BSC	**Design Calculation or Analysis Cover Sheet** *Complete only applicable items.*	1. QA: QA 2. Page 1

3. System Waste Isolation System	4. Document Identifier 000-00C-WIS0-03100-000-00B
5. Title Thermal Loading Study of the TAD Waste Package	
6. Group Thermal Structural Analysis	
7. Document Status Designation ☐ Preliminary ☒ Committed ☐ Confirmed ☐ Cancelled/Superseded	
8. Notes/Comments Pages 7-9, 12, 14, 29-32, 34, 35, 38-43 are affected by revision.	

Attachments	Total Number of Pages
See Section 5	

RECORD OF REVISIONS

9. No.	10. Reason For Revision	11. Total # of Pgs.	12. Last Pg. #	13. Originator (Print/Sign/Date)	14. Checker (Print/Sign/Date)	15. EGS (Print/Sign/Date)	16. Approved/Accepted (Print/Sign/Date)
00A	Initial issue	43	43	Daniel Wang 5/14/07	Tim deBues 5/14/07	Del Mecham 5/14/07	Michael Anderson 5/15/07
00B	Revised to utilize a more conservative (radiation-only) model of heat transfer for loss of ventilation scenarios. References updated. Affected sections are noted with change bars.	43	43	Daniel Wang 2/27/08	Tim deBues 2/28/08	Del Mecham 2/28/08	Michael Anderson 2/28/08

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

FIGURES

Page

TABLES

Page

1.0 PURPOSE

The objective of this calculation is to evaluate the peak temperatures due to thermal loading and boundary conditions of the TAD Waste Package design under nominal Monitored Geologic Repository conditions.

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2.3 DESIGN CONSTRAINTS

None

2.4 DESIGN OUTPUTS

This calculation is performed to support information in the License Application.

3.0 ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 Effective Specific Heat and Density for a TAD

The effective specific heat and density for a TAD are assumed to be the same as for a 21-PWR waste package. Rationale: 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, 6.2, and 6.2.5.

3.1.2 Effective Thermal Conductivity for a TAD

Effective thermal conductivities for the TAD are calculated from the requirements listed in Table 6 of *Transport, Aging, and Disposal Canister System Basis of Specification Requirements Document*, Reference 2.2.15. Rationale: Currently, there is no TAD design available to determine effective thermal conductivity. To comply with the specification, a future TAD design will meet the requirements from which the utilized conductivities were calculated. This assumption is used in Sections 6.1, 6.2, and 6.2.5.

3.1.3 Emissivity for a TAD

The emissivity for a TAD is assumed to be 0.8. Rationale: Currently, there is no TAD design available to determine emissivity. This value is representative of steel surfaces. This assumption is used in Section 6.2.5.

3.1.4 Dimensions of the Drip Shield

Dimensions of the drip shield, corresponding to the drawings in References 2.2.8, 2.2.9, 2.2.16, and 2.2.17 are assumed to be the same as the final definitive design. Rationale: The design is preliminary, and will require verification at the completion of the final definitive design. This assumption is used in Section 6.1.

3.1.5 Drift Wall and Invert Surface Temperatures

It is assumed that the temperature boundary conditions at the drift wall and invert surface remain the same as were calculated in Reference 2.2.14. Rationale: No better temperature data currently exists reflecting the drift invert design change implemented by Reference 2.2.18. The invert height from the bottom of the drift was raised since the release of Reference 2.2.14 from a height of 0.8636 m to 1.3208 m. However, the perimeter of the drift and invert participating in heat exchange with the waste packages in the ANSYS model has only changed from approximately 16.8 m to 16.3 m. This represents a difference of only 2.8% (see Attachment II, file: *affected drift area.xmcd* (originally taken from Reference 2.2.21) for calculation). Taking into account the fourth-power temperature difference that governs radiation heat transfer, this difference is negligible. This assumption is used in Sections 4.3 and 6.3.

3.1.6 Fast and Slow Decay Rates

A 16 kW, faster-than-average decay rate and an 11.8 kW, slower-than-average decay rate for the TAD are assumed as follow in Table 1 and Table 2:

Table 1. TAD Heat Output, 16 kW, Fast Decay

Time (years)	Heat (kW)	Time (years)	Heat (kW)	Time (years)	Heat (kW)
0	1.60E+01	9.50E+01	2.58E+00	5.99E+03	1.47E-01
9.93E-01	1.39E+01	1.95E+02	1.44E+00	6.99E+03	1.39E-01
1.99E+00	1.26E+01	2.95E+02	1.12E+00	7.99E+03	1.30E-01
2.99E+00	1.17E+01	3.95E+02	9.45E-01	8.99E+03	1.22E-01
3.99E+00	1.11E+01	4.95E+02	8.21E-01	9.99E+03	1.16E-01
4.99E+00	1.06E+01	5.95E+02	7.22E-01	2.00E+04	6.72E-02
1.50E+01	8.05E+00	6.95E+02	6.43E-01	3.00E+04	4.62E-02
2.50E+01	6.66E+00	7.95E+02	5.75E-01	4.00E+04	3.36E-02
3.50E+01	5.62E+00	8.95E+02	5.21E-01	5.00E+04	2.52E-02
4.50E+01	4.81E+00	9.95E+02	4.73E-01	6.00E+04	1.89E-02
5.50E+01	4.15E+00	1.99E+03	2.46E-01	7.00E+04	1.47E-02
6.50E+01	3.63E+00	2.99E+03	1.91E-01	8.00E+04	1.26E-02
7.50E+01	3.21E+00	3.99E+03	1.70E-01	9.00E+04	1.05E-02
8.50E+01	2.86E+00	4.99E+03	1.58E-01		

Table 2. TAD Heat Output, 11.8 kW, Slow Decay

Time (years)	Heat (kW)	Time (years)	Heat (kW)	Time (years)	Heat (kW)
0	1.18E+01	6.45E+02	1.21E+00	8.94E+03	2.21E-01
4.63E+00	1.09E+01	7.45E+02	1.08E+00	9.94E+03	2.06E-01
1.46E+01	9.37E+00	8.45E+02	9.72E-01	1.99E+04	1.16E-01
2.46E+01	8.16E+00	9.45E+02	8.82E-01	2.99E+04	7.56E-02
3.46E+01	7.20E+00	1.94E+03	4.62E-01	3.99E+04	5.46E-02
4.46E+01	6.43E+00	2.94E+03	3.57E-01	4.99E+04	4.20E-02
1.45E+02	3.21E+00	3.94E+03	3.17E-01	5.99E+04	3.36E-02
2.45E+02	2.31E+00	4.94E+03	2.92E-01	6.99E+04	2.73E-02
3.45E+02	1.86E+00	5.94E+03	2.71E-01	7.99E+04	2.31E-02
4.45E+02	1.58E+00	6.94E+03	2.52E-01	8.99E+04	2.10E-02
5.45E+02	1.37E+00	7.94E+03	2.35E-01		

Rationale: The decay rates shown are used only to show general trends, and as used, are appropriate for this calculation. This assumption is used in Section 6.4.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Waste Package Representation

It is assumed that a 2-D finite element representation of a cross section of the Waste Package will be representative of the hottest portion of the Waste Package. Rationale: Axial heat transfer does not significantly affect the solution (i.e., the flow of heat in the radial direction dominates the solution). This corresponds to Section 6.2.3.1 of Reference 2.2.25. This assumption is used in Section 6.1.

3.2.2 Heat Transfer Modeling

Modeling of only conduction and radiation heat transfer inside the Waste Package is assumed to provide conservative results for this calculation. Rationale: Some convective heat transfer will occur in the waste package fill gas. However, in a horizontal emplacement configuration, convection is minor compared to thermal radiation (at the expected temperatures), and stable convection cells either do not develop or are difficult to predict. Also, some fill gases, such as helium, have poor buoyancy relative to their thermal conductivity (unlike air, for example), and natural convection has a negligible contribution to total heat transfer. This corresponds to Section 6.2.3.2 of Reference 2.2.25. This assumption is used in Section 6.4.

3.2.3 Emplacement Pallets Are Neglected

Conductive heat transfer between the waste packages and the emplacement pallets, and hence through the pallets into the invert, is neglected. Simplifying assumptions are needed in order to represent the geometry to a reasonable amount of detail. Rationale: The waste package supports have point contact with the waste package in only a few places. Therefore, conduction through the support structure will be limited and can be conservatively neglected. This corresponds to Section 6.2.1.6 of Reference 2.2.25. This assumption is used in Section 6.1.

3.2.4 Pressure of Helium in the Waste Package

The thermal conductivity of helium at atmospheric pressure is assumed to be representative of the conditions which helium in the Waste Package will experience. Rationale: According to p. 255 of Reference 2.2.5, the thermal conductivity of most gasses is pressure independent. Thus, using the thermal conductivity at atmospheric pressure is reasonable. The impact of this assumption is anticipated to be negligible. This assumption is used in Section 6.2.4.

3.2.5 Representation of the Drip Shield

The drip shield is simplified in the computational model as thin, Titanium (Grade 7) plates. Rationale: This is a simplifying assumption to capture the thermal effects of the drip shield. Table 6.1-2 of Reference 2.2.12 indicates that the vast majority of the drip shield components (by mass) are Titanium, and that the majority of Titanium components (by mass) are Titanium Grade 7. Including all the minor features of the drip shield would not impact results, but would increase the size of the computational model, which would increase solution time to an unacceptable level. This assumption is used in Sections 6.2 and 6.2.6.

4.0 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) in the *Basis of Design for the TAD Canister-Based Repository Design Concept* (Reference 2.2.11, Section 11.1.2). Therefore 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 2.2.26), 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, Attachment 12). 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 2.1.4, Table 6-1).

Calculations using the ANSYS V8.0 software were executed on the following Hewlett-Packard (HP) 9000 Series workstations 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 2.2.27). 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 6.0 and the results are presented in Section 7.0 of this calculation. All inputs and outputs are located in Attachment II.

Microsoft Excel 2003, which is a component of Microsoft Office 2003 Professional, is used for plotting results in Section 7.0. The results are confirmed by visual inspection. Microsoft Excel 2003 was executed on a PC running the Microsoft Windows XP SP-2 operating system. Usage of Microsoft Office in this calculation constitutes Level 2 software usage, as defined in IT-PRO-0011 (Reference 2.1.3, Attachment 12). Microsoft Office 2003 Professional is listed in the current *Controlled Software Report*, as well as the *Repository Project Management Automation Plan* (Reference 2.1.4, Table 6-1).

Mathcad version 13.0 is used for calculating drift surface area in Assumption 3.1.5. The results are confirmed by hand calculations. Mathcad was executed on a PC running the Microsoft Windows XP SP-2 operating system. Usage of Mathcad in this calculation constitutes Level 2 software usage, as defined in IT-PRO-0011 (Reference 2.1.3, Attachment 12). Mathcad is listed in the current *Controlled Software Report*, as well as the *Repository Project Management Automation Plan* (Reference 2.1.4, Table 6-1). The Mathcad file is located in Attachment II.

A few calculations were performed by hand in Section 6.2.5.

4.3 METHOD

The solution method employed is a two-dimensional (2-D) finite element analysis using the commercially available code ANSYS V8.0 (Reference 2.2.26) to determine the temperatures in the waste package.

The calculation uses waste package emplacement thermal evaluation results from Reference 2.2.14 (see Assumption 3.1.5) for the drift wall, invert, and drip shield as boundary conditions. Nodal temperature results from Reference 2.2.14 for the drift wall are applied to drift wall keypoints with corresponding locations in the ANSYS model. Likewise, nodal temperature results from Reference 2.2.14 for the invert surface are applied to invert surface keypoints with corresponding locations in the ANSYS model. Nodal temperature results from Reference 2.2.14 for the drip shield are applied to the keypoints where the drip shield contacts the invert surface. The drip shield temperatures from Reference 2.2.14 represent the hottest portion of the drip shield, so applying these temperatures to the keypoints where the drip shield contacts the invert surface is conservative.

Ventilation during the pre-closure period is simulated via a convective boundary condition applied to the waste package surface only. Volumetric heat loads are applied in the region representing the TAD.

The temperature calculation is performed under transient conditions after emplacement of the waste package in the repository. First, the pre-closure period is solved with the convective boundary conditions applied to the waste package surface. Then, the output of the pre-closure solution is used as an initial condition for the post-closure solution, which adds the drip shield and removes the convective boundary condition.

5.0 LIST OF ATTACHMENTS

Table 3. List of Attachments

Attachment	Description	Number of Pages
I	File Listing for Attachment II	5
II	One (1) Compact Disc (CD)	N/A

6.0 BODY OF CALCULATION

6.1 FINITE ELEMENT REPRESENTATION

To investigate the thermal response of the TAD Waste Package in the repository near field, a 2-D Waste Package cross-section representation is used to capture the temperature distribution inside the Waste Package (Assumption 3.2.1). More specifically, a 2-D Waste Package cross-section emplaced in the drift is used in the ANSYS representation (see Figure 1 through Figure 3).

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. Key dimensions for the waste package are listed in Table 4. The TAD diameter is taken from Reference 2.2.15, Section 3.8.1, page 18. Dimensions for the TAD waste package are taken from *TAD Waste Package Sketch* 000-MWK-DSC0-00102-000 REV 00B, Reference 2.2.20.

Table 4. TAD Waste Package Dimensions

Component	Dimension (m)
Outer Corrosion Barrier Outer Diameter	1.8816
Outer Corrosion Barrier Inner Diameter	1.8308
Inner Vessel Outer Diameter	1.8212
Inner Vessel Inner Diameter	1.7196
TAD (Minimum) Outer Diameter	1.6764

The drift invert has a total height of 1.3208 m (52 in.) from the bottom of the drift (Reference 2.2.18).

The vertical emplacement height (defined as the distance between waste package center and top of the invert) of the TAD Waste Package is 1.192 m (Reference 2.2.16).

The waste package supports are not represented in the drift, so that the conduction paths through the waste package supports are neglected (Assumption 3.2.3). The TAD is represented as "floating" inside the inner pressure vessel such that they are concentric, and there is no contact between the TAD and the inner vessel. Likewise, the inner vessel is represented as "floating" concentrically inside the outer corrosion barrier.

The drip shield is required during the repository post-closure period. The drip shield is simplified as titanium plates. The configuration and dimensions of the drip shield are taken from References 2.2.8, 2.2.9, 2.2.16, 2.2.17 (Assumption 3.1.4). The dimensions used in this calculation are noted in Table 5.

Table 5. Drip Shield Dimensions

Item	Dimension (m)	Reference
Overall width	2.53507	Reference 2.2.17
Side height (flat side only)	2.1656	Reference 2.2.9
Drip shield height above invert	2.8862	Reference 2.2.16
Plate thickness	0.015	Reference 2.2.9
Top outer radius of curvature	1.300	Reference 2.2.8

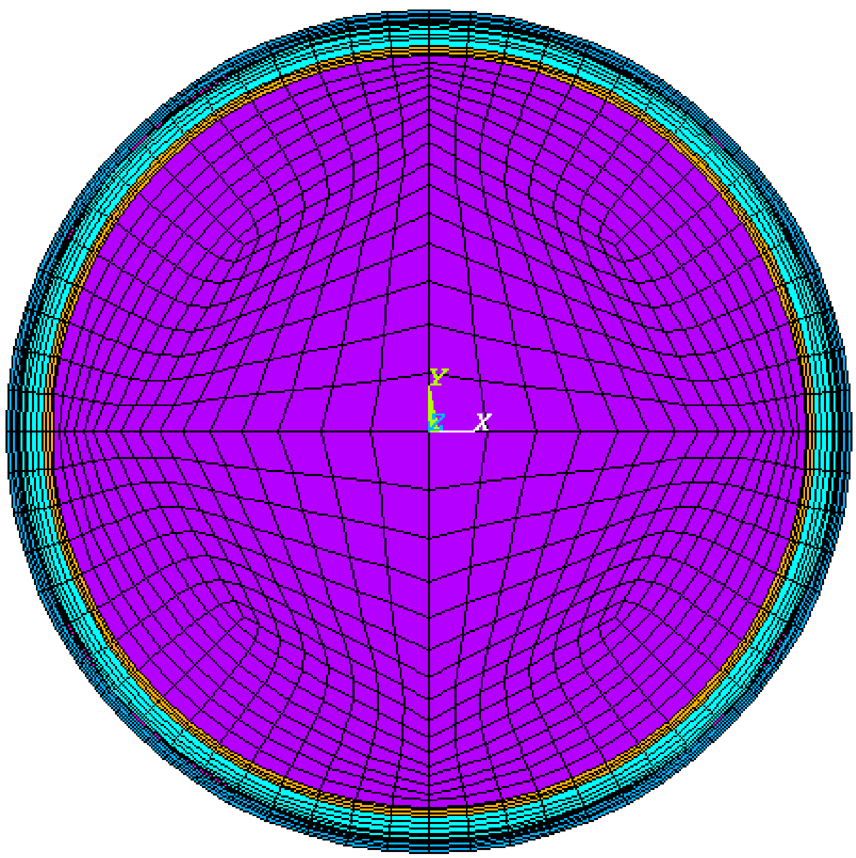

Figure 1. Close-Up View of Waste Package Finite Element Mesh

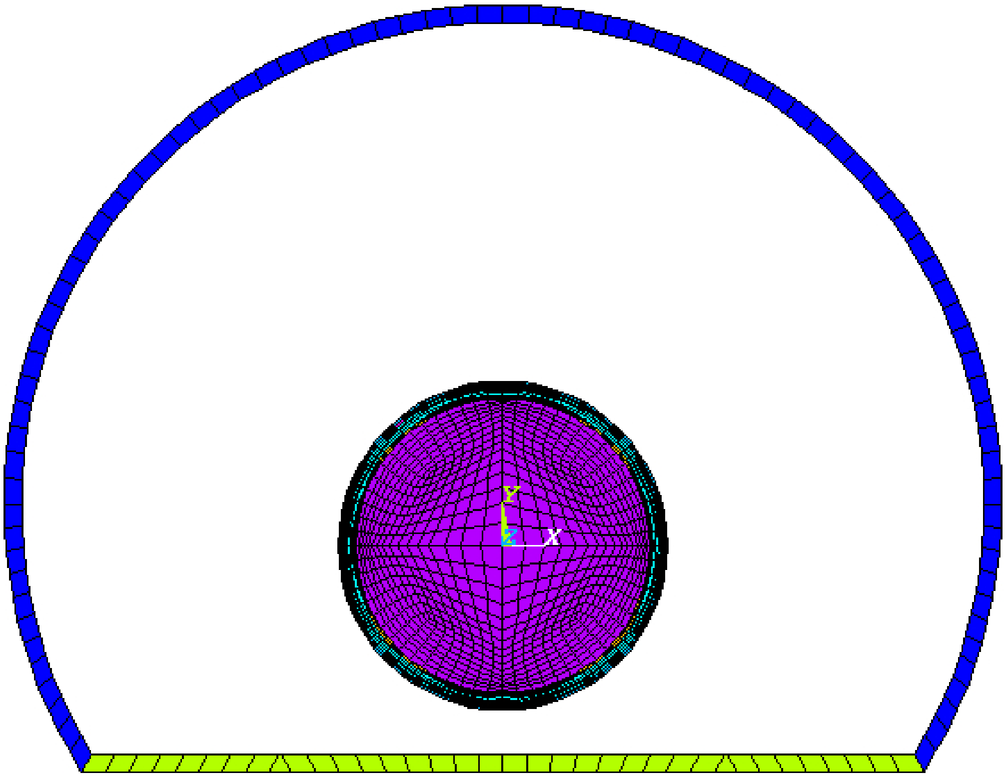

Figure 2. Pre-Closure Finite Element Mesh

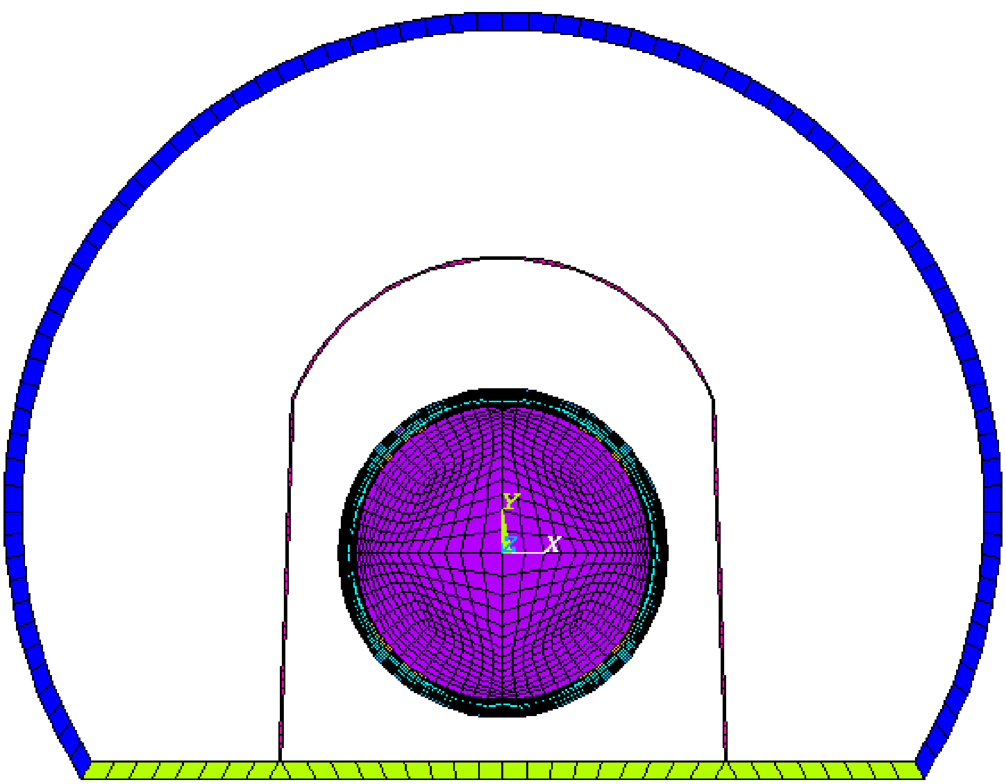

Figure 3. Post-Closure Finite Element Mesh

6.2 THERMAL PROPERTIES

Table 6 lists the materials used in the ANSYS representation of the TAD Waste Package emplaced in the drift.

Table 6. Materials Used in the ANSYS Representation

Component	Material	Reference
Outer Corrosion Barrier	Alloy 22	Reference 2.2.19
Space between Outer and Inner Vessel	Air	N/A
Inner Vessel	316 Stainless Steel	Reference 2.2.19
Waste Package Inner Vessel Fill Gas	Helium	Reference 2.2.13, Section 4.9.5.4.2
Assumed TAD	Homogeneous Solid	Assumptions 3.1.1 and 3.1.2
Drip Shield	Titanium	Assumption 3.2.5

6.2.1 Waste Package Outer Shell Thermal Properties

The outer corrosion barrier is composed of Alloy 22. Table 7 lists the density and emissivity of Alloy 22. The density is taken from Reference 2.2.2, Section II, Part B, SB-575, Section 7.1. The emissivity is taken from Reference 2.2.24, p. 10-297.

Table 8 lists the thermal conductivity of Alloy 22.

Table 9 lists the specific heat of Alloy 22. The values of thermal conductivity and specific heat are taken from Reference 2.2.22, p. 13. The information cited in Reference 2.2.22 is data from the vendor of Alloy 22, and, therefore, is suitable for use in this calculation.

Table 7. Density and Emissivity of Alloy 22

Density (kg/m^3)	Emissivity
8690	0.87

Table 8. 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 9. 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 Air Thermal Properties

Table 10 lists values of density, thermal conductivity, and specific heat of air, taken from Reference 2.2.1, p. 20.59.

Table 10. Density, Thermal Conductivity, and Specific Heat of Air

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	0.0863	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

6.2.3 Waste Package Inner Vessel Thermal Properties

Table 11 lists the density and emissivity of 316 SS. The density is taken from Reference 2.2.3, Table X1.1. The emissivity is taken from Reference 2.2.4, Table 4.3.2 (median value). Table 12 lists values of thermal conductivity, thermal diffusivity, and specific heat of 316 SS. Values for thermal conductivity and thermal diffusivity are taken from Reference 2.2.2, Section II, Part D, Table TCD, p. 663 (material group K). The derivation of specific heat is defined in Equation 1. The specific heat of 316 SS listed in Table 12 is calculated using Equation 1 and the density in Table 11.

$$Specific\ Heat\,(J/kg\cdot K) = \frac{Thermal\ Conductivity\,(W/m\cdot K)}{Density\,(kg/m^3)\times Thermal\ Diffusivity\,(m^2/s)} \qquad \text{(Equation 1)}$$

Table 11. Density and Emissivity of 316 SS

Density (kg/m^3)	Emissivity
7980	0.62

Table 12. 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)	(ft²/hr)	(m²/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

6.2.4 Helium Thermal Properties

Table 13 lists values of density, thermal conductivity, and specific heat of helium, at atmospheric pressure, taken from Reference 2.2.1, p. 20.55 (Assumption 3.2.4).

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

Temperature		Density		Thermal Conductivity		Specific Heat	
(°F)	(°C)	(lb/ft³)	(kg/m³)	(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

6.2.5 TAD Thermal Properties

Currently, there is no TAD design available to determine the necessary 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. The effective density is given in Table 14 and is taken from Reference 2.2.14, Table 29. The effective specific heat is given in Table 15 and is taken from Reference 2.2.14, Attachment IV, CD 2 of 2, file: *\THERMAL_PROPERTIES\21-PWR_homog_cylinder_effective_Cp.mcd.*

Table 14. Effective Density for a TAD

Effective Density (kg/m^3)
3655

Table 15. Effective Specific Heat for a TAD

Temperature (°C)	**Specific Heat (J/kg·K)**
52	392
100	398
200	412
300	425
400	438
500	450
600	464

The effective thermal conductivity for a TAD is calculated from Equation 2 using the values of heat flux and surface temperature given in Table 6 of Reference 2.2.15. Equation 2 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 2.2.5).

$$K_{eff} \text{ (w/m/K)} = Q/(4 \pi L (350 - Ts)) \qquad \text{(Equation 2)}$$

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 2.2.15 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 2.2.15. Hence, the TAD cylindrical surface area is:

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

As explained in Assumption 3.1.2, values of effective thermal conductivity for the TAD are calculated from the requirements listed in Table 6 of Reference 2.2.15. 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

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

6.2.6 Drip Shield Thermal Properties

The drip shield is composed of Titanium Grade 7 (Assumption 3.2.5). Table 17 lists the density and emissivity of Titanium Grade 7. The density is taken from Reference 2.2.2, Section II, Part D, Table NF-2. The emissivity is taken from Reference 2.2.24, Page 10-298 (generalized as that of titanium).

Table 18 lists values of thermal conductivity, thermal diffusivity, and specific heat for Titanium Grade 7. Values for thermal conductivity and thermal diffusivity are taken from Reference 2.2.2, Section II, Part D, Table TCD. The specific heat of Titanium Grade 7 is calculated using Equation 1, using the density in Table 17.

Table 17. Density and Emissivity of Titanium Grade 7

Density (kg/m^3)	Emissivity
4512	0.63

Table 18. Thermal Conductivity, Thermal Diffusivity, and Specific Heat of Titanium Grade 7

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	12.68	21.93	0.359	9.264E-06	524.6
100	37.78	12.52	21.65	0.352	9.084E-06	528.3
150	65.56	12.25	21.19	0.340	8.774E-06	535.2
200	93.33	12.00	20.75	0.331	8.542E-06	538.5
250	121.11	11.85	20.49	0.322	8.310E-06	546.6
300	148.89	11.72	20.27	0.314	8.103E-06	554.4
350	176.67	11.60	20.06	0.306	7.897E-06	563.1
400	204.44	11.45	19.80	0.300	7.742E-06	566.9
450	232.22	11.35	19.63	0.294	7.587E-06	573.4
500	260.00	11.29	19.53	0.290	7.484E-06	578.3
550	287.78	11.23	19.42	0.286	7.381E-06	583.2
600	315.56	11.20	19.37	0.283	7.303E-06	587.8
650	343.33	11.17	19.32	0.280	7.226E-06	592.5
700	371.11	11.15	19.28	0.278	7.174E-06	595.7
750	398.89	11.18	19.34	0.276	7.123E-06	601.7
800	426.67	11.20	19.37	0.275	7.097E-06	604.9
850	454.44	11.23	19.42	0.274	7.071E-06	608.8
900	482.22	11.30	19.54	0.273	7.045E-06	614.8
950	510.00	11.36	19.65	0.272	7.019E-06	620.3
1000	537.78	11.43	19.77	0.271	6.994E-06	626.5
1050	565.56	11.51	19.91	0.270	6.968E-06	633.2
1100	593.33	11.58	20.03	0.270	6.968E-06	637.0

6.2.7 Drift and Invert Thermal Properties

Since the portions of the drift and invert that are modeled have specified temperatures throughout the solution process, only the emissivity of these materials need be specified.

An emissivity value of 0.90 is used for the invert. This value is taken from Reference 2.2.23, Table A.8 (value for sand).

An emissivity value of 0.92 is used for the drift wall. This value is taken from Reference 2.2.23, Table A.8 (median value for rock).

6.3 BOUNDARY CONDITIONS

The temperatures of the drift wall and invert are specified as boundary conditions. The temperatures of the drift wall and invert are taken from Case 1, Case 5, and Case 6 of Reference 2.2.14 (Attachment IV, CD 1 of 2) (see Assumption 3.1.5). Case 1 of Reference 2.2.14 represents a linear heat load of 1.45 kW/m under normal conditions. Case 5 of Reference 2.2.14 represents a linear heat load of 1.45 kW/m with a loss of ventilation during the pre-closure period that begins at 30 days after emplacement and lasts for 30 days. Case 6 of Reference 2.2.14 represents a linear heat load of 1.75 kW/m under normal conditions.

All the computational models in Reference 2.2.14 represent, in three dimensions, a full-pillar repository with 11 whole waste packages and 2 waste package halves. The temperature boundary conditions applied to the drift wall and invert surface in this calculation are taken from temperature values of the drift wall, the invert surface, and the drip shield nearest to the centerline of a waste package modeled in Reference 2.2.14. In order to choose the most appropriate, conservative boundary conditions to apply, the temperature results near several waste packages in Reference 2.2.14 were considered.

For convenience, peak drift wall and invert temperatures for WP2, WP6, and WP12, taken from Case 1, Case 5, and Case 6 of Reference 2.2.14 are presented in Table 19 below.

The 21-PWR waste packages modeled in Reference 2.2.14 have the highest initial heat, but there are several 21-PWR waste packages modeled. Of the 21-PWR waste packages modeled in Reference 2.2.14, the highest drift wall temperatures are recorded near either WP2 or WP6. The highest invert temperatures are recorded near WP2, WP6, or WP12.

While, in some cases, the highest invert temperatures are recorded near WP12, all of the drift wall temperatures recorded near WP12 are consistently lower than those recorded near WP2 and WP6. Therefore, WP12 was removed from consideration.

The peak invert surface and drift wall temperatures recorded near WP2 and WP6 are very close, and both are significantly greater than the peak invert surface and drift wall temperatures recorded near other waste packages such as WP7 (a 5-DHLW/DOE SNF-Short waste package), shown for comparison purposes. Choosing temperature results near either WP2 or WP6 as boundary conditions for this calculation will clearly yield conservative results. Since the temperatures recorded near WP2 and WP6 are so close, the choice of one over the other would not result in a large change in temperatures within the waste package. Therefore, for convenience, the temperatures from Reference 2.2.14 nearest WP2 (for each case) are used as boundary conditions for this calculation.

Table 19. Peak Invert and Drift Wall Temperatures from Cases 1, 5, and 6 of Reference 2.2.14

Case Number From Reference 2.2.14	WP# (WP Type)	Peak Invert Surface Temperature (°C)	Peak Drift Wall Temperature (°C)	Location in Reference 2.2.14
1, Pre-Closure	WP2 (21-PWR)	95	63	Table 49
	WP6 (21-PWR)	96	64	
	WP7 (5-Short)	64	58	
	WP12 (21-PWR)	101	60	
1, Post-Closure	WP2 (21-PWR)	183	161	Table 50
	WP6 (21-PWR)	183	160	
	WP7 (5-Short)	166	157	
	WP12 (21-PWR)	182	156	
5, Pre-Closure	WP2 (21-PWR)	154	110	Table 79
	WP6 (21-PWR)	157	112	
	WP7 (5-Short)	115	100	
	WP12 (21-PWR)	164	101	
5, Post-Closure	WP2 (21-PWR)	183	161	Table 80
	WP6 (21-PWR)	183	160	
	WP7 (5-Short)	166	157	
	WP12 (21-PWR)	182	156	
6, Pre-Closure	WP2 (21-PWR)	104	66	Table 81
	WP6 (21-PWR)	106	67	
	WP7 (5-Short)	67	60	
	WP12 (21-PWR)	112	63	
6, Post-Closure	WP2 (21-PWR)	214	192	Table 82
	WP6 (21-PWR)	214	192	
	WP7 (5-Short)	197	189	
	WP12 (21-PWR)	214	188	

The temperatures from Reference 2.2.14 result from a calculation using an initial 50-year forced ventilation period, 0.1-meter spacing between Waste Packages, and a line heat load of either 1.45 kW/m or 1.75 kW/m. The files used from Reference 2.2.14 are listed in Table 20.

Table 20. Files used From Reference 2.2.14

Case Number From Reference 2.2.14	File Used From Reference 2.2.14, Attachment IV, CD 1 of 2
Case 1	ANSYS_RUNS\BASE_CASE_REFINED\PRECLOSURE\base_case_pre.out
	ANSYS_RUNS\BASE_CASE_REFINED\POSTCLOSURE\base_case_post.out
	ANSYS_RUNS\BASE_CASE_REFINED\POSTCLOSURE\get_dripshield_temps.out
Case 5	ANSYS_RUNS\CASE_05\PRECLOSURE\case_5_pre.out
	ANSYS_RUNS\CASE_05\POSTCLOSURE\case_5_post.out
Case 6	ANSYS_RUNS\CASE_06\PRECLOSURE\case_6_pre.out
	ANSYS_RUNS\CASE_06\POSTCLOSURE\case_6_post.out

Since the drift wall and invert temperatures are specified, ventilation during the pre-closure period is simulated via a convective boundary condition applied to the waste package surface only. Table 6-5 of Reference 2.2.6 gives the heat transfer coefficient on the waste package surface as 2.7 W/m^2-K, at a volumetric air flow rate of 15 m^3/s. The air temperature used is 50°C (122°F) (Reference 2.2.13, Section 4.2.13.5.7). For cases based on Case 5 of Reference 2.2.14, convective heat transfer effects are switched off during the 30-day loss of ventilation scenarios and are switched back on at the end of the 30 days.

6.4 CALCULATION CASES

A range of thermal outputs for the TAD were utilized in the various cases. Heat outputs varied from a minimum of 8 kW up to a maximum of 22 kW, applied as volumetric heat generation rates over the volume of the TAD. The lower heat loads were modeled using a slower-than-average decay rate, and the hotter heat loads were modeled using a faster-than-average decay rate as shown in Table 1 and Table 2 (see Assumption 3.1.6). The heat output for an average decay rate was based on that of a 21-PWR waste package with absorber plates as taken from Table 7 (column 21-PWR AP) of Reference 2.2.10. The decay rate tables utilized were based on initial heat loads of 11.8, 11.5, or 16 kW for the slow, average, and fast decay rates respectively. To obtain the desired heat loads, the tables of heats were multiplied by a scaling factor (8/11.8, 1, 11.8/11.5, 14/11.5, 18/16, 20/16, or 22/16) to obtain the correct starting heat. Convection within the Waste Package was not considered (Assumption 3.2.2). Table 21 below summarizes the details of the calculation cases.

Table 21. Calculation Case Summary

Case #	WP Heat Load (kW)	Line Heat Load (kW/m)	Decay Rate
1	8	1.75	slow
2	11.8	1.45	slow
3 [a]	11.8	1.45	slow
4	11.8	1.45	average
5 [a]	11.8	1.45	average
6	11.8	1.75	average
7	14	1.75	average
8	18	1.75	fast
9	20	1.75	fast
10	22	1.75	fast

(a) Case includes a 30-day loss of ventilation during pre-closure period

Case 1 was run with a TAD of 8 kW heat load with slower-than-average decay under boundary conditions representing a linear heat load of 1.75 kW/m.

Cases 2 through 5 were run with a TAD of the 11.8 kW design basis heat load under boundary conditions representing a linear heat load of 1.45 kW/m. Cases 2 and 3 were modeled using slower-than-average decay rates. Cases 4 and 5 were modeled using an average decay rate. Cases 3 and 5 were identical to Cases 2 and 4 respectively, except that Cases 3 and 5 included a loss of ventilation during the pre-closure period that began at 30 days after emplacement and lasted for 30 days, in which convective heat transfer effects are switched off.

Case 6 was similar to Case 4, with an 11.8 kW average decay rate heat load, except that it utilized a hotter 1.75 kW/m linear heat load boundary condition. Case 7 was run with a TAD of 14 kW at an average decay rate under 1.75 kW/m linear heat load boundary conditions.

Cases 8, 9, and 10 were run with TAD canisters of 18, 20, and 22 kW heat loads respectively. Cases 8 through 10 all modeled waste with faster-than-average decay rates under boundary conditions representing a linear heat load of 1.75 kW/m.

(No loss-of-ventilation cases were included for the 1.75 kW/m linear heat load because this scenario was not evaluated in Reference 2.2.14, and thus no boundary conditions were available.)

All cases have a pre-closure ventilation time of 50 years, and are run to a maximum time of 10,000 years after emplacement to obtain post-closure peak temperature data.

7.0 RESULTS AND CONCLUSIONS

The outputs of this calculation are reasonable compared to the inputs, and the results are suitable for the intended use. While uncertainties have not been quantified, this calculation provides a range of thermal results that can be considered bounding for design guidance at this time. Various heat loads have been used together with nominal conservative assumptions. Future work may quantify the inherent safety margin.

Peak pre-closure temperatures for all cases are shown in Table 22, and peak post-closure temperatures are shown in Table 23. Temperature histories for Cases 1 through 10 are presented in Figure 4 through Figure 13. Figure 14 and Figure 15 present magnified views of the temperature histories during the loss-of-ventilation periods of Cases 3 and 5 respectively.

In all cases, peak temperatures at the center of the TAD stayed well below the 350 °C cladding limit for normal operations in the repository emplacement drifts (Reference 2.2.15, Section 3.7.1), with highest peak TAD core temperature of 280 °C occurring in Case 10 during pre-closure. In Cases 1, 2, 4, 6, and 7, peak TAD core, TAD surface, and waste package surface (outer corrosion barrier) temperatures occurred very soon after closure. TAD surface and waste package surface temperatures in Cases 3, 5, 8, 9, and 10 follow this same trend, but peak TAD core temperatures occur during pre-closure. In all cases, the waste package surface temperature never exceeds 220 °C, and the TAD surface temperature never exceeds 230 °C. In cases with loss-of-ventilation scenarios (Cases 3 and 5), temperatures over the entire TAD waste package spike upwards during the loss-of-ventilation period but quickly return to normal once convection effects (ventilation) are restored.

Table 22. Peak Pre-Closure Temperatures

Case	Total WP Initial Heat (kW)	Line Heat Load (kW/m)	Decay Rate	Maximum Temperature (°C)		
				OUTER CORROSION BARRIER SURFACE	TAD SURFACE	TAD CORE
1	8	1.75	slow	103.8	134.1	157.5
2	11.8	1.45	slow	108.0	154.1	192.4
3 [a]	11.8	1.45	slow	165.7	198.2	231.1
4	11.8	1.45	average	107.8	153.8	192.0
5 [a]	11.8	1.45	average	165.6	198.0	230.8
6	11.8	1.75	average	113.0	157.1	194.4
7	14	1.75	average	118.2	169.6	214.6
8	18	1.75	fast	126.4	189.4	247.8
9	20	1.75	fast	130.7	199.2	264.2
10	22	1.75	fast	134.9	208.6	280.2

(a) Case includes a 30-day loss of ventilation during pre-closure period

Table 23. Peak Post-Closure Temperatures

Case	Total WP Initial Heat (kW)	Line Heat Load (kW/m)	Decay Rate	Maximum Temperature (°C)		
				OUTER CORROSION BARRIER SURFACE	TAD SURFACE	TAD CORE
1	8	1.75	slow	215.0	223.6	233.9
2	11.8	1.45	slow	188.8	205.5	224.3
3 [a]	11.8	1.45	slow	188.8	205.5	224.3
4	11.8	1.45	average	185.4	196.6	209.1
5 [a]	11.8	1.45	average	185.4	196.7	209.1
6	11.8	1.75	average	215.2	224.4	235.5
7	14	1.75	average	216.5	228.0	242.1
8	18	1.75	fast	215.2	224.2	235.2
9	20	1.75	fast	215.9	226.4	239.1
10	22	1.75	fast	216.7	228.5	243.0

(a) Case includes a 30-day loss of ventilation during pre-closure period

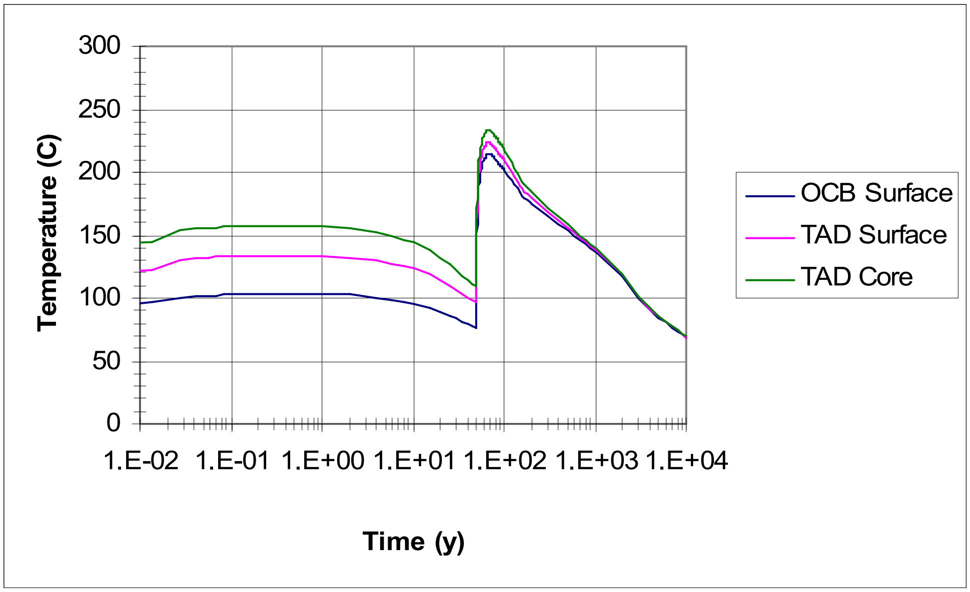

Figure 4. Case 1 Peak Temperature Histories

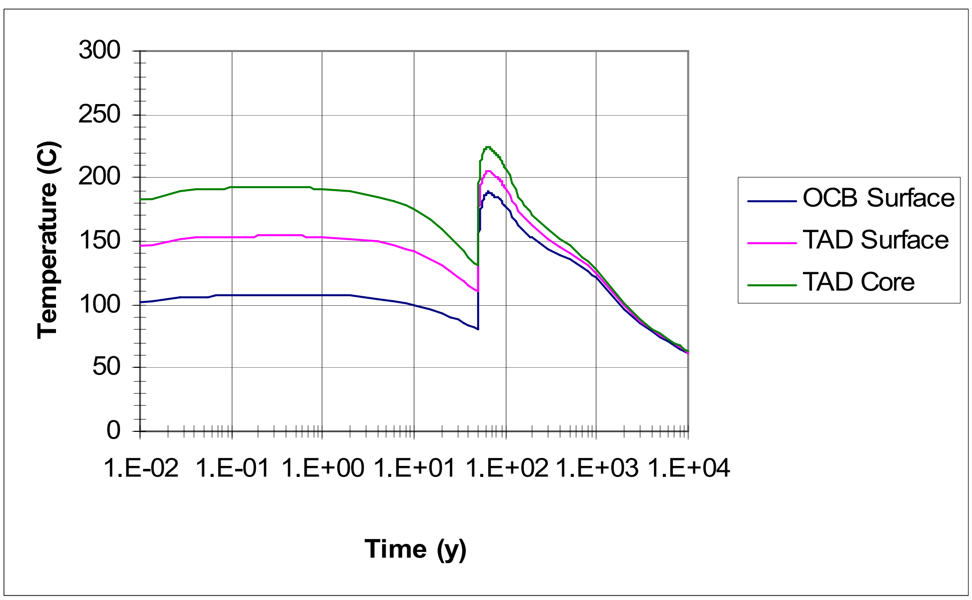

Figure 5. Case 2 Peak Temperature Histories

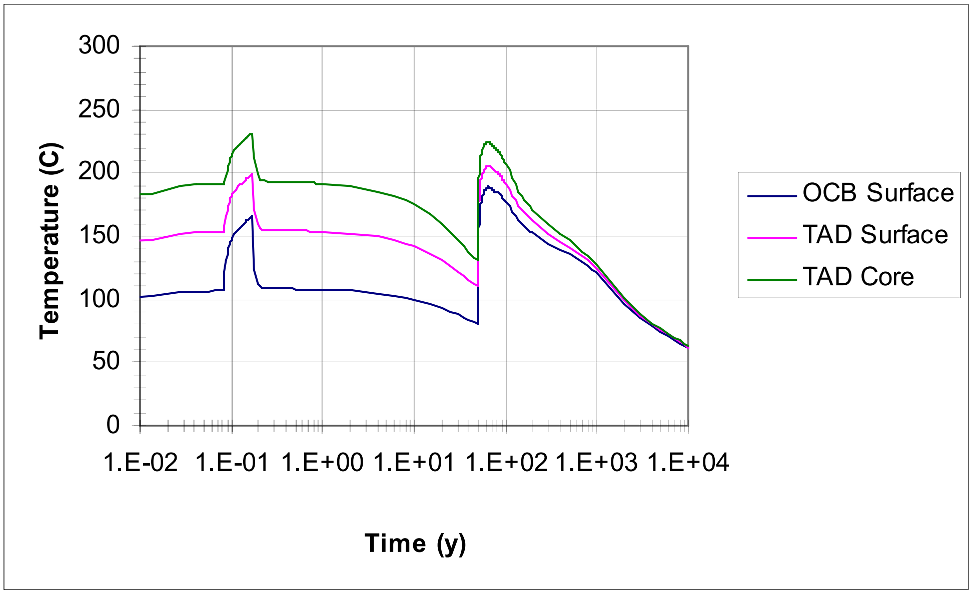

Figure 6. Case 3 Peak Temperature Histories

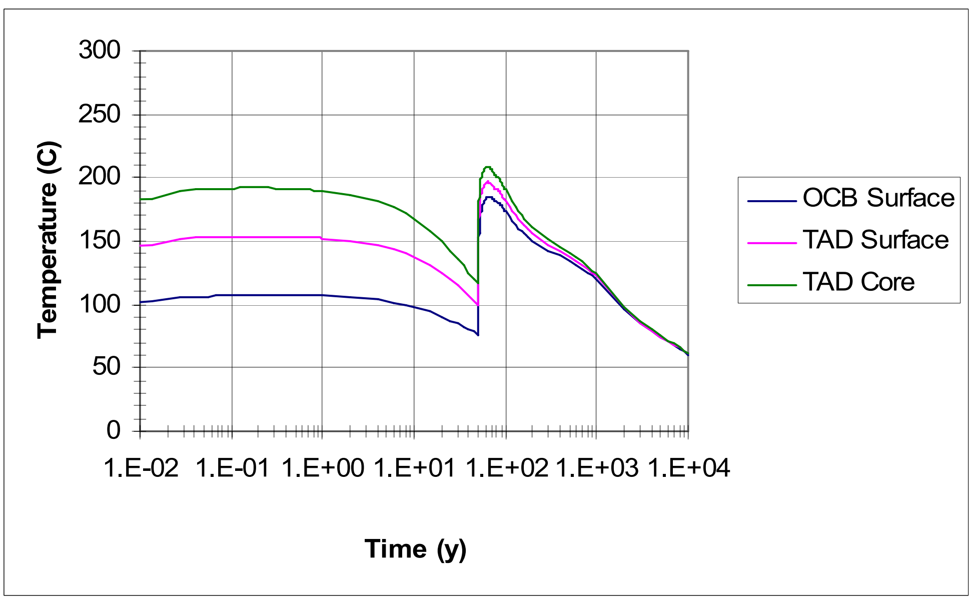

Figure 7. Case 4 Peak Temperature Histories

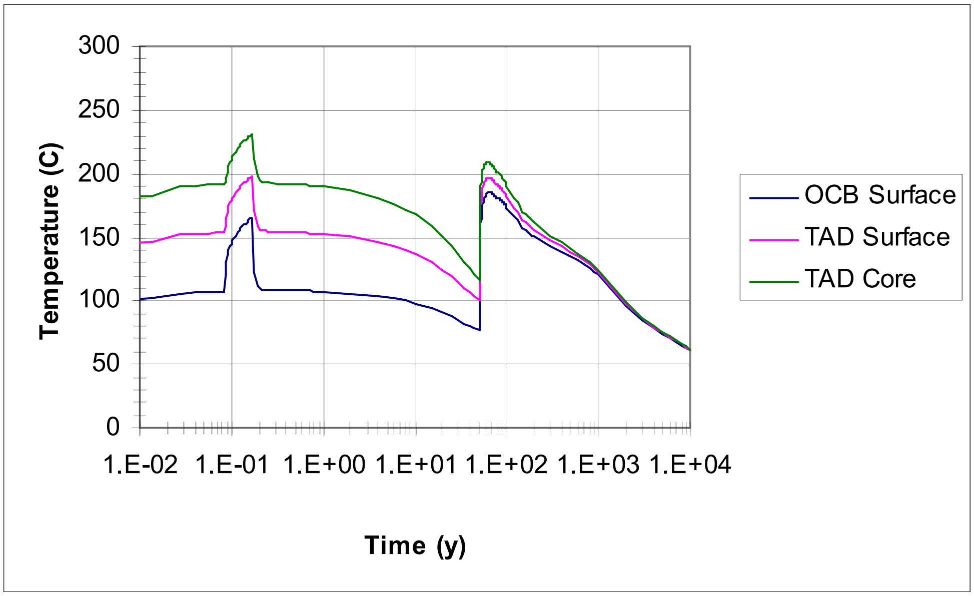

Figure 8. Case 5 Peak Temperature Histories

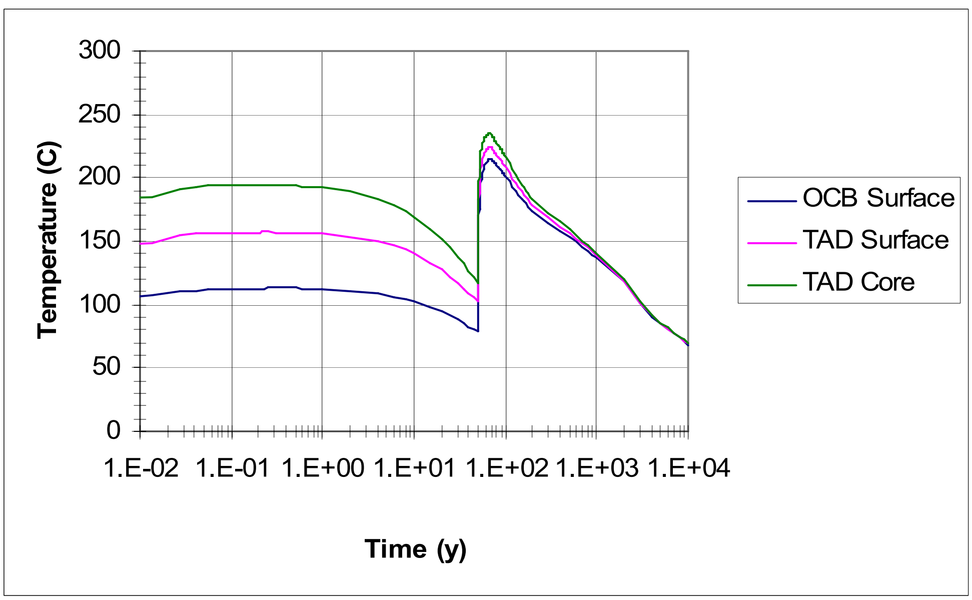

Figure 9. Case 6 Peak Temperature Histories

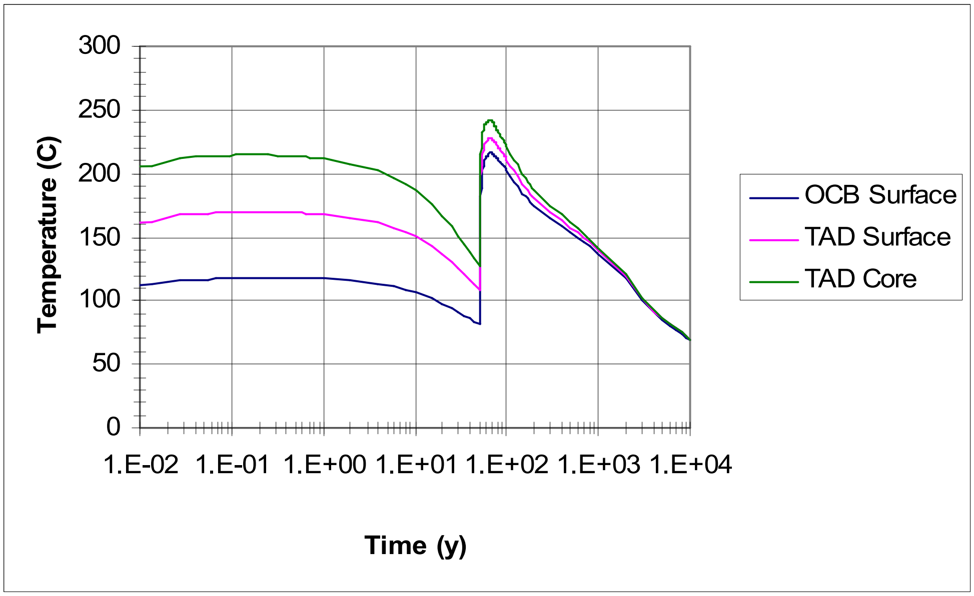

Figure 10. Case 7 Peak Temperature Histories

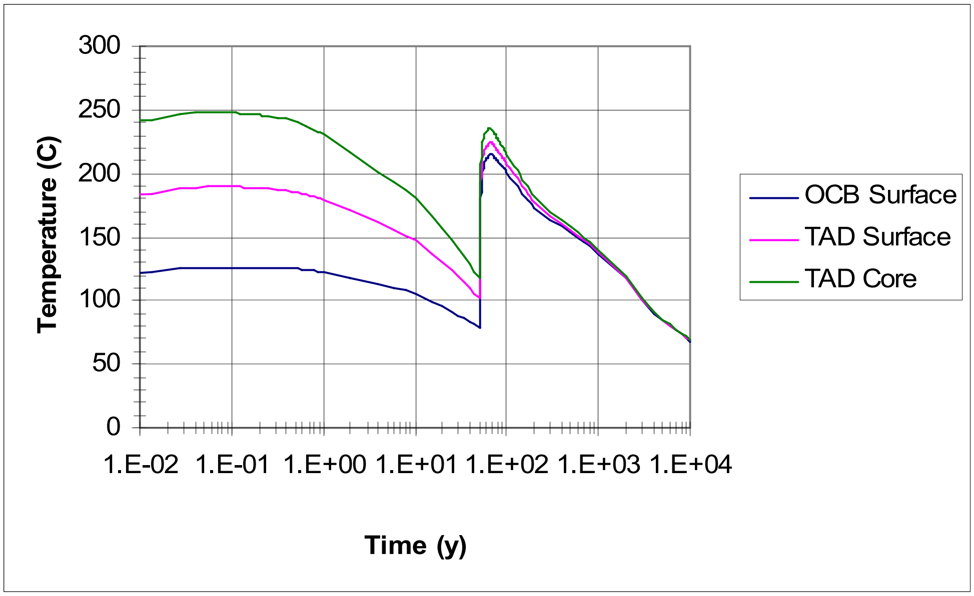

Figure 11. Case 8 Peak Temperature Histories

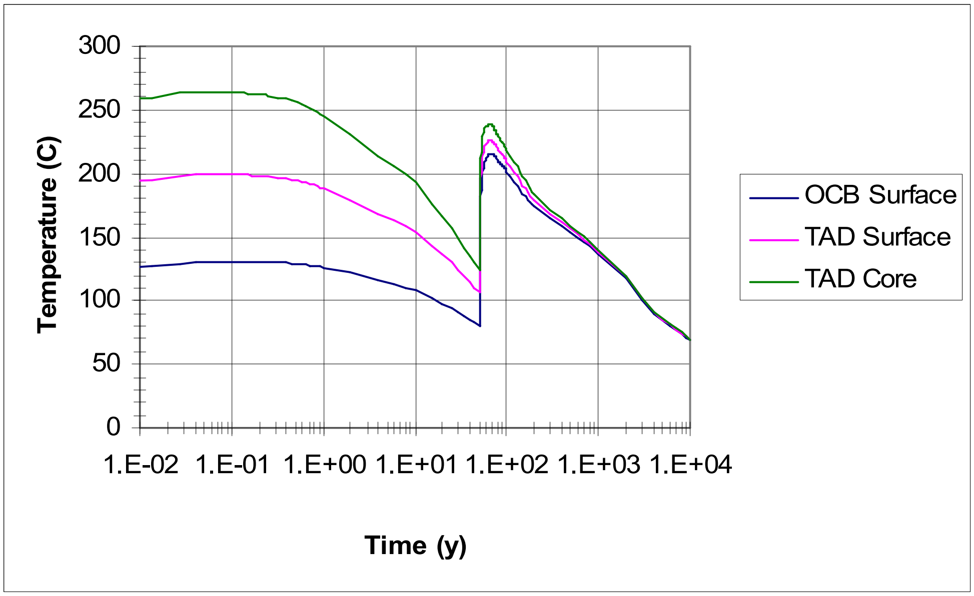

Figure 12. Case 9 Peak Temperature Histories

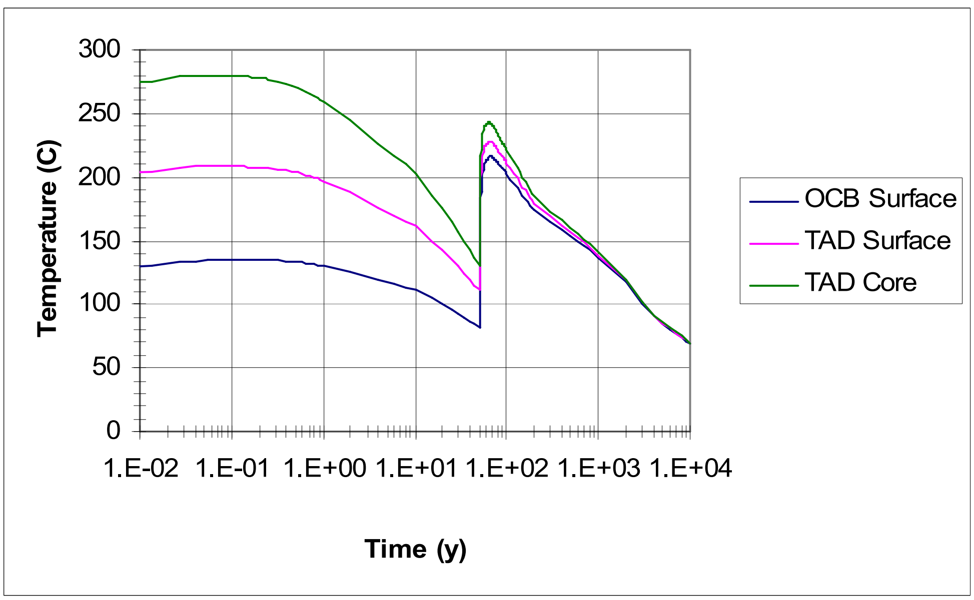

Figure 13. Case 10 Peak Temperature Histories

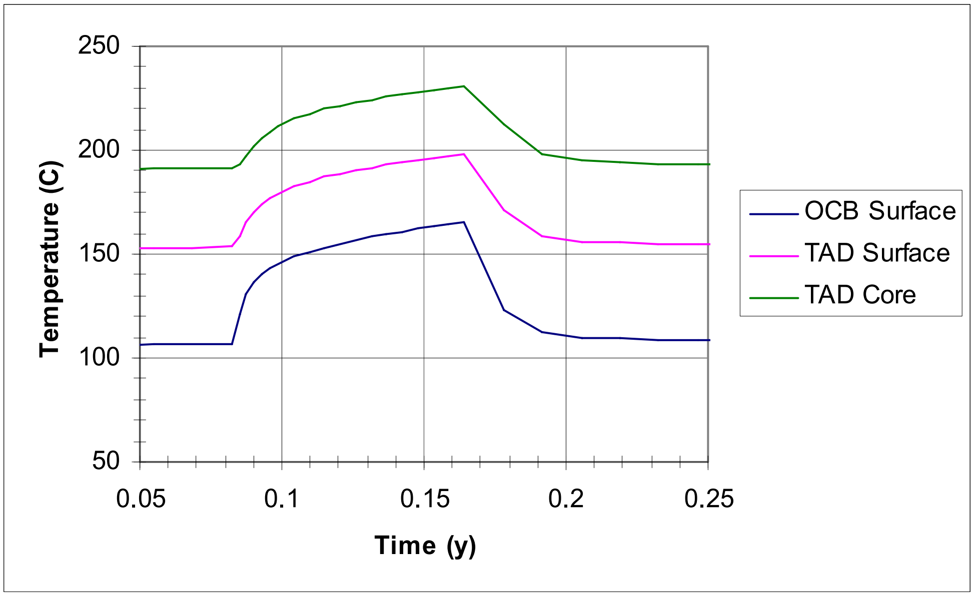

Figure 14. Case 3 Peak Temperature Histories (Close-Up View of Loss of Ventilation Period)

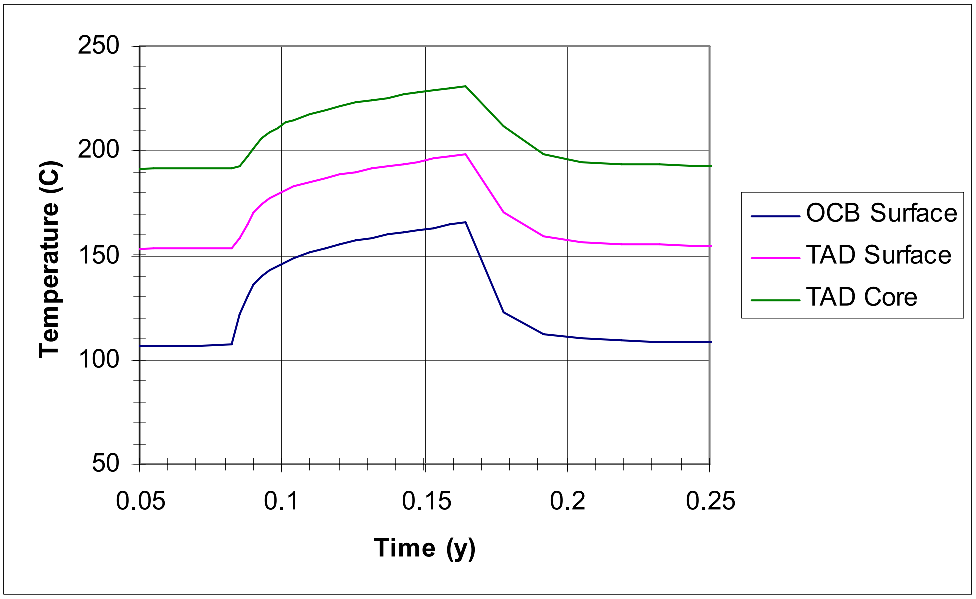

Figure 15. Case 5 Peak Temperature Histories (Close-Up View of Loss of Ventilation Period)

ATTACHMENT I

FILE LISTING FOR ATTACHMENT II

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 Volume Serial Number is 4ED1-71E1

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02/15/2007  10:00 AM             4,167 dwtemps_case6_postcl_dstopwp2.dat
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04/23/2007  02:25 PM            87,552 myCase10_results.xls
04/23/2007  02:18 PM            94,208 myCase1_results.xls
04/23/2007  02:18 PM            93,696 myCase2_results.xls
02/22/2008  09:52 AM           107,008 myCase3_results_00B.xls
04/23/2007  02:21 PM            88,064 myCase4_results.xls
02/22/2008  09:53 AM           104,960 myCase5_results_00B.xls
04/23/2007  02:25 PM            87,552 myCase6_results.xls
04/23/2007  02:23 PM            87,552 myCase7_results.xls
04/23/2007  02:24 PM            88,064 myCase8_results.xls
04/23/2007  02:24 PM            88,064 myCase9_results.xls
02/26/2008  02:01 PM            14,848 PeakTempSummary00B.xls
              11 File(s)        941,568 bytes

     Total Files Listed:
             172 File(s)     16,104,680 bytes
              36 Dir(s)               0 bytes free
```