BSC

Design Calculation or Analysis Cover Sheet

Complete only applicable items.

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Originators: E. Thomas was the primary author compiling this document; D. Wang contributed the text within Section 6.2 and Attachment II; and K. Jaquay and J. Viggato contributed the text within Attachment III.
Checkers: J. Cho was the primary checker for the document; for the Attachment V electronic files, T. deBues checked all ANSYS-related files and Excel file: "2kW_ResultsSummary.xls"; D. Wang checked the MathCad file: "Pressures Rev4.xmcd", and M. Durani checked the Excel file: "Attachment III Creep Stress Excel Workbook.xls".

This document contains color figures

Attachments	Total Number of Pages
Attachment I – Geotechnical Support Information	4
Attachment II – Thermal Support Information	5
Attachment III – ~~Structural~~ Thermal Creep Information ET 2/25/08	9
Attachment IV – File Listing for Attachment V CD	7
Attachment V – Electronic Files	1+CD

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)
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DISCLAIMER

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ACRONYMS

ASME	American Society of Mechanical Engineers
BSC	Bechtel SAIC Company, LLC
BOD	Basis of Design
CPU	Central Processing Unit
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
DDA	Drift Degradation Analysis
DOE	U.S. Department of Energy
DTN	Data tracking number
FEA	Finite element analysis
HP	Hewlett-Packard
IED	Information Exchange Drawing
IV	Inner vessel
LA	License Application
MAPE	Mean Annual Probability of Exceedance
OCB	Outer corrosion barrier
PDC	Project Design Criteria
PGV	Peak ground velocity
PWR	Pressurized Water Reactor
SCA	Seismic Consequence Abstraction
SNL	Sandia National Laboratories
TAD	Transportation, aging, and disposal
TBV	To be verified
TEV	Transport and Emplacement Vehicle
TMRB	Technical Management Review Board
WP	Waste package

1 PURPOSE

The purpose of this document is to evaluate the emplacement drift response to expected (mean) horizontal and vertical peak ground velocities (PGVs) during the 100 year preclosure period. The scope includes examining the geotechnical, thermal, and waste package structural creep effects resulting from a seismically induced rockfall that accumulates around a transportation, aging, and disposal (TAD) waste package. Peak ground velocities and the Mean Annual Probability of Exceedance (MAPE) are rationalized for the potential exposure during the 100-year preclosure period. This analysis does not credit ground support in the emplacement drifts.

Outputs of this calculation provide support to the Preclosure Safety Analysis.

2 REFERENCES

The following design inputs and references support this calculation. The information represents current design details and supports the science and engineering interfaces.

2.1 PROCEDURES/DIRECTIVES

2.1.1 EG-PRO-3DP-G04B-00037, Rev 010, *Calculations and Analyses*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071018.0001

2.1.2 IT-PRO-0011, Rev 007, *Software Management*. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20070905.0007.

2.1.3 Office of Repository Development 2007. *Repository Project Management Automation Plan.* 000-PLN-MGR0-00200-000, Rev. 00E. Las Vegas, Nevada: U.S. Department of Energy, Office of Repository Development. ACC: ENG.20070326.0019.

2.2 DESIGN INPUTS

2.2.1 ANSYS V. 8.0. 2004. HP-UX 11.0, HP-UX 11.22, SunOS 5.8. STN: 10364-8.0-00. [DIRS 170070]

2.2.2 BSC (Bechtel SAIC Company) 2004. *Drift Degradation Analysis.* ANL-EBS-MD-000027 REV 03. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040915.0010; DOC.20050419.0001; DOC.20051130.0002; DOC.20060731.0005. [DIRS 166107]

2.2.3 BSC 2004. *Waste Form, Heat Output, and Waste Package Spacing for an Idealized Drift Segment.* 000-00C-WIS0-00500-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040121.0007; ENG.20050817.0031; ENG.20051019.0002.

2.2.4 BSC 2007. *Basis of Design for the TAD Canister-Based Repository Design Concept.* 000-3DR-MGR0-00300-000-001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071002.0042; ENG.20071026.0033; ENG.20071108.0002; ENG.20071109.0001; ENG.20071120.0023; ENG.20071126.0049; ENG.20071214.0009; ENG.20071213.0005; ENG.20071227.0018; ENG.20080207.0004; ENG.20080212.0003.

2.2.5 BSC 2007. *TAD Thermal Response to Rock Fall*. 000-00C-WIS0-03000-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070731.0044.

2.2.6 BSC 2007. *Drift Cross Section Showing Emplaced Waste Package and Drip Shield*. 800-M00-WIS0-00101-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070412.0003.

2.2.7 BSC 2008. *IED Geotechnical and Thermal Parameters III.* 800-IED-MGR0-00403-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080219.0008.

2.2.8 BSC 2008. *IED Seismic and Seismic Consequence Data*. 800-IED-MGR0-00701-000 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20080215.0004.

2.2.9 DOE (U.S. Department of Energy) 2004. *Validation Test Report for: ANSYS V8.0*. Document Number 10364-VTR-8.0-00. Las Vegas, Nevada: U.S. Department of Energy Office of Repository Development. ACC: MOL.20040422.0376. [DIRS 171758]

2.2.10 MO0301SPASIP27.004. Sampling of Stochastic Input Parameters for Rockfall Calculations and for Structural Response Calculations Under Vibratory Ground Motions. Submittal date: 01/15/2003. [DIRS 161869]

2.2.11 MO0402AVDTM105.001. Acceleration, Velocity, and Displacement Time Histories for the Repository Level at 10-5 Annual Exceedance Frequency. Submittal date: 02/09/2004. [DIRS 168890]

2.2.12 MO0611ROCKFALL.000. Seismic Rockfall Analysis for Emplacement Drifts in Lithophysal Rock Mass Subject to Various Vibratory Ground Motion Levels. Submittal date: 11/28/2006. [DIRS 178831]

2.2.13 MO0703SUMM3DEC.000. Summary of 3DEC Nonlithophysal Rockfall Model Results. Submittal date: 03/15/2007. [DIRS 179895]

2.2.14 MO0703PARUBBLE.000. Effective Thermal Conductivity for Rubble. Submittal date: 03/26/2007. [DIRS 179966]

2.2.15 MO0801HCUHSREB.001. Hazard Curves and Mean Uniform Hazard Spectra for the Repository Block. Submittal date: 01/14/2008. [DIRS 184803]

2.2.16 SNL (Sandia National Laboratories) 2007. *Seismic Consequence Abstraction*. MDL-WIS-PA-000003 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070928.0011. [DIRS 176828]

2.2.17 Knowles, M.K. 2007. "Contract No. DE-AC04-94AL-85000-Drift Length per Simulation for the Nonlithophysal Rockfall Model." Letter from M.K. Knowles (SNL) to R.J. Tosetti (BSC), March 5, 2007, MKK:glm, with enclosure. ACC: LLR.20070314.0020. [DIRS 179805]

DTNs: MO0301SPASIP27.004, MO0402AVDTM105.001, and MO0801HCUHSREB.001 (References 2.2.10, 2.2.11, 2.2.15) are cited in information exchange drawing (IED) *IED Seismic and Seismic Consequence Data* (Reference 2.2.8), and therefore approved and appropriate for the intended use in this calculation.

DTNs: MO0611ROCKFALL.000, MO0703SUMM3DEC.000, and MO0703PARUBBLE.000 (References 2.2.12, 2.2.13, and 2.2.14) are cited in *IED Geotechnical and Thermal Parameters III* (Reference 2.2.7), and therefore approved and appropriate for the intended use in this calculation.

Direct inputs of the *Drift Degradation Analysis* (Reference 2.2.2) documents cited within the body of this calculation are contained in *IED Geotechnical and Thermal Parameters III* (Reference 2.2.7) and are therefore, approved and appropriate as used in this calculation.

The following References are related to Attachment II.

2.2.18 BSC 2004. *Thermal Evaluation of the Waste Package in the Transporter.* 000-00C-DSU0-03700-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040818.0004.

2.2.19 BSC 2007. *Thermal Evaluation of the 5-DHLW/DOE SNF and TAD Waste Packages in the TEV*. 800-00C-DS00-00100-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070731.0043.

The following References are related to Attachment III.

2.2.20 Structural Integrity Associates 2005. *Creep Rupture Properties of Alloy 22*. SIR-05-109, Rev. 1, San Jose, California: Structural Integrity Associates, ACC: MOL.20050426.0375. [DIRS 173553]

2.2.21 ASME 2007. Boiler and Pressure Vessel Code, Section III Part 1 Subsection NH, *Class 1 Components in Elevated Temperature Service*. [New York City, New York]: American Society of Mechanical Engineers. TIC: 259190.

2.2.22 BSC 2007. *Waste Package Component Design Methodology Report*. 000-30R-WIS0-00100-000-004. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071220.0030.

2.2.23 BSC 2007. *Drift Collapse Weight and Thermal Loading of TAD and 5-DHLW/DOE SNF Short Co-Disposal Waste Packages*. 000-00C-MGR0-04400-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071030.0041.

2.2.24 Beer, F.P. and Johnston, E.R., Jr. 1981. *Mechanics of Materials*. New York, New York: McGraw-Hill. TIC: 255414. [ISBN:0-007-004284-5]

2.2.25 BSC 2005. *Waste Package Behavior in Magma*. 000-00C-SSE0-00600-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20050502.0005; ENG.20050817.0027.

2.2.26 ASME 2007. Boiler and Pressure Vessel Code, Section I, Code Case 2226-2, *Ni-Cr-Mo Alloy UNS N06022 for Code Construction for Temperatures up to 1250°F*. [New York City, New York]: American Society of Mechanical Engineers. TIC: 259190

2.2.27 BSC 2005. *Waste Package Damage Due to Interaction with Magma*. CAL-WIS-MD-000013 REV 00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20050706.0006. [DIRS 173802]

2.2.28 Jones, D.P. and Holliday, J.E. 2000. "Elastic-Plastic Analysis of the PVRC Burst Disk Tests with Comparison to the ASME Primary Stress Limits." *Journal of Pressure Vessel Technology*, *122*, 146-151. [New York, New York]: American Society of Mechanical Engineers. TIC: 258969. [DIRS 182173]

2.2.29 EPRI (Electric Power Research Institute) 2004, *Potential Igneous Processes Relevant to the Yucca Mountain Repository: Extrusive-Release Scenario.* EPRI TR-1008169. Palo Alto, California: Electric Power Research Institute. TIC: 256654. [DIRS 171915]

2.2.30 Haynes International, 1997. *Hastelloy C-22 Alloy*. Kokomo, Indiana: Haynes International. TIC: 238121. [DIRS 100896]

2.2.31 Roark, R.J. and Young, W.C. 1975. *Formulas for Stress and Strain*. 5th Edition. New York, New York: McGraw-Hill. TIC: 240746. [ISBN:0-07-053031-9]

2.2.32 ASME 2001. *2001 ASME Boiler and Pressure Vessel Code (includes 2002 addenda)*. New York, New York: American Society of Mechanical Engineers. TIC: 251425.

2.2.33 BSC 2007. *TAD Waste Package Configuration*. 000-MW0-DSC0-00102-000 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070301.0011.

2.2.34 BSC 2007. *TAD Waste Package Configuration*. 000-MW0-DSC0-00103-000 REV 00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20070301.0012.

2.2.35 BSC 2006. *21-PWR Waste Package Internal Pressure Estimate*. 000-00C-DSU0-03500-000-00B. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20061108.0004; ENG.20070402.0003.

Structural Integrity Associates (Reference 2.2.20) and Haynes International (Reference 2.2.30) provide vendor data pertaining to Alloy-22 and are appropriate for use in this calculation.

The following References are related to Attachment V (CD).

2.2.36 Punatar, M.K. 2001. *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3*. TDR-UDC-NU-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20010702.0087. [DIRS 155635]

2.2.37 Rothman, A.J. 1984. *Potential Corrosion and Degradation Mechanisms of Zircaloy Cladding on Spent Nuclear Fuel in a Tuff Repository*. UCID-20172. Livermore, California: Lawrence Livermore National Laboratory. ACC: NNA.19870903.0039. [DIRS 100417]

2.2.38 DOE (U.S. Department of Energy) 2007. *Transportation, Aging and Disposal Canister System Performance Specification*. WMO-TADCS-000001, Rev. 0. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20070614.0007. [DIRS 181403]

2.2.39 Zwillinger, D., ed. 1996. CRC *Standard Mathematical Tables and Formulae*. 30th Edition. Boca Raton, Florida: CRC Press. TIC: 233960. [ISBN 0-8493-2479-3]

Rothman (Reference 2.2.37) provides information concerning fuel rod void volumes and is appropriate for use in this calculation.

2.3 DESIGN CONSTRAINTS

None.

2.4 DESIGN OUTPUTS

This calculation supports the Preclosure Safety Analyses.

3 ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

3.1.1 Use of DTN: MO0801HCUHSREB.001 for Hazard Curves for the Repository Block

It is assumed that DTN: MO0801HCUHSREB.001 (Reference 2.2.15) will be qualified. Furthermore, it is assumed that upon qualification, any change in the horizontal and vertical PGV values obtained from the mean hazard results is not anticipated to be significant or consequential to the conclusions of this calculation.

Rationale: The data from this source DTN are used as input because they are the most recent values for these parameters. The future qualification of this DTN is being tracked in the Document Input Reference System database via TBV-9265. The draft report indicates that the application of the earthquake ground motion data under the subject DTN is subjected to a limitation stated below:

> *Note that in computing the UHS, spectral acceleration (SA) for a period of 3.3 sec was inadvertently used for a period of 3.0 sec. Thus, for periods greater than 2.0 sec the UHS has lower SA (higher AFE) then intended. Users of these data should take into account this limitation when deciding whether the data are adequate for an intended use. Design response spectra based on the UHS and time histories spectrally matched to design response spectra have the same limitation*.

While the potential impact of such a limitation on ground motion time histories (including PGV values) used for computing rockfalls in emplacement drifts (Reference 2.2.2) cannot be evaluated directly because the ground motion time histories corrected for the limitation are not available at the time of completing this calculation, its potential impact is anticipated to be inconsequential based on the following reasoning:

- Response spectral data contained in DTN MO0801HCUHSREB.001 show that spectral acceleration values associated with frequencies 0.3 and 0.5 Hz (periods 3.3 and 2.0 seconds) are significantly lower than those associated with higher frequencies. The narrow frequency range impacted by the limitation is not anticipated to impact ground motion data so significantly that rockfall calculation results will be significantly different.

- In general, PGV measures the amplitude of medium frequencies in the ground motion and is used for underground structures in medium to hard rock while the peak ground displacement measures the amplitude of low-frequencies and is mostly used for surface structures. The limitation applies to wave periods greater than 2.0 seconds or to the frequency at or below 0.5 Hz, which is on the low end of the frequency range of the response spectra. Thus, a low frequency range is not anticipated to play a significant role in velocity time histories in rockfall calculations.

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

3.2.1 Probability of a Rockfall Event

The probability of a rockfall event during the preclosure period is rationalized to a 2×10^{-6} seismic hazard level (annual probability).

Rationale: The MAPE frequency analyzed during preclosure is 1×10^{-5} and described by 15 sets of ground motion characteristics.

Analyses indicate that with 100% burial of any 14 kW waste package there is no breach. Ten (10) years after the hottest waste package (18 kW) has been emplaced it will cool to less than 14 kW heat (Figure 5, Section 6.2), therefore any emplaced 18 kW waste package would have exposure to a potential seismic event for 10 years (see Section 6.2).

With an approximate 25 year duration of waste emplacement and the 10 year exposure for any waste package, an approximate exposure period of 50 years is rationalized for use in this calculation. During preclosure a seismic hazard level with an annual probability of exceedance at 2×10^{-6} can result in an event with a probability of 1/10,000 within a period of 50 years (i.e., 50 years $\times$ 2×10^{-6} 1/year = 10^{-4} = 1/10,000). This assumption is used in Section 6.1.

3.2.2 Drift Length for Simulations

A 20 m length is assumed for the simulated drift length for rockfall simulations.

Rationale: As documented in Reference 2.2.13, the rockfall simulations are based on a model space length of 25 m, but the actual length of drift is smaller, approximately 21.74 m as documented in Reference 2.2.17. Assuming a lower drift length of 20 m per simulation provides a larger rockfall volume per meter of drift, and is therefore bounding as used in this calculation. Reference 2.2.17 is suitable for use in this assumption because it provides information to correct a condition tracked by Condition Report 10115. This Assumption is used in Attachment I, Table 5.

4 METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.1). Part of the output from this calculation is developed to support the waste package thermal modeling and design. 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 2.2.4, Section 11.1.2). Therefore, the approved version of this calculation is designated as “QA: QA.”

4.2 USE OF SOFTWARE

4.2.1 General Software

The software identified in this section is project standard software and considered Level 2 usage in accordance with IT-PRO-0011, *Software Management* (Reference 2.1.2, Attachment 12). The software is listed in the *Repository Project Management Automation Plan* (Reference 2.1.3, Table 6-1). The software was executed on PCs running the Microsoft Windows XP SP-2 operating system.

This document is prepared with the project standard Microsoft Office 2003 Professional software. Emplacement drift figures in Section 6.1.1 were generated in MicroStation Version 07.01.04.16 Windows x86 and are verified by visual inspection. Some calculations have been performed by hand.

Microsoft Excel 2003, a component of Microsoft Office 2003, was used for computations and plotting results in Section 6 and Attachment II. The Excel computations are verified by hand calculations and the plots are verified by visual inspection.

MathCad version 13.0 was used for computations in Attachment III. The MathCad results are verified by hand calculations.

The MathCad and Excel files that support this calculation are on CD in Attachment V.

4.2.2 ANSYS Software

The finite element computer code used for the thermal analysis portion of this calculation is ANSYS V8.0 (Reference 2.2.1), which is identified by 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 2.1.2, Attachment 12). ANSYS V8.0 is qualified, baselined, and listed in the *Qualified and Controlled Software Report* as well as the *Repository Project Management Automation Plan* (Reference 2.1.3, 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: Opus, Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) Tag Number: 151664

CPU Name: Rosebud, CRWMS M&O Tag Number: 150689

CPU Name: Milo, CRWMS M&O Tag Number: 151665

The ANSYS V8.0 evaluations performed within this calculation are fully within the range of validation performed for ANSYS V8.0 (Reference 2.2.9). Therefore, ANSYS V8.0 is appropriate for the thermal analysis as performed in this calculation. Access to, and use of, the code was granted by Software Configuration Management. The details of the ANSYS analyses are described in Section 6.2 and Attachment II of this calculation. All inputs and outputs are located on CD in Attachment V.

4.3 ANALYSIS METHOD

This document reviews the geotechnical, thermal, and waste package creep issues associated with a TAD waste package that has been in a seismic event that may occur during the 100 year preclosure period.

- The horizontal and vertical peak ground velocities (PGV) are rationalized for the expected exposure during the preclosure period.
- The rockfall volume in an emplacement drift (m^3/m tunnel length) is determined based on the maximum PGV identified.
- The maximum emplacement drift rockfall volume is used to determine how much a waste package will be covered.
- The thermal response of a TAD waste package buried in rockfall (rubble) is examined.
- The structural creep of waste package materials is evaluated based on the thermal response.

Finite Element Analysis (FEA) numerical solutions are performed using the commercially available code ANSYS V8.0 (Reference 2.2.1).

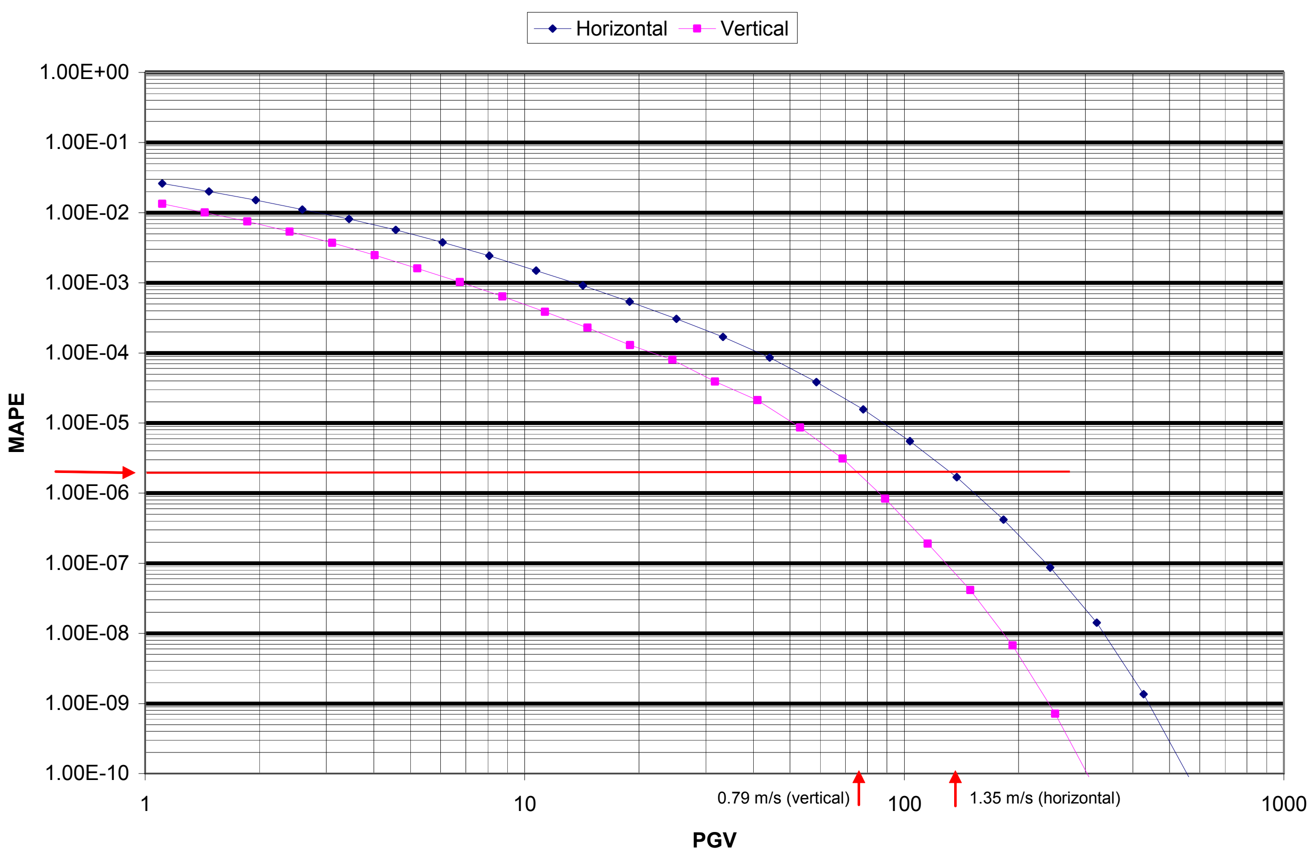
5 LIST OF ATTACHMENTS

6 BODY OF ANALYSIS

The seismic hazard bases for the repository have been re-evaluated and this calculation evaluates effect of the current seismic hazard peak ground velocity curves at the emplacement level. A seismically induced rockfall can accumulate around a waste package, acting as a thermal insulator and potentially restricting airflow in an emplacement drift. This calculation examines the potential for waste package burial based on geotechnical analysis results for the seismic hazard, evaluates the waste package thermal response, and potential for structural creep to demonstrate the probability for this event will not result in a waste package breach.

6.1 GEOTECHNICAL ANALYSIS

The rockfall volume generally varies with rock type and with the peak ground velocities at the emplacement drift. Results from the *Drift Degradation Analysis* (DDA) (Reference 2.2.2) and output DTNs (References 2.2.10, 2.2.12, and 2.2.13) from the *Seismic Consequence Abstraction* (SCA) (Reference 2.2.16) are used to evaluate the rockfall volume in an emplacement drift for the seismic hazard curves illustrated in Figure 1 (Assumption 3.1.1).



Source: Reference 2.2.15; Attachment V/Hazard Curve.xls

Figure 1: Plot of Mean Annual Probability of Exceedance (MAPE) vs. Peak Ground Velocity (PGV)

As illustrated by the red arrows in Figure 1, at a 2×10^{-6} annual probability (Assumption 3.2.1) the horizontal and vertical PGVs are interpolated to be 1.35 m/s and 0.79 m/s respectively (135 cm/s and 79 cm/s). A seismic hazard level with an annual probability of exceedance a 2×10^{-6} can result in an event with a probability of 1/10,000 within a period of 50 years, i.e., a Category 2 event considered by the Preclosure Safety Analysis.

6.1.1 Rockfall in Emplacement Drifts Excavated in Lithophysal Rock

There are no direct rockfall computations done at the 2×10^{-6} seismic hazard level with a horizontal PGV bounded at 1.35 m/s. The existing rockfall results closest to such a horizontal PGV are those corresponding to a bounded horizontal PGV (H1) value of 1.05 m/s with other PGV (H2) and vertical PGV (V) unbounded. The results are available in the DDA (Reference 2.2.2; Reference 2.2.7) and SCA (Reference 2.2.16; Reference 2.2.7).

Per a summary statement in the DDA, for PGV values below 1.5 m/s result in an approximate damage level below 5 m^3/m (Reference 2.2.2, Section 6.4.2.2.2.1; Reference 2.2.7, Excerpt XXII). Both horizontal and vertical PGV values (1.35 and 0.79 m/s respectively) at the 2×10^{-6} seismic hazard level are below 1.5 m/s. Accordingly, the rockfall volume of 5 m^3/m is considered to be representative for emplacement drifts excavated in lithophysal rock. Such a rockfall value is further substantiated by the following discussions:

- From the results of the rockfall volume vs. PGV illustrated in Figure 6-128 of the DDA which correspond to the 10^{-5} seismic hazard level, the rockfall volume corresponding to a 1.35 m/s PGV is estimated to range from 2 to 8 m^3/m of emplacement drift (Reference 2.2.2, Figure 6-128; Reference 2.2.7, Figure 1) with an apparent mean of 5 m^3/m.

- As indirect support to the discussion above, Figures 6-125 and 6-126 of the DDA illustrate rockfall results corresponding to a horizontal PGV value of up to 1.04 m/s and a vertical PGV value of up to 1.52 m/s. These PGV levels are sufficiently close to the 1.35 and 0.79 m/s mentioned above (Section 6.1). The highest rockfall volume presented in each figure is 5.6 and 3.3 m^3/m, respectively (Reference 2.2.2, Figures 6-125 and 6-126). These rockfall volumes all correspond to the Category 1 rock mass condition which only accounts for up to 5% of emplacement drifts in lithophysal rock. Therefore, a rockfall volume of 5 m^3/m is very conservative.

- As presented in Table 1, for the 1.05 m/s level the average rubble volume is 7.82 m^3/m. These rubble volumes were generated by using the scaled 10^{-5} ground motion data listed in Table 6-45 of the DDA (Reference 2.2.2, Table 6-45; Reference 2.2.11; and Reference 2.2.8, Seismic Data Point B). By eliminating those results associated with ground motion sets that have vertical components greater than 200 cm/s (2 m/s) (Table 1, bold entries), an average rubble volume of 5.10 m^3/m is obtained, which strongly indicates the adequacy of a 5 m^3/m rockfall volume for this calculation.

Table 1. Rubble Volume Evaluation

Motion Number	Rubble Volume (m^3/m at 1.05 m/s) Base	Modified*	Vertical Component (cm/sec)	Ground Motion
4	2.26	2.26	70.88	Set 1
8	7.63	7.63	145.25	Set 2
16	3.22	3.22	**398.11**	**Set 3***
12	5.62	5.62	152.27	Set 4
2	3.62	3.62	106.52	Set 5
8	3.11	3.11	173.88	Set 6
14	5.52	5.52	**333.16**	**Set 7***
4	3.42	3.42	98.16	Set 8
10	0.58	0.58	**281.76**	**Set 9***
6	11.84	11.84	50.16	Set 10
9*	21.95	exclude*	120.31	Set 11
1	4.35	4.35	100.6	Set 12
1	0.79	0.79	**318.01**	**Set 13***
7*	28.96	exclude*	92.78	Set 14
11	14.38	14.38	137.53	Set 15
Average Rubble Volume (m^3/m)	7.82	5.10		

Source: non-shaded Reference 2.2.12, results_rockfall.zip/summary.xls; shaded Reference 2.2.11, vts.zip/ mat01v.vts through mat16v.vts

*Ground Motion Sets 3, 7, 9, and 13 (bold/shaded) exceed 200 cm/sec (2 m/s). Only Ground Motion Sets 7 and 9 (red squares) appear in the Motion Number column (non-shaded part of table) and excluded from the Modified Average Rubble Volume.

In summary, as based on existing rockfall results vs. PGV values obtained under 10^{-5} ground motion data reported in the DDA, a mean rockfall volume in an emplacement drift excavated in lithophysal rock subjected to 2×10^{-6} seismic ground motions is estimated to be approximately 5 m^3/m. The 5 m^3/m represents an in situ rock volume which is bulked by 0.25 for the rubble pile, which falls within the conservatively selected range of 0.2 to 0.4 (Reference 2.2.7, Excerpt XIII).

6.1.2 Rockfall in Emplacement Drifts Excavated in Nonlithophysal Rock

The rockfall volume for an emplacement drift excavated in nonlithophysal rock is evaluated at the 2×10^{-6} seismic ground motion for PGVs of 1.35 m/s and 0.79 m/s (Figure 1) as follows.

Rockfall volumes for nonlithophysal rock were analyzed at PGVs of 1.05 m/s and 2.44 m/s (Reference 2.2.13), where the 2.44 m/s PGV bounds the velocities evaluated in this calculation. Results are presented in Attachment I (Table 5). As shown in Table 5 for a PGV of 1.05 m/s the rubble volume averaged 0.255 m^3/m, and for a PGV of 2.44 m/s the rubble volume averaged 0.498 m^3/m (Attachment I, Table 5). For 2×10^{-6} seismic ground motions in nonlithophysal rock, rubble volumes of less than 0.5 m^3/m would not result in a significant burial of a TAD waste package.

6.1.3 Predicting the Rubble Profile over a Waste Package

Figure 2 illustrates that a nominal bulked rubble volume of 8.74 m^3/m is required for a TAD waste package to be 100% buried (Attachment I, Table 6). With a bulking factor of 1.25 the 8.64 m^3/m volume represents an in situ rock volume 6.91 m^3/m (8.64/1.25 = 6.91). The 5 m^3/m in situ rockfall volume (Section 6.1.1) will have a bulked volume of 6.25 m^3/m (5×1.25 = 6.25). The

8.64 m³/m volume required to bury a TAD waste package exceeds the 6.25 m³/m rubble volume that could occur for a 2×10^{-6} seismic event and therefore, a TAD waste package would not likely be completely buried in a 2×10^{-6} seismic event.

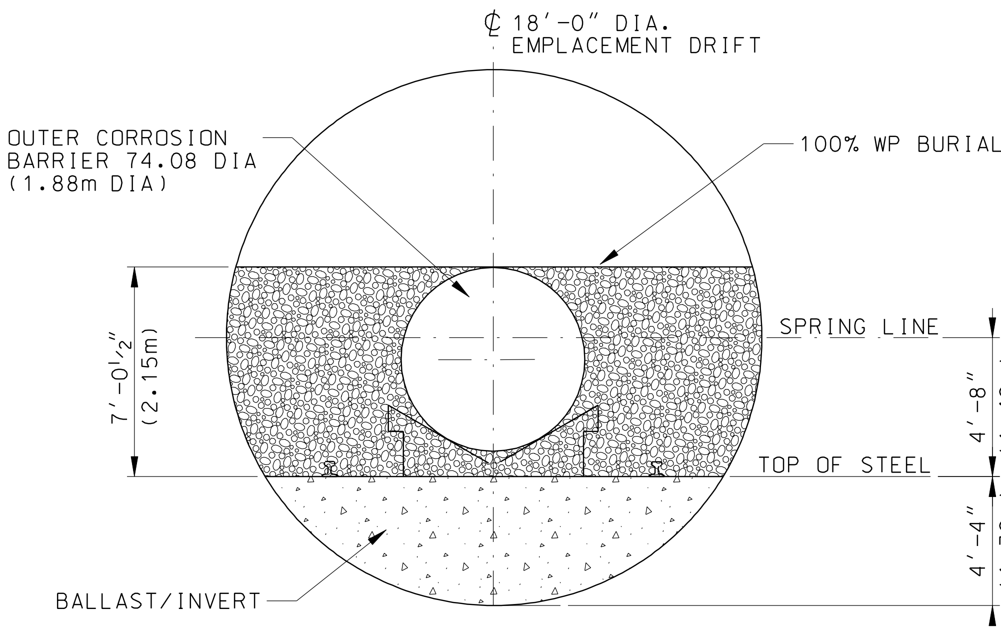


Figure 2. Illustration of Fully Buried TAD Waste Package

Based on the 5 m³/m rockfall volume in an emplacement drift excavated in lithophysal rock, the available space at the sides of a TAD WP, and the dominant rockfall size, a TAD WP is estimated to be covered by rubble in such a manner that the top surface of the TAD WP is exposed to ventilation air. Figure 3 illustrates a possible configuration for a 5 m³/m rockfall, bulked to 6.25 m³/m, and confined within the original emplacement drift excavated diameter.

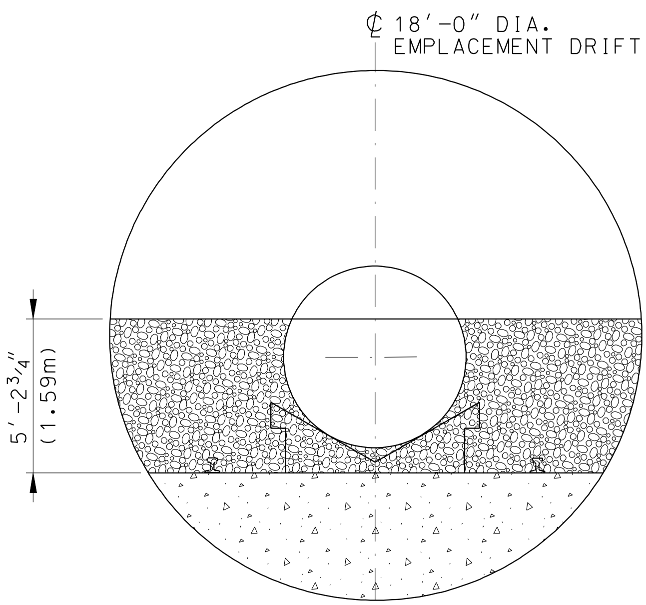


Figure 3. Illustration of 5 m³/m Emplacement Drift Failure Bulked to 6.25 m³/m

As described in the following text and figures, the DDA (Reference 2.2.2) provides the bases for evaluating the rubble profile that would be expected for the 2×10^{-6} seismic event.

As illustrated in Figure 2 and Figure 3, the rubble volume and corresponding profiles do not consider area outside the nominal emplacement drift excavation, i.e., the void created by the rockfall itself. For a rockfall event, the emplacement drift damage mechanism consists primarily of shear failure at the springline of the tunnel coinciding with passage of the compressive stress increase associated with PGV peaks. If the addition of dynamic plus in situ stress is large enough, shear failure occurs primarily at the springline, resulting in development of an elliptical shape of the opening as the rock mass yields and rockfall occurs along the sides (Reference 2.2.2, Section 6.4.2.2.2.1; and Reference 2.2.7, Excerpt XXII). Figure 4 illustrates a rockfall profile for 5 m³/m, bulked to 6.25 m³/m based on this failure pattern. Though the exact geometry and dimensions of the drift remaining after a rockfall is unknown, the figure represents a possible configuration based on the elliptical failure mode.

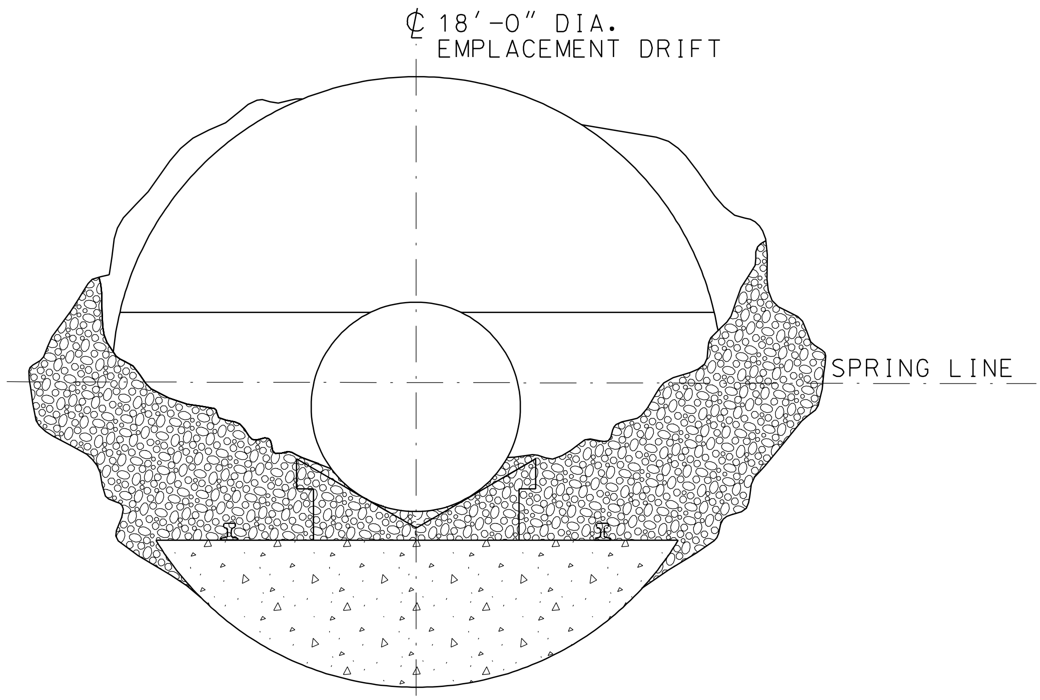


Figure 4. Possible Profile for the 6.25 m³/m Rubble Volume

As illustrated Figure 4 in the profile for a 5 m³/m rockfall, most of the WP remains exposed to the ventilation airflow.

6.1.4 Rubble Profile Evaluation for an 80 Year Exposure Period

Section 6.1.1 evaluated a 50 year timeline to illustrate an 18 kW package. This section addresses the timeline between year 51 and year 80. After an 18 kW WP has been emplaced for approximately 55 years, the heat load decays to approximately 7 kW (Figure 5), which has been evaluated to have no impact from a total drift collapse. The 7 kW TAD WP will survive a MAX burial (Table 4), so there is no consequence for a total drift failure after 80years.

Examining Figure 1 for an 80 year period (1.25×10^{-6} annual probability), the horizontal and vertical PGVs are interpolated to be 1.55 m/s and 0.85 m/s respectively. For evaluation purposes, the 1.55 m/s is only 3% more than the 1.5 m/s PGV, which was found to result in an approximate rubble volume below 5 m^3/m (Section 6.1).

A 14 kW TAD WP will survive a 125% burial (Table 4), and ten years after the hottest waste package (18 kW) has been emplaced it will cool to about 14 kW (Figure 5). The 125% rockfall scenario is not likely for the 51 to 80 year timeline based on the following evaluation.

The 125% rockfall height (Figure 9) provides a bulked rubble volume of approximately 10.96 m^3/m, which equates to an in situ rockfall volume of 8.8 m^3/m (10.96/1.25 = 8.8). The 8.8 m^3/m rockfall is approximately 75% higher than the 5 m^3/m damage level that could occur at 1.5 m/s PGV. It is not reasonable to expect that increasing the 1.5 m/s PGV by 3% to 1.55 m/s would result in a 75% increase in the rubble volume. Therefore, the rockfall height over the first 80 years of the preclosure period would be expected to be less than 125%, and the temperature of the 14 kW waste package would remain below the survivability temperature of 541°C.

6.2 THERMAL ANALYSIS

This section provides the TAD waste package thermal responses to various loading cases of a rock fall (drift collapse) in the emplacement drift. Of primary interest are the waste package outer corrosion barrier (OCB) (Alloy 22) temperatures, as the OCB will be relied upon for waste isolation once fuel cladding temperature limits are exceeded.

The thermal analysis method and files used in this Section parallel the *TAD Thermal Response to Rock Fall* calculation (Reference 2.2.5). The computational model used for the thermal calculations is taken from *TAD Thermal Response to Rock Fall* (Reference 2.2.5, Attachment VI \ANSYSmain4\118kw_057\). The thermal loading computational model, specifically the ANSYS input decks (*.inp), was modified to utilize: a temperature dependant effective thermal conductivity for rock fall material (rubble), an increased line heat load of 2.0 kW/m, and an increased drift air temperature of 100 °C in some instances. Also, an additional finite element model simulating an 80% burial case was added.

A 2.0 kW/m linear heat load is utilized with various waste package heat loads, burial depths, and drift air temperatures. An 18 kW waste package is used as the design basis case, with lower heat loads presented for design support. Various burial cases are evaluated at different heat loads to determine the approximate maximum heat load at which the OCB (Alloy 22) temperature of 541 °C is not exceeded. Waste package survivability is defined herein as the peak OCB (Alloy 22) temperatures not exceeding 541 °C (see Attachment III “RESULTS FOR OUTER CORROSION BARRIER SHELL AT EMPLACEMENT PALLET” for explanation of this thermal limit).

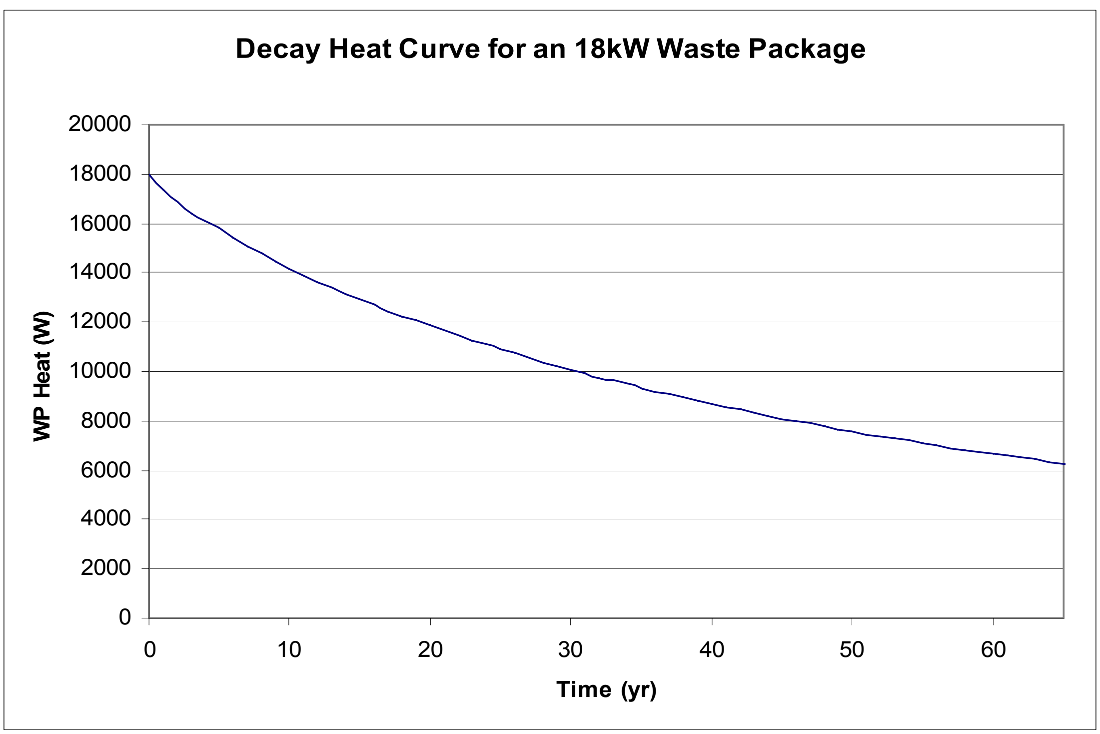
The maximum allowable heat loads are determined for drift air temperatures of 50 and 100 °C. Comparing these maximum allowable heat loads to 18 kW with “nominal” decay heat (depicted in Figure 5), it is possible to estimate the year after which a given burial case is permissible without exceeding temperature limits. Figure 5 is constructed by scaling decay heat data from Reference 2.2.3 (Table 7, Column 21-PWR AP) to 18 kW (see Attachment V, file: NominalDecayCurve.xls).

Table 2 summarizes the thermal cases analyzed and Figure 6 through Figure 10 present the ANSYS representations and corresponding rockfall heights used for the thermal evaluations.

Note: The MAX burial (complete drift collapse) scenario is modeled with no convective heat transfer off the waste package or any other surfaces, therefore the drift air temperature is irrelevant. Therefore, MAX burial case results are equally true for both 50 °C and 100 °C drift air temperatures.

Table 2. Case Summary

Drift Temperature (°C)	WP Heat (kW)	Burial Depth (%)
50	18	MAX
		125
		100
		80
		40
	16	MAX
		125
		100
	14	MAX
		125
		100
	12	125
	8	MAX
	7	MAX
	6	MAX
100	18	125
		100
		80
		40
	16	125
		100
	14	125
	12	125



Source: adapted from Reference 2.2.3, Table 7, Column 21-PWR AP; Attachment V/NominalDecayCurve.xls

Figure 5. "Nominal" Decay Heat Curve for an 18 kW Waste Package

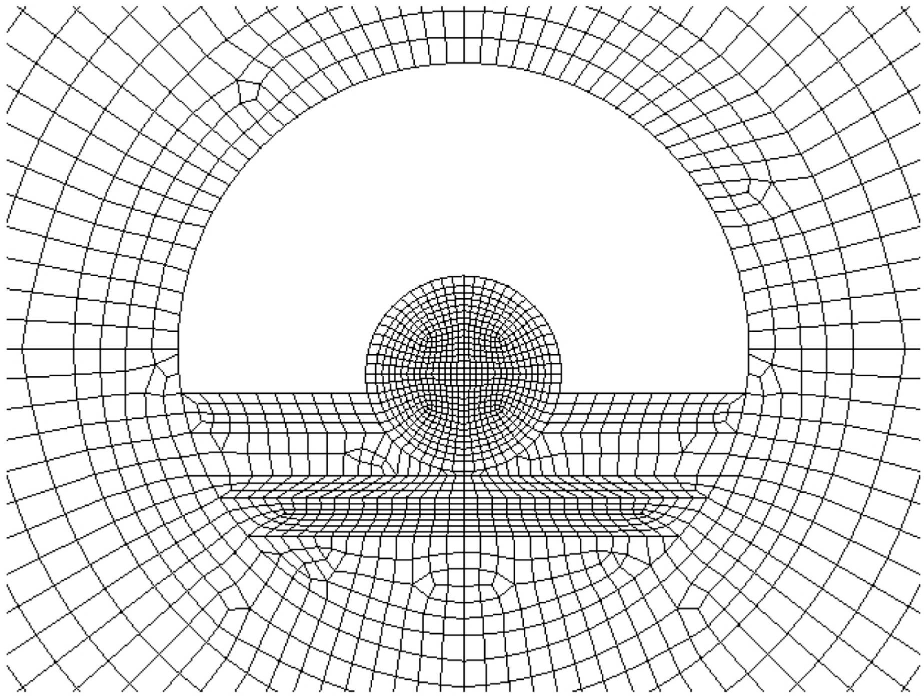


Figure 6. ANSYS Representation with 40% Rockfall Height

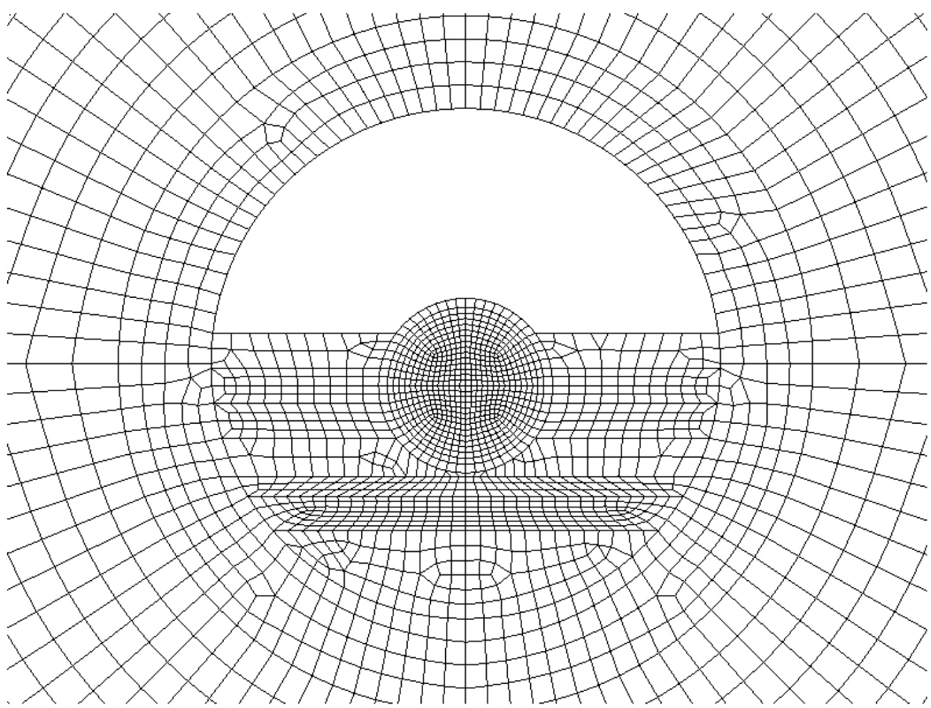


Figure 7. ANSYS Representation with 80% Rockfall Height

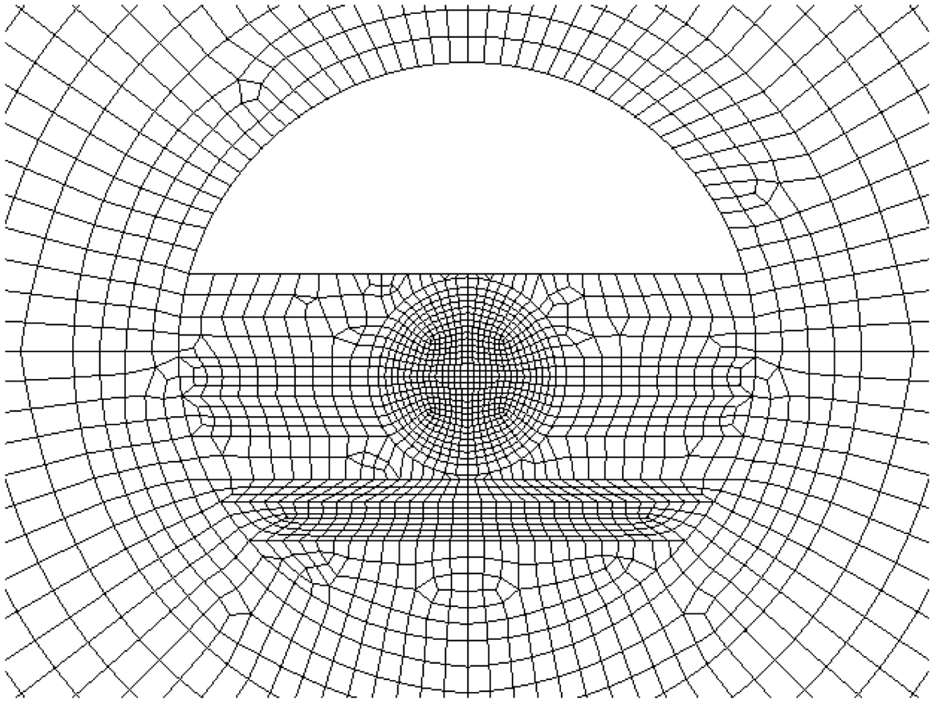


Figure 8. ANSYS Representation with 100% Rockfall Height

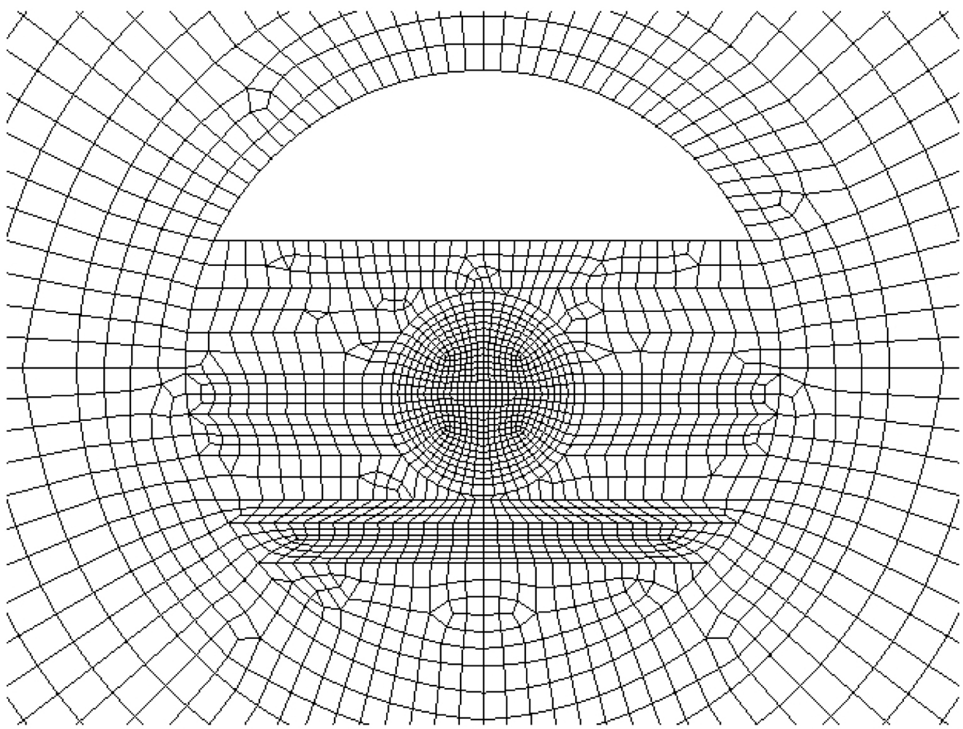


Figure 9. ANSYS Representation with 125% Rockfall Height

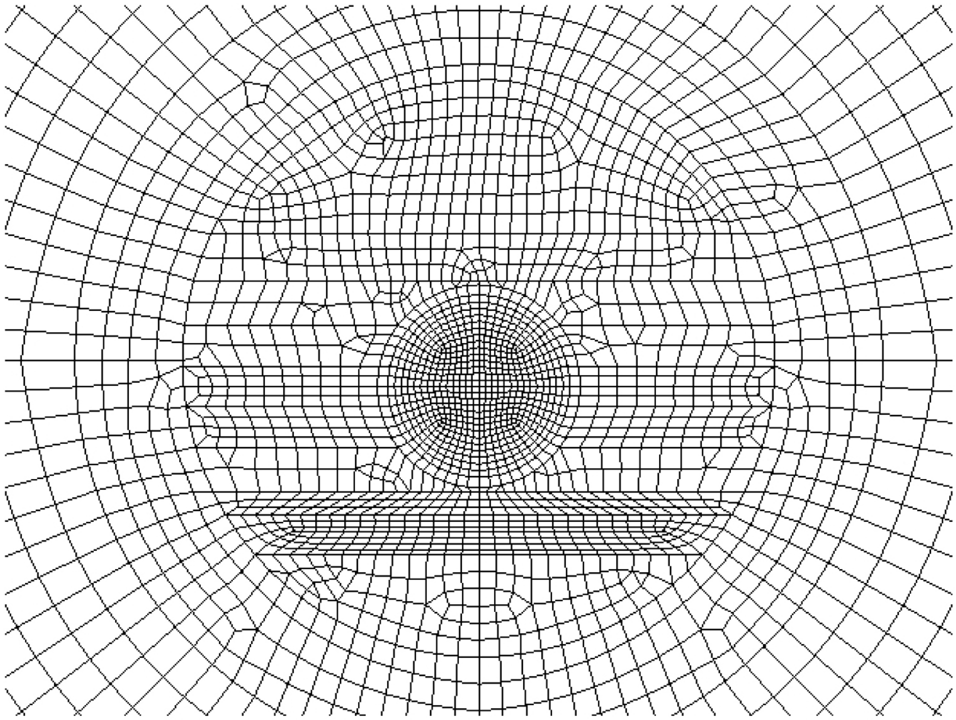


Figure 10. ANSYS Representation with MAX Rockfall Height

6.2.1 New Material Properties

As noted in Section 6.2, new effective thermal conductivity (*K*) data for rockfall material (rubble) was utilized in all cases evaluated. The values of thermal conductivity are calculated from a linearly interpolated average of rubble thermal conductivity data presented in DTN: MO0703PARUBBLE.000 (Reference 2.2.14). From visual inspection, the “high” and “low” curves depicted in DTN: MO0703PARUBBLE.000 (Reference 2.2.14, Figure “High and Low (Uncertainty Range) Rubble *Kth* Values for Use in MSTHM Collapsed-Drift Cases”) are approximated using the following linear regressions:

$$K_{hi}\ (W/m\text{-}K) = 0.75 + (1.25/200)*(Temperature\ (°C) - 50) \qquad \text{Equation 1}$$

$$K_{low}\ (W/m\text{-}K) = 0.25 + (0.25/250)*(Temperature\ (°C) - 50) \qquad \text{Equation 2}$$

Equation 3 is calculated as the average of the high and low linear regressions.

$$K_{avg}\ (W/m\text{-}K) = 0.50 + 0.003625*\ (Temperature\ (°C) - 50) \qquad \text{Equation 3}$$

Solving Equation 3 over a range of temperatures yields the values of thermal conductivity provided in Table 3.

Table 3. Effective Thermal Conductivity of Rockfall Material

Temperature (°C)	Thermal Conductivity (W/m-K)
50	0.5
75	0.5906
100	0.6813
125	0.7719
150	0.8625
200	1.0438
225	1.1344
250	1.2250
275	1.3156
300	1.4063
350	1.5875
400	1.7688

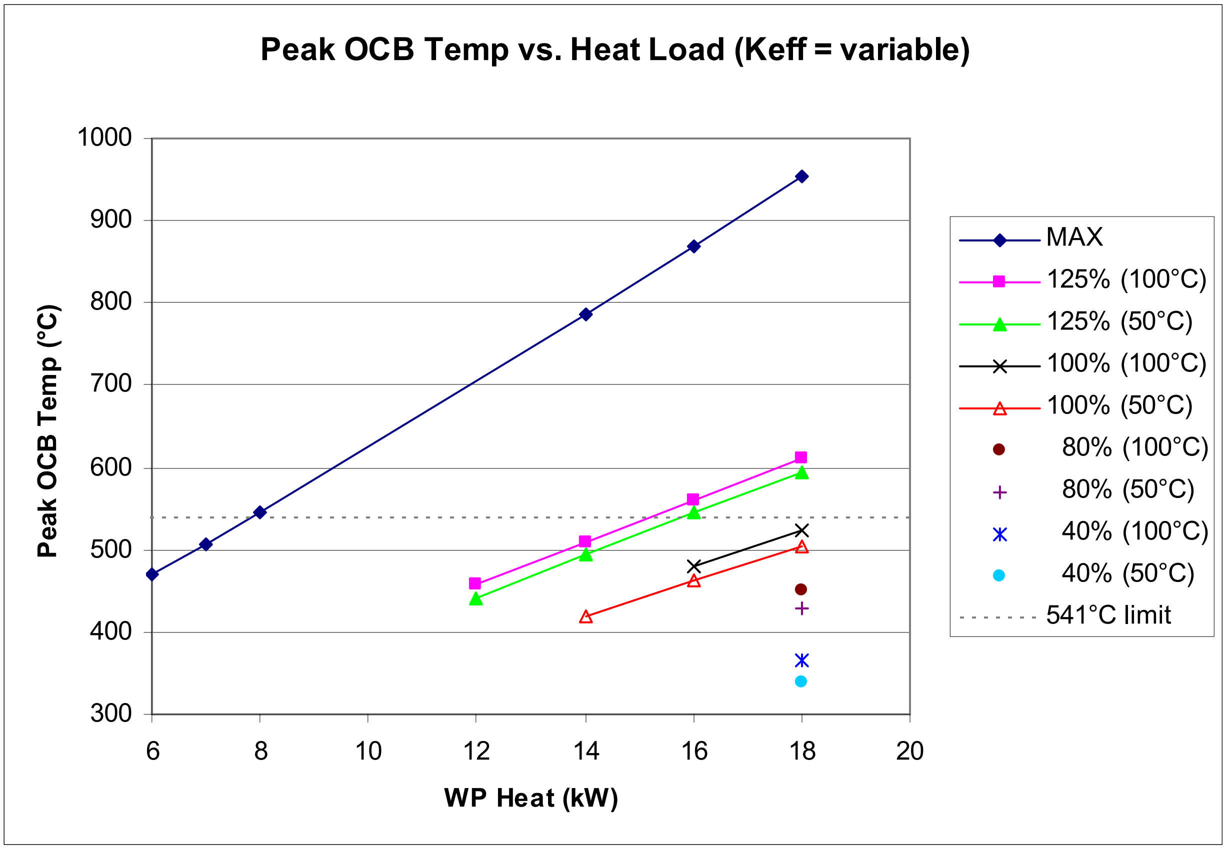
Source: calculated using Equation 3 and Reference 2.2.14

6.2.2 Complete Thermal Evaluation Results Summary

Calculations for a waste package buried under rubble are summarized in Table 4 and Figure 11.

Table 4. Temperature Results Summary

Drift Temperature (°C)	WP Heat (kW)	Burial Depth (%)	Peak OCB Surface Temperature (°C)	Peak Fuel Temperature (°C)
50	18	MAX	955	1055
		125	595	675
		100	504	576
		80	428	492
		40	338	400
	16	MAX	869	956
		125	544	618
		100	462	527
	14	MAX	785	860
		125	493	560
		100	418	477
	12	125	442	501
	8	MAX	544	585
	7	MAX	507	542
	6	MAX	471	500
100	18	125	611	691
		100	523	594
		80	451	515
		40	366	429
	16	125	560	633
		100	481	545
	14	125	509	575
	12	125	458	516



Source: Attachment V/2kW_ResultsSummary.xls tab graph

Figure 11. Peak Waste Package OCB Temperatures vs. Heat Load

The temperature history plots of 18 kW packages in 80% burial conditions are presented in the following subsections. Additional temperature history plots for 18 kW cases at 100°C drift temperature are provided in Attachment II. All temperature history plots (including those not presented here) are located in the electronic files in Attachment V.

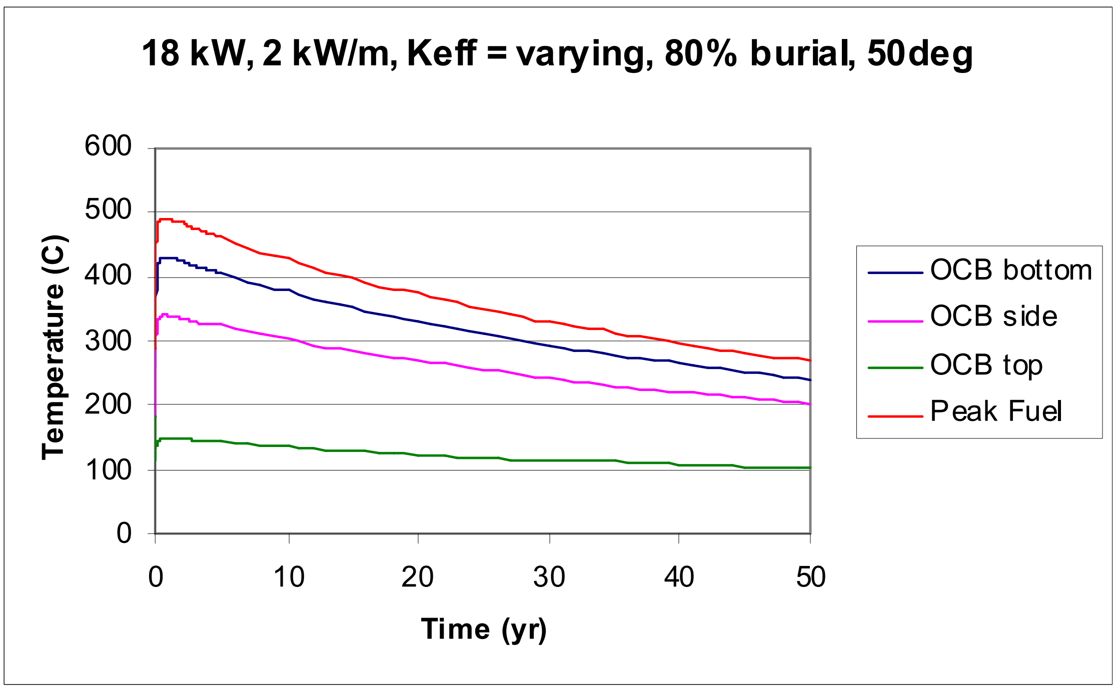
6.2.3 Results Summary for 50° C Drift Air Temperature

An 18 kW waste package is shown to survive an 80% burial scenario, exhibiting a maximum OCB temperature of 428 °C. The temperature history of this case is depicted in Figure 12.

An 18 kW waste package is shown to survive a 100% burial scenario, exhibiting a maximum OCB temperature of 504 °C.

A 14 kW waste package is shown to survive a 125% burial scenario, exhibiting a maximum OCB temperature of 493 °C. From the "nominal" decay heat curve (Figure 5), an 18 kW waste package is seen to decay to 14 kW in approximately 10 years.

A 7 kW waste package is shown to survive a complete drift collapse (MAX burial) scenario, exhibiting a maximum OCB temperature of 507 °C. (This result is valid for both the 50 °C and 100 °C drift air temperatures.) From the "nominal" decay heat curve (Figure 5), an 18 kW waste package is seen to decay to 7 kW in approximately 55 years.



Source: Attachment V/ 18_2_50deg_vKeff\ 18_2_80pct_50deg.xls tab plot

Figure 12. Temperature History of 18 kW, 80% Burial Case at 50° C Drift Temperature

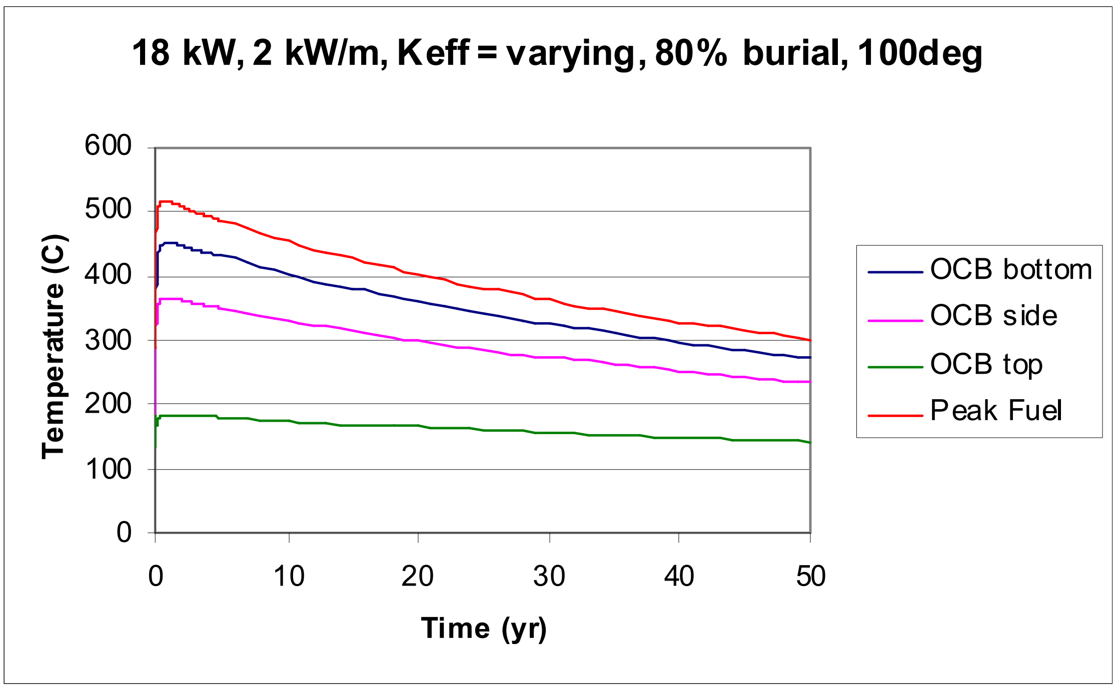
6.2.4 Results Summary for 100° C Drift Air Temperature

An 18 kW waste package is shown to survive an 80% burial scenario, exhibiting a maximum OCB temperature of 451 °C. The temperature history of this case is depicted in Figure 13.

An 18 kW waste package is shown to survive a 100% burial scenario, exhibiting a maximum OCB temperature of 523 °C.

A 14 kW waste package is shown to survive a 125% burial scenario, exhibiting a maximum OCB temperature of 509 °C. From the "nominal" decay heat curve (Figure 5), an 18 kW waste package is seen to decay to 14 kW in approximately 10 years.

The MAX burial case is the same for both the 50 °C and 100 °C drift air temperatures (see Section 6.2.3).



Source: Attachment V/ 18_2_100deg_vKeff\ 18_2_80pct_100deg.xls tab plot

Figure 13. Temperature History of 18 kW, 80% Burial Case at 100° C Drift Temperature

6.3 THERMAL CREEP

With seismically induced rubble insulating a waste package and a corresponding temperature increase of the waste packages components, high internal pressures will be generated in a waste package.

Since the TAD WP would not be buried and a good portion of the TAD WP would be exposed to ventilation airflow and cooling (Sections 6.1 and 6.2), thermal creep would not be a concern. Though the thermal creep is not a concern for the potential TAD WP burial in this calculation, TAD WP structural calculations for creep damage were conducted and included in Attachment III.

7 RESULTS AND CONCLUSIONS

This section summarizes the results for the geotechnical evaluation, the waste package thermal response, and potential for structural creep for an 18 kW waste package buried by a seismically induced rockfall. Figure 1 (Section 6.1) provides the seismic hazard curves used in this calculation.

The outputs of this calculation are reasonable compared to the inputs and the results are suitable for the intended use.

7.1 ROCKFALL EVALUATION RESULTS

The Geotechnical Analysis (Section 6.1) evaluated the potential rockfall for seismic ground motions of 1.35 m/s horizontal and 0.79 m/s vertical PGVs. The rockfall volume in an emplacement drift excavated in lithophysal rock subjected to 2×10^{-6} seismic ground motions is estimated to be 5 m^3/m of in situ rubble, bulked to 6.25 m^3/m (Section 6.1.3). Figure 3 illustrates that when the 6.25 m^3/m rockfall is confined to within the original emplacement drift excavated diameter, a portion of the TAD WP remains exposed to the ventilation airflow. Figure 4 illustrates a likely rockfall profile for shear failure occurring at the emplacement drift springline resulting in an elliptical shaped opening (Section 6.1.3).

The rockfall volume in an emplacement drift excavated in the nonlithophysal rock subjected to 2×10^{-6} seismic ground motions is estimated to be insignificant (Section 6.1.2).

During the preclosure period a slight increase of the 1.5 m/s PGV would not result in an increase of the rubble volume that would exceed the 125% rockfall height, and the temperature of the 14 kW waste package would remain below the survivability temperature of 541°C.

7.2 THERMAL EVALUATION RESULTS

Geotechnical evaluations indicated that the TAD WP would not be completely buried by a rockfall and a good portion of the waste package would be exposed to ventilation airflow. Based on a 6.25 m^3/m rockfall confined to the excavated emplacement drift diameter (Figure 3), approximating ANSYS results for a WP burial height of 80% (Figure 7) and a drift temperature of 100°C are acceptable with an OCB temperature of 451°C (Table 4), which is less than the maximum limiting OCB temperature of 541°C. Based on the likely rockfall profile expected from the elliptical seismic failure (Figure 4), the OCB temperatures would be lower than those presented here.

7.3 THERMAL CREEP RESULTS

Based on a seismic event of 2×10^{-6} in lithophysal rock producing a bulked rockfall volume of approximately 6.25 m^3/m around the TAD WP (Section 6.1.1 and Figure 4), only a portion of the WP is covered and the rest is exposed to airflow. The partially covered waste package is sufficiently cooled to prevent the temperature from reaching the critical temperature that would induce creep damage in the waste package.

7.4 CONCLUSIONS

The amount of rockfall resulting from a 2×10^{-6} annual probability is not sufficient to completely cover the TAD waste package. For a partially covered waste package, the temperature of the OCB rises to a temperature that is less than the critical temperature that would induce waste package thermal creep.

7.5 OTHER DISCUSSIONS

The rockfall analysis does not credit ground support in the emplacement drifts which will limit to a large extent the amount of rockfall and the extent of burial for the evaluations.

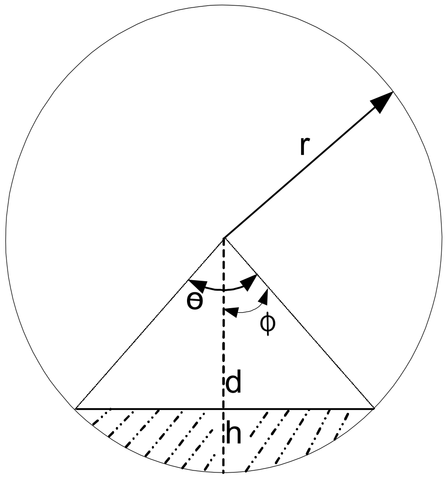
ATTACHMENT I – GEOTECHNICAL SUPPORT INFORMATION

This Attachment contains information that supports the Geotechnical evaluation contained in Section 6.1. Table 5 contains rockfall volume information for the nonlithophysal rock evaluation. Figure 14 and Figure 15 provide information that supports the emplacement drift area calculations. Table 6 contains the emplacement drift area calculations.

Table 5. Rockfall Volumes in Nonlithophysal Rock

Case [a, b]	1.05 m/s PGV Level			2.44 m/s PGV Level	
	Total Vol. (m^3) [a]	Vol. per m (m^3/m) [c]		Total Vol. (m^3) [b]	Vol. per m (m^3/m) [c]
14	1.844	0.092		2.118	0.106
15	7.067	0.353		16.514	0.826
16	4.264	0.213		10.652	0.533
17	0.045	0.002		0.647	0.032
18	0.544	0.027		1.417	0.071
19	7.375	0.369		15.123	0.756
20	0.417	0.021		0.602	0.030
21	1.041	0.052		1.445	0.072
22	1.846	0.092		2.055	0.103
23	5.217	0.261		8.316	0.416
24	1.308	0.065		1.620	0.081
25	14.296	0.715		12.913	0.646
27	5.661	0.283		6.512	0.326
28	3.520	0.176		5.974	0.299
29	1.386	0.069		2.919	0.146
31	0.149	0.007		0.221	0.011
32	0.193	0.010		2.404	0.120
33	0.725	0.036		13.741	0.687
34	2.845	0.142		5.374	0.269
35	1.449	0.072		1.753	0.088
36	2.697	0.135		2.954	0.148
38	42.030	2.101		58.486	2.924
39	8.179	0.409		17.014	0.851
40	21.902	1.095		35.204	1.760
41	2.145	0.107		5.194	0.260
42	0.111	0.006		1.820	0.091
43	6.232	0.312		18.513	0.926
44	8.815	0.441		21.158	1.058
45	2.489	0.124		4.188	0.209
46	0.891	0.045		1.891	0.095
48	0.276	0.014		4.445	0.222
49	24.099	1.205		9.695	0.485
50	5.812	0.291		6.449	0.322
51	1.056	0.053		4.173	0.209
51	15.880	0.794		63.335	3.167
53	4.525	0.226		25.427	1.271
54	6.371	0.319		11.759	0.588
55	1.285	0.064		2.377	0.119
56	6.056	0.303		10.011	0.501
57	1.435	0.072		3.893	0.195
58	0.133	0.007		0.323	0.016
59	2.130	0.106		4.972	0.249
60	0.526	0.026		8.221	0.411
61	0.299	0.015		7.074	0.354
62	1.807	0.090		4.921	0.246
63	0.000	0.000		0.480	0.024
64	13.611	0.681		25.130	1.257
65	3.020	0.151		3.034	0.152
66	2.776	0.139		8.815	0.441
67	7.601	0.380		14.415	0.721
Averages (calculated)		0.255			0.498

Source: [a] Reference 2.2.13, nonlith rockfall characteristics in emplacement drifts with 1e-5 gm
[b] Reference 2.2.13, nonlith rockfall characteristics in emplacement drifts with 1e-6 gm
[c] (Total Vol. (m^3))/(20 m) (where 20 m is from Assumption 3.2.2)



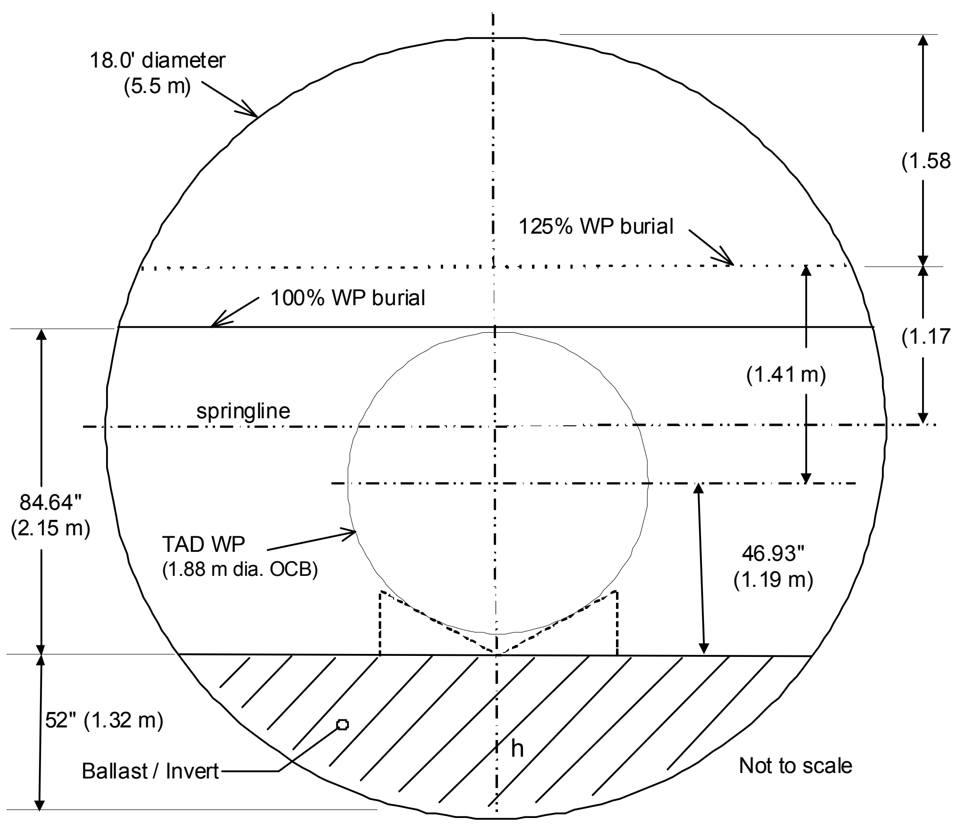
The method used to calculate the circular invert area is:

$$\text{Area} = \frac{r^2}{2}(\theta - \sin\theta) \qquad \theta \text{ is in radians} \qquad \text{(Eq. 4)}$$

Where: r = radius (also = d+h)
d = distance from center to top of invert
h = invert depth
cos ϕ = (d/r)
θ = 2 × ϕ
radian = π × (angle)/180
invert arc length = 0.01745rθ where θ is in degrees
length of invert cord $= 2\sqrt{h(2r-h)}$

Figure 14. Geometric Formulas Used for Calculations

The figure below illustrates the emplacement drift configuration used for the volume calculations. The rubble will fill the area encompassed by the emplacement pallet.



Source: References 2.2.6 and 2.2.33

Figure 15. Emplacement Drift Configuration Used for Area Calculations

Table 6. Emplacement Drift Area Calculations

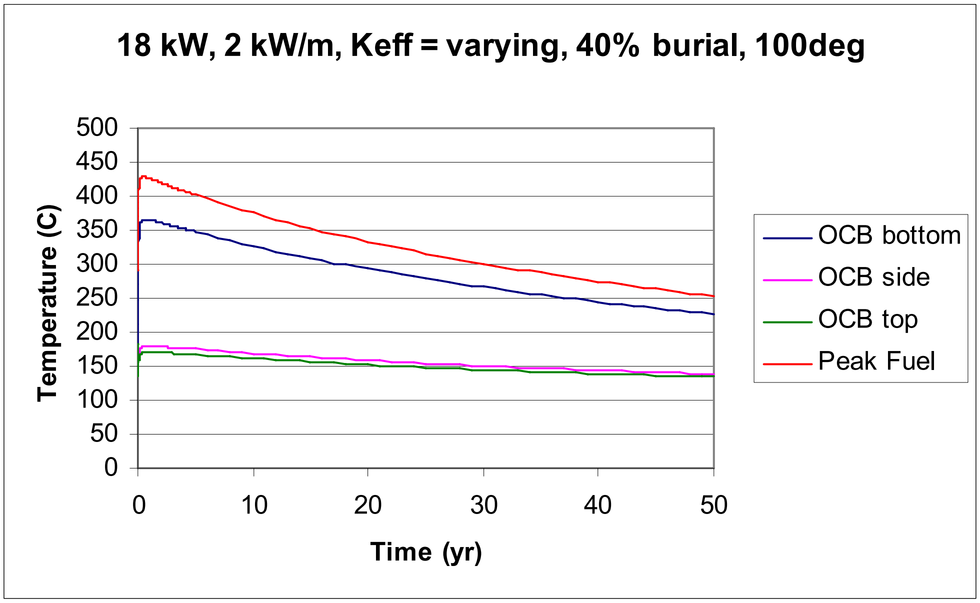
Application Information	Calculation	Result
Emplacement drift = 5.5 m (excavated), r = 2.75 m Invert height h =1.32 m, d = 2.75 m – 1.32 = 1.43 m, TAD WP OCB diameter = 1.88 m, r = 0.94 m		
Area of Emplacement Drift		
Area = πr^2	Area = $\pi (2.75)^2$	23.76 m²
Area of TAD WP		
Area = πr^2	Area = $\pi (0.94)^2$	2.78 m²
Area of Emplacement Drift Invert (Using Figure 15 and Equation 4)		
$\cos \phi = (d/r)$	$\cos \phi = (1.43/2.75) = 0.5200$	$\phi = 58.67°$
$\theta = 2 \times \phi$	$\theta = 2 \times 58.67$	$\theta = 117.3°$, $\sin \theta = 0.88862$
Radian = π x (angle)/180	Radian = 3.14159 x (117.3)/180	$\theta = 2.04727$ radian
Area $= \frac{r^2}{2}(\theta - \sin\theta)$	Area $= \frac{2.75^2}{2}(2.04727 - 0.88862)$	4.38 m³
Area above the top of the TAD Waste Package (Using Figure 15 and Equation 4)		
$\cos \phi = (d/r)$	$\cos \phi = (0.72/2.75) = 0.26182$	$\phi = 74.82°$
$\theta = 2 \times \phi$	$\theta = 2 \times 74.82$	$\theta = 149.64°$, $\sin \theta = 0.50543$
Radian = π x (angle)/180	Radian = 3.14159 x (149.64)/180	$\theta = 2.61171$ radian
Area $= \frac{r^2}{2}(\theta - \sin\theta)$	Area $= \frac{2.75^2}{2}(2.61171 - 0.50543)$	7.96 m³
Volume Required to Bury a TAD Waste Package		
Area of drift – area of invert – area above TAD WP – area WP		23.76-4.38-7.96 -2.78 = 8.64 m²
Area above the top of a 125% Rockfall (Using Figure 15 and Equation 4)		
Emplacement drift = 5.5 m (excavated), r = 2.75 m 125% Rockfall is 25% burial of the WP diameter or (1.5 × r) where 1.5 × 0.94 m = 1.41 m For the open area above the rockfall h =1.58 m, d = 2.75 m – 1.58 = 1.17 m		
$\cos \phi = (d/r)$	$\cos \phi = (1.17/2.75) = 0.42545$	$\phi = 64.82°$
$\theta = 2 \times \phi$	$\theta = 2 \times 64.82$	$\theta = 129.64°$, $\sin \theta = 0.77001$
Radian = π x (angle)/180	Radian = 3.14159 x (129.64)/180	$\theta = 2.26264$ radian
Area $= \frac{r^2}{2}(\theta - \sin\theta)$	Area $= \frac{2.75^2}{2}(2.26264 - 0.77001)$	5.64 m³
Volume of a 125% Rockfall		
Area of drift – area of invert – area above rockfall – area of TAD WP		23.76-4.38-5.64-2.78 = 10.96 m²

ATTACHMENT II – THERMAL SUPPORT INFORMATION

This Attachment contains information that supports the Thermal evaluations in Section 6.2. Electronic files that support this Attachment are located in Attachment V.

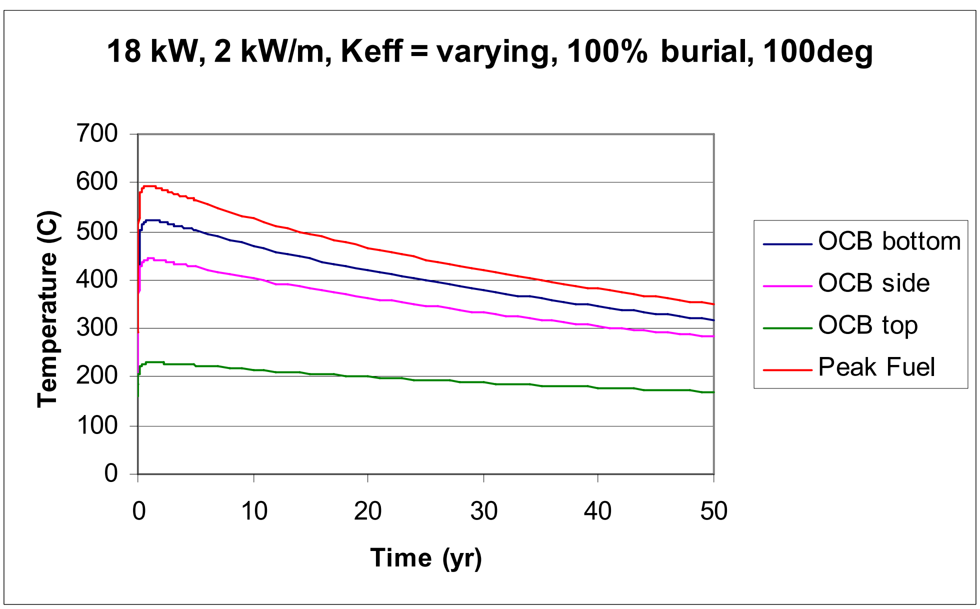
Supplemental Plots

Temperature histories of all burial cases at 18 kW and 100°C drift air temperature not given in Section 6.2 are presented herein. All temperature history plots (including those not presented here) are located in the electronic files in Attachment V.



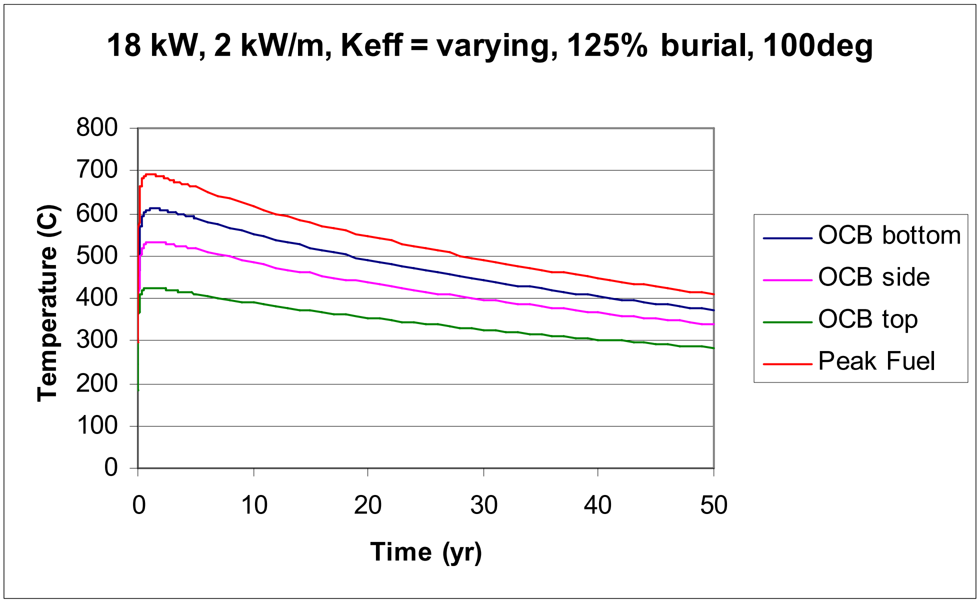
Source: Attachment V/ 18_2_100deg_vKeff\ 18_2_40pct_100deg.xls tab plot

Figure 16. Temperature History of 18 kW, 40% Burial Case at 100° C Drift Temperature



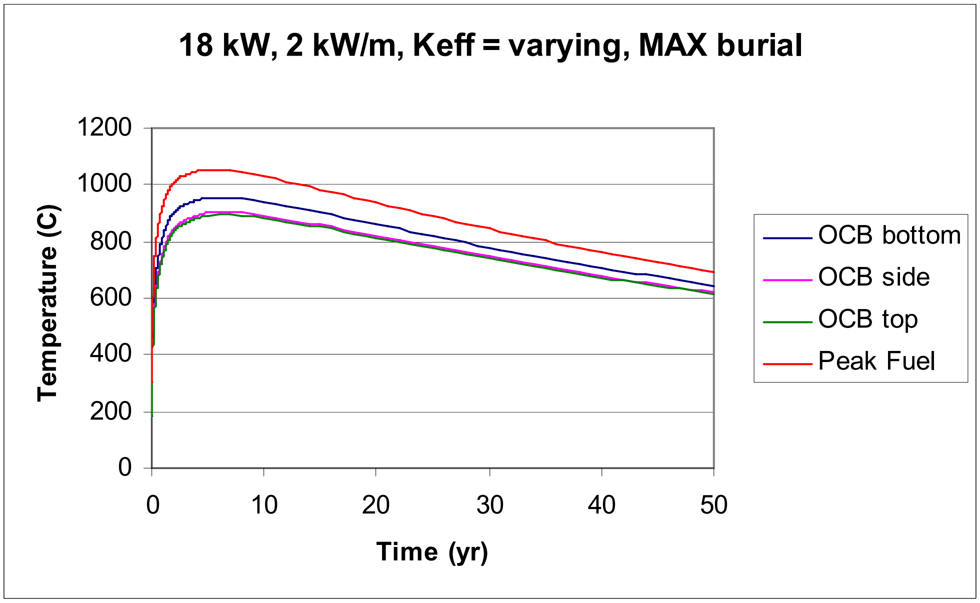
Source: Attachment V/ 18_2_100deg_vKeff\ 18_2_100pct_100deg.xls tab plot

Figure 17. Temperature History of 18 kW, 100% Burial Case at 100° C Drift Temperature



Source: Attachment V/ 18_2_100deg_vKeff\ 18_2_125pct_100deg.xls tab plot

Figure 18. Temperature History of 18 kW, 125% Burial Case at 100° C Drift Temperature



Source: Attachment V/ 18_2_50deg_vKeff\ 18kw_MAX_vKeff.xls tab plot

Figure 19. Temperature History of 18 kW, MAX Burial Case at 100° C Drift Temperature

Combined Rockfall and Loss-of-Ventilation

Several cases with complete loss of ventilation (no convection modeled) are evaluated to determine how quickly the OCB temperature limit is exceeded during a combined rockfall and loss-of ventilation scenario. The times until OCB thermal limits are exceeded for select burial cases are listed in Table 7.

Table 7. Time to OCB Thermal Limit Exceedance During Loss-of-Ventilation

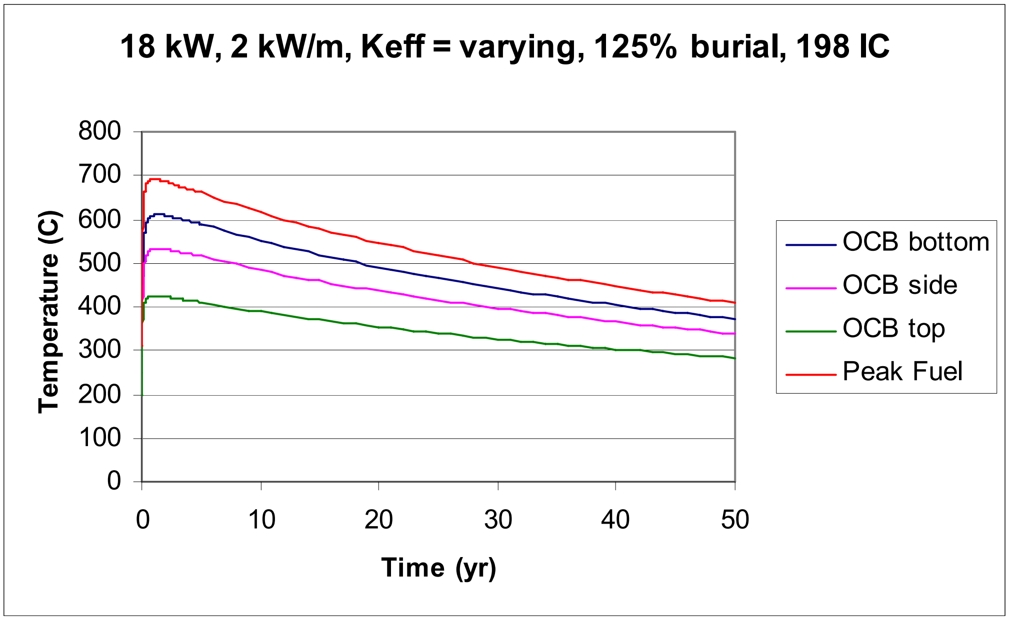
WP Heat (kW)	Burial Depth (%)	Time to 541°C (days)
18	125	58
	100	84
	80	117
	40	168
	Base	635
14	80	365

OCB Initial Condition Sensitivity Study

The finite element models for all cases utilized an initial waste package surface temperature of 183.5°C. This is a legacy program input from Reference 2.2.5 and was the peak surface temperature of a 21-PWR waste package in a waste package transporter (Reference 2.2.18, Table 3, Condition 1). The most recent available data indicates that an 18 kW TAD waste package in a TEV would have a peak OCB temperature of 198°C (Reference 2.2.19, Table 36).

A single case (18 kW, 125% burial, 100°C drift air) was run to evaluate the impacts of the different OCB initial temperatures.

The temperature differentials between the modified (198°C) and original (183.5°C) is most pronounced during the initial 30-day heat-up period and may have some marginal effect on the predicted times to thermal limit exceedance. However, near the peak temperatures, the temperature differentials between the modified and original cases are on the order of 0.01°C and are considered insignificant. The temperature history of the modified case is presented in Figure 20. One may note that it is largely indistinguishable from the temperature history of the original case seen in Figure 18.



Source: Attachment V/ 198test\ 18_2_125pct_100deg_198IC.xls tab plot

Figure 20. Temperature History of 18 kW, 125% Burial Case at 100° C Drift Temperature, with Modified 198°C OCB Initial Condition

ATTACHMENT III –THERMAL CREEP INFORMATION

Though thermal creep has been identified as not a concern in Section 6.3, this Attachment contains information that supports creep damage evaluations for a buried TAD waste package. Electronic files that support this Attachment are located in Attachment V.

INTERNAL PRESSURE INSIDE THE TAD WASTE PACKAGE

The internal pressure inside a TAD waste package (WP) is governed by several constraints which include the initial pressure and temperature and the volume occupied by the helium fill gas. Internal pressures are governed and approximated by using the Ideal Gas Law shown in the equation below:

$$PV = n\overline{R}T \quad \text{Equation 5}$$

where

> P is the pressure in *Pa*
> V is the volume in m^3
> n is the number of molecules of the gas in *moles*
> $\overline{R}$ is the Universal Gas Constant with a value of 8.134 *J/mole·K*
> T is the temperature of the gas in *K*

In the case of an earthquake and burial of the TAD WP under drift rubble, the temperature of the WP would rise due to lack of ventilation and the rubble acting as an insulator over the surface of the WP. As temperature increases, the Alloy 22 Outer Corrosion Barrier (OCB) becomes more ductile and may eventually reach temperatures where thermal creep behavior is induced. An increase in temperature will produce greater pressures of the contained gases over time.

The initial fill pressure in the Inner Vessel (IV) helium is 15 *psig* and the TAD canister is initially pressurized at 1 *atm*. The pressure in the fuel assemblies is 8.3 *MPa* with each fuel rod having a volume of 35 cm^3 (Reference 2.2.35, p. 9). It is necessary to first determine the number of helium and fission gas molecules present in the system during backfill at room temperature and the fill pressures. This is accomplished through the use of Equation 5. Once the total number of helium fill gas and fission gas molecules is known, it is easy to compute resulting pressures with changes in volume and increases in temperature.

The fuel assemblies inside the TAD are modeled conservatively to be 100 percent ruptured and release all of the helium fill gas and fission gases. There are 21 PWR assemblies in each TAD canister and each assembly contains 208 fuel rods, 16 guide tubes and 1 instrument tube. Release paths are used to allow flow into the surrounding IV cavity and subsequently into the OCB cavity.

The total cavity volume for the OCB is calculated, and then the total volume occupied in the cavity by the TAD canister shell, IV shell, and fuel assemblies are subtracted to result in the total gas volume. The new expanded volume is:

$$V_{rupture} = V_{OCB\_cavity} - V_{IV} - V_{TAD\_shell} - V_{fuel\_assemblies} \quad \text{Equation 6}$$

Pressures are analyzed over a range of temperatures and the deflection heights of both bottom and top WP lids. If temperature is high enough, the ductility of the Alloy 22 lids allows for creep deformation and increases in gas volume. The following equation is used for the volume of each individual spherical bulge:

$$V_{inc} = \frac{1}{3}\pi \cdot h^2(3r - h) \qquad \text{Equation 7}$$

where

V is the volume in m^3
h is the height of spherical deflection of lid in *m*
r is the bulge radius as a function of h and the diameter of the lid in *m*

The limiting height for deflection of a lid is the radius of the lid,

The new equation for pressure with expansion of the lids is now:

$$P = \frac{n\overline{R}T}{V_{rupture} + 2 \cdot V_{inc}} \qquad \text{Equation 8}$$

STRUCTURAL FAILURE OF THE TAD WASTE PACKAGE

Previous calculations indicate that two regions of the TAD WP OCB have potential for structural failure following a drift collapse.

- The lower side of the OCB shell adjacent to its contact with the emplacement pallet due to rock rubble weight loading (Reference 2.2.23), and,

- The outer edges and centers of the OCB lids due to thermally induced internal pressure loading (References 2.2.25 and 2.2.27).

A material related concern is expressed in Reference 2.2.26 and repeated in Reference 2.2.27.

From Reference 2.2.26:

"Alloy 22 in the solution annealed condition is subject to severe loss of impact properties at room temperature after exposure in the range of 1000 $°F$ to 1250 $°F$".

Reference 2.2.27 discusses this material concern in detail. This thermal embrittlement issue affects subsequent earthquake induced rock fall and/or removal operations long after the drift collapse when WP temperatures have sufficient time to decay down towards room temperature. These considerations are beyond the scope of this calculation.

RESULTS FOR OUTER CORROSION BARRIER SHELL AT EMPLACEMENT PALLET

This calculation indicates that weight plus pressure creep rupture of the OCB at the emplacement pallet contact region will occur in average strength weldment material after 100,000 hours exposure to maximum drift rubble loading at 541°*C* (1006°*F*). 100,000 hour creep rupture will occur in minimum strength weldment material for the same loadings at 501°*C* (934° *F*).

Calculation

Reference 2.2.27 postulated that the lower surface of the OCB will "slump" under magma weight and temperature loading leads to excessive creep distortions and possible creep rupture. The temperatures following drift collapse are considerably lower, but the same behavior at a lesser magnitude is expected.

Reference 2.2.23 indicates that the OCB outer surface at the emplacement contact region has moderate peak bearing and surface traction (frictional) stresses under weight loading. The peak stress intensities can meet the Reference 2.2.22 tiered screening criterion at the temperatures considered but are not considered appropriate through-wall damage indicators under sustained loadings at higher temperatures. The failure mode that will be addressed in this calculation is creep rupture of the OCB shell due to primary stresses having high shear and membrane components from weight plus thermally-induced internal pressure.

The ANSYS-predicted elastic-plastic weight stresses from Reference 2.2.23 are for self-weight and rock rubble effective traction loadings using WP Code minimum material properties at four different temperatures. The TAD WP 1000°*F* (538°*C*) load case (4A) is used as a baseline for this calculation which will ratio and adjust the predicted results for material and temperature effects. The use of vendor typical short term strength properties and extrapolated test average creep rupture strength provides a mean material response damage prediction.

The rock rubble weight loadings used in Reference 2.2.23 are conservative worst case values for a fully collapsed emplacement drift. The 1000°*F* (538°*C*) weight stresses are adjusted by the ratio R_3 of vendors' typical material true flow stress (average of yield strength and true ultimate strength) at different temperatures to the true flow stress value at 1000°*F* (538°*C*) used in Reference 2.2.23. At temperatures between 700°*F* (371°*C*) and 1350°*F* (732°*C*), this adjustment increases weight stresses by up to 20% and at higher temperatures, it reduces weight stresses by up to 10%.

The average Alloy 22 creep rupture strengths in Reference 2.2.20 are used. These are ASME Section I Code Case 2226-2 (Reference 2.2.26) rule committee data listed in tables and plotted on figures. A best-fit Larson Miller Parameter is also provided in the Code Case data package and is used for times and temperatures outside the Code Case data set.

The weight loading is self-weight plus the rock fall rubble weight. This loading is sustained and is not relieved by WP deformations (primary loading). The rock fall impact loading and possible plastic residual stresses are not addressed herein, but rather the sustained weight plus pressure stresses after the rock fall has occurred and a loss of drift ventilation heats up the WP. The concern is the loss of WP robustness due to material thermal creep as the temperatures increase. Residual stresses due to the impact loading relax out early with creep deformations.

The shock loading under the rock fall can crack the IV upper lid seal welds and allow the gases inside the IV to escape and pressure load the OCB. Therefore, the entire volume of WP gas inventory interior to the OCB boundary will heat up and apply pressure to the OCB per the Ideal Gas Law. Thermal transient stresses during pressure boundary breaches and radial thermal gradients in the WP (including radial creep expansion contacts) are ignored as motion limited and secondary. Pressure stress change due to increased containment volume by creep deformations of the OCB is ignored because the pressure stresses at the emplacement pallet contact region are very small. This is not the case for the pressure stresses in the OCB lids and the volume effects of creep deformations are addressed in that calculation.

Creep rupture triaxiality effects for Alloy 22 are not known. Reference 2.2.21 primary stress intensity limits do not use triaxiality-based adjustments of results and no adjustments are used in this calculation. (It is noted that creep triaxiality adjustments are required for some materials under creep-fatigue loading in the Reference 2.2.21, non-mandatory Appendix I)

Weld material creep rupture strength is typically reduced with elevated temperature exposure and existing Reference 2.2.21 adjustment factors for nickel alloy welds are used. The OCB shell is rolled and welded plate and it is not known at this time if seam welds will be located at the high stress area, therefore, this adjustment may be conservative. Reference 2.2.21 also indicates elevated temperature exposure affects short term material yield and tensile strengths. However, these short term parameters are only used to adjust the baseline $1000°F$ ($538°C$) initial stress response and this long term strength reduction is not appropriate for this temperature adjustment.

For simplicity, it is conservatively modeled that the temperature instantly rises to its maximum value and remains constant for 100,000 hours (approximately 10 years). This allows simplistic use of a stress based damage fraction (versus the Reference 2.2.21 stress/time/temperature based summation of time damage fractions). Attachment V contains Excel worksheets that perform the structural calculations for temperatures between $700°F$ ($371°C$) and $1400°F$ ($760°C$). The key table parameters in order of presentation on Attachment V (file: Attachment III Creep Stress Excel Workbook.xls), Worksheet 1 are:

S_R	Average creep rupture strength
SRF	Weld metal creep rupture strength reduction factor
R_1	ASME temperature reduction factors on yield strength
YS	ASME yield strength at temperature
YS_{RT}	ASME specified room temperature minimum yield strength
$YS_{v\text{-}avg}$	Average of several vendors' typical yield strengths
R_2	ASME temperature reduction factors on ultimate tensile strength
UTS	ASME ultimate tensile strength at temperature
UTS_{RT}	ASME specified room temperature minimum ultimate tensile strength
$UTS_{v\text{-}avg}$	Average of several vendors' typical ultimate tensile strengths
True UTS	Conversion of $UTS_{v\text{-}avg}$ engineering stress to true stress
FS	Vendor average flow stress at temperature
FS_{1000F}	ASME specified minimum property based flow stress at $1000°F$
R_3	Calculation weight stress adjustment factor
VMS_{EWA}	Wall average of element Von Mises effective stresses

PR/t	Classical maximum (hoop) pressure stress equation for cylinder
P_L	ASME local primary membrane stress intensity
DF	Creep rupture damage fraction

Attachment V (file: Attachment III Creep Stress Excel Workbook.xls), Worksheet 3 compares minimum stress rupture data to average creep rupture data in the Reference 2.2.20 Code Case data package. It is determined that a change in temperature of 40°*C* (72°*F*) is equivalent to the 10^5 hr creep rupture strength difference between average and minimum material presented in the Code Case data package.

RESULTS FOR OUTER CORROSION BARRIER LIDS

Worst case calculations indicate that pressure creep rupture of the OCB will not occur at the center of the bottom lid in average strength base material after 100,000 hours unless heated to at least 421°*C* (790°*F*). Pressure rupture will not occur in minimum strength base material at this location until heated to at least 400°*C* (750°*F*) but may occur immediately when that temperature is reached. Significantly higher temperatures can be accommodated without failure if sufficient material ductility is available to hot form the lids into spherical shapes. Demonstration of this capability at both lids will require detailed inelastic FEA calculations with base metal and weldment creep curves, as-welded connection geometry and consideration of possible non-ductile cracking at geometric and material strain risers in heat affected zones near the tip of the top lid closure weld.

<u>Calculations</u>

Weight stresses in the OCB lids are insignificant compared to pressure stresses and are ignored. Two pressure stress fields in the OCB lids are addressed:

- Membrane and bending stresses at the center of the lids: These stress fields can lead to ductile rupture. These are equilibrium (primary, P_L+P_b) stresses and are therefore reasonably predicted using elastic closed form solutions. The bending stresses initially occur alone and plastic deformations balloon out a shrinking radii spherical surface with increasing membrane (stretching) stresses. The centers of the lids are base metal areas where no weld strength reduction factors are needed. The reinforcement provided by the top lid lifting feature makes the bottom lid governing for the central lid stresses. The yielding/creep rotation of the lid at the built-in edges increase stresses at the center of the lid and is conservatively addressed by using a pinned-edge circular plate. Creep deformations of the lid increase the contained volume and reduce the pressure.

- Secondary and peak stresses in the outer edges of the top and bottom lids at the connection to the shell: The details of these connections will be developed in final design to accommodate pressure stresses under this sequence event and others. This final design may include weld zones where weld material strength and creep ductility need to be addressed. The final closure weld will not be solution annealed and it is currently planned to burnish it to introduce surface compressive stresses for stress corrosion cracking concerns. Edge failure at the connections to the shell can occur by cracking if inadequate creep ductility for the edge deformation exists. Evaluation of these locations will require details of the final connections, better weld creep properties and detailed finite element modeling. Although discussion of these stress fields is included in this calculation, accurate calculations can be performed only after the connection details are developed and better weldment creep ductility information is available.

Lid Center Ductile Rupture

The classical (e.g., Reference 2.2.31, page 326, Example 1) strength of materials formula for the surface bending stresses, S_b, at the center of a pressurized flat plate with pinned (simply supported) edges (corner connection has inelastically hinged) is:

$$S_b = \frac{3PR^2\nu}{8t^2}\left(\frac{3}{\nu}+1\right)\text{, where} \qquad \text{Equation 9}$$

P = internal pressure, variable
R = lid edge radii = 0.9144 *m* (36 *in*), Reference 2.2.33
t = lid thickness = 0.0254 *m* (1 *in*), Reference 2.2.34
ν = Poisson's ratio = 0.5 (plastic flow)

Worksheet 2 of Attachment V (file: Attachment III Creep Stress Excel Workbook.xls) contains this equation and calculates the bending stresses for temperature-pressure combinations from the MathCad information in Attachment V (file: Pressures Rev4.xmcd). The pressures used are for an undeformed lid and two values of lid ballooning, a 10 *in* (0.254 *m*) tall spherical bulge and a 0.9144 *m* (36 *in*) radii full hemispherical shape.

The bending stresses in the undeformed lid and 10 *in* (0.254 *m*) bulged lid are computed using the above flat plate bending equation. The membrane stresses, S_m, in the 10 *in* (0.254 *m*) bulged lid and the hemispherical lid are computed using the classical (e.g., Reference 2.2.24, page 327, Equation 6.36) strength of materials formula for a pressurized spherical shell with mid-surface radii, R_s:

$$S_m = \frac{PR_s}{2t} \qquad \text{Equation 10}$$

At all temperatures, the undeformed lid stresses and 10 in (0.254 m) bulged lid stresses were nearly identical. The slightly lower pressure due to deformation was balanced by the additional membrane stresses. The more deformed hemispherical shape results in very low sustained stresses, however the creep strains to get to this shape will be large. Simplistically, in the hemispherical case, the diameters will need to stretch to half-circumferences, expending (π/2-1)*100 = 57% strain. This amount of creep ductility may not exist in the base material. Therefore, because consideration of creep deformations does not provide significant temperature Capability relief until large distortions introduce ductility issues, the undeformed pressure and stress equations should be used.

Lid Edge Ductility Exhaustion

The top lid of the OCB will be on-site welded to the shell after the WP is loaded with waste material, will not be heat treated, nor will there be post-weld access to the inner surfaces. On the other hand, the bottom lid of the OCB will be factory welded to the shell, post-weld heat treated and fillet welded on the accessible interior corner. The top lid at its juncture to the shell currently has a crack like strain riser at the inside corner where the lid rests on a seating ledge before welding. The interior fillet weld on the bottom lid will eliminate any similar surface "cracks". Based on this, the top lid is expected to fail before the bottom lid if the failure is to be at a corner connection.

Fixed edge classical plate equations or flat plate-cylinder continuum (compliance) solutions can be used to predict the bending stresses but not the peak stresses. And these predicted plate bending stresses are overly conservative once the corner connection starts deforming. Therefore, detailed fine mesh finite element analyses (FEA) are needed to predict reasonable response, and as discussed below, these will need to be nonlinear (with plasticity and creep). Such efforts will have to wait until the prototype welding processes are finalized and the actual welded geometry and material properties can be determined and modeled.

Published room temperature flat plate burst tests (Reference 2.2.28) provide insight on flat plate pressure behavior without the crack like strain riser. The test specimens had smooth non-welded rounded corner connection details. When the metal is ductile enough, the pressure failure is ductile rupture in the center of the lid, which balloons into a semi-spherical dome prior to burst. If the material is not adequately ductile, the failure is through-wall cracking (fast fracture) at the corner connection. The elastic FEA cases always predicted failure at the corner connection. Nonlinear FEA correctly predicted the failure location.

The Alloy 22 base metal plastic ductility is very high (70% magnitude at elevated temperature) and the elevated temperature creep ductility of the base metal (strain at creep rupture) reported in Reference 2.2.29 is "on the order of 10 to 30%". Different material flow mechanisms are involved in plasticity and creep. Further complicating the material response is thermal aging effects. Aging tends to reduce ductility. The above data is non-aged data. Thermally aged data exists for Alloy 22, but only for 1000 hours or less.

The worst complication occurs at weld heat affected zones. Attachment V (file: Attachment III Creep Stress Excel Workbook.xls), Worksheet 4 reviews Reference 2.2.30 vendor short term elevated temperature ductility data and indicates 30 to 50% ductility in non-postweld heat treated welds. This is 40 to 80% lower than the base metal ductility. The reduction in weldment creep ductility versus base metal creep ductility may be anywhere between insignificant to the same order of reduction as that observed in the loss of plastic ductility at welds. This leads to a weldment creep ductility uncertainty between 3% and 30% strain.

Cold working also affects ductility. The effect of low plasticity burnishing on the creep ductility of the OCB lid closure weld juncture is local. Ongoing testing of prototype OCB lid closure weld junctures indicates the burnishing provides outer surface cold-working (and compression stresses) for less than 2% of the wall thickness. This, and the expectation that the maximum tension stresses under internal pressure loading will be on the inner surface indicates that the affect of burnishing on the creep strength of the juncture will be minimal.

The geometric details of a flat lid connection can vary widely and will have a significant effect on the pressure failure. The LA design is currently simplistic with a square inner corner and a flush reinforcing sleeve. This creates a stiff detail with very high local stresses, not to mention the weld tip crack. The ideal corner detail would be a toroidal knuckle of a formed or forged curved head. The Reference 2.2.28 burst disk corner detail is a square corner with generous inner radii, somewhere between the LA design and the ideal design. In the room temperature burst tests, material with plastic ductility of 18% (A-533 Grade B low alloy steel) failed at the corner by cracking. Materials with 25% plastic ductility (ABS-C Carbon Steel) and 40% plastic ductility (Type 304 Stainless Steel) failed at the center by ductile rupture.

The evaluation of lid edge ductility exhaustion can not be conducted until there is better knowledge of weldment creep ductility and the final corner details.

OTHER STRUCTURAL FAILURES

The postulated pressure failures of the spent fuel, waste canisters and inner vessel will pressure load the OCB, but will not be otherwise detrimental to OCB performance. Specifically, postulated pressure breach of the spent fuel and the relatively thin-walled waste canisters is expected to only superficially gouge the inner surface of the thicker walled inner vessel. Pressure breach of the inner vessel shell or lids is not expected at the Capability temperatures based on the creep rupture calculation presented below. Pressure failure of the inner vessel top lid seal welds due to rock impacts will increase the pressure on the OCB, but it will not release the mechanically stayed flat head. The direction of the released gases will be radially inward away from the OCB closure lid. Creep distortions of the waste canisters and contents will have no effect on the OCB. Creep distortions of the inner vessel will spread its contact region with the OCB and reduce the weight stresses in the OCB at the emplacement pallet contact region.

<u>Calculation</u>

The SA-240 Type 316 material inner vessel is Code stamped to 150 *psig* (1.03 *MPa*) at 650°*F* (343°*C*) and the calculated inner vessel pressures in Attachment V (file: Pressures Rev4.xmcd) at the highest Capability temperature of 541°*C* (1006°*F*) is 81 *psig* (0.558 *MPa*). The design pressure is scaled by the quotient of the 10^5 *hr*, 541°*C* weld strength reduced stress rupture value R times minimum S_R = 0.65 (Reference 2.2.21, Table I-14.10 B3) times 160 *MPa* (Reference 2.2.21, Table I-14.6B) = 104 *MPa* (15.1 ksi), divided by the 650°*F* Class 2 allowable stress, S = 16.6 *ksi* (114 *MPa*) (Reference 2.2.32, Section II, Part D, Table1A) to determine the minimum creep rupture pressure. This leads to a 150 times 15.1/16.6 = 136 *psig* (0.938 *MPa*) minimum creep rupture pressure. This is greater than the 81 *psig* (0.558 *MPa*) pressure at the highest Capability temperature, and therefore, the inner vessel is not expected to burst before the OCB fails. The inner vessel top lid seal welds however may crack during the rock fall.

ATTACHMENT IV – FILE LISTING FOR ATTACHMENT V CD

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 Volume Serial Number is 4FC3-8DF2

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02/19/2008  09:34 AM           666,525 Pressures Rev4.xmcd
               6 File(s)        841,062 bytes

 Directory of D:\12_2_100deg_vKeff

02/15/2008  05:23 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/14/2008  01:38 PM           209,920 12_2_125pct_100deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
02/14/2008  01:16 PM            96,724 getmaxtemp125_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/29/2008  11:17 AM           493,294 t00_h125_Av.parm
02/14/2008  10:43 AM            95,481 t00_h125_Dv.inp
02/14/2008  01:16 PM         2,061,005 t00_h125_Dv.out
               8 File(s)      2,982,449 bytes

 Directory of D:\12_2_50deg_vKeff

02/20/2008  01:08 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/15/2008  04:33 PM           212,480 12_2_125pct_50deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
02/15/2008  04:10 PM            96,724 getmaxtemp125_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
02/13/2008  09:19 AM            95,786 t00_h125_Av.inp
```

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02/15/2008  04:10 PM         2,234,560 t00_h125_Av.out
02/15/2008  04:10 PM           493,294 t00_h125_Av.parm
02/14/2008  10:42 AM            95,403 t00_h125_Dv.inp
02/15/2008  04:10 PM         2,041,101 t00_h125_Dv.out
              10 File(s)      5,295,373 bytes

 Directory of D:\14_2_100deg_vKeff

02/13/2008  09:28 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  01:05 PM           142,336 14_2_125pct_100deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
01/24/2008  04:12 PM            96,727 getmaxtemp125_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/23/2008  02:36 PM            95,864 t00_h125_Av.inp
01/24/2008  07:02 AM           493,294 t00_h125_Av.parm
01/24/2008  07:13 AM            95,481 t00_h125_Dv.inp
01/24/2008  04:12 PM         2,070,238 t00_h125_Dv.out
               9 File(s)      3,019,965 bytes

 Directory of D:\14_2_50deg_vKeff

02/20/2008  01:10 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/15/2008  04:42 PM           212,480 14kw_MAX_vKeff.xls
02/15/2008  04:39 PM           211,968 14_2_100pct_50deg.xls
02/15/2008  04:36 PM           212,480 14_2_125pct_50deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
02/15/2008  04:11 PM            96,727 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
02/15/2008  04:11 PM            96,724 getmaxtemp125_v.out
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
02/15/2008  04:11 PM            96,678 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/16/2008  03:53 PM            95,757 t00_h100_Av.inp
02/15/2008  04:11 PM         2,175,797 t00_h100_Av.out
02/15/2008  04:11 PM           493,294 t00_h100_Av.parm
01/17/2008  07:06 AM            95,372 t00_h100_Dv.inp
02/15/2008  04:11 PM         2,015,545 t00_h100_Dv.out
02/13/2008  09:19 AM            95,786 t00_h125_Av.inp
02/15/2008  04:11 PM           493,294 t00_h125_Av.parm
02/13/2008  09:20 AM            95,403 t00_h125_Dv.inp
02/15/2008  04:11 PM         2,044,491 t00_h125_Dv.out
01/22/2008  04:32 PM            96,132 t00_hMAX_Av.inp
02/15/2008  04:11 PM           493,294 t00_hMAX_Av.parm
01/22/2008  04:34 PM            95,769 t00_hMAX_Dv.inp
02/15/2008  04:11 PM         2,115,314 t00_hMAX_Dv.out
              24 File(s)     11,361,330 bytes

 Directory of D:\14_2_noVENT_vKeff

02/07/2008  04:40 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  01:21 PM           138,752 14_2_80pct_noVent.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
```

```
01/24/2008  09:20 AM             1,498 getmaxtemp80_v.inp
01/25/2008  09:34 AM            96,671 getmaxtemp80_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/24/2008  09:26 AM            98,237 t00_h80_Av.inp
01/25/2008  07:32 AM           493,294 t00_h80_Av.parm
01/25/2008  08:05 AM            97,853 t00_h80_Dv.inp
01/25/2008  09:34 AM         2,180,177 t00_h80_Dv.out
               9 File(s)      3,131,007 bytes

 Directory of D:\16_2_100deg_vKeff

02/15/2008  05:23 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/14/2008  01:30 PM           209,408 16_2_100pct_100deg.xls
02/04/2008  01:37 PM           139,264 16_2_125pct_100deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
02/14/2008  01:17 PM            96,724 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
01/24/2008  07:02 AM            96,727 getmaxtemp125_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/23/2008  07:39 AM           493,294 t00_h100_Av.parm
02/14/2008  10:44 AM            95,450 t00_h100_Dv.inp
02/14/2008  01:17 PM         2,031,382 t00_h100_Dv.out
01/23/2008  02:36 PM            95,864 t00_h125_Av.inp
01/24/2008  07:02 AM         2,329,661 t00_h125_Av.out
01/24/2008  07:02 AM           493,294 t00_h125_Av.parm
01/23/2008  02:38 PM            95,481 t00_h125_Dv.inp
01/24/2008  07:02 AM         2,087,988 t00_h125_Dv.out
              16 File(s)      8,292,062 bytes

 Directory of D:\16_2_50deg_vKeff

02/07/2008  04:40 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  01:26 PM           139,264 16kw_MAX_vKeff.xls
02/04/2008  01:23 PM           139,264 16_2_100pct_50deg.xls
02/04/2008  01:24 PM           138,752 16_2_125pct_50deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
01/25/2008  10:17 AM            96,727 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
01/21/2008  10:30 AM            96,727 getmaxtemp125_v.out
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
01/23/2008  07:41 AM            96,678 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/16/2008  03:53 PM            95,757 t00_h100_Av.inp
01/17/2008  09:57 AM            95,372 t00_h100_Dv.inp
01/25/2008  10:17 AM         2,027,495 t00_h100_Dv.out
01/17/2008  04:26 PM            95,786 t00_h125_Av.inp
01/18/2008  09:04 PM         2,234,560 t00_h125_Av.out
01/18/2008  09:04 PM           493,294 t00_h125_Av.parm
01/21/2008  08:00 AM            95,403 t00_h125_Dv.inp
01/21/2008  10:30 AM         2,065,222 t00_h125_Dv.out
01/22/2008  04:32 PM            96,132 t00_hMAX_Av.inp
01/23/2008  07:41 AM         2,356,288 t00_hMAX_Av.out
01/23/2008  07:41 AM           493,294 t00_hMAX_Av.parm
```

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01/22/2008  04:34 PM            95,769 t00_hMAX_Dv.inp
01/23/2008  07:41 AM         2,116,024 t00_hMAX_Dv.out
              24 File(s)     13,096,833 bytes

 Directory of D:\18_2_100deg_vKeff

02/07/2008  04:40 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  02:12 PM           138,752 18_2_100pct_100deg.xls
02/04/2008  02:13 PM           139,264 18_2_125pct_100deg.xls
02/04/2008  02:10 PM           139,264 18_2_40pct_100deg.xls
02/04/2008  02:11 PM           139,776 18_2_80pct_100deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
01/23/2008  07:39 AM            96,727 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
01/29/2008  11:17 AM            96,724 getmaxtemp125_v.out
01/29/2008  03:05 PM             1,498 getmaxtemp40_v.inp
01/30/2008  07:23 AM            96,720 getmaxtemp40_v.out
01/24/2008  09:20 AM             1,498 getmaxtemp80_v.inp
01/25/2008  07:33 AM            96,723 getmaxtemp80_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/21/2008  07:56 AM            95,835 t00_h100_Av.inp
01/23/2008  07:39 AM         2,201,785 t00_h100_Av.out
01/23/2008  07:39 AM           493,294 t00_h100_Av.parm
01/21/2008  07:57 AM            95,450 t00_h100_Dv.inp
01/23/2008  07:39 AM         2,045,727 t00_h100_Dv.out
01/23/2008  02:36 PM            95,864 t00_h125_Av.inp
01/29/2008  11:17 AM         2,329,658 t00_h125_Av.out
01/29/2008  11:17 AM           493,294 t00_h125_Av.parm
01/25/2008  03:53 PM            95,481 t00_h125_Dv.inp
01/29/2008  11:17 AM         2,094,211 t00_h125_Dv.out
01/29/2008  03:21 PM            95,683 t00_h40_Av.inp
01/30/2008  07:23 AM         2,040,954 t00_h40_Av.out
01/30/2008  07:23 AM           493,294 t00_h40_Av.parm
01/29/2008  03:22 PM            95,282 t00_h40_Dv.inp
01/30/2008  07:23 AM         2,001,660 t00_h40_Dv.out
01/24/2008  09:24 AM            98,207 t00_h80_Av.inp
01/25/2008  07:33 AM         2,191,098 t00_h80_Av.out
01/25/2008  07:33 AM           493,294 t00_h80_Av.parm
01/24/2008  09:23 AM            97,823 t00_h80_Dv.inp
01/25/2008  07:33 AM         2,070,923 t00_h80_Dv.out
              34 File(s)     20,693,288 bytes

 Directory of D:\18_2_50deg_vKeff

02/15/2008  05:19 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  02:08 PM           128,000 18kw_MAX_vKeff.xls
02/04/2008  02:05 PM           144,384 18_2_100pct_50deg.xls
02/04/2008  02:06 PM           139,264 18_2_125pct_50deg.xls
02/04/2008  02:04 PM           138,752 18_2_40pct_50deg.xls
02/05/2008  01:51 PM           209,408 18_2_80pct_50deg.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
01/18/2008  09:04 PM            96,724 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
```

```
01/18/2008  09:04 PM            96,724 getmaxtemp125_v.out
01/29/2008  03:05 PM             1,498 getmaxtemp40_v.inp
01/30/2008  07:22 AM            96,720 getmaxtemp40_v.out
01/24/2008  09:20 AM             1,498 getmaxtemp80_v.inp
02/05/2008  01:41 PM            96,720 getmaxtemp80_v.out
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
01/29/2008  11:15 AM            96,675 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/16/2008  03:53 PM            95,757 t00_h100_Av.inp
01/18/2008  09:04 PM         2,175,794 t00_h100_Av.out
01/18/2008  09:04 PM           493,294 t00_h100_Av.parm
01/17/2008  01:35 PM            95,372 t00_h100_Dv.inp
01/18/2008  09:04 PM         2,047,186 t00_h100_Dv.out
01/17/2008  04:26 PM            95,786 t00_h125_Av.inp
01/18/2008  09:04 PM         2,234,560 t00_h125_Av.out
01/18/2008  09:04 PM           493,294 t00_h125_Av.parm
01/17/2008  04:27 PM            95,403 t00_h125_Dv.inp
01/18/2008  09:04 PM         2,069,763 t00_h125_Dv.out
01/29/2008  03:06 PM            95,605 t00_h40_Av.inp
01/30/2008  07:22 AM         2,007,716 t00_h40_Av.out
01/30/2008  07:22 AM           493,294 t00_h40_Av.parm
01/29/2008  03:07 PM            95,218 t00_h40_Dv.inp
01/30/2008  07:22 AM         1,888,582 t00_h40_Dv.out
02/04/2008  01:45 PM            98,128 t00_h80_Av.inp
02/05/2008  01:41 PM         2,114,745 t00_h80_Av.out
02/05/2008  01:41 PM           493,294 t00_h80_Av.parm
02/04/2008  01:44 PM            97,744 t00_h80_Dv.inp
01/22/2008  04:32 PM            96,132 t00_hMAX_Av.inp
01/23/2008  07:41 AM           493,294 t00_hMAX_Av.parm
01/25/2008  03:56 PM            95,769 t00_hMAX_Dv.inp
01/29/2008  11:15 AM         2,119,855 t00_hMAX_Dv.out
              40 File(s)     21,360,977 bytes

 Directory of D:\18_2_noVENT_vKeff

02/07/2008  04:40 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/04/2008  02:16 PM           142,848 18_2_100pct_noVent.xls
02/04/2008  02:44 PM           142,336 18_2_125pct_noVent.xls
02/05/2008  01:47 PM           209,408 18_2_40pct_noVent.xls
02/04/2008  02:15 PM           139,264 18_2_80pct_noVent.xls
01/25/2008  04:43 PM           209,408 18_2_Base_noVent.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/25/2008  07:57 AM            95,617 base_case_Av.inp
01/25/2008  04:14 PM         2,323,160 base_case_Av.out
01/25/2008  04:14 PM           493,294 base_case_Av.parm
01/25/2008  07:58 AM            95,203 base_case_Dv.inp
01/25/2008  04:14 PM         2,153,066 base_case_Dv.out
01/16/2008  03:53 PM             1,500 getmaxtemp100_v.inp
01/25/2008  07:33 AM            96,675 getmaxtemp100_v.out
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
01/25/2008  07:33 AM            96,675 getmaxtemp125_v.out
01/29/2008  03:05 PM             1,498 getmaxtemp40_v.inp
02/05/2008  01:40 PM            96,671 getmaxtemp40_v.out
01/24/2008  09:20 AM             1,498 getmaxtemp80_v.inp
01/25/2008  07:33 AM            96,671 getmaxtemp80_v.out
01/25/2008  07:55 AM             1,502 getmaxtempB_v.inp
```

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01/25/2008  04:14 PM            96,667 getmaxtempB_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/24/2008  08:37 AM            95,861 t00_h100_Av.inp
01/25/2008  07:33 AM         2,447,691 t00_h100_Av.out
01/25/2008  07:32 AM           493,294 t00_h100_Av.parm
01/24/2008  08:38 AM            95,476 t00_h100_Dv.inp
01/25/2008  07:33 AM         2,258,398 t00_h100_Dv.out
01/24/2008  08:43 AM            95,890 t00_h125_Av.inp
01/25/2008  07:33 AM         2,362,496 t00_h125_Av.out
01/25/2008  07:32 AM           493,294 t00_h125_Av.parm
01/24/2008  08:44 AM            95,507 t00_h125_Dv.inp
01/25/2008  07:33 AM         2,149,085 t00_h125_Dv.out
02/04/2008  01:40 PM            95,712 t00_h40_Av.inp
02/05/2008  01:41 PM         2,366,778 t00_h40_Av.out
02/05/2008  01:41 PM           493,294 t00_h40_Av.parm
02/04/2008  01:41 PM            95,325 t00_h40_Dv.inp
02/05/2008  01:40 PM         2,179,984 t00_h40_Dv.out
01/24/2008  09:26 AM            98,237 t00_h80_Av.inp
01/25/2008  07:33 AM         2,380,267 t00_h80_Av.out
01/25/2008  07:32 AM           493,294 t00_h80_Av.parm
01/24/2008  09:27 AM            97,853 t00_h80_Dv.inp
01/25/2008  07:33 AM         2,184,323 t00_h80_Dv.out
              42 File(s)     27,591,045 bytes

 Directory of D:\198test

02/07/2008  04:40 PM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/06/2008  03:22 PM           209,408 18_2_125pct_100deg_198IC.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/17/2008  04:28 PM             1,500 getmaxtemp125_v.inp
02/06/2008  03:01 PM            96,724 getmaxtemp125_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
02/06/2008  03:01 PM            95,862 t00_h125_Av.inp
02/06/2008  03:01 PM         2,293,995 t00_h125_Av.out
02/06/2008  03:01 PM           493,294 t00_h125_Av.parm
02/06/2008  03:01 PM            95,479 t00_h125_Dv.inp
02/06/2008  03:01 PM         2,094,392 t00_h125_Dv.out
              10 File(s)      5,405,179 bytes

 Directory of D:\6_2_50deg_vKeff

02/19/2008  10:51 AM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/15/2008  04:22 PM           212,480 6kw_MAX_vKeff.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
02/15/2008  04:09 PM            96,675 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
02/15/2008  04:09 PM           493,294 t00_hMAX_Av.parm
02/14/2008  10:39 AM            95,768 t00_hMAX_Dv.inp
02/15/2008  04:09 PM         2,113,749 t00_hMAX_Dv.out
               8 File(s)      3,037,991 bytes

 Directory of D:\7_2_50deg_vKeff

02/19/2008  10:52 AM    <DIR>          .
```

```
02/20/2008  02:47 PM    <DIR>          ..
02/15/2008  04:27 PM           142,336 7kw_MAX_vKeff.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
02/15/2008  04:10 PM            96,675 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
02/15/2008  04:09 PM           493,294 t00_hMAX_Av.parm
01/23/2008  01:43 PM            95,768 t00_hMAX_Dv.inp
02/15/2008  04:10 PM         2,108,837 t00_hMAX_Dv.out
               8 File(s)      2,962,935 bytes

 Directory of D:\8_2_50deg_vKeff

02/19/2008  10:53 AM    <DIR>          .
02/20/2008  02:47 PM    <DIR>          ..
02/15/2008  04:28 PM           212,480 8kw_MAX_vKeff.xls
01/11/2005  01:20 PM             5,577 AnsysBin1.dat
01/22/2008  04:30 PM             1,500 getmaxtempMAX_v.inp
02/15/2008  04:10 PM            96,675 getmaxtempMAX_v.out
01/17/2008  10:01 AM            18,948 matprops09ev.dat
01/22/2008  04:32 PM            96,132 t00_hMAX_Av.inp
02/15/2008  04:10 PM         2,356,285 t00_hMAX_Av.out
02/15/2008  04:10 PM           493,294 t00_hMAX_Av.parm
01/23/2008  11:08 AM            95,768 t00_hMAX_Dv.inp
02/15/2008  04:10 PM         2,111,761 t00_hMAX_Dv.out
              10 File(s)      5,488,420 bytes

     Total Files Listed:
             258 File(s)    134,559,916 bytes
              42 Dir(s)               0 bytes free
```

ATTACHMENT V – ELECTRONIC FILES

This Attachment contains the electronic files (one CD) that support this calculation.