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DISCLAIMER

The calculations contained in this document were developed by Bechtel SAIC Company, LLC (BSC) and are intended solely for the use of BSC in its work for the Yucca Mountain Project.

CONTENTS

Page

1. PURPOSE 6

2. REFERENCES 7
   2.1 PROCEDURES/DIRECTIVES 7
   2.2 DESIGN INPUTS 7
   2.3 DESIGN CONSTRAINTS 9
   2.4 DESIGN OUTPUTS 9

3. ASSUMPTIONS 9
   3.1 ASSUMPTIONS REQUIRING VERIFICATION 9
   3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION 10

4. METHODOLOGY 12
   4.1 QUALITY ASSURANCE 12
   4.2 USE OF SOFTWARE 12
   4.3 METHOD 13

5. LIST OF ATTACHMENTS 13

6. BODY OF CALCULATION 13
   6.1 MODEL GEOMETRY 13
   6.2 THERMAL PROPERTIES 15
   6.3 BOUNDARY CONDITIONS 23
   6.4 WASTE PACKAGE HEAT OUTPUT 26
   6.5 CALCULATION CASES 26

7. RESULTS AND CONCLUSIONS 26

Attachment I TAD WASTE PACKAGE MESH I-1
Attachment II 5-DHLW/DOE SNF WASTE PACKAGE MESH II-1
Attachment III EFFECTIVE HEAT TRANSFER COEFFICIENTS AT WP OUTER SURFACE III-1
Attachment IV LIST OF FILES ON CD IV-1
Attachment V CD CONTAINING FILES

FIGURES

Page

Figure 1. Temperature Response to Fire for a TAD Waste Package with Gaps 28

Figure 2. Temperature Response to Fire for a TAD Waste Package with No Gaps 29

Figure 3. Temperature Response to Fire for a 5-DHLW/DOE SNF Waste Package with Gap 30

Figure 4. Temperature Response to Fire for a 5-DHLW/DOE SNF Waste Package with No Gaps.....31

TABLES

Page

Table 1. List of Attachments....13
Table 2. Key Dimensions and Materials for the TAD Waste Package Geometry....14
Table 3. Key Dimensions and Materials for the 5-DHLW/DOE-SNF Waste Package Geometry....14
Table 4. Density and Emissivity of Alloy 22....15
Table 5. Thermal Conductivity of Alloy 22....15
Table 6. Specific Heat of Alloy 22....16
Table 7. Density and Emmissivity of 316 SS....16
Table 8. Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 316 SS....17
Table 9. Density and Emissivity of 516 CS....17
Table 10. Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 516 CS....18
Table 11. Density and Emissivity of 304L SS....18
Table 12 Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 304L SS....19
Table 13. Density, Thermal Conductivity, and Specific Heat of Air....19
Table 14. Density, Thermal Conductivity, and Specific Heat of Helium....21
Table 15. Specific Heat and Density for a TAD....21
Table 16. Effective Thermal Conductivity for a TAD....22
Table 17. Thermal Properties Used for a TAD....22
Table 18. Thermal Properties of Glass in SRS Container....23
Table 19. Calculation Cases....26
Table III-1 Effective Heat Transfer Coefficients at WP Outer Surface....III-1

1. PURPOSE

The objective of this calculation is to evaluate the thermal response of the TAD and 5-DHLW/DOE waste packages to a hypothetical fire. The scope of this calculation is limited to the two-dimensional (2-D) representation of the waste packages subjected to an engulfing fire.

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2.3.3 ORD (Office of Repository Development) 2006. *Repository Project Management Automation Plan.* 000-PLN-MGR0-00200-000, Rev. 00D. Las Vegas, Nevada: U.S. Department of Energy, Office of Repository Development. ACC: ENG.20060703.0001.

2.4 DESIGN OUTPUTS

None.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 The effective specific heat and density for a TAD are assumed to be the same as for a 21-PWR waste package. Justification: Currently, there is no TAD design available to determine these effective thermal properties. The 21-PWR waste package was designed for similar thermal performance of the same waste form. Hence, thermal properties are expected to be similar. This assumption is used in Sections 6.1 and 6.2.7.

3.1.2 A constant effective thermal conductivity for the TAD is calculated from the requirements listed in Table 6 of *Transport, Aging, and Disposal Canister System Basis of Specification Requirements Document*, Reference 2.2.11. The highest effective thermal conductivity is used as a constant value. Justification: Currently, there is no TAD design available to determine effective thermal conductivity. To comply with the specification, a future TAD design will meet this requirement and using the highest value is conservative because heating from the fire is maximized. This assumption is used in Sections 6.1 and 6.2.7.

3.1.3 TAD emissivity is assumed to be 0.8. Justification: Currently, there is no TAD design available to determine emissivity. This value is representative of steel surfaces. This assumption is used in Section 6.2.7.

3.1.4 TAD maximum thermal power is assumed to be 25 kW. Justification: Currently, there is no TAD design available which specifies the maximum thermal power. Dual purpose canisters are available at 22 kW and design values for surface facilities are currently using 25 kW. This assumption is used in Section 6.4.

3.1.5 The thermal power is assumed for DHLW canisters to be 1500 watts, and for DOE SNF canisters to be 1970 watts. These values are taken from *Memorandum from M.R. Arenaz (DOE) to W.J. Arthur, III (DOE/ORD)*, Reference 2.2.4. These values are appropriate and expect to flow down in upper tier requirements as documents are revised. This assumption is used in Section 6.4.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 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 6.3 and 6.3.2.

3.2.2 A temperature of 40°C is assumed for the WP surroundings during pre- and post-fire conditions, with a convective heat transfer coefficient evaluated near 38°C. The rationale for this assumption is that the higher temperature is conservative and near the 38°C requirement for fire-exposure testing of transport casks as given in Section 73(b) of 10 CFR 71, P*ackaging and Transportation of Radioactive Material*, Reference 2.2.1, which specifies a maximum of 38°C. The difference in sink temperature is small, has negligible effect on heat transfer coefficient, and even less effect on heat transfer. This assumption is used in Sections 6.3 and 6.3.3.

3.2.3 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 Reference 2.2.1. This assumption is used in Sections 6.3 and 6.3.3.

3.2.4 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 Attachment III.

3.2.5 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 Reference 2.2.1. This assumption is used in Section 6.3.3 and Attachment III.

3.2.6 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 Reference 2.2.1, this assumption is used in Attachment III.

3.2.7 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 Reference 2.2.1, 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. The assumption is used in Sections 6.3, 6.3.1, and 6.3.3.

3.2.8 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 Section 6.3.1.

3.2.9 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 $1.3123(\Delta T^{1/3})$ W/m^2·K, ΔT in degrees-K (equivalent to the equation $0.19\ \Delta T^{1/3}$ Btu/hr·ft^2·F, ΔT in degrees-F, from p.4-88 of Reference 2.2.6). 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 temperature 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 6.3, 6.3.2, and 6.3.3.

3.2.10 It is assumed that heat is transferred within the WP by conduction and radiation modes only (i.e., no credit is taken for heat transfer by convection). The rationale for this assumption is based on two considerations. First, the fire-related peak glass temperature occurs near the point of contact of canister and WP inner pressure vessel (i.e., in the lower sections of a horizontal WP) where convection does not contribute to the heat transport because the flow is effectively stagnant in this region during the normal, or pre-fire, condition. Secondly, for effects on peak temperatures resulting from the fire condition, convection tends to transfer heat away from the high temperature region at the DHLW canister and WP inner pressure vessel point of contact, which diffuses the thermal energy and lowers the peak glass temperature. Therefore, neglecting heat transport by convection is conservative in this case. This assumption is used in Sections 4.3 and 6.

3.2.11 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 Sections 4.3 and 6.

3.2.12 Thermal properties for DHLW glass and for DOE SNF are assumed to be the same as for SRS glass. SRS is representative of DHLW and the properties of the DOE SNF canister in the center of the waste package have little effect on the transient response to a fire. This assumption is used in Section 6.2.8.

3.2.13 The fill volume for DOE SNF is assumed to be the same as for SRS HLW. Since the DOE SNF is located in the center of the waste package, the fill volume is expected to have little effect on the transient response to a fire. This assumption is used in Section 6.1.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.2). The waste packages are classified as Safety Category items (important to safety and important to waste isolation) on the *Q-list* (Reference 2.2.7, Table A-1, p. A-7). Therefore, this document is subject to the requirements of the *Quality Management Directive* (Reference 2.1.1, Sections 2.1.C.1.1.a.i and 17.E), and the approved version is designated as QA: QA.

4.2 USE OF SOFTWARE

The finite element computer code used for this calculation is ANSYS V8.0 (Reference 2.3.1), which is identified by the Software Tracking number 10364-8.0-00. Usage of ANSYS V8.0 in this calculation constitutes Level 1 software usage, as defined in IT-PRO-0011 (Reference 2.1.3, Section 4.1.1). ANSYS V8.0 is qualified, baselined, and listed in the current *Qualified and Controlled Software Report* as well as the *Repository Project Management Automation Plan* (Reference 2.3.3, Table 6-1).

Calculations using the ANSYS V8.0 software were executed on the following Hewlett-Packard (HP) 9000 Series workstation running operating system HP-UX 11.00:

> Central Processing Unit (CPU) Name: Milo, Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) Tag Number: 151665

The ANSYS V8.0 evaluations performed in this calculation are fully within the range of the validation performed for ANSYS V8.0 (Reference 2.3.2). Therefore, ANSYS V8.0 is appropriate for the thermal analysis as performed in this calculation. Access to, and use of, the code for this calculation was granted by Software Configuration Management in accordance with the appropriate procedures. The details of the ANSYS analyses are described in Section 6, and the results are presented in Section 7 of this calculation.

Microsoft Excel 97, which is a component of Microsoft Office 97, is used for plotting results in Section 7. Usage of Microsoft Office in this calculation constitutes Level 2 software usage, as defined in IT-PRO-0011 (Reference 2.1.3, Section 4.1.1). Microsoft Office 97 is listed in the current *Controlled Software Report*, as well as the *Repository Project Management Automation Plan* (Reference 2.3.3, Table 6-1).

Microsoft Excel 97 was executed on a PC running the Microsoft Windows 2000 SP-4 operating system. The results are confirmed by visual inspection.

All inputs and outputs are located on CD in Attachment V.

All other calculations within this document are performed by hand.

4.3 METHOD

Finite Element Analysis (FEA) numerical solutions are performed using the commercially available code ANSYS V8.0 (Reference 2.3.1). Two-dimensional (2-D) representations (see Assumption 3.2.11) of the waste packages subjected to an engulfing fire are used to determine time histories of the radial temperature distributions in the waste packages. Heat is transferred within the waste package by conduction and radiation (see Assumption 3.2.10).

5. LIST OF ATTACHMENTS

Table 1. List of Attachments

Attachment	Description	Number of Pages
I	TAD WASTE PACKAGE MESH	1
II	5-DHLW/DOE SNF WASTE PACKAGE MESH	1
III	EFFECTIVE HEAT TRANSFER COEFFICIENTS AT WP OUTER SURFACE	2
IV	LIST OF FILES ON CD	1
V	CD CONTAINING FILES	N.A.

6. BODY OF CALCULATION

6.1 MODEL GEOMETRY

The geometries used are cylindrical cross sections through the waste packages. The calculational mesh used can be seen in Attachments I and II for the TAD and 5-DHLW/DOE SNF waste packages, respectively.

The TAD waste package geometry consists of a TAD (represented by a single material as discussed in Assumptions 3.1.1 and 3.1.2), the waste package inner pressure vessel and outer corrosion barrier. Helium fills the gap between the TAD and inner vessel. Air fills the gap between the inner vessel and outer corrosion barrier. The TAD diameter is taken from Reference 2.2.11, Section 3.8.1, page18. Key dimensions and materials are listed in Table 2. Key dimensions for the TAD waste package are taken from *TAD Waste Package Configuration* 000-MW0-DSC0-00102-000 REV 00A*,* Reference 2.2.13.

Materials are taken from *TAD Waste Package Configuration* 000-MW0-DSC0-00101-000 REV 00A*,* Reference 2.2.12.

Table 2. Key Dimensions and Materials for the TAD Waste Package Geometry

COMPONENT	MATERIAL	DIMENSION (m)
TAD	Effective Thermal Properties Assumed (See Assumptions 3.1.1 and 3.1.2)	
Minimum Outer Diameter		1.6764
(Min. Radius)		(0.8382)
Inner Pressure Vessel	316 SS	
Inner Diameter		1.7196
(Inner Radius)		(0.8598)
Outer Diameter		1.8212
(Outer Radius)		(0.9106)
Outer Corrosion Barrier	Alloy 22	
Inner Diameter		1.8308
(Inner Radius)		(0.9154)
Outer Diameter		1.8816
(Outer Radius)		(0.9408)

The geometry used for the 5-DHLW/DOE-SNF waste package also has the outer corrosion barrier and inner pressure vessel, but there is more detail internally. A guide tube in the center contains a DOE-SNF canister. Inner divider plates form a star connected to the outside of the guide tube. Outer divider plates connect the inner divider plates to the inner vessel and form five zones, each containing a DHLW canister. Helium fills the void space inside the inner vessel, and air fills the gap between the inner vessel and outer corrosion barrier. Key dimensions and materials are listed in Table 3. Key dimensions for the 5-DHLW/DOE-SNF waste package are taken from *5-DHLW/DOE SNF Short Waste Package for License Application [Sheet 2]*, Reference 2.2.8. Materials are taken from *5-DHLW/DOE SNF Short Waste Package for License Application [Sheet 3],* Reference 2.2.9.

Table 3. Key Dimensions and Materials for the 5-DHLW/DOE-SNF Waste Package Geometry

COMPONENT	MATERIAL	DIMENSION (m)
Inner Pressure Vessel	316 SS (SA-240, UNS S31600)	
Inner Diameter		1.88278
(Inner Radius)		(09414.)
Outer Diameter		1.98438
(Outer Radius)		(0.9922)
Outer Corrosion Barrier	Alloy 22 (UNS N06022)	
Inner Diameter		1.99390
(Inner Radius)		(0.9970)
Outer Diameter		2.04470
(Outer Radius)		(1.0224)
Guide Tube	516 CS (SA-516, UNS-K02700)	
Inner Diameter		0.5015
(Inner Radius)		(0.25075)
Outer Diameter		0.565
(Outer Radius)		(0.2825)
Inner Divider Plates	516 CS (SA-516, UNS-K02700)	
Thickness		0.0254
Outer Divider Plates	516 CS (SA-516, UNS-K02700)	
Thickness		0.0127

The heat generation is input into ANSYS as a volumetric heat generation rate. Therefore, the volume of each canister is needed.

Table 3.3.1 of Reference 2.2.17 indicates that the interior volume of the SRS HLW canister is 0.736 m^3, and gives a fill volume of 85%, or 0.6256 m^3. This fill volume is suitable for use in determining the volumetric heat generation rate.

From Figure C-4 of Reference 2.2.18, the length of the DOE SNF canister cavity is determined to be approximately 2.72 m. The outer diameter and shell thickness are 0.457 m, and 0.009525 m, respectively (Figure C-4 of Reference 2.2.18). Using these values in Equation 1, the interior volume of the DOE SNF canister cavity is determined to be 0.410 m^3. The fill volume fraction is assumed to be the same as for SRS HLW (85%), making the fill volume 0.349 m^3 (see Assumption 3.2.13). This fill volume is suitable for use in determining the volumetric heat generation rate.

$$V = \pi (D/2 - t)^2 L \qquad \text{(Equation 1)}$$

Where, V is interior volume
D is outer diameter
t is shell thickness, and
L is the length

6.2 THERMAL PROPERTIES

6.2.1 Waste Package Outer Shell Thermal Properties

The outer corrosion barrier is composed of Alloy 22. Table 4 lists the density and emissivity of Alloy 22. The density is taken from Reference 2.2.3, Section II, Part B, SB-575, Section 7.1. The emissivity is taken from Reference 2.2.21, p. 10-297.

Table 5 lists the thermal conductivity of Alloy 22. Table 6 lists the specific heat of Alloy 22. The values of thermal conductivity and specific heat are taken from Reference 2.2.19, p. 13. The information cited in Reference 2.2.19 is data from the vendor of Alloy 22, and, therefore, is suitable for use in this calculation.

Table 4. Density and Emissivity of Alloy 22

Density (kg/m^3)	Emissivity
8690	0.87

Table 5. Thermal Conductivity of Alloy 22

Temperature (°C)	**Thermal Conductivity (W/m·K)**
48	10.1
100	11.1

200	13.4
300	15.5
400	17.5
500	19.5
600	21.3

Table 6. Specific Heat of Alloy 22

Temperature (°C)	Specific Heat (J/kg·K)
52	414
100	423
200	444
300	460
400	476
500	485
600	514

6.2.2 Waste Package Inner Vessel Thermal Properties

Table 7 lists the density and emissivity of 316 SS. The density is taken from Reference 2.2.5, Table X1.1. The emissivity is taken from Reference 2.2.6, Table 4.3.2 (median value). Table 8 lists values of thermal conductivity, thermal diffusivity, and specific heat of 316 SS. Values for thermal conductivity and thermal diffusivity are taken from Reference 2.2.3, Section II, Part D, Table TCD, p. 663 (material group K). Specific heat is calculated using Equation 2 which is simply the definition of thermal diffusivity.

$$Specific\ Heat\,(J/kg\cdot K) = \frac{Thermal\ Conductivity\,(W/m\cdot K)}{Density\,(kg/m^3)\times Thermal\ Diffusivity\,(m^2/s)} \qquad \text{(Equation 2)}$$

Table 7. Density and Emissivity of 316 SS

Density (kg/m^3)	Emissivity
7980	0.62

Table 8. Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 316 SS

Temperature		Thermal Conductivity		Thermal Diffusivity		Specific Heat (J/kg·K)
(°F)	(°C)	(Btu/hr-ft-F)	(W/m-K)	(ft^2/hr)	(m^2/s)	
70	21.11	8.2	14.18	0.139	3.587E-06	495.4
100	37.78	8.3	14.35	0.140	3.613E-06	497.9
150	65.56	8.6	14.87	0.142	3.665E-06	508.6
200	93.33	8.8	15.22	0.145	3.742E-06	509.7
250	121.11	9.1	15.74	0.147	3.794E-06	519.9
300	148.89	9.3	16.08	0.150	3.871E-06	520.7
350	176.67	9.5	16.43	0.152	3.923E-06	524.9
400	204.44	9.8	16.95	0.155	4.000E-06	531.0
450	232.22	10.0	17.30	0.157	4.052E-06	534.9
500	260.00	10.2	17.64	0.160	4.129E-06	535.4
550	287.78	10.5	18.16	0.162	4.181E-06	544.3
600	315.56	10.7	18.51	0.165	4.258E-06	544.6
650	343.33	10.9	18.85	0.167	4.310E-06	548.2
700	371.11	11.2	19.37	0.170	4.387E-06	553.3
750	398.89	11.4	19.72	0.172	4.439E-06	556.6
800	426.67	11.6	20.06	0.175	4.516E-06	556.7
850	454.44	11.9	20.58	0.177	4.568E-06	564.6
900	482.22	12.1	20.93	0.179	4.619E-06	567.7
950	510.00	12.3	21.27	0.182	4.697E-06	567.6
1000	537.78	12.5	21.62	0.184	4.748E-06	570.5
1050	565.56	12.8	22.14	0.187	4.826E-06	574.9
1100	593.33	13.0	22.48	0.189	4.877E-06	577.7
1150	621.11	13.2	22.83	0.191	4.929E-06	580.4

6.2.3 Carbon Steel Thermal Properties

Table 9 lists the density and emissivity of 516 CS. The density is taken from Reference 2.2.3, Section II, Part A, SA-20, 14.1. The emissivity is taken as the median of the values given in Reference 2.2.6, Table 4.3.2. Table 10 lists values of thermal conductivity, thermal diffusivity, and specific heat of 516 CS. Values for thermal conductivity and thermal diffusivity are taken from Reference 2.2.3, Section II, Part D, Table TCD (p.662, Material Group B). The specific heat of 516 CS is calculated using Equation 2, using the density in Table 9.

Table 9. Density and Emissivity of 516 CS

Density (kg/m^3)	Emissivity
7850	0.80

Table 10. Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 516 CS

Temperature		**Thermal Conductivity**		**Thermal Diffusivity**		**Specific Heat (J/kg·K)**
(°F)	**(°C)**	**(Btu/hr-ft-F)**	**(W/m-K)**	**(ft^2/hr)**	**(m^2/s)**	
70	21.11	27.5	47.56	0.529	1.365E-05	443.8
100	37.78	27.6	47.73	0.512	1.321E-05	460.2
150	65.56	27.6	47.73	0.496	1.280E-05	475.1
200	93.33	27.6	47.73	0.486	1.254E-05	484.8
250	121.11	27.4	47.39	0.467	1.205E-05	500.9
300	148.89	27.2	47.04	0.453	1.169E-05	512.6
350	176.67	27.0	46.70	0.440	1.135E-05	523.9
400	204.44	26.7	46.18	0.428	1.105E-05	532.6
450	232.22	26.3	45.49	0.413	1.066E-05	543.7
500	260.00	25.9	44.79	0.398	1.027E-05	555.6
550	287.78	25.5	44.10	0.387	9.987E-06	562.5
600	315.56	25.0	43.24	0.374	9.652E-06	570.7
650	343.33	24.5	42.37	0.360	9.290E-06	581.0
700	371.11	24.0	41.51	0.346	8.929E-06	592.2
750	398.89	23.5	40.64	0.332	8.568E-06	604.3
800	426.67	23.0	39.78	0.318	8.206E-06	617.5
850	454.44	22.6	39.09	0.305	7.871E-06	632.6
900	482.22	22.1	38.22	0.291	7.510E-06	648.4
950	510.00	21.5	37.18	0.277	7.148E-06	662.6
1000	537.78	21.0	36.32	0.263	6.787E-06	681.7
1050	565.56	20.5	35.45	0.249	6.426E-06	702.9
1100	593.33	19.9	34.42	0.237	6.116E-06	716.8
1150	621.11	19.3	33.38	0.219	5.652E-06	752.4

6.2.4 Thermal Properties of 304L SS

Table 11 lists the density and emissivity of 304L SS. The density is taken from Reference 2.2.5, Table X1.1. The emissivity is taken from Reference 2.2.6, Table 4.3.2 (median value).

Table 12 lists values of thermal conductivity, thermal diffusivity, and specific heat of 304L SS. Values for thermal conductivity and thermal diffusivity are taken from Reference 2.2.3, Section II, Part D, Table TCD, p. 663 (material group J). The specific heat of 304L SS is calculated using Equation 2, using the density in Table 11.

Table 11. Density and Emissivity of 304L SS

Density (kg/m^3)	Emissivity
7940	0.62

Table 12 Thermal Conductivity, Thermal Diffusivity, and Specific Heat of 304L SS

Temperature		Thermal Conductivity		Thermal Diffusivity		Specific Heat (J/kg·K)
(°F)	(°C)	(Btu/hr-ft-F)	(W/m-K)	($\mathrm{ft^2}$/hr)	($\mathrm{m^2}$/s)	
70	21.11	8.6	14.87	0.151	3.897E-06	480.7
100	37.78	8.7	15.05	0.152	3.923E-06	483.1
150	65.56	9.0	15.57	0.154	3.974E-06	493.3
200	93.33	9.3	16.08	0.156	4.026E-06	503.2
250	121.11	9.6	16.60	0.158	4.077E-06	512.8
300	148.89	9.8	16.95	0.160	4.129E-06	517.0
350	176.67	10.1	17.47	0.162	4.181E-06	526.2
400	204.44	10.4	17.99	0.165	4.258E-06	532.0
450	232.22	10.6	18.33	0.167	4.310E-06	535.7
500	260.00	10.9	18.85	0.170	4.387E-06	541.2
550	287.78	11.1	19.20	0.172	4.439E-06	544.7
600	315.56	11.3	19.54	0.174	4.490E-06	548.2
650	343.33	11.6	20.06	0.177	4.568E-06	553.2
700	371.11	11.8	20.41	0.179	4.619E-06	556.4
750	398.89	12.0	20.75	0.181	4.671E-06	559.6
800	426.67	12.2	21.10	0.184	4.748E-06	559.6
850	454.44	12.5	21.62	0.186	4.800E-06	567.2
900	482.22	12.7	21.96	0.189	4.877E-06	567.2
950	510.00	12.9	22.31	0.191	4.929E-06	570.1
1000	537.78	13.2	22.83	0.194	5.006E-06	574.3
1050	565.56	13.4	23.18	0.196	5.058E-06	577.1
1100	593.33	13.6	23.52	0.198	5.110E-06	579.8
1150	621.11	13.8	23.87	0.201	5.187E-06	579.5

6.2.5 Air Thermal Properties

Table 13 lists values of density, thermal conductivity, and specific heat of air, taken from Reference 2.2.2, p. 20.59.

Table 13. Density, Thermal Conductivity, and Specific Heat of Air

Temperature		Density		Thermal Conductivity		Specific Heat	
(°F)	(°C)	($\mathrm{lb/ft^3}$)	($\mathrm{kg/m^3}$)	(Btu/hr-ft-F)	(W/m-K)	(BTU/lb-F)	(J/kg-K)
0	-17.78	0.0863	1.3824	0.01326	0.0229	0.2402	1005.6
20	-6.67	0.0827	1.3247	0.01372	0.0237	0.2402	1005.6
40	4.44	0.0794	1.2719	0.01419	0.0246	0.2403	1006.0
60	15.56	0.0763	1.2222	0.01465	0.0254	0.2403	1006.0

80	26.67	0.0735	1.1774	0.01510	0.0261	0.2404	1006.4
100	37.78	0.0709	1.1357	0.01554	0.0269	0.2405	1006.9
120	48.89	0.0684	1.0957	0.01599	0.0277	0.2407	1007.7
140	60.00	0.0661	1.0588	0.01642	0.0284	0.2408	1008.1
160	71.11	0.0640	1.0252	0.01685	0.0292	0.2410	1009.0
180	82.22	0.0620	0.9931	0.01728	0.0299	0.2412	1009.8
200	93.33	0.0601	0.9627	0.01771	0.0306	0.2414	1010.6
220	104.44	0.0583	0.9339	0.01813	0.0314	0.2417	1011.9
240	115.56	0.0567	0.9082	0.01854	0.0321	0.2420	1013.1
260	126.67	0.0551	0.8826	0.01896	0.0328	0.2423	1014.4
280	137.78	0.0536	0.8586	0.01937	0.0335	0.2426	1015.7
300	148.89	0.0522	0.8362	0.01978	0.0342	0.2430	1017.3
320	160.00	0.0508	0.8137	0.02019	0.0349	0.2433	1018.6
340	171.11	0.0496	0.7945	0.02059	0.0356	0.2437	1020.3
360	182.22	0.0484	0.7753	0.02099	0.0363	0.2442	1022.4
380	193.33	0.0472	0.7561	0.02140	0.0370	0.2446	1024.0
400	204.44	0.0461	0.7385	0.02180	0.0377	0.2451	1026.1
420	215.56	0.0451	0.7224	0.02220	0.0384	0.2455	1027.8
440	226.67	0.0441	0.7064	0.02260	0.0391	0.2460	1029.9
460	237.78	0.0431	0.6904	0.02299	0.0398	0.2465	1032.0
480	248.89	0.0422	0.6760	0.02339	0.0405	0.2471	1034.5
500	260.00	0.0413	0.6616	0.02378	0.0412	0.2476	1036.6
520	271.11	0.0405	0.6487	0.02418	0.0418	0.2482	1039.1
540	282.22	0.0397	0.6359	0.02457	0.0425	0.2487	1041.2
560	293.33	0.0389	0.6231	0.02496	0.0432	0.2493	1043.7
580	304.44	0.0381	0.6103	0.02536	0.0439	0.2499	1046.2
600	315.56	0.0374	0.5991	0.02575	0.0446	0.2505	1048.7
620	326.67	0.0367	0.5879	0.02614	0.0452	0.2511	1051.2
640	337.78	0.0360	0.5767	0.02653	0.0459	0.2517	1053.8
660	348.89	0.0354	0.5671	0.02692	0.0466	0.2524	1056.7
680	360.00	0.0348	0.5574	0.02731	0.0473	0.2530	1059.2
700	371.11	0.0342	0.5478	0.02770	0.0479	0.2536	1061.7
720	382.22	0.0336	0.5382	0.02808	0.0486	0.2543	1064.6
740	393.33	0.0330	0.5286	0.02847	0.0493	0.2549	1067.2
760	404.44	0.0325	0.5206	0.02885	0.0499	0.2555	1069.7
780	415.56	0.0320	0.5126	0.02924	0.0506	0.2562	1072.6
800	426.67	0.0315	0.5046	0.02962	0.0513	0.2568	1075.1

6.2.6 Helium Thermal Properties

Table 14 lists values of density, thermal conductivity, and specific heat of helium, at atmospheric pressure, taken from Reference 2.2.2, p. 20.55.

Table 14. Density, Thermal Conductivity, and Specific Heat of Helium

Temperature		Density		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(lb/ft^3)	(kg/m^3)	(Btu/hr-ft-F)	(W/m-K)	(BTU/lb-F)	(J/kg-K)
0	-17.78	0.01192	0.19094	0.08064	0.1396	1.2412	5196.3
20	-6.67	0.01142	0.18293	0.08304	0.1437	1.2412	5196.3
40	4.44	0.01096	0.17556	0.08542	0.1478	1.2412	5196.3
60	15.56	0.01054	0.16883	0.08776	0.1519	1.2412	5196.3
80	26.67	0.01015	0.16259	0.09008	0.1559	1.2411	5195.9
100	37.78	0.00979	0.15682	0.09238	0.1599	1.2411	5195.9
120	48.89	0.00945	0.15137	0.09465	0.1638	1.2411	5195.9
140	60.00	0.00914	0.14641	0.09690	0.1677	1.2411	5195.9
160	71.11	0.00884	0.14160	0.09912	0.1715	1.2411	5195.9
180	82.22	0.00857	0.13728	0.10133	0.1754	1.2411	5195.9
200	93.33	0.00831	0.13311	0.10351	0.1791	1.2411	5195.9
240	115.56	0.00783	0.12542	0.10783	0.1866	1.2411	5195.9
280	137.78	0.00741	0.11870	0.11207	0.1940	1.2411	5195.9
320	160.00	0.00703	0.11261	0.11624	0.2012	1.2411	5195.9
360	182.22	0.00669	0.10716	0.12036	0.2083	1.2411	5195.9
400	204.44	0.00637	0.10204	0.12441	0.2153	1.2411	5195.9
440	226.67	0.00609	0.09755	0.12841	0.2222	1.2411	5195.9
480	248.89	0.00583	0.09339	0.13236	0.2291	1.2411	5195.9
520	271.11	0.00559	0.08954	0.13626	0.2358	1.2411	5195.9
560	293.33	0.00537	0.08602	0.14011	0.2425	1.2411	5195.9
600	315.56	0.00517	0.08282	0.14392	0.2491	1.2411	5195.9
640	337.78	0.00498	0.07977	0.14768	0.2556	1.2412	5196.3
680	360.00	0.00481	0.07705	0.15141	0.2620	1.2412	5196.3
720	382.22	0.00465	0.07449	0.15509	0.2684	1.2412	5196.3
760	404.44	0.00449	0.07192	0.15874	0.2747	1.2412	5196.3
800	426.67	0.00435	0.06968	0.16236	0.2810	1.2412	5196.3

6.2.7 TAD Thermal Properties

Currently, there is no TAD design available to determine these effective thermal properties. As explained in Assumption 3.1.1, the effective specific heat and density for a TAD are assumed to be the same as for a 21-PWR waste package. They are given in Table 15 and are taken from Reference 2.2.14, Tables 28 and 29, respectively.

Table 15. Specific Heat and Density for a TAD

Effective Density (kg/m^3)	Specific Heat (J/kg·K)
3655	438

The effective thermal conductivity for a TAD is calculated from Equation 3 and results for the three points given in Table 6 of Reference 2.2.11. Equation 3 is the analytic solution for a cylindrical heat source with uniform volumetric heating (See Bird Stewart and Lightfoot, Section 9.2, pp 267-269, Reference 2.2.16).

$$K_{eff}\ (\mathrm{w/m/K}) = Q/(4\,\pi\,L\,(350 - Ts)) \qquad \text{(Equation 3)}$$

Where, Q is the total heat (watts) in the TAD
L is the length (m) of the TAD
Ts is the surface temperature (°C) of the TAD

The three points in Table 6 of Reference 2.2.11 use heat flux, so the TAD surface area is needed to determine total heat. The TAD cylindrical surface area is calculated from the minimum length (5.372 m) and minimum diameter (1.67 m) given on p.18 of Reference 2.2.11. Hence, the TAD cylindrical surface area is:

$$A = \pi\, D\, L = \pi\,(1.67\ \mathrm{m})\,(5.372\ \mathrm{m}) = 28.18\ \mathrm{m}^2$$

As explained in Assumption 3.1.2, a constant effective thermal conductivity for the TAD is calculated from the requirements listed in Table 6 of Reference 2.2.11. The effective thermal conductivities for a TAD for the three given surface temperatures are shown in Table 16.

Table 16. Effective Thermal Conductivity for a TAD

TAD Surface Temperature (°C)	K_{eff} (w/m/K)
274	4.29
232	4.21
181	4.08

The highest effective thermal conductivity (4.29 w/m/K) is used as a constant value. This is conservative because heating from the fire is maximized.

TAD emissivity is assumed to be 0.8 (See Assumption 3.1.3).

Table 17 lists the thermal properties that are used for the TAD.

Table 17. Thermal Properties Used for a TAD

Property	Value
Density	3655 kg/m^3
Specific Heat	438 J/kg/K
Thermal Conductivity	4.29 w/m^2/K
Emissivity	0.8

6.2.8 Glass Thermal Properties

Thermal properties for the DHLW glass are listed in Table 18. These same properties are used for the smeared internals of the DOE-SNF canister (see Assumption 3.2.12). The thermal conductivity is taken from p. 584 of *Nuclear Chemical Engineering*, Reference 2.2.15, and is the mid-range value for a temperature range of 100C to 500C. The density and specific heat were assumed equal to that of Pyrex glass at 300K (Assumption 3.2.12) and taken from Table A.3 of Reference 2.2.20.

Table 18. Thermal Properties of Glass in SRS Container

Density (kg/m^3)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
2225.0	1.1	835.0

6.3 BOUNDARY CONDITIONS

Boundary conditions are set at the outer surface of the waste package. The temperature of the surroundings is set at one of two values, corresponding to the normal ambient or fire condition (Assumptions 3.2.2 and 3.2.3). A constant heat flux is imposed at the outer surface of the WP corresponding to the absorption rate of incident solar radiation (Assumption 3.2.7).

The modes of heat transfer between the outer corrosion barrier and the immediate surroundings at the surface facility include radiation and free convection (Assumptions 3.2.1 and 3.2.9). 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.

6.3.1 Solar Heat Flux

The total solar energy incident on the curved surface of a transport cask over a 12-hour period is assumed to be 400 cal/cm^2 (Assumption 3.2.7). Using a conservative value of 1.0 for the solar absorptivity at the WP outer surface (Assumption 3.2.8), the average rate of absorption of this energy is calculated as follows:

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

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

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

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

6.3.2 Combined Radiation/Convection

The radiation 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 3.2.1). 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. 610, Reference 2.2.20) and the expression for the effective emissivity, ε_{eff}, is (p. 699, Reference 2.2.20)

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

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,

$$\begin{aligned} q_r &= (\sigma)(\varepsilon_{eff})(A)(T_1^2 + T_2^2)(T_1 + T_2)(T_1 - T_2) \\ &= [(\sigma)(\varepsilon_{eff})(T_1^2 + T_2^2)(T_1 + T_2)](A)(T_1 - T_2) \\ &= (h_r)(A)(T_1 - T_2) \end{aligned}$$

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, Reference 2.2.6) (Assumption 3.2.9).

$$\begin{aligned} h_c &= 0.19\,(\Delta T)^{1/3} \ \text{Btu/hr}\cdot\text{ft}^2\cdot\text{F, with } \Delta T \text{ in degrees Fahrenheit, for } D^3\Delta T > 100 \ \text{ft}^3\cdot\text{F}, \\ &= 1.3123\,(\Delta T)^{1/3} \ \text{W/m}^2\cdot\text{K, with } \Delta T \text{ in degrees Kelvin or Celsius.} \end{aligned}$$

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

6.3.3 Fire Conditions

The conditions defined for the fire accident in Section 73(c)(4) of 10 CFR 71 (Reference 2.2.1) 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. (Assumption 3.2.3)
>
> The effective value of emissivity for gases in the flame shall be at least 0.9. (Assumption 3.2.5)
>
> 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 3.2.9).
>
> No credit shall be taken for artificial cooling of the waste package after termination of exposure to the flame.

For transport package testing, Reference 2.2.1 Section 73(b) specifies a maximum temperature of 38°C (Assumption 3.2.2) for the temperature of ambient air before and after the specified 30-minute duration of the fire. Reference 2.2.1 Section 71(c)(1) 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. (Assumption 3.2.7)

Based on the above requirements, the fire accident evaluated with the WP at the surface facility 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.

6.4 WASTE PACKAGE HEAT OUTPUT

The maximum thermal loads were used. For a TAD this was assumed to be 25 kW (see Assumption 3.1.4). For DHLW canisters this was 1500 watts, and for DOE SNF canisters it was 1970 watts. These values are taken from *Memorandum from M.R. Arenaz (DOE) to W.J. Arthur, III (DOE/ORD)*, Reference 2.2.4 (see Assumption 3.1.5). For a waste package loaded with maximum heat in every position the total heat is 5 times 1500 watts plus 1970 watts, or 9470 watts.

6.5 CALCULATION CASES

Two cases were evaluated for each of the waste packages. One case included uniform gaps filled with gas. The other case had no gaps and instead had full contact between solid surfaces. For the cases with no gaps, the outer diameters were reduced by the gap thickness to keep the same solid mass as for the case with gaps. In all cases the fire duration was 30 minutes. These two cases are designed to bound the possible response to fire. Including the gaps results in the highest initial temperatures for the waste package internals. With no gaps, the highest heat transfer to the waste package internals occurs.

The case identifiers are listed in Table 19.

Table 19. Calculation Cases

Case	**Description**
Case1	TAD waste package with Gaps
Case2	TAD waste package with No Gaps
5packcase1	5-DHLW/DOE SNF waste package with Gap
5packcase2	5-DHLW/DOE SNF waste package with No Gap

7. RESULTS AND CONCLUSIONS

The outputs of this calculation are reasonable compared to the inputs, and the results are suitable for the intended use. The results are shown Figures 1 through 4 (prepared with Excel 97) and have been visually verified. As expected, the results show lower initial temperatures when there are no gaps, and that the fire causes somewhat larger temperature increases when there are no gaps. The fire has the largest effect on the waste package outer corrosion barrier and pressure vessel, and these also cool down the fastest after the fire.

With the gaps, all of the TAD stayed well below 400°C during and after the fire. With both gaps completely closed, the exterior of the TAD reached about 450°C for a short time, but rapidly cooled down. In both cases these temperatures are far below the temperature limit for accident conditions of

570°C listed in Section 11.2.3.4.3 of *Basis of Design for the TAD Canister-Based Repository Design Concept*, Reference 2.2.10.

With the gap, the canisters experienced temperature increases of 30°C or less, the largest change occurring in the cooler part of the canister nearest the waste package wall. With no gap, the canisters experienced temperature increases of 50°C or less, the largest change occurring in the cooler part of the canister nearest the waste package wall. All glass temperatures remained well below the temperature limit for HLW of 400°C (see Section 13 of Reference 2.2.18).

These results show that even an all engulfing fire with duration of 30 minutes will not adversely affect the contents of a waste package. Since fire controls should make any potential fire much less challenging, there should be negligible impact to waste package contents.

While uncertainties have not been quantified, this calculation provides bounding thermal results. Limiting heat loads have been used together with bounding limits ranging from nominal gaps to no gaps. There is clearly a large inherent safety margin.

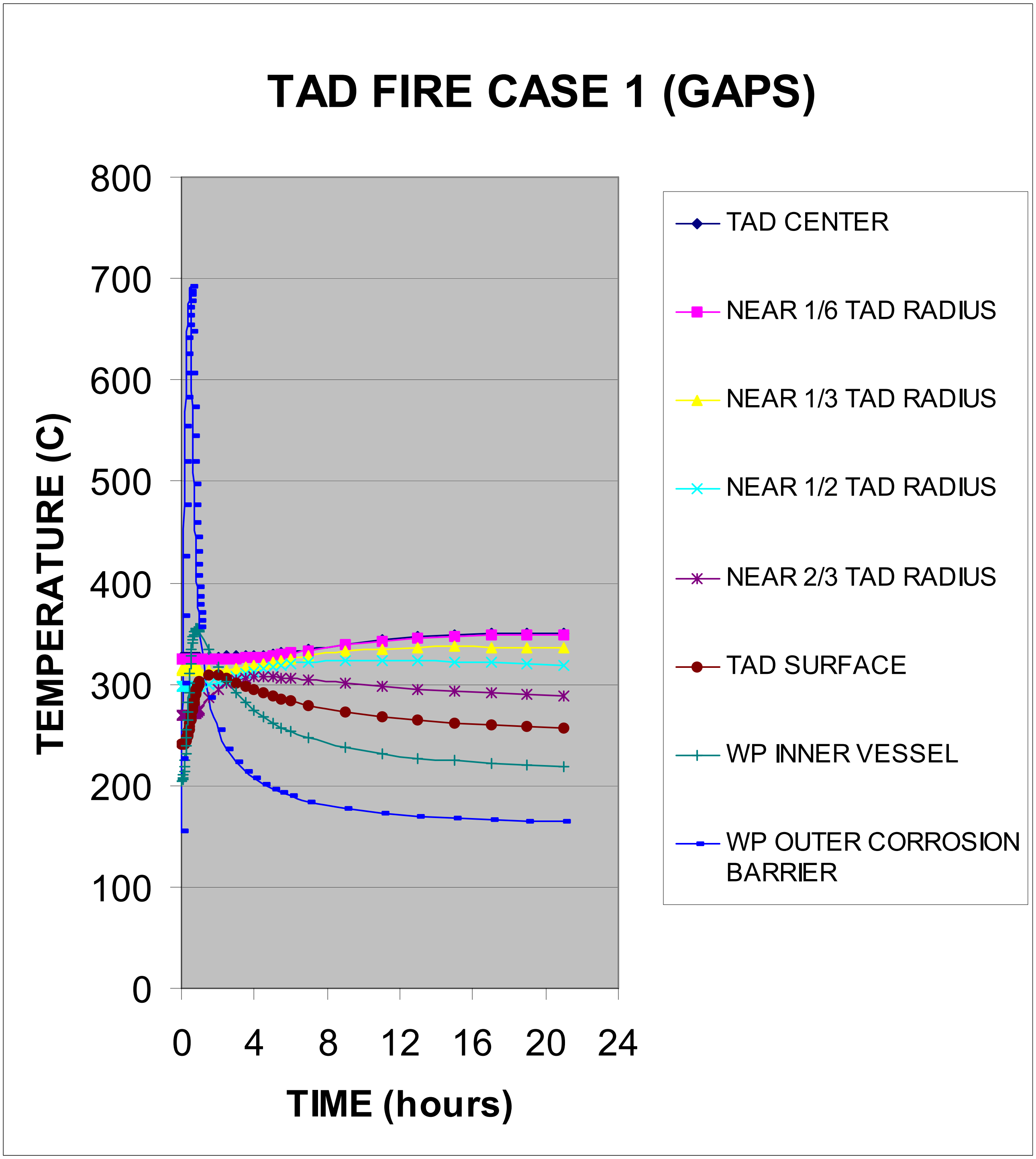


Figure 1. Temperature Response to Fire for a TAD Waste Package with Gaps

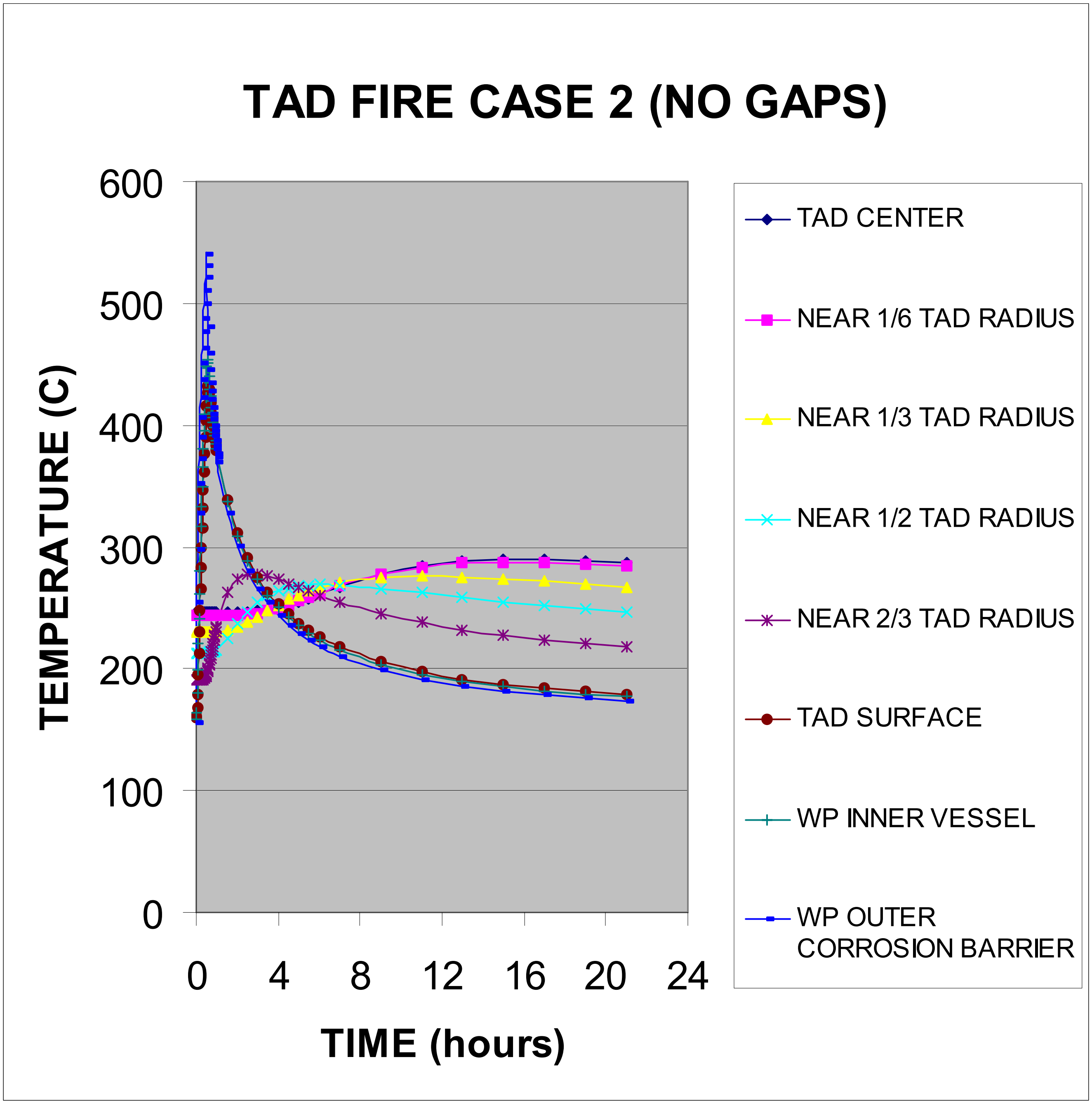


Figure 2. Temperature Response to Fire for a TAD Waste Package with No Gaps

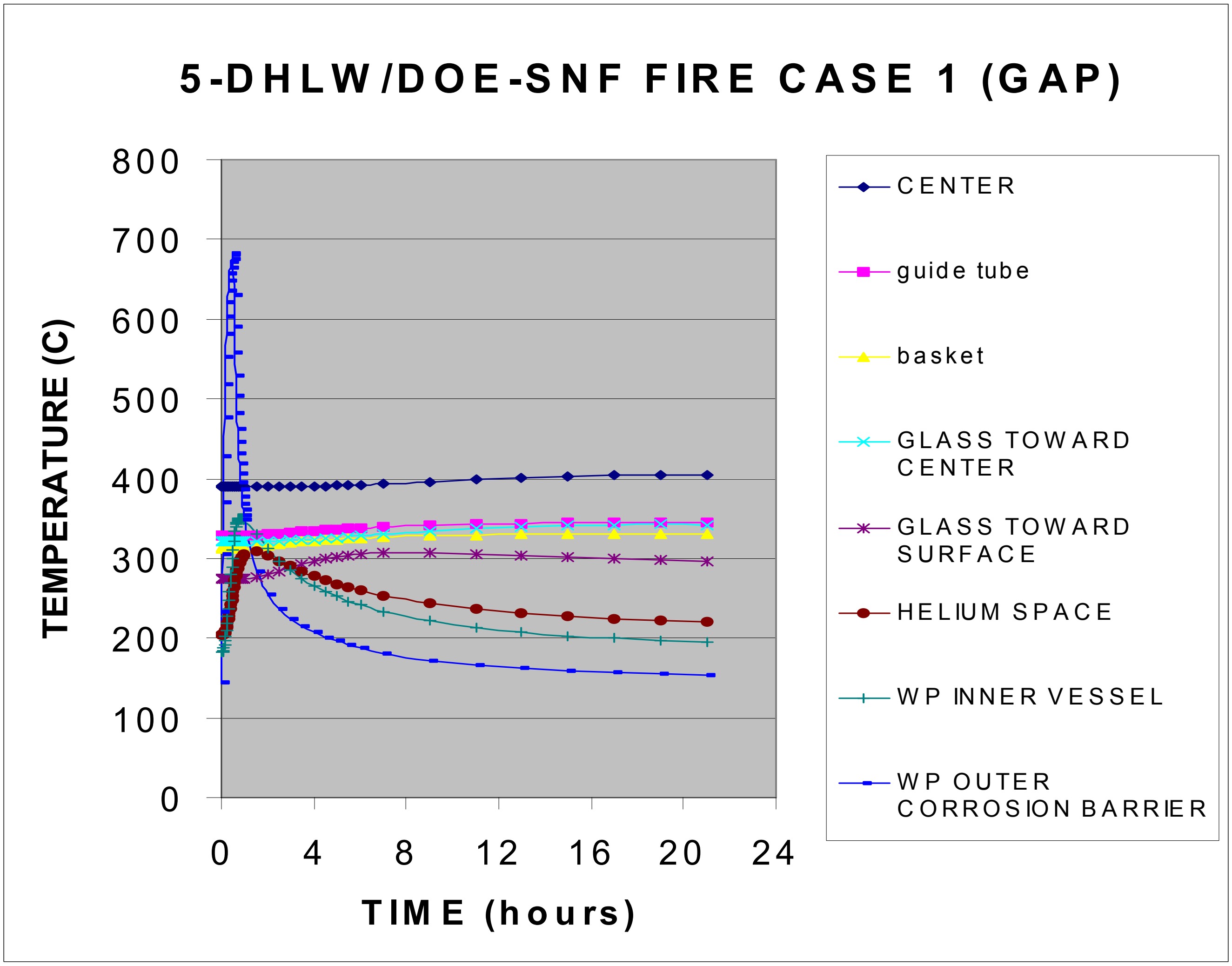


Figure 3. Temperature Response to Fire for a 5-DHLW/DOE SNF Waste Package with Gap

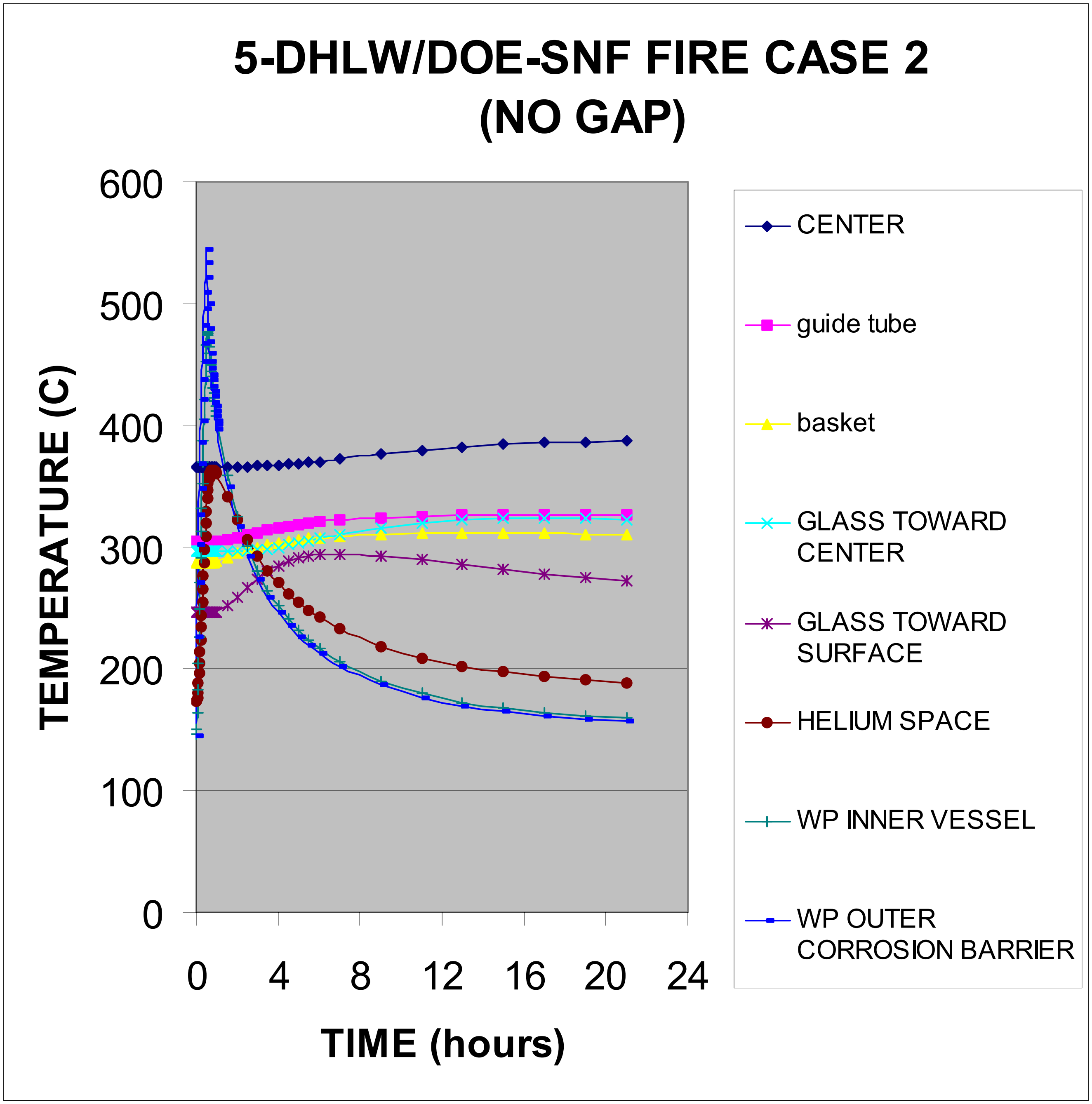
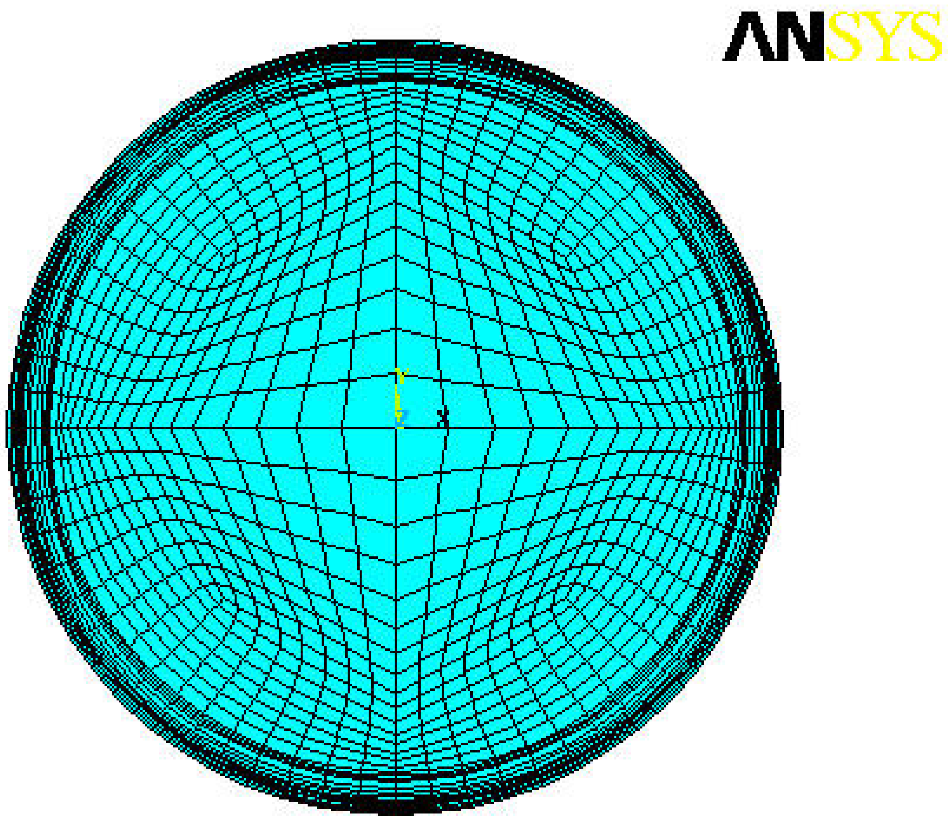
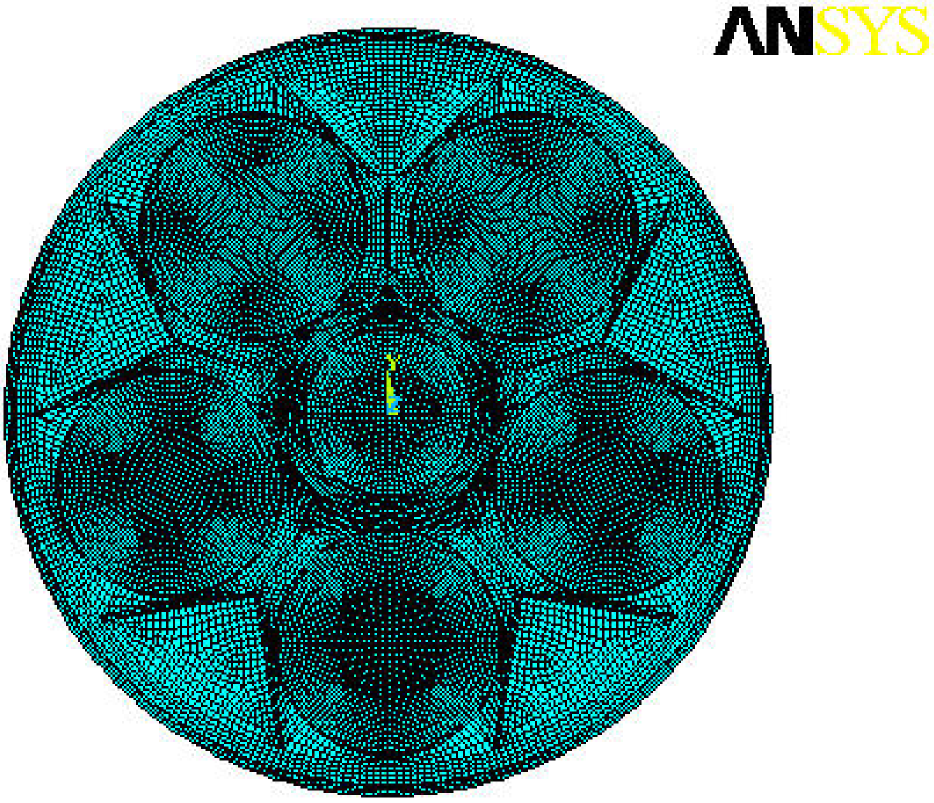


Figure 4. Temperature Response to Fire for a 5-DHLW/DOE SNF Waste Package with No Gaps

ATTACHMENT I TAD WASTE PACKAGE MESH



ATTACHMENT II 5-DHLW/DOE SNF WASTE PACKAGE MESH



ATTACHMENT III EFFECTIVE HEAT TRANSFER COEFFICIENTS AT WP OUTER SURFACE

This attachment determines the effective heat transfer coefficients at the Waste Package outer surface. Values of the effective heat transfer coefficient at the waste package (WP) outer surface are given in Table III-1 for various conditions (Assumptions 3.2.4 to 3.2.6). An example calculation is included.

Table III-1 Effective Heat Transfer Coefficients at WP Outer Surface

Condition	w/o flame	w/ flame
Emissivity:		
Alloy 22	0.87	1
Surroundings	1	1
Effective	0.87	1
Temperature, °C:		
Surroundings	37.78	800
Free-Convection Multiplier	0	1
	Effective Heat Transfer Coefficient, W/m^2-K	
Temperature of WP Surface, °C		
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 -

$$h_R = (\sigma)(\varepsilon_{EFF}) [(T_{SURR})^2 + (T_{WPOS})^2] (T_{SURR} + T_{WPOS})$$

$$= (5.67\text{E-}8)(1.0) [(1073.15)^2 + (310.93)^2] (1073.15 + 310.93)$$

$$= 98.0 \text{ W/m}^2\cdot\text{K}$$

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 -

$$h_{EFF} = h_R + h_C$$

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

ATTACHMENT IV LIST OF FILES ON CD

```
Volume in drive D is 070124_1528
 Volume Serial Number is 943C-266B

 Directory of D:\

01/24/2007  08:48a              58,096 5packcase1
01/24/2007  03:32p           1,423,672 5packcase1.out
01/24/2007  08:48a              56,477 5packcase2
01/24/2007  03:33p           1,413,420 5packcase2.out
01/24/2007  08:54a              47,104 5packfirecase1.xls
01/24/2007  08:54a              47,104 5packfirecase2.xls
01/24/2007  08:48a              19,747 case1
01/24/2007  03:32p             687,486 case1.out
01/24/2007  08:48a              17,006 case2
01/24/2007  03:32p             646,690 case2.out
01/24/2007  08:47a              10,755 matprop_5pack.dat
01/24/2007  08:53a              47,104 tadfirecase1.xls
01/24/2007  08:54a              47,104 tadfirecase2.xls
              13 File(s)      4,521,765 bytes
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Total Files Listed:

13 File(s) 4,521,765 bytes

0 Dir(s) 0 bytes free