	412.5
0.25	9	271.6	288.1	282.1	270.5	402.7	463.5
0.33	9	318.6	335.6	328.6	313.6	457.3	510.3
0.42	9	363.4	379.5	372.1	354.7	504.8	551.0
0.50	9	405.0	419.3	411.8	392.7	**544.7**	**585.4**
0.58	9	**430.4**	**437.1**	**431.6**	**414.5**	508.2	505.0
0.67	9	429.1	432.8	425.4	412.6	484.9	481.2
0.75	9	422.1	424.7	416.4	405.9	463.6	461.0
0.83	9	413.9	415.8	407.2	398.1	444.9	443.0
0.92	9	405.4	406.9	398.3	390.1	428.6	427.2
1.00	9	397.0	398.1	389.8	382.5	414.3	413.3
1.08	9	388.9	389.8	381.8	375.1	401.6	400.8
1.17	9	381.2	381.9	374.3	368.2	390.2	389.6
1.25	9	373.9	374.4	367.3	361.6	379.9	379.5
1.33	9	366.9	367.3	360.7	355.5	370.6	370.4
1.42	9	360.4	360.6	354.5	349.7	362.1	362.0
1.50	8	355.0	354.3	349.0	344.2	354.5	354.5
2.00	7	333.2	325.8	323.9	317.9	322.9	325.6
2.50	6	322.0	308.4	308.4	301.1	300.1	306.7
3.00	5	314.5	301.0	301.0	293.5	283.5	296.8
3.50	4	307.8	297.5	297.4	289.6	271.9	288.9
4.00	4	302.4	295.6	295.6	289.8	262.7	283.3
4.50	C	300.7	294.6	294.5	290.9	255.0	278.8
5.00	3	301.5	295.2	295.2	293.1	248.6	274.8
5.50	A	302.3	297.3	297.3	296.3	243.1	271.1
6.00	2	304.5	300.0	300.0	298.7	238.4	267.8
7.00	1	309.8	305.1	305.1	301.5	230.7	261.9
8.00	1	312.6	307.7	307.7	302.2	224.8	256.9
9.00	1	313.4	308.3	308.3	301.5	220.0	252.6
10.00	1	312.8	307.6	307.6	299.9	216.1	248.7
11.00	1	311.4	306.0	306.0	297.7	212.7	245.4
12.00	1	309.3	303.8	303.8	295.2	209.8	242.3
13.00	1	306.9	301.3	301.3	292.5	207.3	239.5
14.00	1	304.4	298.7	298.7	289.8	205.1	236.9
15.00	1	301.7	295.9	295.9	287.1	203.0	234.5
16.00	1	299.1	293.2	293.2	284.4	201.2	232.3
17.00	1	296.5	290.6	290.6	281.8	199.5	230.3
18.00	1	294.0	288.0	288.0	279.3	197.9	228.4
19.00	1	291.6	285.6	285.6	276.9	196.5	226.6
20.00	1	289.4	283.2	283.2	274.7	195.1	224.9

Table 6-4. Case 4 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (^oC)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	249.8	243.8	243.8	237.2	173.8	198.1
0.08	1	249.8	243.8	243.8	237.2	271.2	349.9
0.17	1	249.8	243.8	243.8	237.2	342.8	412.5
0.25	9	271.5	288.1	282.0	270.4	402.7	463.5
0.33	9	318.3	335.5	328.5	313.4	457.3	510.3
0.42	9	363.0	379.4	372.0	354.4	504.7	551.0
0.50	9	404.5	419.0	411.6	392.4	**544.7**	**585.4**
0.58	9	**429.7**	**436.8**	**431.2**	**414.1**	508.2	505.0
0.67	9	428.3	432.1	424.9	412.0	484.8	481.2
0.75	9	421.4	424.1	415.8	405.2	463.5	460.9
0.83	9	413.1	415.1	406.6	397.4	444.7	442.8
0.92	9	404.7	406.2	397.6	389.5	428.4	427.1
1.00	9	396.3	397.5	389.1	381.8	414.1	413.1
1.08	9	388.3	389.2	381.1	374.5	401.4	400.5
1.17	9	380.6	381.3	373.7	367.6	389.9	389.3
1.25	9	373.3	373.8	366.7	361.1	379.6	379.2
1.33	9	366.4	366.8	360.2	354.9	370.3	370.0
1.42	9	359.9	360.1	354.0	349.2	361.8	361.7
1.50	8	354.3	353.8	348.5	343.8	354.2	354.2
2.00	7	332.3	325.6	323.8	317.7	322.6	325.4
2.50	6	320.5	308.5	308.5	301.0	299.9	306.6
3.00	5	312.7	301.0	301.0	293.5	283.4	296.8
3.50	4	306.1	297.5	297.4	289.6	271.9	288.9
4.00	E	301.1	295.5	295.5	289.8	262.7	283.4
4.50	C	299.7	294.5	294.4	291.0	255.1	278.9
5.00	3	300.6	295.2	295.2	293.2	248.6	274.8
5.50	B	301.7	297.3	297.3	296.3	243.2	271.2
6.00	2	304.0	300.0	300.0	298.7	238.5	267.8
7.00	1	309.1	305.1	305.1	301.4	230.8	261.9
8.00	1	311.6	307.5	307.5	302.0	224.9	256.9
9.00	1	312.2	308.0	308.0	301.3	220.1	252.6
10.00	1	311.5	307.2	307.2	299.6	216.2	248.8
11.00	1	309.8	305.4	305.4	297.3	212.9	245.4
12.00	1	307.7	303.2	303.2	294.8	210.0	242.3
13.00	1	305.2	300.6	300.6	292.0	207.5	239.5
14.00	1	302.6	297.9	297.9	289.3	205.2	236.9
15.00	1	299.9	295.2	295.2	286.5	203.1	234.5
16.00	1	297.3	292.4	292.4	283.8	201.3	232.3
17.00	1	294.7	289.8	289.8	281.2	199.6	230.2
18.00	1	292.2	287.2	287.2	278.7	198.0	228.3
19.00	1	289.8	284.7	284.7	276.3	196.5	226.5
20.00	1	287.5	282.4	282.4	274.0	195.2	224.8

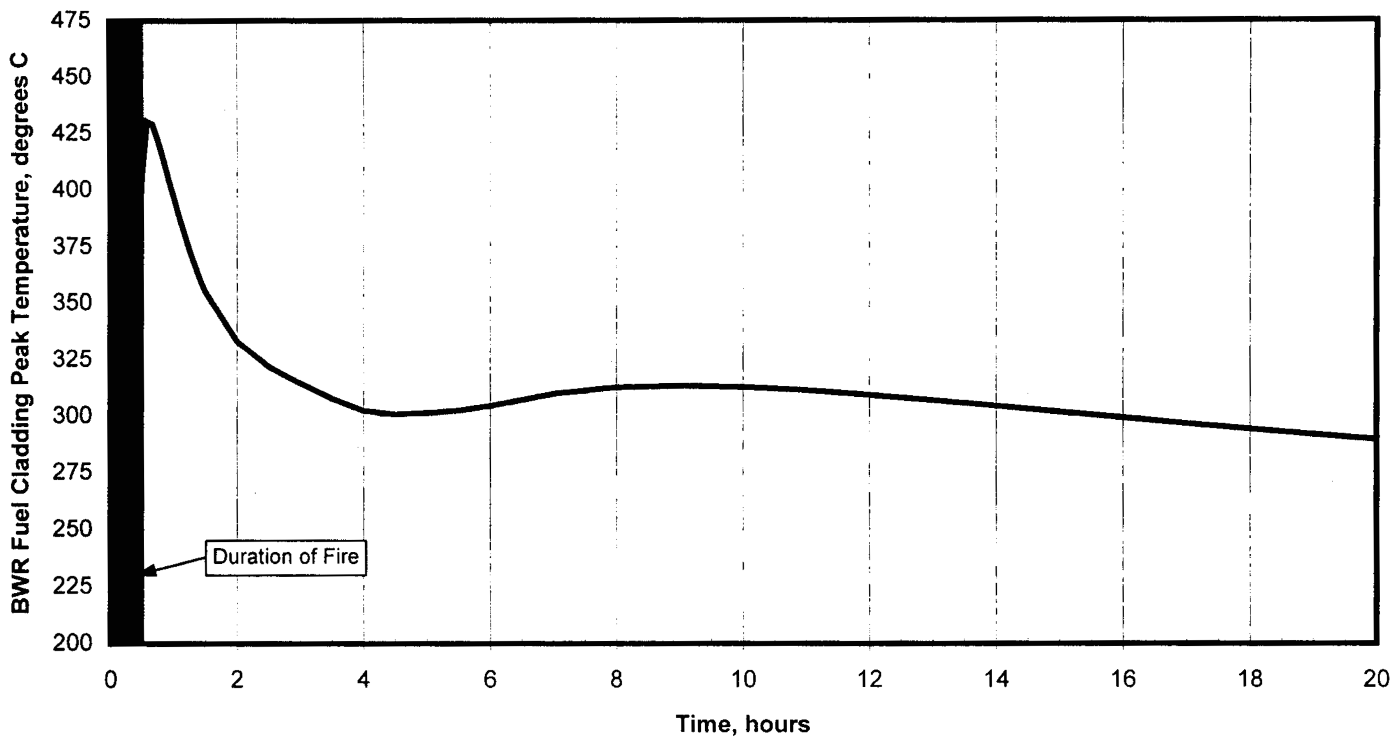

Figure 6-4. Temperature Time History of BWR Fuel Cladding for Cases 3 & 4

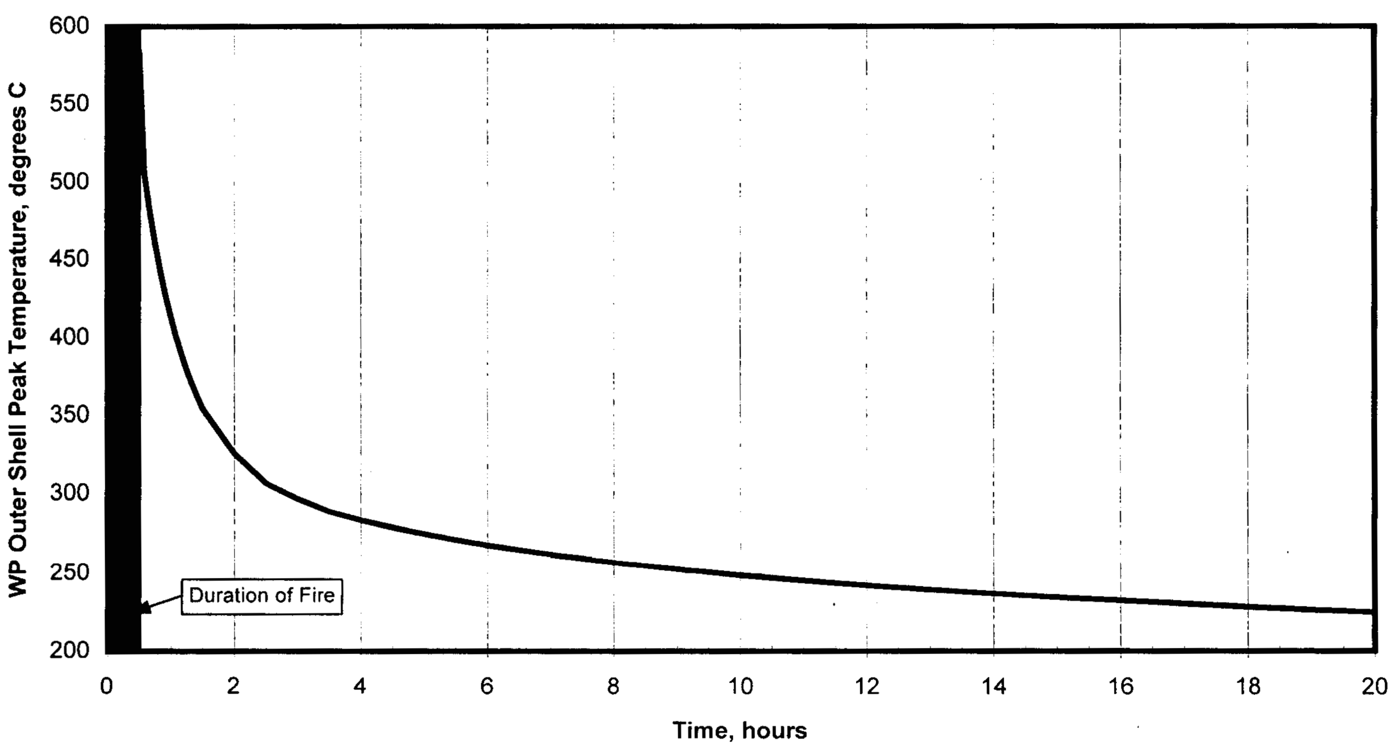

Figure 6-5. Temperature Time History of WP Outer Shell for Cases 3 & 4

6.3 CASES 5 & 6: WP WITHOUT GAPS, 1.2 X MAX. DESIGN THERMAL LOAD

The last two cases evaluate the effects of the BWR fuel properties in a 44-BWR WP with no gaps assumed in the WP and basket configuration, and a 20% increase in the design thermal load of the BWR fuel. Case 5 uses BWR effective thermal conductivities representative of BWR fuel with a channel; Case 6 uses BWR effective thermal conductivities representative of BWR fuel without a channel.

Table 6-5 lists the peak temperature in each of the WP components before (t = 0 hr), during (t > 0 to 0.5 hr) and after (t > 0.5 hr) the hypothetical fire accident for the Case 5 configuration. Although the peak temperature (590°C) of the WP outer shell was reached at the end of the 30-minute fire, the peak cladding temperature (439°C) was reached about 5 minutes after the fire. This was due to the high thermal conductivity of the WP configuration with no gaps. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-5.

Table 6-6 lists the peak temperature in each of the WP components before, during and after the hypothetical fire accident for the Case 6 configuration. The small effect of the difference in effective thermal conductivities of the BWR fuel with and without a channel is evident in the results. The calculated highest fuel cladding temperature for this case is within 1°C of that calculated for Case 5. The calculated highest temperature for all other WP components are also within 1°C. The highest temperature calculated for each WP component is indicated by bolded text in Table 6-6.

Figure 6-1 shows the peak BWR cladding temperature locations in the finite element representation that correspond to the temperature values given in Tables 6-5 and 6-6. Figure 6-6 shows the BWR fuel cladding peak temperature time history for Cases 5 and 6 from the information in Tables 6-5 and 6-6. The peak temperature location changes with time as indicated in Tables 6-5 and 6-5. Figure 6-7 shows the WP outer shell peak temperature time history for Cases 5 and 6.

The 20% increase in the thermal load for the BWR fuel resulted in an increase of about 8°C in the calculated BWR fuel cladding peak temperature. However, the pre-fire peak temperature of BWR cladding was about 27°C higher in the cases with the higher thermal load. Therefore, the temperature rise resulting from the hypothetical fire was actually smaller for the cases with the assumed higher thermal load.

The increase in the calculated peak temperature of the WP outer shell was about 5°C. The peak pre-fire temperature of the WP outer shell was about 17°C higher in the cases with the higher thermal load. This higher initial shell temperature reduced the temperature difference for the heat transfer from the fire and resulted in the smaller rise in temperature due to the effects of the fire.

6.4 RESULTS COMPARISON

Figure 6-8 compares the calculated BWR cladding peak temperature time history results for the 44-BWR WP for the hypothetical fire accident with: (1) assumed gaps in WP and the maximum design thermal load (Cases 1 & 2), (2) no gaps in WP and the maximum design thermal load (Cases 3 & 4), and (3) no gaps in WP and a 20% increase in the maximum design thermal load (Cases 5 & 6). Figure 6-9 compares the WP outer shell temperatures for these same configurations.

Table 6-5. Case 5 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (^oC)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	278.1	270.7	270.7	262.7	186.8	215.5
0.08	1	278.1	270.7	270.7	262.7	281.6	358.7
0.17	1	278.1	270.7	270.7	262.7	352.2	420.4
0.25	9	282.9	299.5	293.6	282.8	410.8	470.4
0.33	9	329.4	346.4	339.7	325.4	464.4	516.4
0.42	9	373.7	389.7	382.5	366.0	511.0	556.4
0.50	9	414.7	428.8	421.6	403.4	**550.2**	**590.1**
0.58	9	**438.8**	**445.2**	**439.8**	**423.9**	512.4	508.6
0.67	9	436.8	440.3	433.2	421.3	488.9	485.5
0.75	9	429.6	432.0	424.0	414.4	467.6	465.2
0.83	9	421.2	423.0	414.7	406.5	449.1	447.3
0.92	9	412.6	413.9	405.6	398.5	432.9	431.6
1.00	9	404.1	405.1	397.1	390.7	418.7	417.8
1.08	9	396.0	396.7	389.1	383.4	406.1	405.3
1.17	9	388.3	388.7	381.6	376.4	394.7	394.3
1.25	9	380.9	381.2	374.6	369.9	384.5	384.3
1.33	9	373.9	374.1	368.1	363.7	375.4	375.3
1.42	8	368.6	367.4	362.3	357.9	367.4	367.2
1.50	7	363.9	361.1	357.3	352.5	361.1	361.0
2.00	F	344.2	334.8	333.1	327.1	329.9	334.6
2.50	5	335.1	321.3	321.3	313.5	307.3	318.3
3.00	5	328.5	316.1	316.1	308.3	292.2	309.0
3.50	4	322.8	314.4	314.4	308.0	280.8	302.3
4.00	D	320.3	313.9	313.9	309.8	271.6	297.3
4.50	3	321.6	314.9	314.8	312.6	264.1	292.8
5.00	A	323.1	317.7	317.7	316.5	257.8	288.8
5.50	2	326.2	321.1	321.1	319.6	252.4	285.1
6.00	2	329.7	324.7	324.7	321.8	247.8	281.8
7.00	1	334.7	329.5	329.5	324.3	240.3	275.9
8.00	1	337.1	331.8	331.8	324.8	234.5	271.0
9.00	1	337.6	332.2	332.2	323.9	229.9	266.7
10.00	1	336.8	331.2	331.2	322.2	226.0	263.0
11.00	1	335.2	329.5	329.5	319.9	222.8	259.7
12.00	1	333.0	327.2	327.2	317.3	220.1	256.7
13.00	1	330.6	324.7	324.7	314.6	217.7	254.0
14.00	1	328.0	322.0	322.0	311.9	215.5	251.5
15.00	1	325.4	319.3	319.3	309.2	213.6	249.2
16.00	1	322.8	316.6	316.6	306.5	211.9	247.1
17.00	1	320.2	314.0	314.0	304.0	210.2	245.1
18.00	1	317.8	311.5	311.5	301.5	208.8	243.3
19.00	1	315.4	309.1	309.1	299.2	207.4	241.6
20.00	1	313.2	306.8	306.8	297.0	206.1	240.0

Table 6-6. Case 6 Calculated Peak Temperatures versus Time

Time (hrs)	Location of Peak Cladding Temp. (Figure 6-1)	Peak Temperature of Component (^oC)					
		BWR Cladding	WP Basket	Neutron Absorber	Thermal Shunt	WP Inner Shell	WP Outer Shell
0.00	1	276.1	269.9	269.9	262.0	186.7	215.4
0.08	1	276.1	269.9	269.9	262.0	281.6	358.7
0.17	1	276.1	269.9	269.9	262.0	352.2	420.4
0.25	9	282.8	299.4	293.6	282.7	410.8	470.4
0.33	9	329.2	346.4	339.6	325.3	464.4	516.4
0.42	9	373.3	389.6	382.4	365.7	511.0	556.4
0.50	9	414.2	428.5	421.3	403.0	**550.2**	**590.1**
0.58	9	**438.1**	**444.8**	**439.4**	**423.4**	512.3	508.6
0.67	9	436.1	439.6	432.7	420.8	488.8	485.4
0.75	9	428.9	431.3	423.4	413.8	467.5	465.1
0.83	9	420.5	422.3	414.0	405.8	448.9	447.2
0.92	9	411.9	413.2	405.0	397.8	432.7	431.4
1.00	9	403.5	404.5	396.5	390.1	418.5	417.5
1.08	9	395.4	396.1	388.5	382.7	405.8	405.1
1.17	9	387.7	388.2	381.0	375.8	394.4	394.0
1.25	9	380.3	380.7	374.0	369.3	384.3	384.0
1.33	9	373.4	373.6	367.5	363.2	375.0	375.0
1.42	8	367.8	366.9	361.8	357.4	366.9	366.8
1.50	8	363.0	360.7	356.8	352.1	360.6	360.5
2.00	7	343.2	334.6	333.1	326.8	329.6	334.4
2.50	D	333.6	321.4	321.4	313.5	307.1	318.2
3.00	5	326.4	316.1	316.1	308.3	292.1	309.0
3.50	4	320.8	314.3	314.3	307.9	280.7	302.3
4.00	B	319.2	313.7	313.7	309.7	271.6	297.3
4.50	3	320.5	314.7	314.7	312.5	264.1	292.8
5.00	A	322.2	317.5	317.5	316.4	257.8	288.8
5.50	2	325.4	320.9	320.9	319.5	252.5	285.1
6.00	2	328.8	324.5	324.5	321.7	247.9	281.8
7.00	1	333.6	329.3	329.3	324.0	240.4	275.9
8.00	1	335.7	331.4	331.4	324.4	234.6	271.0
9.00	1	336.0	331.6	331.6	323.4	230.0	266.7
10.00	1	335.0	330.5	330.5	321.6	226.2	263.0
11.00	1	333.2	328.7	328.7	319.3	223.0	259.7
12.00	1	331.0	326.3	326.3	316.6	220.2	256.7
13.00	1	328.4	323.7	323.7	313.9	217.8	254.0
14.00	1	325.8	321.0	321.0	311.1	215.7	251.5
15.00	1	323.1	318.2	318.2	308.4	213.7	249.2
16.00	1	320.5	315.5	315.5	305.7	212.0	247.0
17.00	1	318.0	312.9	312.9	303.1	210.3	245.0
18.00	1	315.5	310.4	310.4	300.7	208.8	243.2
19.00	1	313.2	308.0	308.0	298.4	207.4	241.5
20.00	1	310.9	305.7	305.7	296.2	206.2	239.9

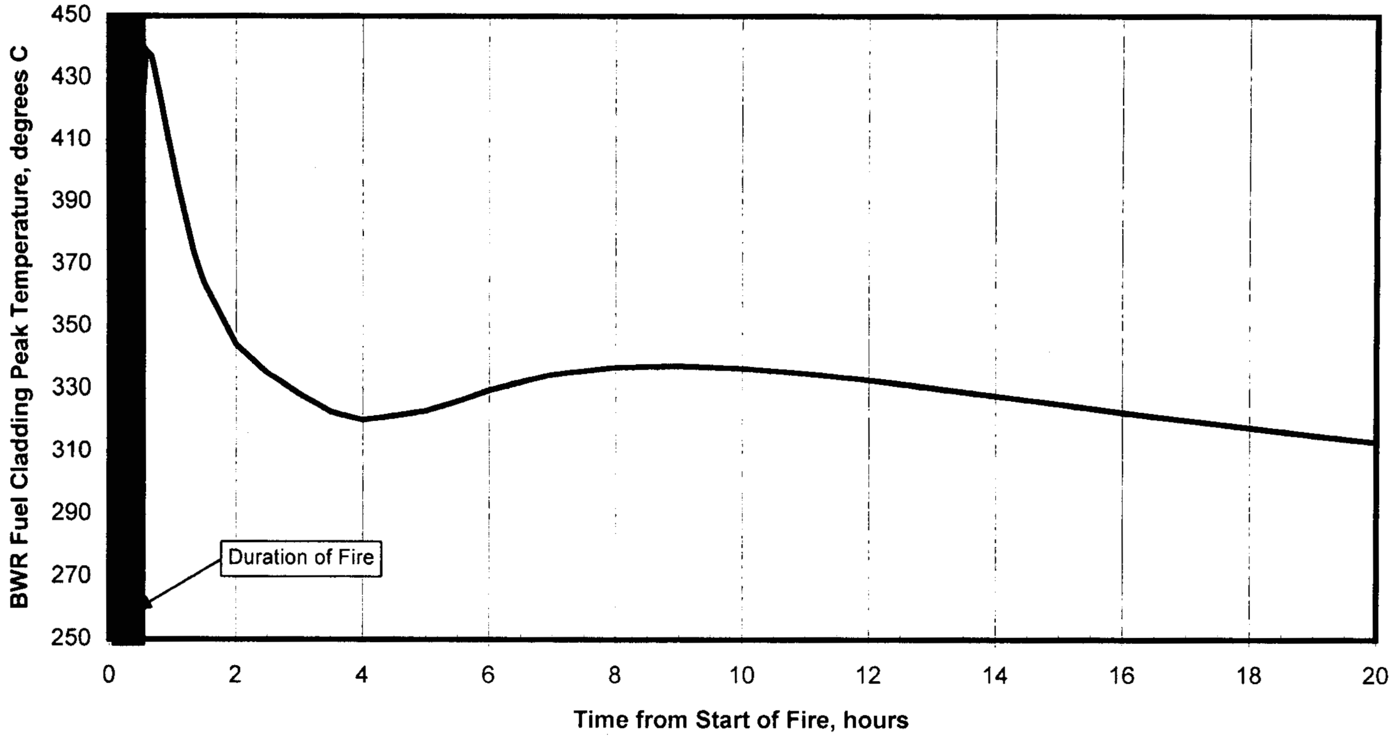

Figure 6-6. Temperature Time History of BWR Fuel Cladding for Cases 5 & 6

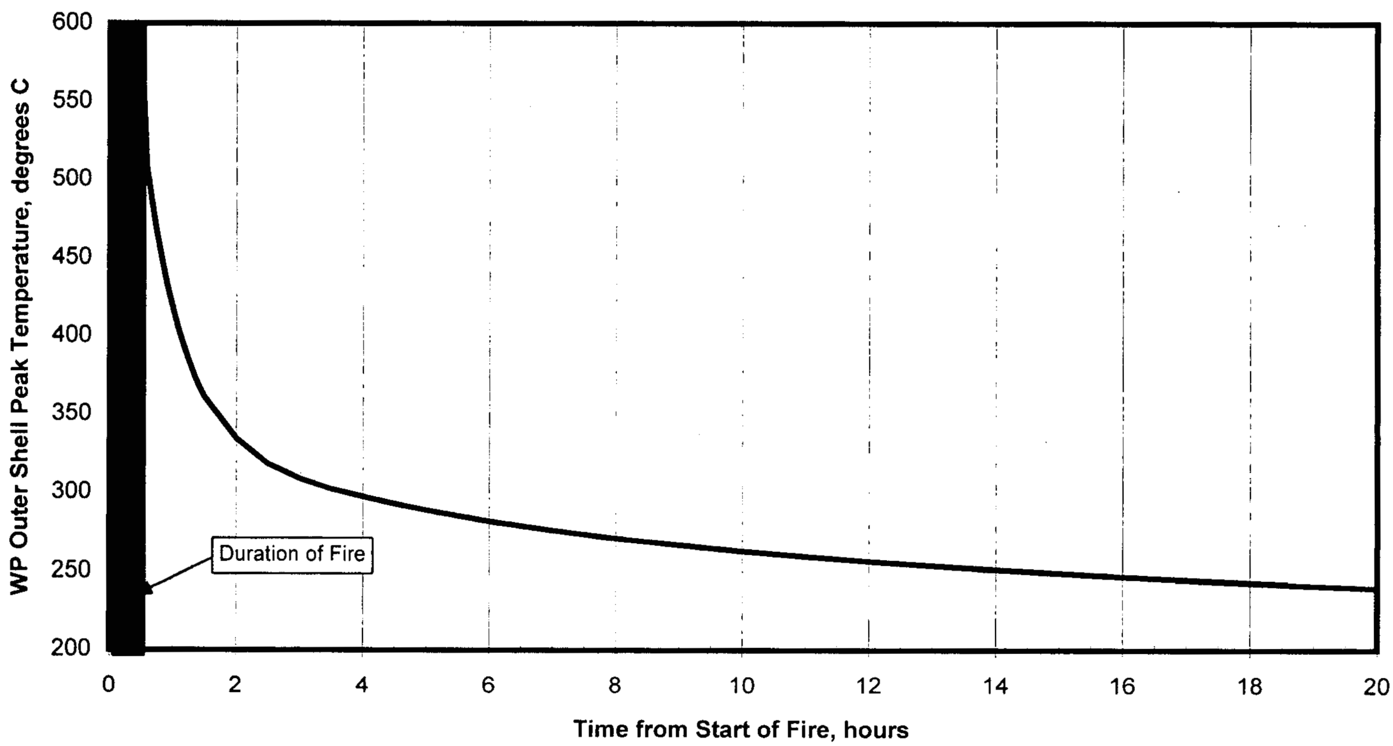

Figure 6-7. Temperature Time History of WP Outer Shell for Cases 5 & 6

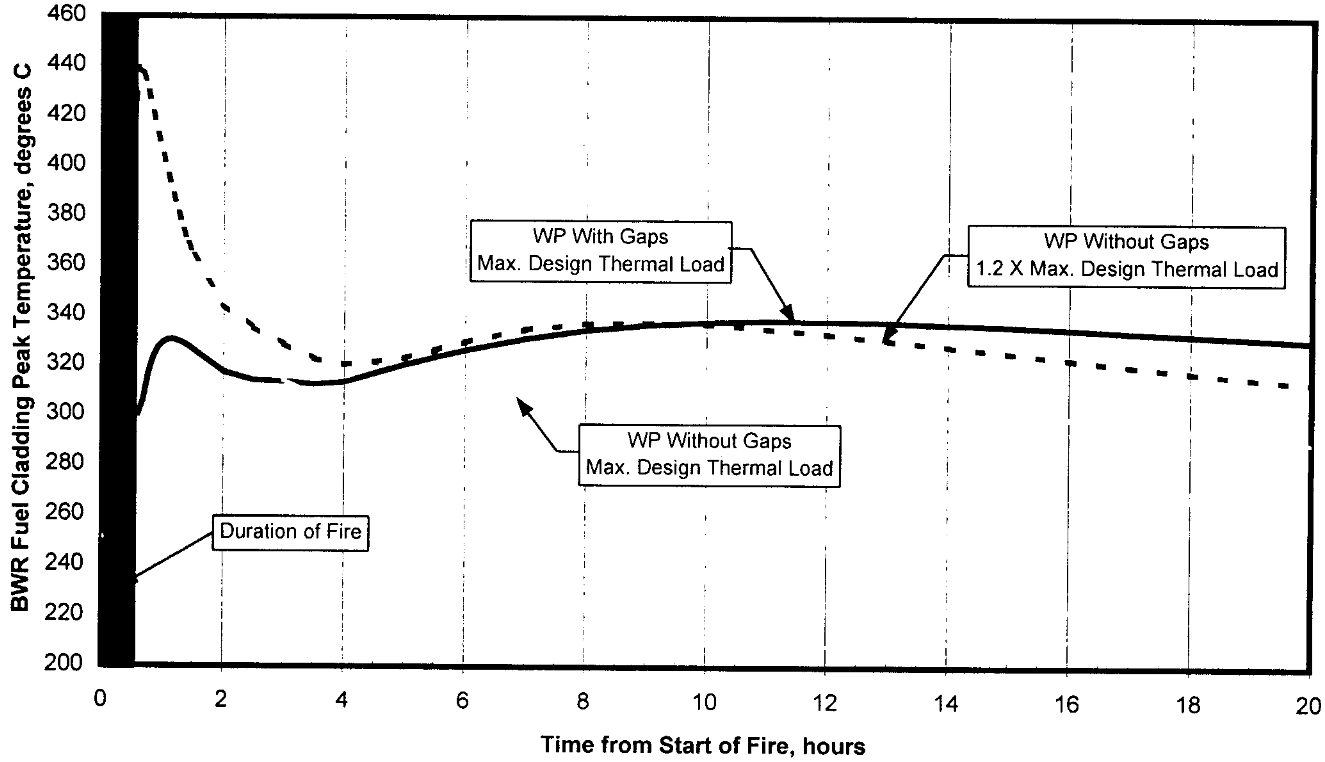

Figure 6-8. Thermal Response of BWR Cladding in 44-BWR WP to Fire Accident

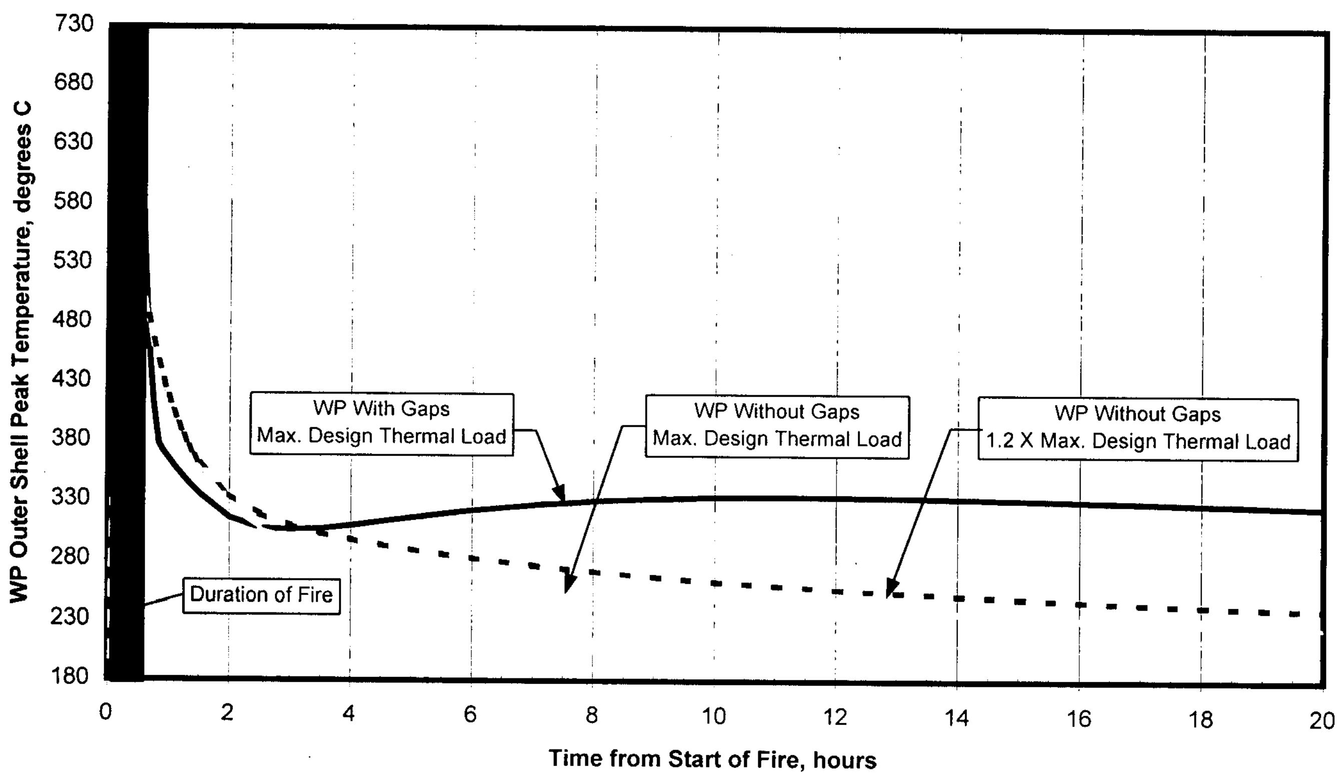

Figure 6-9. Thermal Response of WP Outer Shell in 44-BWR WP to Fire Accident

7. REFERENCES

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14. Not used.

15. Not used.

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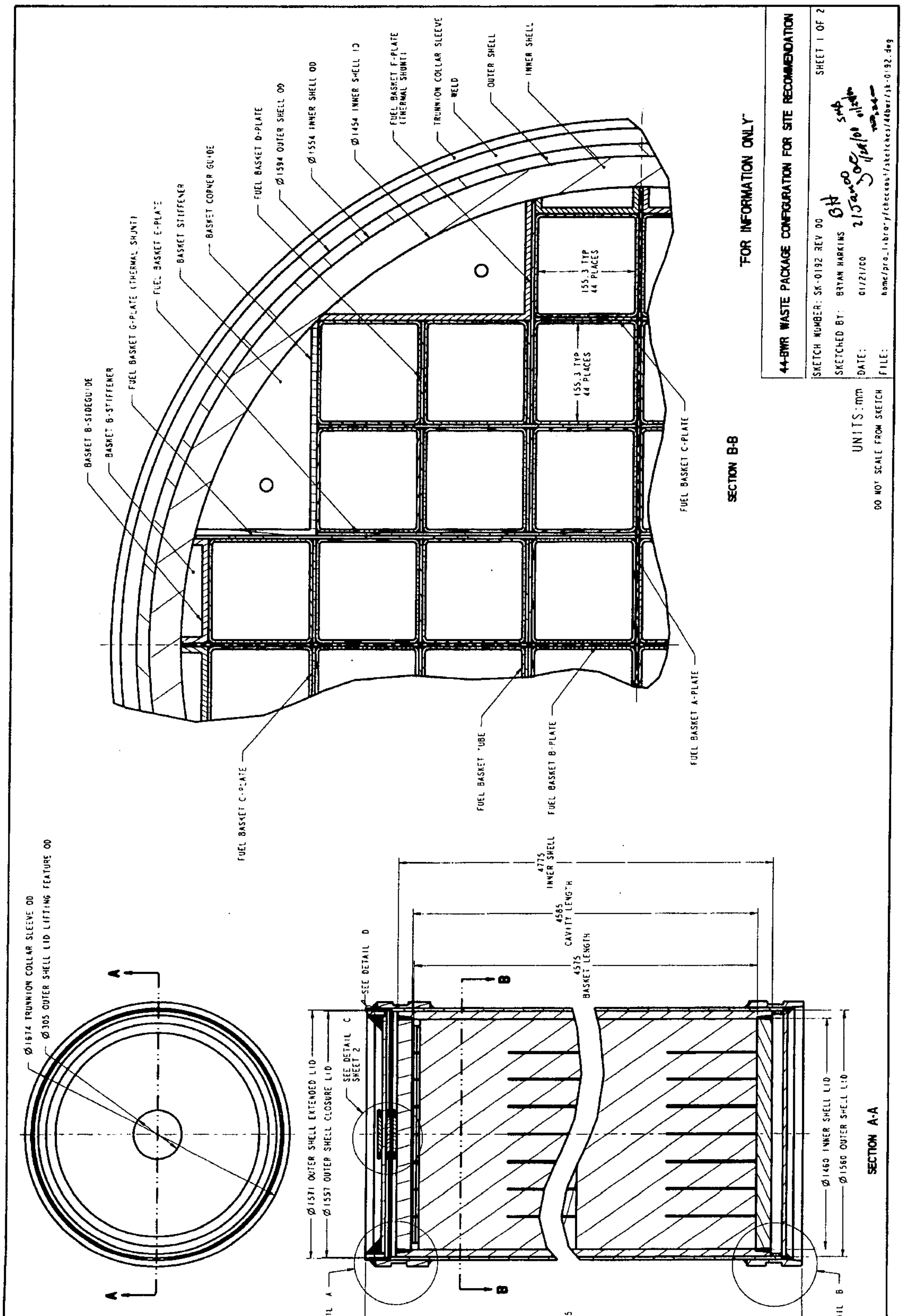
8. ATTACHMENTS

The list of attachments is provided in Table 8-1.

Table 8-1. Supporting Documentation

Attachment Number	Description	Size (pages)
I	44-BWR Waste Package Configuration for Site Recommendation Sketch Number: SK-0192 REV 00	2
II	44-BWR Waste Package Assembly Weld Configuration Sketch Number: SK-0193 REV 00	1
III	Effective Heat Transfer Coefficient at Waste Package Outer Surface	2
IV	File (propwp01.dat) containing tables of material properties	3
V	List of ANSYS output files contained on CD	1
VI	CD containing ANSYS files	1 CD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DATE: 01/21/00
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SECTION B-B
SECTION A-A
155.3 TYP 44 PLACES
FUEL BASKET A-PLATE
FUEL BASKET B-PLATE
FUEL BASKET C-PLATE
FUEL BASKET D-PLATE
FUEL BASKET E-PLATE
FUEL BASKET TUBE
BASKET STIFFENER
BASKET CORNER GUIDE
BASKET B-SIDEGUIDE
BASKET B-STIFFENER
FUEL BASKET G-PLATE (THERMAL SHUNT)
FUEL BASKET F-PLATE (THERMAL SHUNT)
TRUNNION COLLAR SLEEVE
WELD
OUTER SHELL
INNER SHELL
Ø1594 OUTER SHELL OD
Ø1554 INNER SHELL OD
Ø1454 INNER SHELL ID
Ø1674 TRUNNION COLLAR SLEEVE OD
Ø305 OUTER SHELL LID LIFTING FEATURE OD
Ø1571 OUTER SHELL EXTENDED LID
Ø1557 OUTER SHELL CLOSURE LID
Ø1460 INNER SHELL LID
Ø1560 OUTER SHELL LID
4775 INNER SHELL
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4575 BASKET LENGTH
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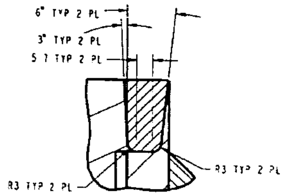
SEE DETAIL A SHEET 2
SEE DETAIL B SHEET 2
SEE DETAIL C SHEET 2
SEE DETAIL D



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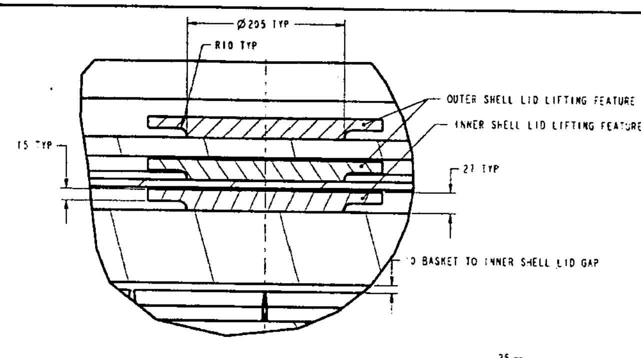

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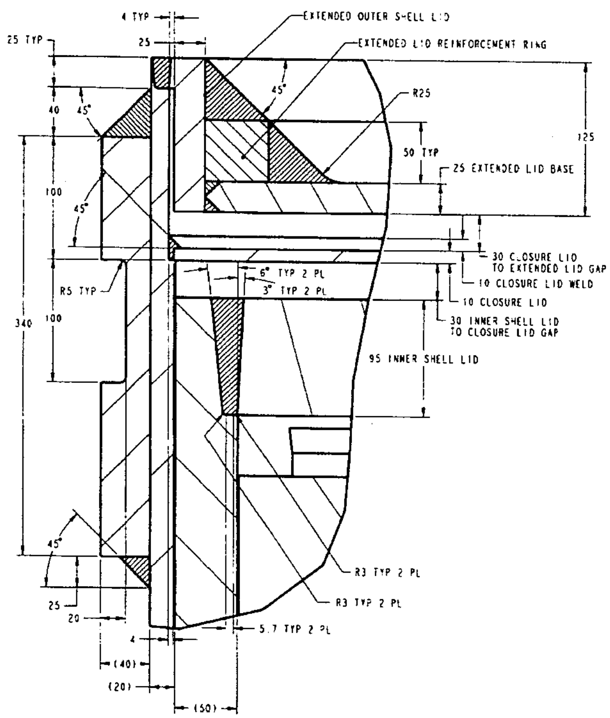

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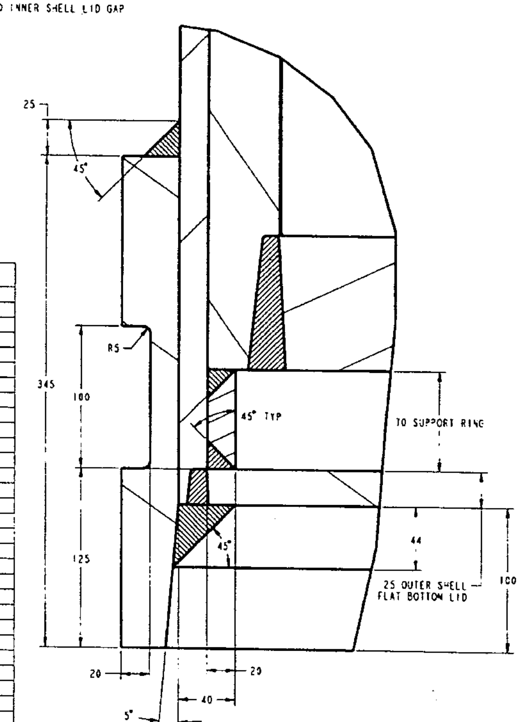


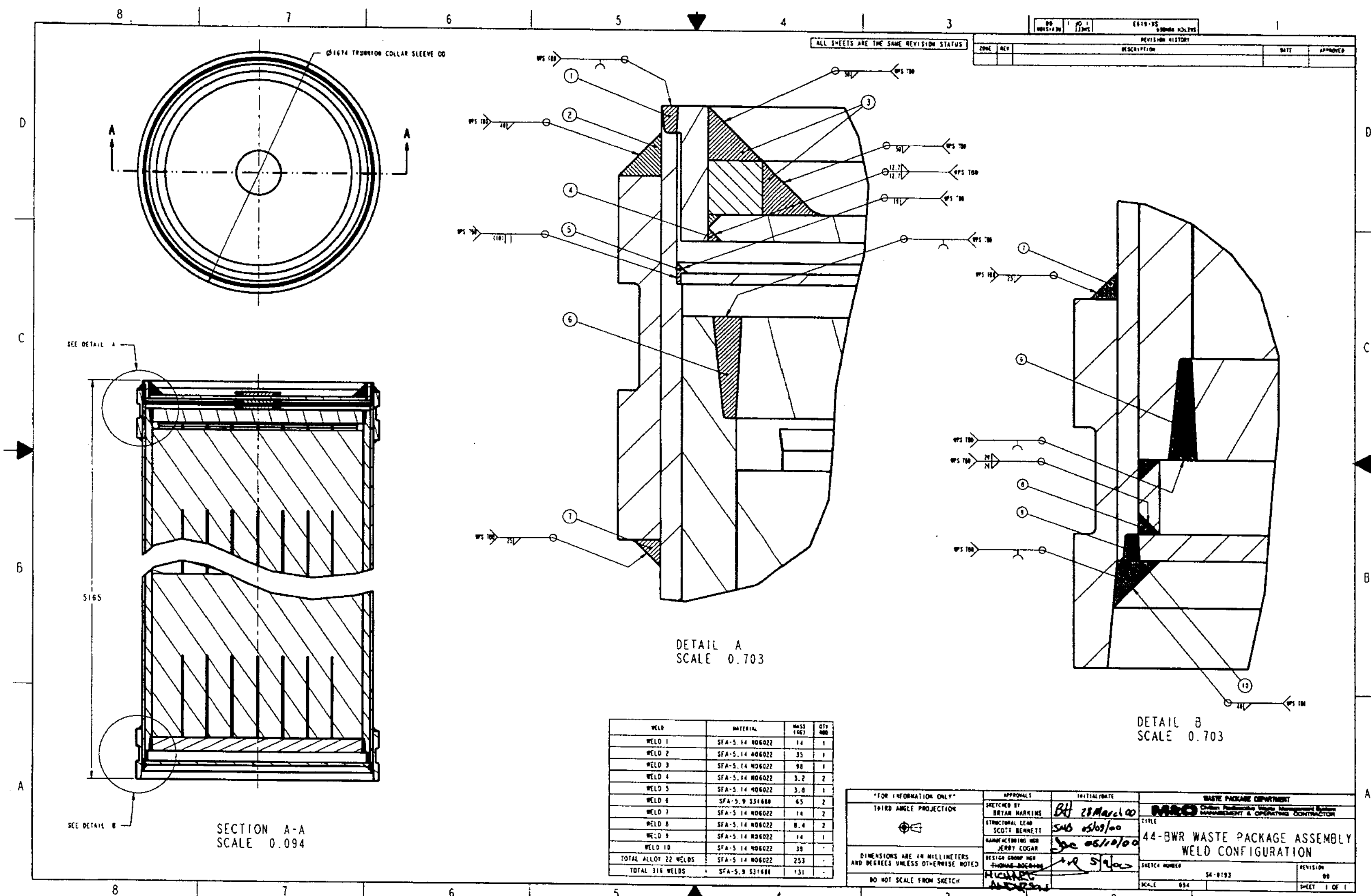
DETAIL B

COMPONENT NAME	MATERIAL	THICKNESS	MASS (KG)	QTY RQD
BASKET B-SIDEGUIDE	SA-516 K02700	10	9	32
BASKET B-STIFFENER	SA-516 K02700	10	0.31	64
BASKET CORNERGUIDE	SA-516 K02700	10	46	32
BASKET STIFFENER	SA-516 K02700	10	2.7	64
FUEL BASKET A-PLATE	NEUTRONIT A 978	5	63	4
FUEL BASKET B-PLATE	NEUTRONIT A 978	5	63	4
FUEL BASKET C-PLATE	NEUTRONIT A 978	5	15	16
FUEL BASKET D-PLATE	NEUTRONIT A 978	5	44	16
FUEL BASKET E-PLATE	NEUTRONIT A 978	5	44	16
FUEL BASKET F-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET G-PLATE	SB-209 A96061 T4	5	21	8
FUEL BASKET TUBE	SA-516 K02700	5	113	44
INNER SHELL	SA-240 S31600	50	8886	1
INNER SHELL LID	SA-240 S31600	95	1251	2
INNER SHELL LID LIFTING FEATURE	SA-240 S31600	27	12	1
OUTER SHELL	SB-575 N06022	20	4275	1
EXTENDED OUTER SHELL LID	SB-575 N06022	25	135	1
EXTENDED OUTER SHELL LID BASE	SB-575 N06022	25	381	1
OUTER SHELL LID LIFTING FEATURE	SB-575 N06022	27	13	2
EXTENDED LID REINFORCEMENT RING	SB-575 N06022	50	99	1
OUTER SHELL FLAT CLOSURE LID	SB-575 N06022	10	165	1
OUTER SHELL FLAT BOTTOM LID	SB-575 N06022	25	412	1
UPPER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	517	1
LOWER TRUNNION COLLAR SLEEVE	SB-575 N06022	40	507	1
INNER SHELL SUPPORT RING	SB-575 N06022	20	42	1
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	-	253	**
TOTAL 316 WELDS	SFA-5.9 S31680	-	131	**
WASTE PACKAGE ASSEMBLY	-	-	28068	1
BWR FUEL ASSEMBLY	-	-	328.4*	44
WASTE PACKAGE ASSEMBLY WITH SNF	-	-	42517	1

* CRWMS M&O 1997 WASTE CONTAINER CAVITY SIZE DETERMINATION. BBAA00000-01717-0200-00026 REV 00 LAS VEGAS, NV: CRWMS M&O ACC: MOL.19980106.0061

** REFER TO SK-0193 REV 00 "SINGLE CRM 44-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION"

SK-0192 REV 00 | SHEET 2 OF 2



WELD	MATERIAL	MASS (KG)	QTY REQ
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WELD 2	SFA-5.14 N06022	35	1
WELD 3	SFA-5.14 N06022	98	1
WELD 4	SFA-5.14 N06022	3.2	2
WELD 5	SFA-5.14 N06022	3.8	1
WELD 6	SFA-5.9 S31600	65	2
WELD 7	SFA-5.14 N06022	14	2
WELD 8	SFA-5.14 N06022	8.4	2
WELD 9	SFA-5.14 N06022	14	1
WELD 10	SFA-5.14 N06022	39	-
TOTAL ALLOY 22 WELDS	SFA-5.14 N06022	253	-
TOTAL 316 WELDS	SFA-5.9 S31600	131	-

"FOR INFORMATION ONLY"	APPROVALS	INITIAL/DATE
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	DESIGN GROUP MGR ~~THOMAS DOERING~~ RICHARD ANDERSON	5/9/00
DO NOT SCALE FROM SKETCH		

WASTE PACKAGE DEPARTMENT
M&O Civilian Radioactive Waste Management System MANAGEMENT & OPERATING CONTRACTOR

TITLE
44-BWR WASTE PACKAGE ASSEMBLY WELD CONFIGURATION

SKETCH NUMBER SK-0193 | REVISION 00
SCALE 094 | SHEET 1 OF 1

Heat Transfer Coefficients at Waste Package Outer Surface

Values of heat transfer coefficient at the waste package (WP) outer surface are given in the table below for various conditions. An example calculation is included.

Condition	w/o flame	w/ flame
Emissivity:		
Alloy 22	0.87	1
Surroundings	1	1
Effective	0.87	1
Temperature of Surroundings (°C)	38.0	800
Free-Convection Multiplier	0	1
Temperature of WP Surface (°C)	**Effective Heat Transfer Coefficient ($W/m^2 \cdot K$)**	
37.78	5.9	110.0
100	8.0	117.5
150	10.0	124.3
200	12.4	131.7
250	15.2	139.8
300	18.6	148.6
350	22.4	158.2
400	26.7	168.6
450	31.6	179.8
500	37.2	191.9
550	43.3	204.9
600	50.2	218.9
650	57.8	233.8
700	66.1	249.6
750	75.3	266.1
800	85.3	280.3

An example calculation of effective heat transfer coefficient at the WP outer surface follows:

Conditions:

Temperature of surroundings (e.g., for flame)

$$T_{SURR} = 800°C + 273.15$$
$$= 1073.15K$$

Temperature of WP outside surface

$$T_{WPOS} = 37.78°C + 273.15$$

$= 310.93°K$

Emissivity of surroundings

$$\varepsilon_{SURR} = 1.0$$

Emissivity of WP outer surface

$$\varepsilon_{WPOS} = 1.0$$

Effective emissivity:

$$\varepsilon_{EFF} = [(1/\varepsilon_{WPOS}) + (1/\varepsilon_{SURR}) - 1]^{-1}$$
$$= [(1/1.0) + (1/1.0) - 1]^{-1}$$
$$= 1.0$$

Effective heat transfer coefficient for radiation:

$$h_R = (\sigma)(\varepsilon_{EFF})[(T_{SURR})^2 + (T_{WPOS})^2](T_{SURR} + T_{WPOS})$$
$$= (5.67E\text{-}8)(1.0)[(1073.15)^2 + (310.93)^2](1073.15 + 310.93)$$
$$= 98.0 \text{ W/m}^2\cdot\text{K}$$

Film coefficient for heating:

$$h_C = (1.3123)(T_{SURR} - T_{WPOS})^{1/3}$$
$$= (1.3123)(1073.15 - 310.93)^{1/3}$$
$$= 12.0 \text{ W/m}^2\cdot\text{K}$$

Total effective heat transfer coefficient:

$$h_{EFF} = h_R + h_C$$
$$= 98.0 + 12.0$$
$$= 110.0 \text{ W/m}^2\cdot\text{K}$$

This attachment presents a listing of the ANSYS input file of material properties.

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Table V-1 in this attachment presents the list of ANSYS output files that contain the ANSYS input file listing and the thermal analysis results for this calculation. These files are contained on the compact disk (CD) (Attachment VI) associated with this file.

Table V-1. List of Files Contained on the CD

File Name	Date	Time	Size
Case1.out	12/08/00	11:50 PM	672 KB
Case2.out	12/17/00	11:02 AM	671 KB
Case3.out	2/16/01	6:57 PM	626 KB
Case4.out	2/19/01	1:19 AM	626 KB
Case5.out	2/19/01	3:13 PM	643 KB
Case6.out	2/19/01	11:00 PM	626 KB

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SPECIAL INSTRUCTION SHEET DR 4-25-01 MKC Page: 1 of: 1

Complete Only Applicable Items

This is a placeholder page for records that cannot be scanned or microfilmed

2. Record Date	3. Accession Number
04/05/2001	ATT-TO MOL.20010425.0001
4. Author Name(s)	**5. Author Organization**
JAMES R. SMOTREL	N/A

6. Title
THERMAL RESPONSE OF THE 44-BWR WASTE PACKAGE TO A HYPOTHETICAL FIRE ACCIDENT

7. Document Number(s)	8. Version
CAL-UDC-TH-000004	REV 00

9. Document Type	10. Medium
DATA	CD-ROM

11. Access Control Code
PUB

12. Traceability Designator
DC # 27733

13. Comments
THIS IS A SPECIAL PROCESS CD-ROM ENCLOSED AS ATTACHMENT VI, AND CAN BE LOCATED THROUGH THE RPC

NOTE: SEE ATTACHMENT OF ELECTRONIC SOURCE FILE VERIFICATION FORM PER AP-17.1Q/ICN 3, SECTION 5.1 (C), ELECTRONIC RECORDS

DC# 27133

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ELECTRONIC SOURCE FILE VERIFICATION

QA: N/A

1. DOCUMENT TITLE: Thermal Response of the 44-BWR Waste Package to a Hypothetical Fire Accident	
2. DOCUMENT IDENTIFIER: CAL-UDC-TH-000004	3. REVISION DESIGNATOR: 00

ELECTRONIC SOURCE FILE INFORMATION

4. ELECTRONIC SOURCE FILE NAME WITH FILE EXTENSION PROVIDED BY THE SOFTWARE: CAL-UDC-TH-000004 R00.DOC		
5. DATE LAST MODIFIED: ~~4/5/2001~~ 4/9/2001 JS 4/10/01	6. ELECTRONIC SOURCE FILE APPLICATION: (I.E., EXCEL, WORD, CORELDRAW) word	7. FILE SIZE IN KILOBYTES: 2348 ~~2352~~ KB JS 4/10/01
8. FILE LINKAGE INSTRUCTIONS/INFORMATION: N/A		

9. FILE CUSTODIAN: (I.E., DC, OR DC APPROVED CUSTODIAN) DC	10. FILE LOCATION FOR DC APPROVED CUSTODIAN: (I.E., SERVER, DIRECTORY) CD
11. PRINTER SPECIFICATION (I.E., HP4SI) INCLUDING POSTSCRIPT INFORMATION (I.E., PRINTER DRIVER) AND PRINTING PAGE SETUP: (I.E., LANDSCAPE, 11 X 17 PAPER) Printer Driver: HP LaserJet 4Si Paper: 8 1/2 x 11 Portrait	
12. COMPUTING PLATFORM USED: (I.E., SUN) IBM Compatible	13. OPERATING EQUIPMENT USED: (I.E., UNIX, SOLARIS) Windows 95
14. ADDITIONAL HARDWARE/SOFTWARE REQUIREMENT USED TO CREATE FILE(S): N/A	15. ACCESS RESTRICTIONS: (IF ANY) N/A

COMMENTS/SPECIAL INSTRUCTIONS

16. N/A

Attachment VI for CAL-UDC-TH-000004 Rev 0 is provided to Document Control on a CD.

CERTIFICATION

17. NAME (Print and Sign) James R. Smotrel [signature]			18. DATE: 4/10/01
19. ORGANIZATION: WPP	20. DEPARTMENT: WPD	21. LOCATION/MAILSTOP: 1030E/423	22. PHONE: 295-4595

DC USE ONLY

23. DATE RECEIVED: 04/18/2001	24. DATE REVIEWED: 04-20-2001	25. DATE FILES TRANSFERRED: 04-20-2001
26. NAME (Print and Sign): Marina Blackwell [signature]		27. DATE: 04-20-2001