# APPENDIX 3-1

ISSUE SUMMARY
Form SOP-0402-03, Revision 2



DESIGN CONTROL SUMMARY

CLIENT: **BNFL Inc.**
UNIT NO.:
PROJECT NAME: **Big Rock Point Major Component Removal**
PROJECT NO.: **10525-020**
CALC. NO.: **N-10525-020-0001**
TITLE: Reactor Vessel Heat Rates and Shielding
EQUIPMENT NO.:

☐ NUCLEAR SAFETY-RELATED
☐ NOT NUCLEAR SAFETY-RELATED
☒ IMPORTANT TO SAFETY - CATEGORY A

QA SERIAL NO.

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Initial Issue: 39 pages issued as Revision 0.

INPUTS/ ASSUMPTIONS
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☐ UNVERIFIED

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| REVIEWER* | | DATE: |
| APPROVER | | DATE: |

* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

**NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS**

| Sargent & Lundy LLC | Calc For Reactor Vessel Heat Rates and Shielding | | | | Calc No. N-10525-020-0001 | |
|---|---|---|---|---|---|---|
| | | | | | Rev. 1 | Date 12/08/00 |
| | X | Important to Safety - Category A | | Non-Safety Related | Page 2 | |

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|---|---|---|---|
| Client | BNFL, Inc. | | |
| Project | Big Rock Point Major Component Removal | | |
| Proj. No | 10525-020 | Equip. No. | |

| | | |
|---|---|---|
| Prepared by | G. Douglas Cole | Date |
| Reviewed by | Roman Kahn | Date |
| Approved by | William J. Johnson | Date |

# Table of Contents

f. Attachment F: Gamma-ray Transmission Fractions for Concrete (147 lb/ft$^3$ density) and Iron; "Radiological Health Handbook", Revised Edition, January 1970, U.S. Department of Health, Education and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological Health; 1 page;

g. Attachment G: Program ISOSHLD-PC Output, 14 pages.

## 1.0 Purpose and Scope

### 1.1 Purpose

The purpose of this calculation is to determine upper bound heat generation rates which originate with the radioactive components that comprise the integrated unit of Big Rock Point's Reactor Vessel Assembly and Internals (RVAI). The heat generation rates in turn depend on the radioactivity caused by the products of neutron activation on the various component's constituent metals. A secondary purpose of this calculation employs the radioactivity determinations to provide general shielding design information whereby surface and two meter dose rates from the packaged RVAI may be estimated.

### 1.2 Scope

The scope of this calculation is limited to the heat rates of the vessel and the vessel internals; it will not account for heat sources outside the radioactive RVAI components. The shielding design information and the dose rates are general and preliminary only; shielding design information will be sufficiently connected to detailed computer-supported models in a future calculation. Achieving detailed heat rate determinations in association with specific RVAI components is necessary to the extent that only those for the Grid Bar (i.e. Top Guide) End Pieces are identified as distinct from the total.

### 1.3 Background

The RV Assembly and Internals will be physically processed to obtain an integrated unit. The RV Internals are already fixed in position, but a low-density cement grout will be pumped into the RV to surround the remaining internals. This operation serves to prevent the movement of superficial radioactive contaminants. The grout will also form a readily identifiable boundary at the RV's nozzles and orifices. It is expected that the RV Head will not be a part of the RV integrated unit. Some other enclosure, like a steel plate, will be attached to the remaining RV Assembly and Internals.

The RVAI unit will be packaged for the purposes of transport to and near surface burial at the Barnwell, South Carolina Waste Management Facility. The packaged RVAI is the essential item that is a part of the Reactor Vessel Transportation System (RVTS). To create the RVTS package, the RVAI unit will be positioned in the package and surrounded by more cement grout. This grout will maintain the RVAI's optimal position, and also serve to insulate and radiologically shield the RVAI. The package itself will provide additional radiological shielding and be of sufficient construction to withstand the expected rigors of handling, transport and burial.

In many aspects, the package's outer surface is the physical point where the engineered adequacy of the RVTS is determined by virtue of its structural strength, its surface dose rates, its maximum temperature and pressure. Also to be determined are the package's internal pressure, the bounding dimensions of the overall package and its constituent steel shielding. More specifically, it will be necessary to associate heat rates with specific components not only because of the likelihood of disproportionate amounts of heat production, but also because of their potentially problematic locations.

Aspects of federal regulation with regard to low-level radioactive waste, especially in Chapter 10 of the Code of Federal Regulations, Parts 20, 61 and 71, are accommodated in this calculation. Part 61 allows flexibility with respect to scaling from better characterized radionuclide concentrations to estimate concentrations which, in this case, are those of the as-yet unclassified (for burial) RVAI. Federal, state and facility waste transportation requirements with respect to shipment manifesting also compel the indicated scaling approach, which also provides activity estimates for H-3 and C-14, especially, but also Tc-99.

## 2.0 References


2.1 "Big Rock Point Reactor Vessel and Internals Characterization and Classification", Report WMG-9902, Revision 1, June 1999, WMG Project 8057;

2.2 "Trojan Nuclear Plant Reactor Vessel and Internals Removal Project Safety Analysis Report", PGE-1076, Revision 1, July 1999, Portland General Electric Company;

2.3 Program ISOSHLD-PC, Program 03.7.310-1.0/O, June 1, 1999, Sargent & Lundy$^{LLC}$;

2.4 "Dose Rate Evaluation 3 Meters from Big Rock Point's Reactor Vessel", Prepared by A.G. Klazura, April 14, 1999, Sargent & Lundy$^{LLC}$;

2.5 "PR-2 and PR-7 Series Specifications", DOSITEC, Inc., Sheet #8201-0293;

2.6 "Handbook of Chemistry and Physics", Edited by D.R. Lide et al., 78$^{th}$ Edition, 1997-98, CRC Press$^{LLC}$;

2.7 "Radiological Health Handbook", Revised Edition, January 1970, U.S. Department of Health, Education and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological Health;

2.8 Code of Federal Regulations, Title 10, Volume 2, Part 61, Revised January 1, 1999, U.S. Government Printing Office via GPO Access, "Waste Classification" (...61.55), "(8) *Determination of concentrations in wastes.*"

2.9 "Revised Characterization and Classification Results; WMG Project 8057", Revision to Reference 2.1, March 10, 2000, WMG Inc.;

2.10 "Concentration Averaging of Grid Bar End Pieces for Disposal of BRP Reactor Vessel and Internals", Report WMG-20024-20091, October 2000, WMG Inc., 16 Bank Street, Peekskill, NY;

2.11 "Nuclear Power Plants No Longer in Service", Nuclear News, March 2000, Vol.43, Number 3, pg. 57, American Nuclear Society Inc., LaGrange Park, IL, USA;

2.12 "Reactor Vessel Transport System Radiation Source Term", Calculation No. N-10525-020-004, Rev. 1, Big Rock Point Major Component Removal, December 2000, Sargent & Lundy LLC .


## 3.0 Design Input

3.1 Units (Reference 2.6, pgs. 1-24 – 1-31, 1-38):

a. 1 Curie (Ci) = 3.7 E+10 Bequerels = 3.7 E+10 disintegrations (dis.) /second;

b. 1 electronvolt (eV) = 1.602 E-19 joules (J);

c. 1 British Thermal Unit (BTU, mean) = 1.056 E+3 J;

d. 1 hour = 3.600 E+3 seconds (sec).

3.2 Dose Rate-Activity Basis (RVAI's Thermal Shield (TS), Reference 2.1, Appendix A, Exhibit 2, positions "F", "G", and "H"; see Attachment A): Table 3-1 demonstrates that most of the TS dose rates are well within the calibrated ranges of the PR-2 radiation monitor, as is the average dose rate. These dose rates are associated with the TS activity of 7.45 E+3 Curies (see Attachment B).

Table 3-1. Thermal Shield Characteristics

| Azimuthal Position by elevation | Dose Rate |
|---|---|
| 604' 144° (F) | 1500 R/hour |
| 606' 144° (F) | 1625 R/hour |
| 604' 162° (G) | 1500 R/hour |
| 606' 162° (G) | 2125 R/hour |
| 604' 180° (H) | 1500 R/hour |
| 606' 180° (H) | 1375 R/hour |
| average | 1604 R/hour |

3.3 Component Characteristics (Reference 2.1, Table 4-1, and Reference 2.9, Attachment A; see Attachment B): These data are excerpted from the referenced table and attachment. The RV Cladding weight datum is from Reference 2.1, Table 4-11. The references state that these activities have been decayed to a date of September 1, 2002. Also note that the Neutron Windows' and Top Guide's entries have not been included since they will not be part of the RVAI.

Table 3-2. Reactor Vessel (RV) Component Characteristics

| Component | Weights | Corrected Total Activtiy (Ci) |
|---|---|---|
| Thermal Shield | 1.30 E+4 lbs | 7.40 E+3 |
| Steam Baffle | 1.64 E+3 lbs | 1.08 E+1 |
| Sparger | 1.30 E+2 lbs | 8.60 E -1 |
| Top Guide Plate | 8.13 E+2 lbs | 1.14 E+3 |
| Seal Housing | 1.07 E+3 lbs | 1.30 E+2 |
| Thermal Shield Retainer | 5.47 E+2 lbs | 1.14 E+2 |
| Seal Weights | 5.08 E+3 lbs | 1.10 E+3 |
| Core Support Plate | 2.54 E+3 lbs | 1.4 E -1 |
| Inlet Diffuser | 1.98 E+2 lbs | 2.24 E -2 |
| Inlet Baffle | 2.32 E+3 lbs | 1.63 E -1 |
| RV Insulation | 5.18 E+3 lbs | 5.81 E+1 |
| RV Cladding | 5.03 E+3 lbs | 2.45 E+2 |
| RV Wall | 2.03 E+5 lbs | 1.11 E+3 |

3.4 PR-2 Energy Response and Accuracy (Reference 2.5; see Attachment E).

a. Energy Response: +/- 30% from 80 KeV to 3 MeV;

b. Accuracy: +/- 15% for all ranges from 20% to 80% of full scale, calibrated with Cs-137.

3.5 Radionuclide Total Disintegration Energy (Reference 2.6, "Table of the Isotopes", pgs. **11**-41 – **11**-146). See Table 3-4.

3.6 Trojan Reactor Vessel Package Radioactivity Fractions (Reference 2.2, Table 1-2; see Attachment D, "Activity, Activation (Curies)").

Table 3-3. Trojan RV Radionuclide Curies and Radionuclide Energy Characteristics

| Nuclide | Activation (Curies) | Fraction | Total Disintegration Energy (MeV) |
|---|---|---|---|
| H-3 | 6.55 E+2 | 3.26 E -4 | 0.01859 |
| C-14 | 2.18 E+2 | 1.08 E -4 | 0.1565 |
| Sb-125 | 4.04 E -1 | 2.01 E -7 | 0.767 |
| Mn-54 | 2.16 E+3 | 1.07 E -3 | 1.377 |
| Eu-152 | 2.54 E+1 | 1.26 E -5 | 1.86 |
| Fe-55 | 6.97 E+5 | 3.47 E -1 | 0.2316 |
| Co-60 | 1.15 E+6 | 5.72 E -1 | 2.824 |
| Ni-59 | 9.53 E+2 | 4.74 E -4 | ---- |
| Ni-63 | 1.57 E+5 | 7.81 E -2 | 0.067 |
| Nb-94 | 3.29 E+0 | 1.64 E -6 | 2.045 |
| Tc-99 | 7.06 E -1 | 3.51 E -7 | 0.294 |
| Total | 2.01 E+6 | 1.0 | |

3.7 Section 6.9.1 of Reference 2.12 provides the total Curie content for the Grid Bar End Pieces (GBEP) to be 1800 Curies.

3.8 Table 6.3.2-2 of Reference 2.12 is translated below as Table 3-4 for the purpose of distinguishing the RV Wall radionuclide activities from the distribution used for all other RVAI components. The primary differences are in the Fe-55 and Co-60 activities. The reason for the different distribution is primarily that the RV Wall is the only carbon steel component. The Curie activities in the final column will be used in the Calculation section (Section 6.5).

<u>Table 3-4 RV Wall Inventory</u>

| | Trojan Nuclide Distrib'n | | WMG Co-60 | Mod. Co-60 | Inc. Fe55 |
|---|---|---|---|---|---|
| nuclide | Ratio | Ci | Ci | | |
| H3 | 3.26E-04 | 3.62E-01 | 3.62E-01 | 3.62E-01 | 3.62E-01 |
| C14 | 1.09E-04 | 1.21E-01 | 1.21E-01 | 1.21E-01 | 1.21E-01 |
| SB125 | 2.01E-07 | 2.23E-04 | 2.23E-04 | 2.23E-04 | 2.23E-04 |
| MN54 | 1.08E-03 | 1.19E+00 | 1.19E+00 | 1.19E+00 | 1.19E+00 |
| EU152 | 1.26E-05 | 1.40E-02 | 1.40E-02 | 1.40E-02 | 1.40E-02 |
| FE55 | 3.47E-01 | 3.85E+02 | 3.85E+02 | 3.85E+02 | 7.90E+02 |
| CO60 | 5.73E-01 | 6.36E+02 | 2.01E+02 | 2.31E+02 | 2.31E+02 |
| NI59 | 4.75E-04 | 5.27E-01 | 5.27E-01 | 5.27E-01 | 5.27E-01 |
| NI63 | 7.82E-02 | 8.68E+01 | 8.68E+01 | 8.68E+01 | 8.68E+01 |
| NB94 | 1.64E-06 | 1.82E-03 | 1.82E-03 | 1.82E-03 | 1.82E-03 |
| TC99 | 3.52E-07 | 3.90E-04 | 3.90E-04 | 3.90E-04 | 3.90E-04 |
| Total | 1.00E+00 | 1.11E+03 | 6.75E+02 | 7.05E+02 | 1.11E+03 |

3.9 Transmission Fractions (Reference 2.7, pgs. 149; Attachment F).

3.10 The Top Guide Grid Bar End Pieces (GBEP), physical dimensions and dose rates (Reference 2.10).

a. Grid Bar End Pieces (cut; page 2 of 10): 5-5/8" x 7/8" x 6" ;

b. 6" GBEP (Table 2-2): 15; Locales 1– 7 and 11–18;

c. Grid Bar End Pieces (cut; page 2 of 10): 5-5/8" x 7/8" x 10" ;

d. 10" GBEP (Table 2-2): 3; Locales 8 – 10 .

e. Survey Information (Table 2-2):

| | |
|---|---|
| Locale 1 | 3250 R/hour; |
| Locale 2 | 2380 R/hour; |
| Locale 3 | 5420 R/hour; |
| Locale 4 | 11340 R/hour; |
| Locale 5 | 8980 R/hour; |
| Locale 6 | 8590 R/hour; |
| Locale 7 | 7540 R/hour; |
| Locale 8 | 3030 R/hour; |
| Locale 9 | 12880 R/hour; |
| Locale 10 | 3340 R/hour; |
| Locale 11 | 10660 R/hour; |
| Locale 12 | 15850 R/hour; |
| Locale 13 | 10800 R/hour; |
| Locale 14 | 11820 R/hour; |
| Locale 15 | 15990 R/hour; |
| Locale 16 | 13030 R/hour; |
| Locale 17 | 4130 R/hour; |
| Locale 18 | 2670 R/hour . |

## 4.0 Assumptions

4.1 With the exception of the Neutron Windows and Top Guide, the Curie contents associated with RV components in Reference 2.1 are assumed to be correct because the estimates appear to have been based on dose rates that were measured with a calibrated PR-2 radiation monitor.

4.2 Only the Thermal Shield had survey information unequivocally associated with it **and** that was within the calibrated ranges of the PR-2 monitor. However, the characteristics of all of the other components listed in Table 4-1 of Reference 2.1 and Attachment A of Reference 2.9, are assumed to be as acceptable as those for the Thermal Shield.

4.3 The RV Insulation, Wall, and Cladding components include contributions from the RV Head even though it is likely that the RV Head will not be part of the RVAI nor in the RVTS. It should also be pointed out that there is no RV Cladding entry in Reference 2.1, Table 4-1. That information must be taken from Table 4-11 of Reference 2.1 (weight) and Attachment A of Reference 2.9 (Curies).

4.4 The relative radionuclide abundances from the Trojan RV activation activities are assumed to provide a more reliable and complete radionuclide profile for all of the Big Rock RVAI components except the RV Wall. This assumption is compelling for the following reasons:

a. The Trojan RV packaging, shipment, and burial, as well as the supporting Safety Analysis Report (Reference 2.2), were complete with full regulatory compliance in 1999;

b. While the June 1999 WMG Report (Reference 2.1) appears generally thorough, tritium (H-3) has a characterization that includes the designation, "<LLD>". It would be advantageous to be able to manifest a H-3 activity, especially, without the LLD designation. Employing the Trojan profile allows a basis by which to do this;

c. The RV Wall and Insulation components are not as fully characterized as all the other components in the WMG Report; this calculation applies the same profile, i.e. Trojan's, to all of the RVAI components as an integrated unit;

d. There is reasonable consistency between the Big Rock RVAI (0.53 from Attachment B [page 2, "LLRW Subtotals" Corrected Co-60 to the Corrected Total Activities ratio]) and the Trojan RV (0.57 from Table 3.4) when comparing Co-60 abundances; utilizing the Trojan profile effectively conservatively skews the Big Rock RVAI to greater Co-60 Curies;

e. The radionuclide decay time from the end of reactor operations to that for the activity determinations is the same for Big Rock's characterization (August 1997 to September 2002; see Attachment B, page 2, title) as for Trojan's (November 1992 to November 1997; Reference D, Note 1). See Reference 2.11 for the August 1997 and November 1992 dates ("closed" dates).

This approach depends on the concepts given in Reference 2.8. The scaling implied above relies on the Trojan RV relative radionuclide abundances as meeting the regulation's intent with respect to "indirect methods [which] can be correlated to actual measurements".

4.5 The dose rate information in Section 3.10 makes clear that the GBEP activities are not symmetric. All the GBEP are situated in a narrow axial band above the annular components and completely within an approximate 180° azimuthal distribution. There are apparent peaks in this azimuthal distribution, as well, with one 90° section having more activity than the other section. The ratio of the more-to-less active section, on average, is about 3:2. There are activity peaks in each section as well, which would imply activity "hot" spots in both sections, again with average ratios each of 3:2. A conservative result of this approach would be to assume that half of total GBEP activity is in a single hot spot, essentially within an infinitesimal azimuthal angle roughly at the axial level of the Top Guide Plate.

4.6 An important assumption is that all of the radionuclide disintegration energy is deposited in the surrounding materials. Thus, 100% of the disintegration energy is converted to heat.

4.7 The Program ISOSHLD-PC is useful to this calculation by virtue of its capabilities to estimate heat rates. Dose rate results are also available from ISOSHLD, but the program is not so employed for this calculation.

4.8 The working outer diameter of the RVTS is assumed to be 13 feet. With a centered RVAI unit of radius 61.25 inches, the thickness of 16.75 inches is the difference between the RVAI's outer radius (i.e. RV Insulation's outer radius; Reference 2.1 Table 2-1) and that for the RVTS. The thickness measurement therefore spans the RV Insulation's outermost surface to the exterior of the RVTS, using the axial cross section.

4.9 The assumption of a dose-rate-to-distance relationship of $1/r$ instead of $1/r^2$ accounts for the RVAI being more like a "line" radiation source than a point source. Actual exterior, and especially side axial, dose rate measurements are a necessary check on such an assumption, but are as yet not available.

4.10 Application of the Transmission Fractions (Reference 2.7, pgs. 149) requires the assumption that all of the dose is due to Co-60. In the case of the concrete transmission of gamma rays, the fraction must be increased by a factor of approximately 3 to account for the lower density of the grout (i.e., 50 $lbs/ft^3$ as compared to concrete at 147 $lbs/ft^3$ indicated in the referenced curves).

## 5.0 Methodology and Acceptance Criteria

5.1 This calculation's methodology primarily relies on the total Curie contents associated with the various RV components from Reference 2.1. After the GBEP' total Curie content is recalculated, which is indirectly from Reference 2.1, it is summed with all the other RV component's Curie contents to produce a total for the RVAI. This total is then apportioned for specific radionuclide Curies (radionuclide profile) based on the relative abundance of the various radionuclides from the already shipped and buried Trojan RV package. The above assumptions finally allow the estimation of heat rates for the entire RVAI.

The 3-meter dose rates for the various components from Reference 2.4 can be summed to obtain a total dose rate directly associated with the referenced total Curie content. The RVAI Curie content will be compared to the Reference 2.4 Curies to determine a new 3-meter dose rate appropriate to the estimated RVAI Curie content. This dose rate can then be proportioned for different distances and proposed shielding situations.

5.2 The acceptance criteria are largely based on meeting the requirements of 10 CFR 71, such that:

a. Under normal conditions of transport, there would be no loss or dispersal of radioactive contents from the RVTS package, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging;

b. Account must be taken of the behavior of the RVTS materials under irradiation;

c. The RVTS package must be designed, constructed, and prepared for transport so that in still air and in the shade, no accessible surface of the package would have a temperature exceeding 122°F in a nonexclusive use shipment, or 185°F in an exclusive use shipment.

d. The conditions defined as normal for transport are evaluated as applicable and are given in 10 CFR 71.71 .

5.3 The acceptance criteria must generally account for the dose rate limits applicable to the RVTS package (10 CFR 71.47), such that:

a. External (contact) dose rates shall not exceed 200 millirem/hour on any accessible surface;

b. In the case of an open transport vehicle, the dose rates shall not exceed 200 millirem/hour at any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the package, and on the lower external surface of the vehicle;

c. At any point two meters from, in the case of an open vehicle, the vertical planes projected from the outer edges of the conveyance, 10 millirem/hour must not be exceeded.

However, the intent of this calculation is not to provide design details of the RVTS. The above limits are thus used as guidelines only, with RVTS package design elements generally estimated after reasonably conservative Curie content, heat rate, and dose rate assumptions are applied. The shielding design information and the dose rates are general and preliminary only; shielding design information will be sufficiently connected to detailed computer-supported models in a future calculation.

## 6.0 Calculations

6.1 Calculate the total Curies for the RVAI unit, including all RV components except the RV Wall and the GBEP.

The Top Guide, which is separate from the Top Guide Plate, is excluded because this component will not be included in the RVAI. The total Curie content is the sum of the Curies that will be included in the RVAI.

The RV Insulation, Wall, and Cladding components include contributions from the RV Head even though it is likely that the RV Head will not be in the RVTS. It should also be pointed out that there is no RV Cladding entry in Reference 2.1 , Table 4-1 (Attachment B). That information must be taken from Reference 2.9, Attachment A. The Cladding activity is 2.45 E+2 Curies.

The following information is from Table 3-2.

| Component | Activity |
|---|---|
| Thermal Shield | 7.40 E+3 Curies |
| Steam Baffle | 1.08 E+1 Curies |
| Sparger | 8.60 E -1 Curies |
| Top Guide Plate | 1.14 E+3 Curies |
| Seal Housing | 1.30 E+2 Curies |
| TS Retainer | 1.14 E+2 Curies |
| Seal Weights | 1.10 E+3 Curies |
| Core Support Plate | 1.40 E -1 Curies |
| Inlet Diffuser | 2.24 E -2 Curies |
| Inlet Baffle | 1.63 E -1 Curies |
| RV Insulation | 5.81 E+1 Curies |
| RV Cladding | 2.45 E+2 Curies |
| Total | **1.02 E+4 Curies** |

6.2 Invoking the Accuracy item from Reference 2.5, the potential 15% under-response would be applied to the total Curies. This percentage is applicable only within the calibrated range of the radiation monitor. Therefore,

1.02E+4 Curies x 1.15 = **1.173 E+4 Curies** .

It should be noted that this consideration is separate from and in addition to the 1.25 factor cited in Reference 2.1, which is intended to specifically correct for a Cs-137 calibrated instrument actually performing measurements in predominantly Co-60 fields.

6.3 Calculate the total Curies for the RVAI unit, including all RV components, the GBEP, but not including the activities from the RV Wall.

The activity for the GBEP has been determined independently to be 1800 Curies (see Section 3.7). Thus, the total is...

1.173 E+4 + 1.8 E+3 Curies = **1.353 E+4 Curies** .

6.4 Calculate the radionuclide profile comprising the RVAI's Curie content.

The fractional radionuclide abundances for the Trojan RV package shall be applied to the total Curie content for the Big Rock RVAI. The radionuclide abundances expressed as fractions are taken from Table 3-3.

| Nuclide | | Fraction | | Activity |
|---|---|---|---|---|
| H-3 | 1.35 E+4 Curies x | (3.26 E-4) | = | 4.41 E+0 Curies; |
| C-14 | 1.35 E+4 Curies x | (1.08 E-4) | = | 1.46 E+0 Curies; |
| Sb-125 | 1.35 E+4 Curies x | (2.01 E-7) | = | 2.72 E -3 Curies; |
| Mn-54 | 1.35 E+4 Curies x | (1.07 E-3) | = | 1.45 E+1 Curies; |
| Eu-152 | 1.35 E+4 Curies x | (1.26 E-5) | = | 1.70 E -1 Curies; |
| Fe-55 | 1.35 E+4 Curies x | (3.47 E-1) | = | 4.70 E+3 Curies; |
| Co-60 | 1.35 E+4 Curies x | (5.72 E-1) | = | 7.72 E+3 Curies; |
| Ni-59 | 1.35 E+4 Curies x | (4.74 E-4) | = | 6.41 E+0 Curies; |
| Ni-63 | 1.35 E+4 Curies x | (7.81 E-2) | = | 1.06 E+3 Curies; |
| Nb-94 | 1.35 E+4 Curies x | (1.64 E-6) | = | 2.22 E -2 Curies; |
| Tc-99 | 1.35 E+4 Curies x | (3.51 E-7) | = | 4.75 E -3 Curies. |
| | | 1.0 | | |

6.5 Calculate the radionuclide profile comprising the RV Wall's Curie content.

The radionuclide activities for the RV Wall are obtained by multiplying the activities from Table 3-4 by the instrument underresponse factor, similar to Step 6.2, as follows:

| Nuclide | | Factor | | Activity |
|---|---|---|---|---|
| H-3 | 3.62 E -1 Curies x | 1.15 | = | 4.16 E -1 Curies; |
| C-14 | 1.21 E -1 Curies x | 1.15 | = | 1.39 E -1 Curies; |
| Sb-125 | 2.23 E -4 Curies x | 1.15 | = | 2.56 E -4 Curies; |

| | | | |
|---|---|---|---|
| Mn-54 | 1.19 E+0 Curies | x 1.15 | = 1.37 E+0 Curies; |
| Eu-152 | 1.40 E -2 Curies | x 1.15 | = 1.61 E -2 Curies; |
| Fe-55 | 7.90 E+2 Curies | x 1.15 | = 9.09 E+2 Curies; |
| Co-60 | 2.31 E+2 Curies | x 1.15 | = 2.66 E+2 Curies; |
| Ni-59 | 5.27 E -1 Curies | x 1.15 | = 6.06 E -1 Curies; |
| Ni-63 | 8.68 E+1 Curies | x 1.15 | = 9.98 E+1 Curies; |
| Nb-94 | 1.82 E -3 Curies | x 1.15 | = 2.09 E -3 Curies; |
| Tc-99 | 3.90 E -4 Curies | x 1.15 | = 4.48 E -4 Curies. |
| Total | | | **1.27 E+3 Curies** . |

6.6 Convert the various radionuclide's Curies to energy deposition rate.

The energy deposition rate is determined by converting Curies to disintegration rate, then using the total energy per disintegration values found in Reference 2.6 . The activity column first sums the radionuclide activities from Steps 6.4 and 6.5 .

| Nuclide | Activity | Total Energy / dis. | Total Energy |
|---|---|---|---|
| H-3 | 4.83 E+0 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.01859 MeV/dis.) | = 3.32 E +9 MeV/sec; |
| C-14 | 1.60 E+0 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.1565 MeV/dis.) | = 9.27 E +9 MeV/sec; |
| Sb-125 | 2.98 E-3 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.767 MeV/dis.) | = 8.45 E +7 MeV/sec; |
| Mn-54 | 1.59 E+1 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (1.377 MeV/dis.) | = 8.09 E+11 MeV/sec; |
| Eu-152 | 1.87 E-1 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (1.86 MeV/dis.) | = 1.28 E+10 MeV/sec; |
| Fe-55 | 5.61 E+3 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.2316 MeV/dis.) | = 4.81 E+13 MeV/sec; |
| Co-60 | 8.00 E+3 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (2.824 MeV/dis.) | = 8.36 E+14 MeV/sec; |
| Ni-59 | [7.02 E+0 Ci x(3.7 E+10 dis.sec$^{-1}$/Ci)] | x ( no entry ) | = not applicable ; |
| Ni-63 | 1.16 E+3 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.067 MeV/dis.) | = 2.87 E+12 MeV/sec; |
| Nb-94 | 2.43 E-2 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (2.045 MeV/dis.) | = 1.84 E +9 MeV/sec; |
| Tc-99 | 4.88 E-3 Ci x (3.7 E+10 dis.sec$^{-1}$/Ci) | x (0.294 MeV/dis.) | = 5.30 E +7 MeV/sec. |

-----------------------------------------------------------------------------------------------------------

Total **8.88 E+14 MeV/sec.**

6.7 Convert the total energy deposition rate to heat rate:

8.88 E+14 MeV/sec x (3.6 E+3 sec/hour) x (1.0 E+6 eV /MeV )
x (1.602 E-19 J /eV) x (1.0 BTU / 1.056 E+3 J) =

**4.85 E+2 BTU/hour** .

6.7 Provide confirmatory results utilizing ISOSHLD-PC (Reference 2.3).

The radionuclide profile from Step 6.4 may be employed in ISOSHLD-PC to confirm the approximate value of the total heat rate. However, this code does not allow the input of values for Ni-59 and Ni-63. Instead, the nickel isotopic Curies are "rolled into" the C-14 value with appropriate alterations for the differences in total disintergration energies. With those changes, the total heat rate was estimated to be **3.98 E+2 BTU/hour** . The difference with the value in Step 6.6 is not significant given the differences in the nuclide disintegration energy libraries. The preferred library is that from Table 3-3; thus, the conservative value from Step 6.6 will be carried forward.

6.8 Determine the average heat rate in the GBEP and necessary distributions.

The data from Step 6.3 (above) can be used to determine the average heat rate contribution of the eighteen GBEP. The following fraction's denominator is the RVAI's total Curies comprised of the sum from Step 6.3 and that from Step 6.5 ...

4.85 E+2 BTU/hour x (1.80 E+3 Ci/ 1.48 E+4 Ci) =

**5.9 E+1 BTU/hour.**

Table 2-2 and Figure 2-1 of Reference 2.10 imply a gross distrubution of the GBEP activity in a narrow axial band above the annular components and completely within a 180$^{\circ}$ azimuthal distribution. The heat rate thus is concentrated completely on one half of the outer circular cross section of the RVAI.

This distribution is not uniform however. It can be conservatively assumed, per Section 4.5, that the maximum point-source heat rate is half of the total heat rate. That peak point heat rate would thus be 2.95 E+1 BTU/hour.

6.9 The maximum dose rate is expected to occur directly opposite the location of the Top Guide Plate at the side (axially) of the RVAI. It is assumed that a thickness of 16.75 inches, i.e. 42.5 cm, spans the RV Insulation's outermost surface to the RVTS surface, along the entire axial side of the RVTS.

The following approach applies a proportionality based on the information-only Evaluation cited in Reference 2.4, where the RVAI's unshielded cumulative three meter dose rate is 4.53 rem/hour. Thus, from the Evaluation:

| Component | Dose Rate with Build-up (R/hour) | Comment |
|---|---|---|
| RV Liner | 0.0731 | |
| RV Wall | 1.465 | Activity homogeneously distributed; |
| RV Insulation | 1.809 | |
| Top Guide Plate | 0.345 | Estimate; includes GBEP; |
| Thermal Shield | 0.585 | |
| Seal Weights | 0.257 | Three seal weights estimated. |
| Total | 4.53 | |

6.10 Provide a general determination of the maximum dose rate on the surface of the proposed RVTS package. This amounts to hypothetically moving a dose rate detector from 300 cm (Step 6.9) to 42.5 cm from the side surface of the RVAI. A 1/r relationship will be assumed, with the radius, r, measured from the cylindrical source's center, as follows:

| | | |
|---|---|---|
| Distance, RVAI center to RVAI exterior | (61.25") | 155.58 cm; |
| Distance, RVAI center to RVAI exterior + 300 cm | | 455.58 cm; |
| Distance, RVAI center to RVAI exterior + 42.5 cm | | 198.08 cm . |

The dose rates at the RVTS package's side surface, i.e. 42.5 cm from the RVAI's side, are thus:

4.53 R/hour x ( 455.58 cm / 198.08 cm) = 1.04 E+1 R/hour .

6.11 General shielding considerations suggest a working thickness of 3 inches of the RVTS side thickness be constructed of steel to reduce the RVTS surface dose rate maximum. The transmission factors are taken from Reference 2.7, pgs. 149 (Attachment F) with the conservative assumption that all of the radiation is from Co-60.

1.04 E+1 R/hour x 0.14 = 1.46 R/hour;

...and with the remainder 13.73 inches filled with 50 lbs/ft$^3$ grout,

1.04 E+1 R/hour x ( 0.14) x ( 0.118) = **1.72 E -1 R/hour** .

At two meters from the surface of this proposed RVTS package,

1.72 E -1 R/hour x ( 198.08 cm / 355.58 cm ) = **9.60 E -2 R/hour** .

## 7.0 Summary and Conclusions

This calculation provides a total heat rate value of about 500 BTU/hour. The contribution from the GBEP is about 12% of this total, or about 60 BTU/hour. It is estimated that the GBEPs' heat rate, about 30 BTU/hour, peaks on one side of the RVAI's exterior and at a point axially just above what would be the position of the Top Guide Plate. Additional thermodynamic properties may now be determined via appropriate modeling such that internal and surface temperatures, internal pressure, and insolence effects, among others, are estimated.

A calculation subsequent to this one will employ detailed computer modeling and sensitivity analyses to realistically determine shielding design details for the RVTS package. The general shielding aspects given in this calculation are instructive in their implications. With a suggested thickness of 3 inches of steel, symmetric both axially and radially, the proposed RVTS package is a massive structure probably sufficient to meet the package's contact regulatory limit but not sufficient for the package's 2-meter dose rates.

## 8.0 Attachments

A. Exhibit 2, "BRP Thermal Shield Characterization Survey Form – 2: Azimuthal Distribution", Report WMG-9902, Revision 1, June 1999, Appendix A, 1 page;

B. Table 4-1, "Estimated Component Activity and NRC Classification Status", Report WMG-9902, Revision 1, June 1999; and "Comparison of Activities and Part 61 Classification at Big Rock Point as of September 1, 2002", Attachment A, Corrected Total Activity (Ci), Revised Characterization and Classification Results; WMG Report 8057, March 10, 2000; 2 pages;

C. Figures 2-2 and 2-3, Radial and Axial Thermal Flux Distributions, Report WMG-9902, Revision 1, June 1999, 2 pages;

D. Table 1-2, "Reactor Vessel Package Radioactivity and $A_2$ Fractions", Trojan Nuclear Plant Safety Analysis Report, PGE-1076, Revision 1, July 1999, 1 page;

E. "PR-2 and PR-7 Series Specifications", DOSITEC, Inc., Sheet #8201-0293, 1 page;

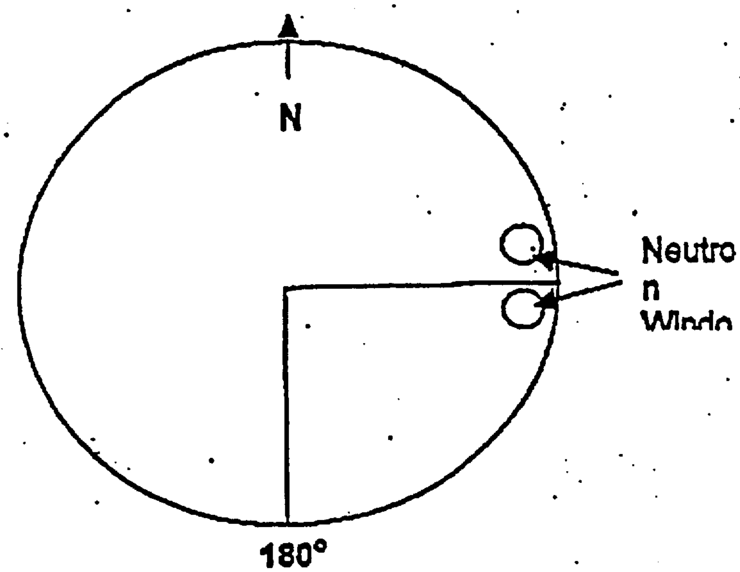
F. Gamma-ray Transmission Fractions for Concrete (147 lb/ft$^3$ density) and Iron; "Radiological Health Handbook", Revised Edition, January 1970, U.S. Department of Health, Education and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological Health; 1 page;

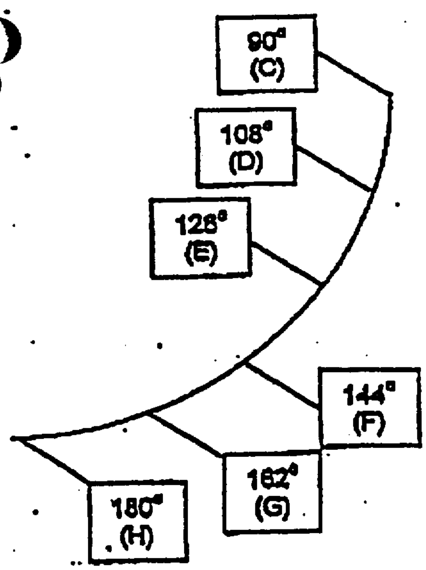
G. Output: "Big Rock RPV+Internals Source", Program ISOSHLD-PC, 14 pages.

## Exhibit 2

### BRP Thermal Shield Characterization Survey Form – 2: Azimuthal Distribution

(Six measurements 18° apart with approximately 31 linear inches between survey locations)




| | 604' (R/hr) 2 | 606' (R/hr) 2 | 608' (R/hr) |
|---|---|---|---|
| C | NOT TAKEN 3 | NOT TAKEN 3 | NOT TAKEN 3 |
| 1 D | 12,500 | 15,000 | |
| 1 E | 3125 | 3125 | |
| 1 F | 1500 | 1625 | |
| 1 G | 1500 | 2125 | |
| 1 H | 1500 | 1375 | |

Instrument Used: PR-2 S/N: 469

Calibration Due: 11-3-99 Standoff Inches 6" (12" Dia)

Performed By: M. Stevens D. Shedlock Date: 12-16-98

Reviewed By:________ Date:________

NOTES:
1 All readings taken at 6" distance using 12" dia. standoff.
2 All readings have been corrected to Co-60 using a corr factor of 1.25 as per Palisades Procedure HP 9.72
3 Readings not taken due to not being physically able to reach this

## TABLE 4-1
## Estimated Component Activity and NRC Classification Status

| | Drawing Numbers | Wetted Surface Area (ft²) | Volume (ft³) | Weight (lbs) | Total Curies | Co-60 Curies | Part 61 Table 1 Fraction | Part 61 Table 2 Fraction |
|---|---|---|---|---|---|---|---|---|
| **GTCC Material** | | | | | | | | |
| Top Guide | 197E861 | 2.05E+01 | 3.05E+00 | 1.53E+03 | 4.84E+04 | 2.12E+04 | 8.56 | 11.87 |
| | **Subtotal** | **2.05E+01** | **3.05E+00** | **1.53E+03** | **4.84E+04** | **2.12E+04** | | |
| **LLRW Internals** | | | | | | | | |
| Steam Baffle | 794E830 | 1.82E+02 | 3.27E+00 | 1.64E+03 | 1.09E+01 | 4.95E+00 | 0.02 | < 0.01 |
| Sparger | M248 Sh 46-1, 41-2 | 2.05E+01 | 2.60E-01 | 1.30E+02 | 8.78E-01 | 3.97E-01 | 0.03 | < 0.01 |
| Top Guide Plate | 197E118 | 3.90E+1 | 1.63E+00 | 8.13E+02 | 1.17E+03 | 5.38E+02 | 0.41 | 0.54 |
| Seal Housing | 706E276 | 3.00E+1 | 2.15E+00 | 1.07E+03 | 1.45E+02 | 6.60E+01 | 0.04 | 0.05 |
| Thermal Shield | 197E853 | 4.14E+02 | 2.59E+01 | 1.30E+04 | 7.45E+03 | 3.83E+03 | 0.18 | 0.20 |
| Thermal Shield Retainer (6 units) | 237E956 | 1.39E+01 | 1.09E+00 | 5.47E+02 | 1.18E+02 | 5.94E+01 | 0.07 | 0.08 |
| Seal Weights (12 units) | 706E276, 104R175 | 2.59E+02 | 1.02E+01 | 5.08E+03 | 8.54E+02 | 5.89E+02 | 0.08 | 0.04 |
| Neutron Windows (4 units) | 107C353-9 | 4.48E+01 | 2.46E+00 | 1.23E+03 | 1.37E+04 | 6.92E+03 | 2.09 | 2.67 |
| Core SOupport Plate | 762-D229, E201-809-3 | 1.53E+02 | 5.08E+00 | 2.54E+03 | 1.4E-01 | 1.36E-01 | 0.01 | < 0.01 |
| Inlet Diffuser '2 units) | 795E369 | 2.44E+01 | 3.97E-01 | 1.98E+02 | 2.24E-02 | 2.18E-02 | 0.02 | < 0.01 |
| ,nlet Baffle | 795E421 | 1.78E+02 | 4.64E+00 | 2.32E+03 | 1.63E-01 | 1.59E-01 | 0.01 | < 0.01 |
| | **Subtotal** | **1.36E+03** | **5.71E+01** | **2.85E+04** | **2.35E+04** | **1.20E+04** | | |
| **Reactor Vessel Assembly** | | | | | | | | |
| Reactor Vessel | 197E853, 104R175, F 230-791-2 | 7.69E+02 | 4.14E+02 | 2.03E+05 | 7.98E+02 | 2.82E+02 | < 0.01 | < 0.01 |
| Reactor Vessel Insulation | 795E369 | NA | 2.59E+02 | 5.18E+03 | 5.21E+01 | 3.05E+01 | < 0.01 | < 0.01 |
| | **Subtotal** | **7.69E+02** | **6.73E+02** | **2.08E+05** | **8.49E+02** | **3.13E+02** | | |
| **Reactor and Internals** | **TOTAL** | **2.15E+03** | **7.33E+02** | **2.38E+05** | **7.27E+04** | **3.35E+04** | | |

## Comparison of Activities and Part 61 Classification at Big Rock Point as of September 1, 2002
### (Note Results Include Surface Contaminants)

| Component Name | Original Total Activity (Ci) | Corrected Total Activity (Ci) | Percent Error | Original Co-60 Activity (Ci) | Corrected Co-60 Activity (Ci) | Percent Error | Original Part 61 Table 1 Fraction | Corrected Part 61 Table 1 Fraction | Percent Error | Original Part 61 Table 2 Fraction | Corrected Part 61 Table 2 Fraction | Percent Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Greater Than Class C Waste** | | | | | | | | | | | | |
| Top Guide | 4.84E+04 | 5.35E+04 | 9.63% | 2.12E+04 | 2.42E+04 | 12.65% | 8.55 | 9.78 | 12.59% | 11.85 | 12.79 | 7.33% |
| GTCC Subtotals | 4.84E+04 | 5.35E+04 | 9.63% | 2.12E+04 | 2.42E+04 | 12.65% | | | | | | |
| **Low Level Radioactive Waste (LLRW)** | | | | | | | | | | | | |
| Steam Baffle | 1.09E+01 | 1.08E+01 | -0.94% | 4.95E+00 | 4.92E+00 | -0.62% | 0.02 | 0.02 | -0.05% | < 0.01 | < 0.01 | NA |
| Sparger | 8.78E-01 | 8.60E-01 | -2.16% | 3.97E-01 | 3.96E-01 | -0.25% | 0.03 | 0.03 | -0.02% | < 0.01 | < 0.01 | NA |
| Top Guide Plate | 1.17E+03 | 1.14E+03 | -2.95% | 5.39E+02 | 5.40E+02 | 0.40% | 0.41 | 0.41 | 0.32% | 0.54 | 0.51 | -6.94% |
| Seal Housing | 1.45E+02 | 1.30E+02 | -11.53% | 6.60E+01 | 6.08E+01 | -8.59% | 0.04 | 0.04 | -7.71% | 0.05 | 0.05 | -14.22% |
| Thermal Shield | 7.45E+03 | 7.40E+03 | -0.66% | 3.83E+03 | 3.94E+03 | 2.66% | 0.18 | 0.19 | 2.42% | 0.20 | 0.19 | -4.61% |
| Thermal Shield Retainer (8 Units) | 1.18E+02 | 1.14E+02 | -3.59% | 5.94E+01 | 5.94E+01 | -0.09% | 0.07 | 0.07 | -0.26% | 0.08 | 0.07 | -7.54% |
| Seal Weights (12 Units) | 8.54E+02 | 1.10E+03 | 22.46% | 5.89E+02 | 7.32E+02 | 19.49% | 0.08 | 0.09 | 17.85% | 0.04 | 0.05 | 28.74% |
| Neutron Windows (4 Units) | 1.37E+04 | 1.34E+04 | -2.24% | 6.92E+03 | 6.99E+03 | 1.11% | 2.09 | 2.11 | 0.93% | 2.67 | 2.52 | -6.06% |
| Core Support Plate | 1.40E-01 | 1.40E-01 | 0.00% | 1.36E-01 | 1.36E-01 | 0.00% | 0.01 | 0.01 | 0.00% | < 0.01 | < 0.01 | NA |
| Inlet Diffuser (2 Units) | 2.24E-02 | 2.24E-02 | 0.00% | 2.18E-02 | 2.18E-02 | 0.00% | 0.02 | 0.02 | 0.00% | < 0.01 | < 0.01 | NA |
| Inlet Baffle | 1.63E-01 | 1.63E-01 | 0.00% | 1.59E-01 | 1.59E-01 | 0.00% | 0.01 | 0.01 | 0.00% | < 0.01 | < 0.01 | NA |
| LLRW Subtotals | 2.35E+04 | 2.33E+04 | -0.66% | 1.20E+04 | 1.23E+04 | 2.61% | | | | | | |
| **Reactor Vessel Assembly** | | | | | | | | | | | | |
| Vessel Cladding | 2.09E+02 | 2.45E+02 | 14.90% | 1.30E+02 | 1.53E+02 | 14.76% | 0.04 | 0.04 | 6.13% | 0.01 | 0.01 | 15.15% |
| Reactor Vessel Wall | 5.90E+02 | 1.11E+03 | 46.66% | 1.52E+02 | 2.01E+02 | 24.42% | < 0.01 | < 0.01 | NA | < 0.01 | < 0.01 | NA |
| Vessel Insulation | 5.21E+01 | 5.81E+01 | 10.26% | 3.05E+01 | 3.45E+01 | 11.56% | < 0.01 | < 0.01 | NA | < 0.01 | < 0.01 | NA |
| Reactor Vessel Subtotals | 8.51E+02 | 1.41E+03 | 39.63% | 3.13E+02 | 3.88E+02 | 19.48% | | | | | | |
| Package Totals | 2.43E+04 | 2.47E+04 | 1.63% | 1.23E+04 | 1.27E+04 | 3.12% | | | | | | |
| Grand Total | 7.27E+04 | 7.83E+04 | 7.10% | 3.35E+04 | 3.69E+04 | 9.37% | | | | | | |

6.1.3 Radiological Hazards
- Contaminated Surfaces
- Activated material in the reactor vessel and surroundings

6.2 Limitations

6.2.1 Access to reactor vessel nozzles can only be accomplished after the following components are removed: refueling tank, aggregate retainer, block walls, some mirror insulation, some reactor vessel supports, some ventilation duct work and asbestos insulation.

6.2.2 No load shall be suspended above the Spent Fuel Pool.

6.2.3 Heavy loads shall follow the designated Safe Load Path specified in reference 3.8.

## 7.0 PREREQUISITES

7.1 The WMC is ready to accept materials from this MWP

7.2 Asbestos insulation has been removed from piping up to walls.

7.3 All systems having components to be removed have been declared "Out of service" and "Available for decommissioning."

7.4 During the pre-job briefing the Handling and Lay down Instructions have been read and understood.

7.5 Hot Work Permits have been issued for this MWP.

7.6 Reactor Vessel grid bars and neutron windows have been removed.

7.7 Reactor Vessel and Refueling Tank have been drained.

7.8 Reference 3.10 is field complete.

7.9 Plant stack HEPA filtering system is in operation.

7.10 All Prerequisites have been completed.

____________________ / __________
Signature / Date

## Table 1-2

### Reactor Vessel Package Radioactivity and $A_2$ Fractions

| Nuclide | Activity [1] | | $A_2$ Limit (Curies) | Fraction $A_2$ Value |
|---|---|---|---|---|
| | Surface Contamination (Curies) | Activation (Curies) | | |
| H-3 | 8.11E-02 | 6.55E+02 | 1080 | 6.07E-01 |
| C-14 | 1.15E-01 | 2.18E+02 | 54.1 | 4.03E+00 |
| Sb-125 | 1.67E+00 | 4.04E-01 | 24.3 | 8.53E-02 |
| Ce-144 | 4.64E-02 | | 5.41 | 8.58E-03 |
| Mn-54 | 8.57E-02 | 2.16E+03 | 27.0 | 8.00E+01 |
| Eu-152 | | 2.54E+01 | 24.3 | 1.05E+00 |
| Fe-55 | 2.77E+01 | 6.97E+05 | 1080 | 6.45E+02 |
| Co-60 | 9.92E+01 | 1.15E+06 | 10.8 | 1.06E+05 |
| Ni-59 | | 9.53E+02 | 1080 | 8.82E-01 |
| Ni-63 | 2.00E+01 | 1.57E+05 | 811 | 1.94E+02 |
| Nb-94 | | 3.29E+00 | 16.2 | 2.03E-01 |
| Sr-90 | 9.24E-01 | | 2.7 | 3.42E-01 |
| Tc-99 | | 7.06E-01 | 24.3 | 2.91E-02 |
| Pu-238 | 8.35E-02 | | 0.00541 | 1.54E+01 |
| Pu-239/240 | 9.33E-02 | | 0.00541 | 1.72E+01 |
| Pu-241 | 5.07E+00 | | 0.27 | 1.88E+01 |
| Pu-242 | 4.70E-04 | | 0.00541 | 8.69E-02 |
| Cm-242 | 1.56E-05 | | 0.27 | 5.78E-05 |
| Cm-243 | 3.60E-02 | | 0.00811 | 4.44E+00 |
| Cm-244 | 3.41E-02 | | 0.0108 | 3.16E+00 |
| Am-241 | 1.10E-01 | | 0.00541 | 2.03E+01 |
| Total[2] | 155.2 | 2.01E+06 | | 1.08E+05 |

Notes: 1. Activity values have been decayed to 11/01/97.
2. Total does not include the contribution from U-234 (7.02E-03 Ci surface contamination and no activation), which is negligible.


*PR-7 Underwater Monitor*

# PR-2 and PR-7 Series Specifications

## DETECTION

| | |
|---|---|
| **Detector Type** | Energy-compensated solid-state CdTe or Si-Detector |
| **Radiation** | X and Gamma Ray |
| **Energy Response** | ±30% from 80 Kev to 3 Mev. |
| **Dose Rate Range** | |
| **Model PR-2L** | 0-0.05, 0-0.5, and 0-5 R/hr |
| **Model PR-2M** | 0-5, 0-50, and 0-500 R/hr |
| **Model PR-2H** | 0-50, 0-500, and 0-5,000 R/hr |
| ~~**Model PR-2XH**~~ | ~~0-500, 0-5,000, and 0-50,000 R/hr~~ |
| **Model PR-7** | 0-0.05, 0-0.5, 0-5, 0-50, 0-500, 0-5,000 and 0-50,000 R/hr |
| **Accuracy** | ±15% for all ranges from 20% to 80% of full scale, calibrated with Cs137 |

## UNDERWATER PROBE

| | |
|---|---|
| **Depth Capability** | Up to 150 ft (45 m) |
| **Housing** | Nickel-plated Aluminum; 0.5" Wall, 0.2" bottom |
| **Detector Location** | 10 mm from bottom center |
| **Connector** | Quick-connect to Cable |
| **Dimensions** | 2.375" dia. x 5" length (60 mm dia. x 127 mm length) |
| **Weight** | 1.5 lbs (0.7 kg) |

## METER UNIT

| | |
|---|---|
| **Display** | Analog Meter |
| **Response Time** | 5 to 20 seconds, 0 to 90% of final reading |
| **Battery.** | one 9 volt Alkaline battery with 100 hours life |
| **Dimension(approx.)** | |
| **PR-2** | 2.50" x 4.50" x 1.75" (65 mm x 114 mm x 45 mm) |
| **PR-7** | 2.62" x 4.75" x 1.50" (66 mm x 121 mm x 38 mm) |
| **Weight** | 1 lb (0.5 kg). |
| **Calibration** | Potentiometer adjustment per range; independent of cable length, up to 500 ft for PR-2, and up to 2000 feet for PR-7 |

## CABLE

50 ft (15 m), 2.5 lbs (1.1 kg) standard; up to 2000 ft (600 m) available

## GENERAL DESCRIPTION

The Dositec Portable Remote Monitor PR-2 and PR-7 Series ( PR-2L, PR-2M, PR-2H, PR-2XH and PR-7 ) are designed for remote underwater survey applicatons in gamma radiation fields up to 5, 500, 5,000, 50,000 and 50,000 R/hr, respectively. They can be used at distances up to 2000 feet; the Underwater Probe can be used to a depth of 150 feet.

Each of the PR-2 and PR-7 Series Monitors Consists of an Underwater Probe, a Meter Unit, and a Cable. The PR-2 and PR-7 Series Monitors employ energy-compensated solid-state detectors, which do not require high voltage. Power is supplied by a 9 volt Alkaline battery included.

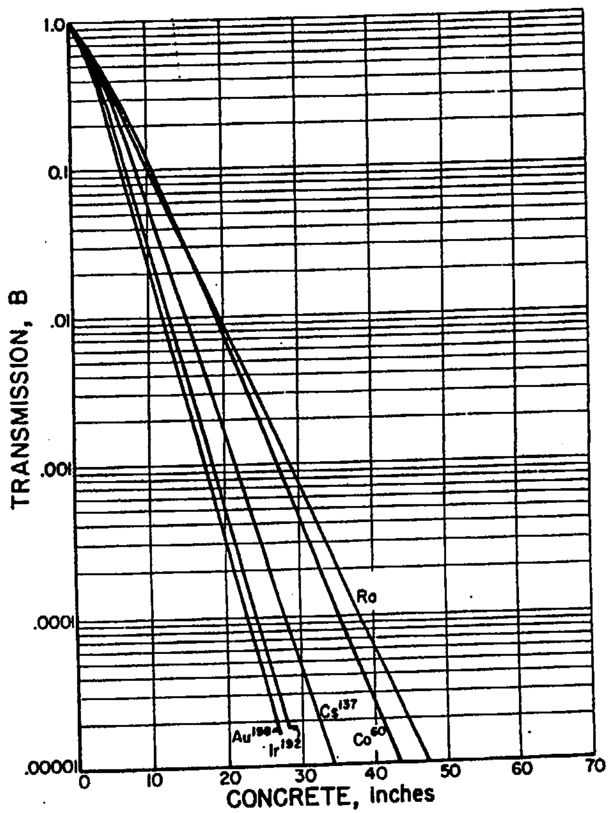
Each of the PR-2 and PR-7 Series Monitors has an Analog Meter, which indicates radiation dose rates in three linear ranges for PR-2 and seven linear ranges for PR-7.

Calibration of the PR-2 and PR-7 Series Monitor is performed by simple adjustment of the potentiometers on the meter unit. Calibration is independent of cable length, up to 500 feet for PR-2 and 2000 feet for PR-7. For longer distances, recalibration is required.

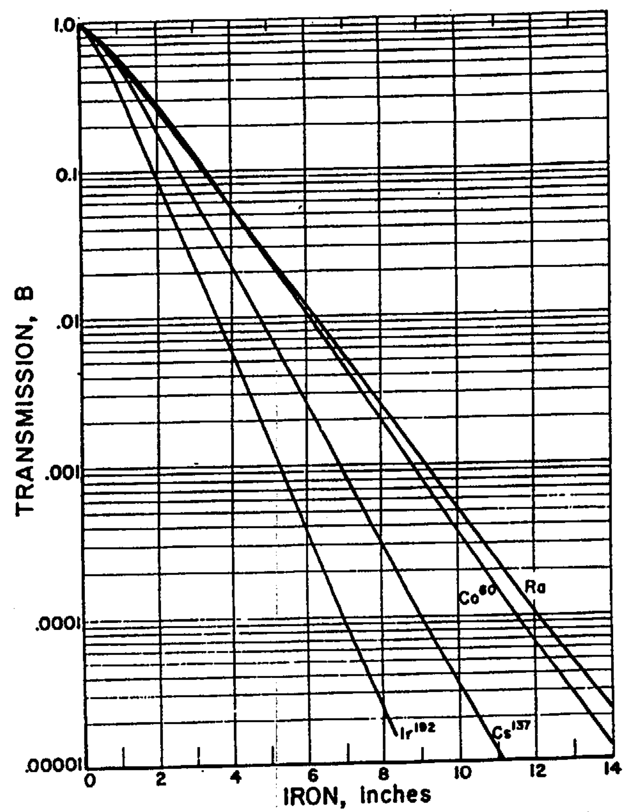
Rec'd.
Ø7FEB

DOSITEC, INC.
4 Avenue E
Hopkinton MA 01748-2211

*All Specifications Subject to Change Without Notice*




Transmission through concrete (density 147 lb/ft$^3$) of gamma rays from radium [14]; cobalt 60, cesium 137, gold 198 [7]; iridium 192 [15].




Transmission through iron of gamma rays from radium [14]; cobalt 60, cesium 137 [7]; iridium 192 [15].

```
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       Page :          1
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       Date : 11/21/2000
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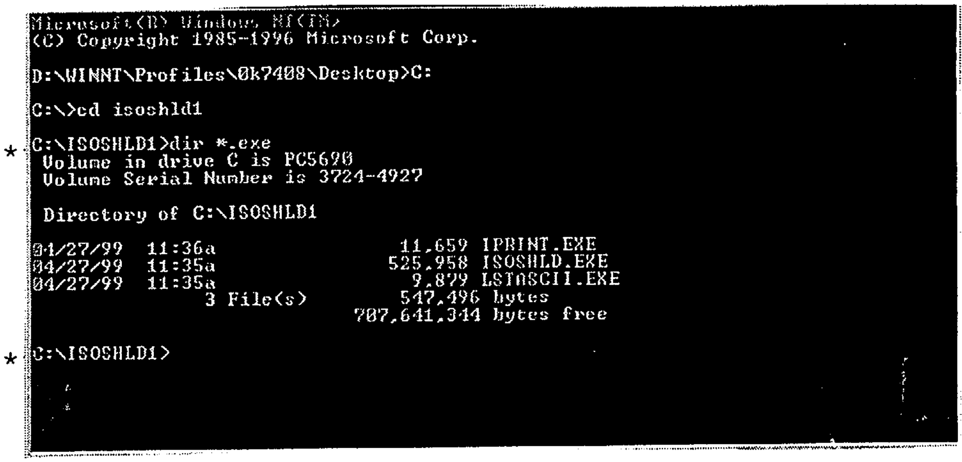


```
*********************************************************
*
* ISOSHLD-PC
* Big Rock RPV+Internals, DIT Run1;
* "Big Rock RPV+Internals Source"
*
*********************************************************
* M1. Source Mode MODE=2
  2
*
* A1. Title
 Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Heat Calcul
*
* B1. Control option NEXT
* NEXT
  1
*
* C1a and C1b, Source strength parameters and
* ISOGROUP Nobles Halogens Allothers NSKIP
  9   452, 496.85 473, 15.85 474, 5608.1   481, 8000.0  141,0.0050
      451, 4.83   111,0.024  269, 0.003    408, 0.187
*
  0     1.0    1.0    1.0    1.0    1.0
*
* D1. Material composition data
* NCMP  MATS
  1     1
*
* Material #    Partial Densities
  26            7.86
*
* E1. Dose Rate Calculation Parameters
* ISPEC NBRS NCON NEPS
```

```
  3     1    2    0
*
* E2.
* LINESP NTERP OPTION KLEEN IHEAT
  1      2     0      1     1
*
* E3a. Geometry data
* IGEOM NSHLD JBUF (comp#, unit, T)
  0    1     20    1,3, 3.0
*
* E3b. Additional geometry data
* (unit,SLTH)
   1,185.0
*
* E3c
  0   7.89
*
* F1. Dose point location
□
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 * (unit, X) (unit, DELR)
   1,92.5     1,7.63
 *
 * END of Isoshld data
 7
□
 Program : ISOSHLD-PC
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        Date : 11/21/2000
 Created : 11:35:42  04/27/1999
        Time : 16:02:31.24
```

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              **********   **********  **********  **********  **      **  **          *******
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              **********   **********  **********  **********  **      **  **          ********
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                   **      **      **  **      **  **      **  **      **  **          **       *
  **  **
                   **      **      **  **      **  **      **  **      **  **          **       **
  **  **
                   **      **          **      **  **          **      **  **          **       **
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                   **      **          **      **  **          **      **  **          **       **
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                   **      **          **      **  **          **      **  **          **       **
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                   **      **          **      **  **          **      **  **          **       **
  **  **
                   **      **********  **      **  **********  **********  **          **       **  *****
  **  **
                   **      **********  **      **  **********  **********  **          **       **  *****
  **  **
                   **              **  **      **          **  **      **  **          **       **
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                   **              **  **      **          **  **      **  **          **       **
  **  **
                   **              **  **      **          **  **      **  **          **       **
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                   **              **  **      **          **  **      **  **          **       **
  **  **
                   **      **      **  **      **  **      **  **      **  **       **  **      **
  **  **
                   **      **      **  **      **  **      **  **      **  **       **  **      *
  **  **
              **********   **********  **********  **********  **      **  ****
**********
```

Sargent & Lundy Engineers
Chicago, Illinois

MODE = 2 (1-2-3-4) = (RIBD Source-Curie Source-Photons/sec Source-Curie Source fro
m File)

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Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Hea
t Calcul

Isotope Selection Data

A Scale Factor of 1.000E+00 has been Applied to All Isotope Activities

Isotope Activities(Curies)

| NB 94 | TC 99 | SB 125 | EU 152 | H 3 | C 14 | MN 54 | FE 55 | CO 60 |
|---|---|---|---|---|---|---|---|---|
| 2.400E-02 | 5.000E-03 | 3.000E-03 | 1.870E-01 | 4.830E+00 | 4.969E+02 | 1.585E+01 | 5.608E+03 | 8.000E+0 |

3

Program : ISOSHLD-PC
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Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Heat Calc

Shield Composition Data

```
     Shield Material                        Material Density(gm/cm**3)
                          1          2          3          4          5          6          7
 8          9          10
       Iron          7.860E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
```

Shield Attenuation Data

```
                                              Linear Attenuation Coefficients(1/cm)
      Energy     Energy
      Group      (MeV)            1          2          3          4          5          6          7
 8          9          10

            1    1.500E-02   4.393E+02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            2    2.000E-02   1.965E+02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            3    3.000E-02   6.180E+01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            4    4.000E-02   2.712E+01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            5    5.000E-02   1.447E+01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            6    6.000E-02   8.827E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            7    8.000E-02   4.305E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            8    1.000E-01   2.679E+00 0.000E+00 0.000E+00 0.000E+00 0.000E[illegible] [illegible]E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
            9    1.500E-01   1.434E+00 0.000E+00 0.000E+00 0.000E+00 0.000E
```

```
00E+00 0.000E+00 0.000E+00
         10      2.000E-01        1.085E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         11      3.000E-01        8.355E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         12      4.000E-01        7.231E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         13      5.000E-01        6.513E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         14      6.000E-01        5.985E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         15      8.000E-01        5.225E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         16      1.000E+00        4.686E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         17      1.500E+00        3.827E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         18      2.000E+00        3.345E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         19      3.000E+00        2.843E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         20      4.000E+00        2.601E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         21      5.000E+00        2.471E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         22      6.000E+00        2.401E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         23      8.000E+00        2.349E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         24      1.000E+01        2.352E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
         25      1.500E+01        2.430E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.0
00E+00 0.000E+00 0.000E+00
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## Shield Buildup Data

### Exposure Buildup Factors for Water

| E (MeV) \ mfp = | .5 | 1.0 | 3.0 | 5.0 | 7.0 | 10.0 | 15.0 | 20.0 | 25.0 | 30.0 | 35.0 | 40.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .015 | 1.11E+00 | 1.18E+00 | 1.34E+00 | 1.43E+00 | 1.49E+00 | 1.57E+00 | 1.68E+00 | 1.76E+00 | 1.82E+00 | 1.87E+00 | 1.90E+00 | 1.94E+00 |
| .020 | 1.25E+00 | 1.43E+00 | 1.88E+00 | 2.16E+00 | 2.38E+00 | 2.66E+00 | 3.07E+00 | 3.43E+00 | 3.73E+00 | 3.97E+00 | 4.16E+00 | 4.38E+00 |
| .030 | 1.73E+00 | 2.34E+00 | 4.29E+00 | 5.91E+00 | 7.40E+00 | 9.58E+00 | 1.33E+01 | 1.74E+01 | 2.14E+01 | 2.56E+01 | 3.03E+01 | 3.65E+01 |
| .040 | 2.20E+00 | 3.48E+00 | 9.15E+00 | 1.56E+01 | 2.29E+01 | 3.51E+01 | 5.93E+01 | 8.84E+01 | 1.23E+02 | 1.63E+02 | 2.08E+02 | 2.59E+02 |
| .050 | 2.54E+00 | 4.46E+00 | 1.52E+01 | 3.07E+01 | 5.13E+01 | 9.21E+01 | 1.87E+02 | 3.20E+02 | 5.05E+02 | 7.61E+02 | 1.09E+03 | 1.46E+03 |
| .060 | 2.68E+00 | 4.98E+00 | 2.00E+01 | 4.57E+01 | 8.40E+01 | 1.69E+02 | 3.92E+02 | 7.42E+02 | 1.28E+03 | 2.12E+03 | 3.31E+03 | 4.69E+03 |
| .080 | 2.61E+00 | 5.06E+00 | 2.39E+01 | 6.21E+01 | 1.27E+02 | 2.88E+02 | 7.78E+02 | 1.64E+03 | 3.11E+03 | 5.65E+03 | 9.57E+03 | 1.44E+04 |
| .100 | 2.41E+00 | 4.66E+00 | 2.33E+01 | 6.41E+01 | 1.37E+02 | 3.31E+02 | 9.58E+02 | 2.13E+03 | 4.24E+03 | 8.02E+03 | 1.39E+04 | 2.08E+04 |
| .150 | 2.12E+00 | 3.90E+00 | 1.89E+01 | 5.25E+01 | 1.14E+02 | 2.83E+02 | 8.55E+02 | 1.95E+03 | 3.88E+03 | 7.30E+03 | 1.28E+04 | 2.00E+04 |
| .200 | 1.97E+00 | 3.48E+00 | 1.57E+01 | 4.19E+01 | 8.85E+01 | 2.12E+02 | 6.11E+02 | 1.34E+03 | 2.61E+03 | 4.79E+03 | 8.35E+03 | 1.32E+04 |
| .300 | 1.77E+00 | 2.92E+00 | 1.16E+01 | 2.89E+01 | 5.78E+01 | 1.28E+02 | 3.34E+02 | 6.72E+02 | 1.19E+03 | 1.99E+03 | 3.11E+03 | 4.38E+03 |
| .400 | 1.68E+00 | 2.66E+00 | 9.55E+00 | 2.22E+01 | 4.18E+01 | 8.66E+01 | 2.06E[illegible] | [illegible] | [illegible] | [illegible]97E+02 | 1.47E+03 | 1.97E+03 |
| .500 | 1.63E+00 | 2.50E+00 | 8.26E+00 | 1.81E+01 | 3.26E+01 | 6.40E+01 | 1.42E[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

```
94E+02  8.44E+02  1.10E+03
    .600    1.59E+00  2.38E+00  7.35E+00  1.54E+01  2.68E+01  5.02E+01  1.05E+02  1.78E+02  2.72E+02  3.
95E+02  5.43E+02  6.90E+02
    .800    1.53E+00  2.21E+00  6.18E+00  1.21E+01  1.98E+01  3.48E+01  6.72E+01  1.07E+02  1.55E+02  2.
15E+02  2.85E+02  3.52E+02
   1.000    1.49E+00  2.10E+00  5.43E+00  1.00E+01  1.58E+01  2.64E+01  4.81E+01  7.35E+01  1.03E+02  1.
39E+02  1.79E+02  2.17E+02
   1.500    1.44E+00  1.94E+00  4.39E+00  7.41E+00  1.09E+01  1.68E+01  2.80E+01  4.02E+01  5.37E+01  6.
87E+01  8.49E+01  1.01E+02
   2.000    1.40E+00  1.84E+00  3.84E+00  6.14E+00  8.67E+00  1.28E+01  2.01E+01  2.80E+01  3.63E+01  4.
52E+01  5.45E+01  6.34E+01
   3.000    1.35E+00  1.71E+00  3.22E+00  4.80E+00  6.44E+00  8.96E+00  1.33E+01  1.78E+01  2.24E+01  2.
72E+01  3.19E+01  3.64E+01
   4.000    1.31E+00  1.62E+00  2.85E+00  4.08E+00  5.30E+00  7.15E+00  1.03E+01  1.34E+01  1.65E+01  1.
96E+01  2.27E+01  2.59E+01
   5.000    1.28E+00  1.55E+00  2.59E+00  3.59E+00  4.57E+00  6.02E+00  8.46E+00  1.09E+01  1.33E+01  1.
56E+01  1.79E+01  2.03E+01
   6.000    1.26E+00  1.51E+00  2.42E+00  3.27E+00  4.10E+00  5.33E+00  7.38E+00  9.46E+00  1.15E+01  1.
34E+01  1.50E+01  1.65E+01
   8.000    1.22E+00  1.42E+00  2.16E+00  2.83E+00  3.47E+00  4.41E+00  5.95E+00  7.49E+00  8.98E+00  1.
04E+01  1.18E+01  1.34E+01
  10.000    1.19E+00  1.36E+00  1.98E+00  2.54E+00  3.07E+00  3.84E+00  5.12E+00  6.40E+00  7.63E+00  8.
78E+00  9.94E+00  1.13E+01
  15.000    1.14E+00  1.27E+00  1.71E+00  2.11E+00  2.49E+00  3.03E+00  3.94E+00  4.85E+00  5.74E+00  6.
53E+00  7.23E+00  7.95E+00
□
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  Gamma Immersion Calculation   Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Heat
Calcul

 Cylindrical Source   Cylindrical Shields   Distance to Detector 7.620E+00 (cm) Detector Elevation = 9.25
0E+01 (cm)

                                            Length =             1.850E+02 (cm)

5E+04 (cc)
```

Buildup Data for Water with Effective Atomic Number of 8.00 Used.

Shield Number 1
Thickness (cm) 7.620E+00
Composition 1

| Energy # | Energy (MeV) | Influx (MeV/cm2) | Carbon Factor (mrad/hr)/ (MeV/cm2-sec) | Dose/Photon (mrad/hr)/ (photon/sec) | Number of Integration Points | Convergence Criterion EPSIL |
|---|---|---|---|---|---|---|
| 1 | 1.500E-02 | 0.000E+00 | 3.099E-02 | 0.000E+00 | 27 | 5.000E-02 |
| 2 | 2.000E-02 | 4.041E-10 | 1.198E-02 | 4.841E-12 | 9983 | 5.000E-02 |
| 3 | 3.000E-02 | 1.617E-08 | 3.433E-03 | 5.552E-11 | 903 | 5.000E-02 |
| 4 | 4.000E-02 | 7.909E-08 | 1.768E-03 | 1.398E-10 | 1107 | 5.000E-02 |
| 5 | 5.000E-02 | 2.606E-07 | 1.348E-03 | 3.513E-10 | 667 | 5.000E-02 |
| 6 | 6.000E-02 | 6.256E-07 | 1.221E-03 | 7.638E-10 | 715 | 5.000E-02 |
| 7 | 8.000E-02 | 1.919E-06 | 1.181E-03 | 2.267E-09 | 675 | 5.000E-02 |
| 8 | 1.000E-01 | 3.728E-06 | 1.244E-03 | 4.638E-09 | 307 | 5.000E-02 |
| 9 | 1.500E-01 | 8.160E-06 | 1.417E-03 | 1.156E-08 | 3351 | 5.000E-03 |
| 10 | 2.000E-01 | 1.213E-05 | 1.532E-03 | 1.859E-08 | 2811 | 5.000E-03 |
| 11 | 3.000E-01 | 1.833E-05 | 1.659E-03 | 3.042E-08 | 2611 | 5.000E-03 |
| 12 | 4.000E-01 | 2.428E-05 | 1.705E-03 | 4.140E-08 | 2035 | 5.000E-03 |
| 13 | 5.000E-01 | 3.030E-05 | 1.716E-03 | 5.199E-08 | 999 | 5.000E-03 |
| 14 | 6.000E-01 | 3.641E-05 | 1.711E-03 | 6.230[illegible] | [illegible] | [illegible]-03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 15 | 8.000E-01 | 4.937E-05 | 1.670E-03 | 8.244E-08 | [illegible] | 5.000E-03 |
| 16 | 1.000E+00 | 6.310E-05 | 1.613E-03 | 1.018E-07 | 667 | 5.000E-03 |
| 17 | 1.500E+00 | 1.008E-04 | 1.480E-03 | 1.491E-07 | 619 | 5.000E-03 |
| 18 | 2.000E+00 | 1.407E-04 | 1.371E-03 | 1.929E-07 | 619 | 5.000E-03 |
| 19 | 3.000E+00 | 2.214E-04 | 1.210E-03 | 2.679E-07 | 767 | 5.000E-03 |
| 20 | 4.000E+00 | 2.995E-04 | 1.100E-03 | 3.294E-07 | 827 | 5.000E-03 |
| 21 | 5.000E+00 | 3.737E-04 | 1.025E-03 | 3.830E-07 | 923 | 5.000E-03 |
| 22 | 6.000E+00 | 4.453E-04 | 9.734E-04 | 4.334E-07 | 939 | 5.000E-03 |
| 23 | 8.000E+00 | 5.736E-04 | 8.986E-04 | 5.154E-07 | 939 | 5.000E-03 |
| 24 | 1.000E+01 | 6.902E-04 | 8.467E-04 | 5.844E-07 | 1043 | 5.000E-03 |
| 25 | 1.500E+01 | 9.501E-04 | 7.601E-04 | 7.222E-07 | 1087 | 5.000E-03 |

Aitken iterated interpolation is done using 2 points.

Dose rates from decay gammas are calculated using discrete spectral energies.

□

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Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Hea
t Calcul

Source Spectrum and Dose Rates at Specifie

| al Rate /hr) | Photon Group # | Average Energy (MeV) | Decay Gammas (photons/sec) | Output Bremsstrahlung Gammas (photons/sec) | Total Gammas (photons/sec) | Dose/Phot (mrad/hr)/ (photons/sec) | Tot Dose (mrad |
|---|---|---|---|---|---|---|---|
| E+00 | 1 | 1.500E-02 | 5.871E+13 | 3.729E+12 | 6.244E+13 | 0.000E+00 | 0.000 |
| E+01 | 2 | 2.500E-02 | 4.068E+07 | 5.682E+11 | 5.682E+11 | 1.854E-11 | 1.053 |
| E+01 | 3 | 3.500E-02 | 1.455E+09 | 3.481E+11 | 3.495E+11 | 9.107E-11 | 3.189 |
| E+01 | 4 | 4.500E-02 | 3.677E+09 | 2.049E+11 | 2.086E+11 | 2.274E-10 | 4.721 |
| E+01 | 5 | 5.500E-02 | 0.000E+00 | 1.290E+11 | 1.290E+11 | 5.272E-10 | 6.800 |
| E+01 | 6 | 6.500E-02 | 0.000E+00 | 9.160E+10 | 9.160E+10 | 1.034E-09 | 9.469 |
| E+02 | 7 | 7.500E-02 | 0.000E+00 | 6.277E+10 | 6.277E+10 | 1.776E-09 | 1.115 |
| E+02 | 8 | 8.500E-02 | 1.073E+03 | 4.470E+10 | 4.470E+10 | 2.753E-09 | 1.231 |
| E+02 | 9 | 9.500E-02 | 0.000E+00 | 1.060E+11 | 1.060E+11 | 3.934E-09 | 4.170 |
| E+02 | 10 | 1.500E-01 | 1.975E+09 | 4.320E+10 | 4.518E+10 | 1.156E-08 | 5.139 |
| E+01 | 11 | 2.500E-01 | 5.488E+08 | 8.985E+08 | 1.447E+09 | 2.437E-08 | 3.511 |
| E+01 | 12 | 3.500E-01 | 1.903E+09 | 1.332E+06 | 1.904E+09 | 3.588E-08 | 6.727 |
| E+01 | 13 | 4.750E-01 | 4.592E+08 | 6.641E+05 | 4.598E+08 | 4.934E-08 | 2.079 |
| E+03 | 14 | 6.500E-01 | 4.952E+10 | 2.364E+05 | 4.952E+10 | 6.735E-08 | 3.553 |
| E+04 | 15 | 8.250E-01 | 5.884E+11 | 7.119E+04 | 5.884E+11 | 8.487E-08 | 5.050 |
| E+02 | 16 | 1.000E+00 | 1.921E+09 | 1.988E+04 | 1.921E+09 | 1.018E-07 | 1.985 |
| E+07 | 17 | 1.225E+00 | 5.920E+14 | 1.892E+03 | 5.920E+14 | 1.232E-07 | 7.449 |
| | 18 | 1.475E+00 | 1.487E+09 | 0.000E+00 | 1.487E | [illegible] | [illegible] |

```
E+02
                    19   1.700E+00   0.000E+00     0.000E+00     0.000E+00     1.668E-0    0.000
E+00
                    20   1.900E+00   0.000E+00     0.000E+00     0.000E+00     1.842E-07   0.000
E+00
                    21   2.100E+00   0.000E+00     0.000E+00     0.000E+00     2.006E-07   0.000
E+00
                    22   2.300E+00   0.000E+00     0.000E+00     0.000E+00     2.160E-07   0.000
E+00
                    23   2.500E+00   0.000E+00     0.000E+00     0.000E+00     2.311E-07   0.000
E+00
                    24   2.700E+00   0.000E+00     0.000E+00     0.000E+00     2.460E-07   0.000
E+00
                    25   3.000E+00   0.000E+00     0.000E+00     0.000E+00     2.679E-07   0.000
E+00
                    26   6.143E+00   0.000E+00     0.000E+00     0.000E+00     4.396E-07   0.000
E+00
                    27   7.112E+00   0.000E+00     0.000E+00     0.000E+00     4.802E-07   0.000
E+00

                                 6.514E+14     5.328E+12     6.567E+14                 7.454
E+07

                 Elapsed time for this calculation is  7.700E-01 (seconds).
□
 Program : ISOSHLD-PC
        Page :          9
 Number  : 03.7.310-1.0 0
        Date : 11/21/2000
 Created : 11:35:42  04/27/1999
        Time : 16:02:32.01


   Heat Rate Calculation   Big Rock RPV+Internals: Reactor Vessel Assembly and Internals Decay Heat Calcu
l

 Total Radiation Heating in the System
      Units Assume Total Curie Inventory Input
      No Shields, No Geometry. Just Heating.

     Group         Total Group            Group           Total Group            Group          Total
 System
```

| :Rate | | Production Rate | Output Bremsstrahlun | Production Rate | Average Energy | Hea |
|---|---|---|---|---|---|---|
| J/hr | | Photons/sec | Photons/sec | Betas/sec | MeV | BT |
| 3E-01 | 1 | 5.871E+13 | 3.729E+12 | 0.000E+00 | 1.500E-02 | 5.12 |
| 1E-03 | 2 | 4.068E+07 | 5.682E+11 | 0.000E+00 | 2.500E-02 | 7.77 |
| 2E-03 | 3 | 1.455E+09 | 3.481E+11 | 0.000E+00 | 3.500E-02 | 6.69 |
| 5E-03 | 4 | 3.677E+09 | 2.049E+11 | 0.000E+00 | 4.500E-02 | 5.13 |
| 0E-03 | 5 | 0.000E+00 | 1.290E+11 | 0.000E+00 | 5.500E-02 | 3.88 |
| 7E-03 | 6 | 0.000E+00 | 9.160E+10 | 0.000E+00 | 6.500E-02 | 3.25 |
| 5E-03 | 7 | 0.000E+00 | 6.277E+10 | 0.000E+00 | 7.500E-02 | 2.57 |
| 8E-03 | 8 | 1.073E+03 | 4.470E+10 | 0.000E+00 | 8.500E-02 | 2.07 |
| 8E-03 | 9 | 0.000E+00 | 1.060E+11 | 0.000E+00 | 9.500E-02 | 5.50 |
| 7E-03 | 10 | 1.975E+09 | 4.320E+10 | 0.000E+00 | 1.500E-01 | 3.70 |
| 9E-04 | 11 | 5.488E+08 | 8.985E+08 | 0.000E+00 | 2.500E-01 | 1.97 |
| 6E-04 | 12 | 1.903E+09 | 1.332E+06 | 0.000E+00 | 3.500E-01 | 3.64 |
| 5E-04 | 13 | 4.592E+08 | 6.641E+05 | 0.000E+00 | 4.750E-01 | 1.19 |
| 1E-02 | 14 | 4.952E+10 | 2.364E+05 | 0.000E+00 | 6.500E-01 | 1.76 |
| 6E-01 | 15 | 5.884E+11 | 7.119E+04 | 0.000E+00 | 8.250E-01 | 2.65 |
| 1E-03 | 16 | 1.921E+09 | 1.988E+04 | 0.000E+00 | 1.000E+00 | 1.05 |
| 7E+02 | 17 | 5.920E+14 | 1.892E+03 | 0.000E+00 | 1.225E+00 | 3.96 |
| 0E-03 | 18 | 1.487E+09 | 0.000E+00 | 0.000E+00 | 1.475E+00 | 1.20 |
| 0E+00 | 19 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 1.700E+00 | 0.00 |

| | | | | | |
|---|---|---|---|---|---|
| 20 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 1.900E+00 | 0.000E+00 |
| 21 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 2.100E+00 | 0.000E+00 |
| 22 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 2.300E+00 | 0.000E+00 |
| 23 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 2.500E+00 | 0.000E+00 |
| 24 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 2.700E+00 | 0.000E+00 |
| 25 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 3.000E+00 | 0.000E+00 |
| 26 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 6.143E+00 | 0.000E+00 |
| 27 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 7.112E+00 | 0.000E+00 |
| Total | 6.514E+14 | 5.328E+12 | 0.000E+00 | | 3.975E+02 |

# APPENDIX 3-2

ISSUE SUMMARY
Form SOP-0402-03, Revision 3B



DESIGN CONTROL SUMMARY

| | | | |
|---|---|---|---|
| CLIENT: | BNFL Inc. | UNIT NO.: | QA SERIAL NO. |
| PROJECT NAME: | Big Rock Point Major Component Removal | | |
| PROJECT NO.: | 10525-020 | ☐ NUCLEAR SAFETY-RELATED | |
| CALC. NO.: | M-10525-020-001 | ☐ NOT NUCLEAR SAFETY-RELATED | |
| TITLE: | Thermal Response of Reactor Vessel Transport System | ☒ IMPORTANT TO SAFETY - CATEGORY A | |
| EQUIPMENT NO.: | | | |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Initial Issue: 50 pages issued as Revision 0.

INPUTS/ ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

| | | | |
|---|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 0 | |
| STATUS: | Approved | DATE FOR REV.: 6/07/00 | |
| PREPARER | Mark C. Handrick | DATE: | |
| REVIEWER * | Michael A. Gardner | DATE: | |
| APPROVER | Robert J. Peterson | DATE: | |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Revised to address localized heat load due to activity of Grid Bar End Pieces, as described in Calculation No. N-10525-020-004, Revision 1.
Revision 1: All pages superseded.
64 pages issued as Revision 1.

INPUTS/ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

| | | | |
|---|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 1 | |
| STATUS: | Approved | DATE FOR REV.: | 2/12/01 |
| PREPARER | Mark C. Handrick Mark Handrick | DATE: | 2/08/01 |
| REVIEWER* | Michael E. Duffy Robert J Peterson for M Duffy | DATE: | 2/9/01 |
| APPROVER | Robert J. Peterson Robert J Peterson | DATE: | 2/12/01 |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

INPUTS/ASSUMPTIONS
☐ VERIFIED
☐ UNVERIFIED

| | | | |
|---|---|---|---|
| REVIEW METHOD: | | REV. | |
| STATUS: | | DATE FOR REV.: | |
| PREPARER | | DATE: | |
| REVIEWER* | | DATE: | |
| APPROVER | | DATE: | |

* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

**NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS**

## TABLE OF CONTENTS

## 1.0 Purpose and Scope

One of the tasks associated with the decommissioning of Big Rock Point Nuclear Plant is removal and transportation of the Reactor Vessel to its final disposal site. A Reactor Vessel Transport System (RVTS) has been specifically designed for transportation and disposal of the Big Rock Point Nuclear Plant Reactor Vessel. The purpose of this calculation is to determine the thermal response of the RVTS under design conditions prescribed in Title 10 of the Code of Federal Regulations, Part 71, "Packaging and Transportation of Radioactive Materials". The RVTS thermal response will be evaluated to ensure that compliance with 10 CFR 71 is met.

Package approval standards are identified in 10 CFR 71 Subpart E. Demonstration of compliance with these standards is specified in 10 CFR 71.41(a), repeated below.

> "The effects on a package of the tests specified in §71.71 ("Normal conditions of transport"), and the tests specified in §71.73 ("Hypothetical accident conditions"), and §71.61 (Special requirements for irradiated nuclear fuel shipments"), must be evaluated by subjecting a specimen or scale model to a specific test, or by another method of demonstration acceptable to the Commission, as appropriate for the particular feature being considered."

The general standards for all transportation packages are identified in 10 CFR 71.43. The standards applicable to the thermal response of the RVTS, paragraphs 10 CFR 71.43(f) and 10 CFR 71.43(g) respectively, are listed below.

> "A package must be designed, constructed, and prepared for shipment so that under the tests specified in §71.71 ("Normal conditions of transport") there would be no loss or dispersal of radioactive contents, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging."

> "A package must be designed, constructed, and prepared for transport so that in still air at 38 °C (100 °F) and in the shade, no accessible surface of a package would have a temperature exceeding 50 °C (122 °F) in a nonexclusive use shipment, or 85 °C (185 °F) in an exclusive use shipment."

The RVTS temperature distribution results of this calculation will be used in external analyses to assess the structural integrity of the RVTS under the Normal Conditions of Transport (NCT), and the Hypothetical Accident Conditions (HAC). This calculation will also document the maximum accessible surface temperature of the RVTS to demonstrate compliance with 10 CFR 71.43(g) for an exclusive use transportation package.

Specifically, this calculation will document the thermal response of the RVTS under four conditions as outlined below. The basis for the selection of these scenarios is documented in Section 4.2.

Case 1: The maximum accessible surface temperature with an ambient temperature of 100 °F and no solar insolation will be evaluated to ensure that the steady-state surface temperature of the container does not exceed 185 °F.

Case 2: Under NCT with an ambient temperature of 100 °F in still air, and with a solar insolation of 400 g-cal/cm$^2$ (for curved surfaces) for a 12-hour period.

Case 3: Under NCT with an ambient temperature of -40 °F in still air, and without solar insolation.

Case 4: Under HAC where the RVTS is fully engulfed in a hydrocarbon fuel/air fire, with an average flame temperature of at least 800 °C (approximately 1475 °F) for a period of 30 minutes.

The thermal analysis documented in this calculation is based on the RVTS design parameters outlined in the Big Rock Point Restoration Project Reactor Vessel Removal Package Design Criteria, the RVTS shielding design, and the schematic drawing of the RVTS as included in Attachment C.

Revision 1 of this calculation addresses the heat load associated with the Grid Bar End Pieces (GBEP). The GBEP are the stubs that remain in the reactor vessel after the Top Guide Grid Bars were cut and removed (Reference 7.26). The Top Guide Grid Bars are attached to the Top Guide Plate, located near the top of the active region of the reactor vessel. Additional details of the GBEP modeling are included in Section 4.1 of this calculation.

The initial WMG, Inc. radiation source term characterization (Reference 7.11) did not anticipate leaving GBEP in the reactor vessel. Reference 7.26 determined that the activity associated with the GBEP is 1800 Curies. The total heat load of the RVTS is evaluated in Reference 7.9, including the GBEP contribution, and is used in the RVTS thermal model documented in this calculation.

## 2.0 Design Inputs

2.1 The following Reactor Vessel dimensional data is provided by the indicated references.

| Parameter | Value | Reference |
|---|---|---|
| *Reactor Vessel* | | |
| RV Base Metal Inner Radius | 53 7/32" | Ref. 7.12 |
| RV Base Metal Thickness | 5.25" | Ref. 7.12 |
| SS Cladding Thickness | 5/32" | Ref. 7.12 |
| Distance from Inside Base of RV to Bottom of Thermal Shield | 7'-3.75" | Ref. 7.14 |
| Distance from Inside Base of RV to Top of Thermal Shield | 14'-11.75" | Ref. 7.14 |
| Distance from Inside Base of RV to RV Head Flange Mating Surface | 23'-6" | Ref. 7.14 |
| *Other Components* | | |
| Thermal Shield Inner Radius | 50" | Ref. 7.16 |
| Thermal Shield Thickness | 1.5" | Ref. 7.16 |
| Thermal Shield Length | 92.0" | Ref. 7.16 |
| SS Insulation Thickness | 3" | Ref. 7.11, page 36 |
| Top Guide Plate Thickness | 1" | Ref. 7.11, page 27 |
| Seal Weights (12 total) | 1" x 18" x 81" | Ref. 7.11, page 31 |

2.2 The dimensions and materials of the RVTS modeled in this calculation are listed below. These are based on the RVTS design specifications, and are consistent with those given in Reference 7.24 and the schematic drawing of the RVTS, Reference 7.30 (see Attachment C).

| Description | Dimension / Material |
|---|---|
| RVTS Outer Diameter | 13' |
| RVTS Modeled Length | 24'-11.25" |
| RVTS Minimum Wall Thickness | 3" |
| RVTS Bottom Plate Thickness | 4" |
| RVTS Top Lifting Plate Thickness | 4" |
| RVTS Material | ASTM A516 Grade 70 |
| Internal Grout (refer to Assumption 3.3) | Low Density Cellular Concrete (30 $lb_m/ft^3$) |
| External Grout (refer to Assumption 3.3) | Low Density Cellular Concrete (50 $lb_m/ft^3$) |
| RVTS Wall Thickness in Modeled Active Region | 7" |
| Vertical Length of 4" Plate in Modeled Active Region | 96" |

2.3 The Reactor Vessel and RV internal components are comprised of the following materials, with references as cited.

| Component | Material | Reference |
|---|---|---|
| Thermal Shield | Type 304 Stainless Steel | Ref. 7.11, page 3 |
| Reactor Vessel Internal Components | Type 304 Stainless Steel | Ref. 7.11, page 3 |
| Reactor Vessel Wall | SA-302 Grade B | Ref. 7.13 |
| Reactor Vessel Cladding | Type 304 Stainless Steel | Ref. 7.13, Ref. 7.11 |
| Reactor Vessel Insulation | Type 304 Stainless Steel Foil | Ref. 7.17 |

2.4 Reference 7.21 gives the following densities and chemical compositions (in percent) of the various types of steel used in the HEATING model.

Carbon Steel A516 Grade 70: density = 0.284 $lb_m/in^3$ (490.8 $lb_m/ft^3$)
Alloy Steel A302 Grade B: density = 0.283 $lb_m/in^3$ (489.0 $lb_m/ft^3$)
Type 304 Stainless Steel: density = 0.290 $lb_m/in^3$ (501.1 $lb_m/ft^3$)

| Steel Type | Carbon | Manganese | Silicon | Molybdenum | Nickel | Chromium |
|---|---|---|---|---|---|---|
| SA-516 Grade 70 | 0.31 max | 0.85 – 1.20 | 0.15 – 0.30 | N/A | N/A | N/A |
| SA-302 Grade B | 0.25 max | 1.15 – 1.50 | 0.15 – 0.30 | 0.45 – 0.60 | N/A | N/A |
| Type 304 SS | 0.08 | 2.0 | 1.0 | N/A | 8 – 12 | 18 – 20 |

Based on the chemical compositions of the various types of steels, the thermal conductivity and thermal diffusivity of the steels is obtained from Reference 7.5 for use in the HEATING model, as shown below.

| | A 516-70 Steel (C-Mn-Si) | | 302 Grade B Steel (Mn-1/2Mo) | | Stainless Steel Type 304 (18Cr-8Ni) | |
|---|---|---|---|---|---|---|
| Temp. | Thermal Conductivity | Thermal Diffusivity | Thermal Conductivity | Thermal Diffusivity | Thermal Conductivity | Thermal Diffusivity |
| (°F) | (Btu/hr-ft-°F) | ($ft^2/hr$) | (Btu/hr-ft-°F) | ($ft^2/hr$) | (Btu/hr-ft-°F) | ($ft^2/hr$) |
| 70 | 23.6 | 0.454 | 23.3 | 0.455 | 8.6 | 0.151 |
| 200 | 24.4 | 0.422 | 24.4 | 0.437 | 9.3 | 0.156 |
| 400 | 24.2 | 0.386 | 24.6 | 0.398 | 10.4 | 0.165 |
| 600 | 23.1 | 0.346 | 23.5 | 0.353 | 11.3 | 0.174 |
| 800 | 21.7 | 0.298 | 22.0 | 0.300 | 12.2 | 0.184 |
| 1200 | 18.2 | 0.197 | 18.6 | 0.193 | 14.0 | 0.203 |
| 1500 | 15.1 | 0.169 | 15.5 | 0.164 | 15.3 | 0.216 |

2.5 The following physical properties of Low Density Cellular Concrete (LDCC) are given in Chapter 24, Table 4 of Reference 7.10.

| Description | Density ($lb_m/ft^3$) | Thermal Conductivity (Btu-in/hr-ft-°F) | Thermal Conductivity (Btu/hr-ft-°F) | Specific Heat (Btu/$lb_m$-°F) |
|---|---|---|---|---|
| Lightweight Aggregate: perlite, vermiculite, and polystyrene beads | 40 | 1.4 – 1.5 | 0.117 – 0.125 | 0.15 – 0.23 |
| Foam and Cellular Concrete | 60 | 2.1 | 0.175 | - |
| Foam and Cellular Concrete | 40 | 1.4 | 0.117 | - |
| Foam and Cellular Concrete | 20 | 0.8 | 0.0667 | - |

Interpolating between the data presented for cellular concrete, the following thermal conductivities are used in the HEATING model:

For LDCC with a density of 50 $lb_m/ft^3$ (refer to Assumption 3.3), $k$ = 0.146 Btu/hr-ft-°F
For LDCC with a density of 30 $lb_m/ft^3$ (refer to Assumption 3.3), $k$ = 0.0917 Btu/hr-ft-°F

2.6 Table A-3 of Reference 7.3 and Table A.4 of Reference 7.4 provide the following physical properties of air at atmospheric pressure.

| Temperature | Thermal Conductivity, *k* | Prandtl Number, *Pr* | Property Group, $\rho^2 g\beta/\mu^2$ |
|---|---|---|---|
| (°F) | (Btu/hr-ft-°F) | (N/A) | (1/ft$^3$-°F) |
| -100 | 0.01046 | 0.737 | 1.34E7 |
| 0 | 0.0133 | 0.73 | 4.20E6 |
| 100 | 0.0154 | 0.72 | 1.76E6 |
| 200 | 0.0174 | 0.72 | 8.50E5 |
| 400 | 0.0212 | 0.689 | 2.58E5 |
| 600 | 0.0250 | 0.685 | 1.06E5 |
| 800 | 0.0286 | 0.697 | 4.98E4 |

2.7 Reference 7.7, Appendix D, provides the following data for emissivity of steel:
Sheet with skin due to rolling, $\varepsilon$ = 0.66

2.8 Reference 7.9 provides the following Curie content for various reactor vessel components, from which decay heat loads are obtained. The total Curie content for the reactor vessel and internals is given by Reference 7.9 as 1.481E4 Curies. After appropriate margins are included, the total heat load due to the reactor vessel and internals is given as 485 Btu/hr. The individual decay heat loads for the various reactor vessel components are computed below, based on the fractional Curie content of the respective component. Components not specifically identified below are grouped together, and modeled as a homogeneous heat load in the low density cellular concrete of the active fuel region.

| Component or Region | Curies, *Ci* | Fraction of Total Curie Content; ~ *Ci* / 1.481E4 | Decay Heat Load; = Fraction * 485 (Btu/hr) |
|---|---|---|---|
| Thermal Shield | 8510 | 0.575 | 278.8 |
| Top Guide Plate | 1311 | 0.089 | 43.0 |
| Top Guide Grid Bar End Pieces | 1800 | 0.122 | 59.0 |
| Seal Weights (12 total) | 1265 | 0.085 | 41.4 |
| Reactor Vessel Insulation | 66.8 | 0.005 | 2.19 |
| Reactor Vessel Cladding | 281.8 | 0.019 | 9.23 |
| Reactor Vessel Wall | 1277 | 0.086 | 41.8 |
| Miscellaneous Components in Active Fuel Region | 294.4 | 0.02 | 9.64 |
| **Totals** | **1.481E4** | **1.00** | **485.1** |

2.9 The ambient temperature boundary conditions are specified by Reference 7.1 as shown below for the various scenarios analyzed in this calculation.

| Case No. | Case Description | Ambient Temperature |
|---|---|---|
| | | |
| Case 1 | Maximum Surface Temperature | 100 °F |
| Case 2 | Normal Conditions of Transport with Solar Insolation | 100 °F |
| Case 3 | Normal Conditions of Transport without Solar Insolation | -40 °F |
| Case 4 | Hypothetical Accident Condition | -20 to 100 °F before and after test<br>1475 °F during 30 minute test |

## 3.0 <u>Assumptions</u>

3.1 The hemispherical portion of the lower reactor vessel head is modeled as flat plate, as shown in Figure 1. This modeling simplification is reasonable, as the decay heat sources are primarily located in the active fuel region.

3.2 For the HAC scenario, the ambient temperature is 1475 °F for the 30-minute duration of the fire. 10 CFR 71.73(a) specifies that the hypothetical accident fire thermal analysis be performed after the RVTS has been subjected to free drop and puncture tests. Potential damage resulting from these tests are considered minimal to the RVTS and of no significant effect, likely limited to small surface indentations and/or deformations. These types of damage will have negligible impact on the ability of the RVTS surface to transfer heat to the ambient. Therefore the HEATING model for the HAC analysis is unchanged from the NCT analysis.

3.3 The LDCC internal filler is assumed to have a density of 30 $lb_m/ft^3$, and the LDCC external filler is assumed to have a density of 50 $lb_m/ft^3$. These values represent the lower bound of the respective density ranges to be used in the RVTS, specifically 30 $lb_m/ft^3$ to 36 $lb_m/ft^3$ for the internal LDCC filler, and 50 $lb_m/ft^3$ to 60 $lb_m/ft^3$ for the external LDCC filler. The use of lower bound densities is conservative for maximizing the temperature response of the RVTS under the transient conditions associated with the HAC. For the steady-state analyses of the Maximum Accessible Surface Temperature, and the NCT, the choice of LDCC density is arbitrary, as the steady-state temperature distribution is independent of material density.

3.4 Laminar natural convection heat transfer is assumed to occur at the surface of the RVTS, conservatively neglecting any possible turbulent natural convection heat transfer mechanisms. This assumption is conservative for the purposes of maximizing the computed RVTS surface temperature, as potentially turbulent natural convection mechanisms would transfer more heat from the RVTS surface to the ambient.

3.5 The cask end plates are modeled as vertical plates for the purposes of computing natural convection heat transfer coefficients. This assumption is appropriate, as the RVTS will be transported in the horizontal position, therefore the end plates will be in the vertical orientation.

3.6 The densities of all materials employed in the HEATING model are assumed to be constant. Material density has no effect on computed steady-state temperature profiles.

3.7 The emissivity of the steel transportation cask is assumed to be 0.66, consistent with the value listed in Appendix D of Reference 7.7 for rolled steel. The RVTS may be covered with an epoxy-based coating, similar to the type cited in the correspondence from Carboline Company (see Attachment D). The epoxy coating mentioned in Attachment D has an emittance, or emissivity, of 0.91. The author of the Carboline correspondence indicates that he is uncertain whether thermal emittance is the same physical quantity as thermal emissivity. The two words are used interchangeably when discussing thermal radiant heat transfer. Since the epoxy coating emissivity is greater than that of steel, the use of the steel-based emissivity of 0.66 is conservative for the purposes of maximizing the RVTS surface temperature.

3.8 The RVTS support cradle can potentially cause local obstructions to convective-driven air currents at the RVTS cylindrical surface, which adversely affect natural convective heat transfer from the RVTS surface to the ambient. To account for any local obstructions, the natural convection heat transfer coefficient computed in Section 5.3.2 will be conservatively reduced by 25 percent. A review of Drawing No. SD-10525-020-002 (Reference 7.31) indicates that considerably less than 25 percent of the RVTS surface area is obstructed by tie-downs, supports, etc. Therefore, the use of a 25 percent reduction in the natural convection heat transfer coefficient is conservative.

3.9 Physical properties of steels at –40 °F are assumed to be identical to those at 70 °F, as listed in Design Input 2.4, for use in the HEATING model. The lowest temperature value cited in ASME Boiler and Pressure Vessel Code, Section II, Part D, for the steels modeled in this calculation is 70 °F. A review of Design Input 2.4 shows that there is negligible change in thermal conductivity of A516 Grade 70 steel in the temperature range of 70 °F to 200 °F. Therefore, this assumption has a negligible impact on the temperature profiles used to evaluate the thermal stresses of the RVTS shell for the Case 3 analyses.

3.10 The specific heat of LDCC is taken as 0.15 $Btu/lb_m$-°F, which is the lowest value given in Design Input 2.5. Selecting the lowest value will conservatively maximize the RVTS temperatures during the HAC transient.

3.11 The thermal conductivities of the LDCC are assumed to be constant. The assumption of uniform thermal conductivity of low-density concrete is appropriate based on Figure 6.7.1 of the *ACI Manual of Concrete Practice, Part 3 – 1998* (Ref. 7.20). This figure shows that the thermal conductivities of lightweight concretes have little variation for a temperature range of 0 °F to 1800 °F.

3.12 The total decay heat load for the RVTS is 485 BTU/hr per Design Input 2.8. Of this value, only 9.64 BTU/hr, or approximately 2 percent of the total, is attributable to miscellaneous components inside the thermal shield. Specifically, these include the steam baffle, sparger, seal housing, TS retainer, core support plate, inlet diffuser, and the inlet baffle (see Calculation No. N-10525-020-0001, Reference 7.9). A detailed geometric model of these internal components is not required, given the low heat loads of these components when compared to the total heat load of the RVTS.

## 4.0 Methodology and Acceptance Criteria

### 4.1 RVTS Thermal Model Development

The thermal analysis of the RVTS will be performed using the HEATING7.2f computer code. HEATING is a finite difference thermal analysis code capable of solving steady-state and transient thermal analysis problems in one, two, or three dimensions in a rectangular, cylindrical, or spherical coordinate system. HEATING was developed by Oak Ridge National Laboratory, and the solutions algorithms have been verified against a large number of representative problems presented in the literature having analytical solutions. The code is capable of modeling conduction, radiation, and natural or forced convection heat transfer mechanisms. A flexible input structure allows the user to model a wide variety of boundary conditions, encompassing all of the postulated scenarios required per 10 CRF 71.

The three-dimensional RVTS model consists of the following regions, listed in the direction of increasing radius: reactor vessel internal components and LDCC internal filler, stainless steel cladding, the reactor vessel wall, stainless steel insulation, LDCC exterior filler, and the RVTS cask steel wall. The LDCC filler acts to stabilize the reactor vessel internal components, immobilize any potential loose radioactive contamination, and to fill any gaps or voids in the RVTS. In the Active Fuel Region, the thermal shield, seal weights, and top plate are modeled. The axial, or vertical, dimensions of the RVTS are modeled to encompass edge effects for the upper and lower RVTS end plates. The RVTS cask wall thickness in the active fuel region is 7 inches thick. This is accomplished by welding a 4-inch plate to the 3-inch thick RVTS wall, as shown in Reference 7.24. This 4-inch thick plate is 96 inches in length, and extends approximately four inches above the thermal shield, encompassing the active fuel region as shown in Reference 7.14. For the purposes of this calculation, the active region is assumed to be that 96-inch axial region of the RVTS which is surrounded by the 4-inch steel plate, as shown in Reference 7.24. A section view of the HEATING model is shown in Figure 1 on page 12. A section view of the model including dimensions, consistent with Design Input 2.1, is shown in Figure 2.

In the active region, the thermal shield, seal weights, top guide plate, and top plate grid bar end pieces are modeled in detail, as these components represent approximately 87 percent of the total RVTS heat load as shown in Design Input 2.8. The thermal shield is 92 inches in length and 1.5 inches thick. The seal weights are located in the annular region between the thermal shield and the reactor vessel wall. The seal weights span an axial length of approximately 84 inches, from the top guide plate to the bottom of the thermal shield as shown in Reference 7.27. There are 12 seal weights, spaced in approximately equal intervals along the circumference of the thermal shield as shown in Reference 7.18. The top guide plate is a circular plate one inch thick, with a diameter of 99.1875 inches per Reference 7.29. To simplify the HEATING model, the top plate is assumed to have a diameter of 100 inches, abutting the thermal shield as shown in Reference 7.27. A plan view of the active region is presented in Figure 3 on page 14, showing the radial dimensions of the top plate, thermal shield, reactor vessel wall, and stainless steel insulation. A section view of the active region is presented in Figure 4, illustrating the axial dimension of the top plate, seal weights, and the thermal shield.

The center portion of the top plate is cut out to accommodate the fuel assemblies, as shown in References 7.14 and 7.29. To simplify the HEATING model, the top plate is modeled with a smooth inner diameter of 88 inches as shown in Figure 6. The top guide grid bars are hinged to the top plate at equally spaced intervals along one-half of the circumference of the top plate, per a review of Reference 7.28. A plan view of the top plate showing the spacing of the grid bar hinge points is shown in Figure 5 on page 16. The grid bars have been cut off from the top plate at the hinge points, however the grid bar end stubs which remain are a radioactive source term which contribute to the total RVTS heat load as described in References 7.9 and 7.26.

The heat load associated with the grid bar end pieces (59.0 Btu/hr) is partitioned, and added to the heat load of the top plate for three distinct regions between 0° and 180 °, as shown in Figure 6. Reference 7.9 states that small, localized regions of high activity, or hot spots, may be present in the top plate. Following the guidance provided in Assumption 4.5 of Reference 7.9, one-half of the total GBEP heat load will be modeled as a hot spot on the top plate. The hot spot is modeled with azimuthal boundaries of 89° and 91°, representative of a small, localized heat source. The remaining 50% of the GBEP heat load is divided equally between the two regions of the top plate with GBEP activity, with azimuthal boundaries of 0° to 89°, and 91° to 180° respectively.

Per Design Input 2.8, the total heat load of the top plate is 43.0 Btu/hr. The combined heat load of the top plate and the GBEP is 102.0 Btu/hr. The partitioning of the GBEP heat load and the top plate heat load are given below, as shown in Figure 6.

| | | |
|---|---|---|
| Region 16 (0° to 89°): | (89/360)*43.0 + (0.25)*59.0 | = 25.38 Btu/hr |
| Region 17 (89° to 91°): | (2/360)*43.0 + (0.50)*59.0 | = 29.74 Btu/hr |
| Region 18 (91° to 180°): | (89/360)*43.0 + (0.25)*59.0 | = 25.38 Btu/hr |
| Region 19 (180° to 360°): | (180/360)*43.0 | = 21.50 Btu/hr |
| Total | | 102.0 Btu/hr |

The table below lists the regions of the RVTS model, which correspond to the numbered components shown in Figures 1 through 6.

| Region No. | Region Description |
|---|---|
| 1 | 4" Thick Bottom End Plate of RVTS Cask |
| 2 | 3" Thick Side Wall of RVTS Cask Below Active Region |
| 3 | 7" Thick Side Wall of RVTS Cask In Active Region |
| 4 | 3" Thick Side Wall of RVTS Cask Above Active Region |
| 5 | 4" Top Lifting Plate of RVTS Cask |
| 6 | External LDCC (50 $lb_m/ft^3$) below Reactor Vessel |
| 7 | Annular External LDCC (50 $lb_m/ft^3$) Along Reactor Vessel Below Active Region |
| 8 | Annular External LDCC (50 $lb_m/ft^3$) Along Reactor Vessel In Active Region |
| 9 | Annular External LDCC (50 $lb_m/ft^3$) Along Reactor Vessel Above Active Region |
| 10 | 3" Stainless Steel Insulation around Reactor Vessel |
| 11 | 5.25" Bottom Portion of Reactor Vessel Wall |
| 12 | 5.25" Side Wall of Reactor Vessel |
| 13 | Stainless Steel Cladding on Inside Wall of Reactor Vessel |
| 14 | Interior LDCC (30 $lb_m/ft^3$) Filler Below Active Region |
| 15 | Interior LDCC (30 $lb_m/ft^3$) Filler Above Active Region |
| 16 | Top Guide Plate including 25% of Heat Load of the Grid Bar End Pieces (0° – 89°) |
| 17 | Top Guide Plate including 50% of Heat Load of the Grid Bar End Pieces (89° – 91°) |
| 18 | Top Guide Plate including 25% of Heat Load of the Grid Bar End Pieces (91° – 180°) |
| 19 | Top Guide Plate without Grid Bar End Pieces (180° – 360°) |
| 20 | Thermal Shield (92" in length) |
| 21 - 32 | Seal Weights in Annular Region between Thermal Shield and RV Wall (12 total) |
| 33 - 45 | Interior LDCC (30 $lb_m/ft^3$) Filler in between the Seal Weights |
| 46 | Interior LDCC (30 $lb_m/ft^3$) Filler in Active Region below Top Guide Plate |
| 47 | Interior LDCC (30 $lb_m/ft^3$) Filler within Top Guide Plate (cutout region) |
| 48 | Interior LDCC (30 $lb_m/ft^3$) Filler in Active Region above Top Guide Plate within Thermal Shield |
| 49 | Interior LDCC (30 $lb_m/ft^3$) between RV Wall and Thermal Shield above Seal Weights |

**Figure 1**
**Section View of RVTS Model**

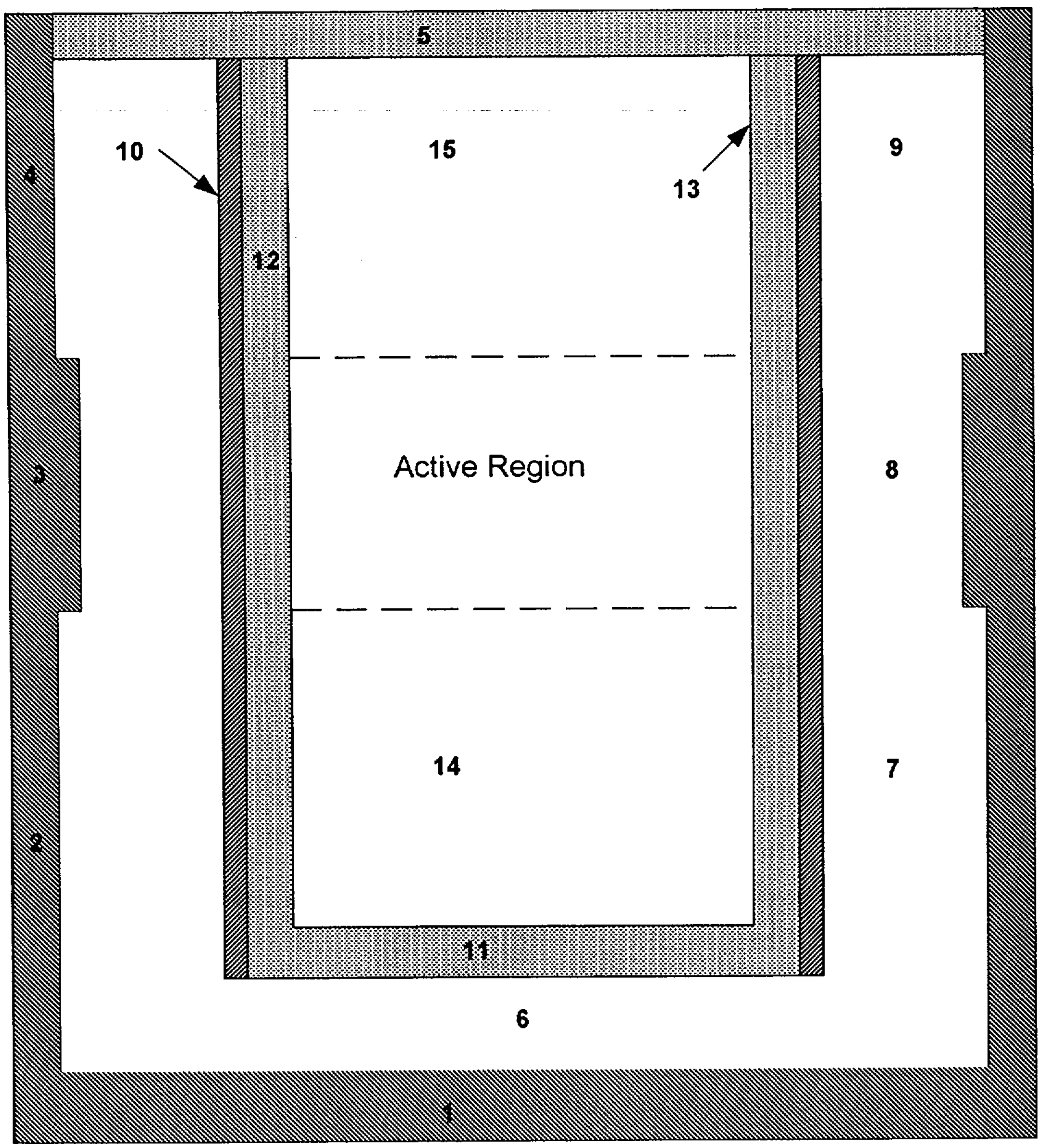


FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

| | | | | |
|---|---|---|---|---|
| Calc For Thermal Response of Reactor Vessel Transport System | | | | Calc No. M-10525-020-001 |
| | | | | Rev. 1 \| Date |
| X | Important to Safety - Category A | | Non-Safety Related | Page 15 |

| | | | | |
|---|---|---|---|---|
| Client | BNFL, Inc. | Prepared by | Mark C. Handrick | Date |
| Project | Big Rock Point Major Component Removal | Reviewed by | Michael E. Duffy | Date |
| Proj. No | 10525-020 Equip. No. | Approved by | Robert J. Peterson | Date |

FIGURE WITHHELD UNDER 10 CFR 2.390

**Figure 5**
**Top Guide Plate**

FIGURE WITHHELD UNDER 10 CFR 2.390

FIGURE WITHHELD UNDER 10 CFR 2.390

Table 2 lists all the dimensional data used to construct the HEATING model, based on the regions identified in Table 1. The linear dimensions are converted from inches to feet, the angular dimensions are converted from degrees to radians, and the regional volume is computed. For those regions which contain a decay heat source term, the decay heat load is divided by the region volume to obtain a volumetric heat load (Btu/hr-ft$^3$) for use in the model.

Table 3 lists the thermal conductivity, $k$, thermal diffusivity, $\alpha$, and specific heat, $c_p$, for the various steels of the HEATING model. The thermal conductivity and thermal diffusivity listed under Design Input 2.4 are used to compute the specific heat according to the following definition: $\alpha = k / (\rho^* c_p)$

## 4.2 Applied Boundary Conditions for the RVTS Model

The boundary conditions applied at the RVTS outer surface are consistent with the requirements of Reference 7.1. The ambient temperatures are specified as 100 °F for the Maximum Surface Temperature (Case 1) and the NCT with Solar Insolation (Case 2) scenarios. For the NCT without Solar Insolation (Case 3), the ambient temperature is specified as -40 °F, per 10 CFR 71.71(c)(2). The Case 4 analysis models the RVTS completely engulfed in a hydrocarbon fuel/air fire at 1475 °F.

A total solar insolation of 400 g cal/cm$^2$ on the curved RVTS surfaces, for a 12-hour period, is specified for the Case 2a scenario. For the flat, vertical end plates of the RVTS, a total insolation of 200 g cal/cm$^2$ is specified per 10 CFR 71.71(c)(1).

For Case 1 through Case 3, heat transfer from the RVTS outer surface to the ambient is modeled with parallel heat transfer mechanisms of laminar natural convection and radiation. The natural convection heat transfer coefficient is computed in Section 5.3.2, based on correlations for natural convection applicable to horizontal cylinders. The RVTS end plates are treated as flat vertical plates for the purposes of computing the natural convection heat transfer coefficient, with details presented in Section 5.3.3. Radiation heat transfer is governed by the emissivity of the RVTS outer surface, taken as $\varepsilon = 0.66$ per Design Input 2.7. Cases 1, 2, and 3 are modeled with the HEATING steady-state solution option.

Two scenarios are run for the NCT without solar insolation. In Case 3a, the ambient air temperature is –40 °F, as specified in 10 CFR 71.71(c)(2). In Case 3b, the ambient air temperature is –20 °F. This case is used to develop the initial temperature distribution in the RVTS for use in the Case 4 analysis.

To determine the sensitivity of the model results on the RVTS surface emissivity, the Case 1a scenario is duplicated using an emissivity value of $\varepsilon = 0.0$. This scenario is named Case 1b. The results of Case 1b show that the computed RVTS surface temperature increases by approximately 2.5 °F for an emissivity value of 0.0. This relatively small temperature increase indicates that the model results for Case 1 are not particularly sensitive to the value of RVTS surface emissivity.

Case 2b is a sensitivity run to determine the potential effects of crushed stainless steel insulation surrounding the reactor vessel. If this insulation is crushed, the displaced volume will be filled with the 50 $lb_m/ft^3$ LDCC, and the thermal properties of this region will change, with a corresponding change in the computed temperature gradient. For the Case 2b scenario, the thermal conductivity of the insulation region is modeled as that of 50 $lb_m/ft^3$ LDCC, or 0.146 Btu/hr-ft-°F per Design Input 2.5. The density and specific heat of the stainless steel insulation region are unchanged for the Case 2b scenario, as the density and specific heat values for the insulation are smaller than that of the 50 $lb_m/ft^3$ LDCC, which is conservative for the purposes of maximizing temperatures.

For the hypothetical accident fire of Case 4, the ambient temperature is 1475 °F for the 30-minute duration of the fire. 10 CFR 71.73(a) specifies that the hypothetical accident fire thermal analysis be performed after the RVTS has been subjected to free drop and puncture tests. Potential damage resulting from these tests are considered minimal to the RVTS and of no significant effect, likely limited to small surface indentations and/or deformations. These types of damage will have negligible impact on the ability of the RVTS surface to transfer heat to the ambient. Therefore the HEATING model for the HAC analysis is unchanged from the NCT analysis.

During the fire, heat is transferred from the fire/flame environment to the RVTS surface by the parallel mechanisms of forced convection and radiation. The forced convection heat transfer coefficient is computed in Section 5.3.5, based on the methodology presented in Reference 7.22. The emissivity coefficient for radiation heat transfer is specified as 0.9, consistent with Reference 7.1, §71.73(c)(4).

Cases 4a and 4b are modeled with the HEATING transient solution option. The initial temperature distributions of the RVTS are obtained from the results of the Case 1a and Case 3b analyses, where the ambient temperatures are 100 °F and –20 °F respectively. The hydrocarbon fire boundary conditions are then imposed for a period of 30 minutes. After the 30 minute period, the fire boundary conditions are removed, replaced with the natural convection boundary conditions used in the Case 1a and Case 3b analyses. For Case 4a, the ambient temperature is taken as 100 °F after the 30 minute duration of the postulated fire. For Case 4b, the ambient temperature is taken as -20 °F after the 30 minute duration of the postulated fire. A cooldown period of 60 minutes is modeled, to examine potential thermal lag effects on the RVTS internal temperature distribution. No significant material or geometrical deformation is expected to occur as a result of the HAC, therefore the steady-state temperature distribution of the RVTS following removal of the applied heat sources is essentially the same as the initial temperature profile employed for Cases 4a and 4b.

Two additional sensitivity cases are modeled to examine the effect of a potential gap between the 3-inch RVTS wall and the 4-inch shield plate welded to the RVTS wall in the active region. Per Note 10 of Reference 7.30 (Attachment C), a maximum permissible gap of 0.0625 inches is allowed between the RVTS wall and the shield plate. To determine the potential effects of such a gap, the RVTS model is conservatively modified to create a 0.125-inch gap between the 3-inch RVTS wall and the 4-inch shield plate, as shown in Figure 7 on the following page. The gap is assumed to exist along the entire circumference of the shield plate to conservatively estimate the temperature gradient across the gap. Thermal radiation heat transfer across the gap region is modeled per the methodology given in Reference 7.2, as discussed in Section 5.3.6. The first sensitivity run, Case Gap1, employs the thermal boundary conditions of Case 1a. The second sensitivity run, Case Gap2, employs the thermal boundary conditions of Case 2a where solar insolation effects are modeled.

FIGURE WITHHELD UNDER 10 CFR 2.390

A summary of the applied boundary conditions is shown below for all cases analyzed in this calculation.

| Case No. | Ambient Temp. | Total Solar Insolation for a 12-hour Period | Convection at RVTS Surface | Radiation at RVTS Surface |
|---|---|---|---|---|
| | (°F) | (g cal/cm$^2$) | | |
| Case 1a | 100 | 0.0 | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case 1b | 100 | 0.0 | Natural convection to ambient | None, ε = 0.0 |
| Case 2a | 100 | 400 (curved surfaces) 200 (flat vertical surfaces) | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case 2b | 100 | 400 (curved surfaces) 200 (flat vertical surfaces) | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case 3a | -40 | 0.0 | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case 3b | -20 | 0.0 | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case 4a | 100 | 0.0 | Forced convection from flame at 1475 °F to RVTS | Flame at 1475 °F to RVTS, ε = 0.9 |
| Case 4b | -20 | 0.0 | Forced convection from flame at 1475 °F to RVTS | Flame at 1475 °F to RVTS, ε = 0.9 |
| Case Gap1 | 100 | 0.0 | Natural convection to ambient | RVTS to ambient, ε = 0.66 |
| Case Gap2 | 100 | 400 (curved surfaces) 200 (flat vertical surfaces) | Natural convection to ambient | RVTS to ambient, ε = 0.66 |

## 4.3 Acceptance Criteria

The acceptance criteria for the thermal analysis of the RVTS is provided by Reference 7.1. For the Case 1 analysis, Reference 7.1 §71.43(g) specifies that the maximum accessible surface of a transportation package not exceed 85 °C (185 °F) in an exclusive use shipment. The RVTS is considered an exclusive transportation package, therefore the RVTS design meets the 10 CFR 71.43 acceptable criteria if the maximum RVTS surface temperature computed by the HEATING model under the Case 1 boundary conditions is less than 185 °F.

In addition to the specific acceptance criteria for maximum accessible surface temperature, general approval standards for all radioactive material transportation packages are specified in 10 CFR 71.41(a) and 10 CFR 71.43(f), repeated below respectively.

"The effects on a package of the tests specified in §71.71 ("Normal conditions of transport"), and the tests specified in §71.73 ("Hypothetical accident conditions"), and §71.61 (Special requirements for irradiated nuclear fuel shipments"), must be evaluated by subjecting a specimen or scale model to a specific test, or by another method of demonstration acceptable to the Commission, as appropriate for the particular feature being considered."

"A package must be designed, constructed, and prepared for shipment so that under the tests specified in §71.71 ("Normal conditions of transport") there would be no loss or dispersal of radioactive contents, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging."

Compliance with 10 CFR 71.43(f) will be ensured in external structural analyses of the RVTS, based on the temperature distributions documented in this calculation. The temperature distribution inside the RVTS can be used to determine the maximum internal pressure, considering initial gas trapped inside the RVTS, the vapor pressure from the moisture within the concrete matrix, and the gas pressure from radiolysis for the duration of transport. The reported temperature distributions can also be used to evaluate the stresses due to thermal gradients across the various portions of the RVTS.

The temperature distribution in the RVTS following the HAC, Case 4, can be used to ensure that the RVTS design meets the requirements given in 10 CFR 71.51(a)(2).

### 4.4 Computer Programs Used

The following computer programs were used in the preparation of this calculation:

- HEATING 7.2f, Multidimensional, Finite-Difference Heat Conduction Analysis, Sargent & Lundy Program No. 03.7.564-7.2
- Microsoft Excel 97, Sargent & Lundy Program No. 03.2.081-1.0

These computer programs are maintained by S&L's Software Center as validated for safety-related use. HEATING7.2f and Microsoft Excel 97 were executed through S&L's network server SNL4A_SYS3 on PC No. 5765. The validation of data computed using Microsoft Excel 97 is implicit in the detailed review of the calculation, in compliance with S&L's Quality Assurance Procedure SOP-0402.

## 5.0 Calculations

### 5.1 Nomenclature

| | |
|---|---|
| $A_s$ | Surface area ($ft^2$) |
| $c_p$ | Specific heat ($Btu/lb_m$-°F) |
| $g$ | Gravitational acceleration (32.174 ft/sec$^2$) |
| $D$ | Diameter (ft) |
| $Gr$ | Grashof number |
| $h$ | Heat transfer coefficient (Btu/hr-ft$^2$-°F) |
| $k$ | Thermal conductivity (Btu/hr-ft-°F) |
| $L$ | Length (ft) |
| $Nu$ | Nusselt Number |
| $Pr$ | Prandtl Number |
| $q$ | Heat rate (Btu/hr) |
| $q''$ | Heat flux (Btu/hr-ft$^2$) |
| $q'''$ | Volumetric heat generation rate (Btu/hr-ft$^3$) |
| $Ra$ | Rayleigh Number |
| $Re$ | Reynolds Number |
| $t$ | Time (hr) |
| $T$ | Temperature (°F) |
| $\Delta T$ | Temperature difference (°F) |
| $V$ | Flame velocity (ft/sec) |
| $\beta$ | Coefficient of thermal expansion (°R$^{-1}$) |
| $\rho$ | Density ($lb_m/ft^3$) |
| $\varepsilon$ | Emissivity |
| $\sigma$ | Stephan-Boltzmann Constant (0.1714 x $10^{-8}$ Btu/hr-ft$^2$-°R) |
| $\mu$ | Dynamic viscosity of fluid ($lb_m$/hr-ft) |
| $\nu$ | Kinematic viscosity of fluid (ft$^2$/hr, ft$^2$/sec) |
| | Subscripts |
| air | Air |
| L | Characteristic length |
| s | Surface |

### 5.2 RVTS Dimensional and Material Property Data

#### 5.2.1 Surface Area of RVTS

The RVTS is a circular cylinder with a diameter of 13 feet, and a total length of 24.9375 feet per Figure 2. The outer surface area of the RVTS is computed as shown below.

Cylindrical shell: $A_s = \pi*D*L = \pi*(13.0)*(24.9375) = 1018.47\ ft^2$

Circular end plates: $A_s = 2*[(\pi/4)*D^2] = 2*(\pi/4)*(13.0)^2 = 2*(132.73) = 265.46\ ft^2$

Total surface area: $A_s = 1018.47\ ft^2 + 265.46\ ft^2 = 1283.93\ ft^2$

### 5.2.2 Stainless Steel Insulation

The Reactor Vessel is surrounded by a three-inch thick blanket of insulation, comprised of corrugated foils of type 304 stainless steel, as shown in Reference 7.17. Since the insulation is not a solid region, the air gaps between the stainless steel foils must be considered, and a set of composite material properties chosen for input to the HEATING model. Reference 7.19 is a test report documenting the thermal transference of Johns-Manville metallic pipe and flat panel insulation. The flat panels tested contained five insulating layers, with a foil thickness of 0.003 inches (see Figure 4 of Reference 7.19). This configuration is very similar to the reactor vessel insulation, which has six layers and a foil thickness of 0.003 inches, as shown on Reference 7.17. Therefore, the material property information contained in Reference 7.19 can be considered as representative of the insulation surrounding the reactor vessel.

The density of the stainless steel insulation region is obtained from the data listed in Reference 7.19. The flat panel dimensions are given as 23.875" x 23.875" x 3", and the panel weight is listed as 12.75 $lb_m$. Dividing the insulation mass by the volume results in a density of 12.88 $lb_m/ft^3$ as shown below.

Volume = 23.875" x 23.875" x 3" = 1710.0 $in^3$ = 0.99 $ft^3$
Density = 12.75 $lb_m$ / 0.99 $ft^3$ = 12.88 $lb_m/ft^3$.

The specific heat of the insulation region is taken as that of type 304 stainless steel, which is appropriate considering the mass of air within the insulation region is negligible compared to the stainless steel mass. The thermal conductivity of the insulation region is obtained from the thermal test data provided in Table 1 of Reference 7.19.

The test data reported includes temperatures on both the hot and cold side of the insulation panel, as well as the heat flux to the ambient. The test data is used to obtain an effective thermal conductivity of the insulation, through the use of Fourier's law of heat conduction, shown below.

$$q'' = k\frac{dT}{dx} \qquad \text{(Eq. 5-1)}$$

For a rectangular geometry, the temperature gradient is linear, and the effective thermal conductivity of the insulation can be obtained by rearranging Equation 5-1.

$$k = q''\frac{\Delta x}{\Delta T} \qquad \text{(Eq. 5-2)}$$

The value of $\Delta x$ is three inches, or 0.25 feet. The temperature difference and heat flux values are obtained directly from the test report, and the effective thermal conductivity of the insulation can be computed using Equation 5-2. The thermal conductivities computed below are used as input for the HEATING model, being dependent on the average insulation temperature listed below.

| Hot Surface Temp. | Cold Surface Temp. | Temperature Difference, $\Delta T$ | Average Temp. | Heat Flux $q''$ | Effective Thermal Conductivity |
|---|---|---|---|---|---|
| (°F) | (°F) | (°F) | (°F) | (Btu/hr-ft$^2$) | (Btu/hr-ft-°F) |
| 316 | 126 | 190 | 221 | 17.61 | 0.0232 |
| 393 | 146 | 247 | 269.5 | 26.88 | 0.0272 |
| 506 | 170 | 336 | 338 | 45.45 | 0.0338 |
| 601 | 195 | 406 | 398 | 64.97 | 0.040 |

### 5.2.3 Computation of HEATING Regions Volumes

Each region of the HEATING model is assigned a minimum and maximum coordinate, in the $(r,\theta,z)$ coordinate system, which defines the boundary of the individual region. The volume of each region is then computed, using the equation shown below.

$$Volume = \frac{1}{2}\left(R_{\max}^2 - R_{\min}^2\right)\left(\theta_{\max} - \theta_{\min}\right)\left(Z_{\max} - Z_{\min}\right) \qquad \text{(Eq. 5-3)}$$

where:
$R$ = radius boundary (ft)
$\theta$ = azimuthal boundary (radians)
$Z$ = axial boundary (ft)

Table 2 lists all the dimensional data used to construct the HEATING model, based on the regions identified in Table 1. For those regions which contain a decay heat source term, the decay heat load provided by Design Input 2.7 is divided by the region volume to obtain a volumetric heat load (Btu/hr-ft$^3$) for use in the model.

## 5.3 Thermal Boundary Conditions

### 5.3.1 Solar Insolation Heat Loads

Per Reference 7.1, a solar insolation of 400 g-cal/cm$^2$ is specified for curved surfaces for a 12-hour period. The value of 400 g-cal/cm$^2$ is equal to 1474.7 Btu/ft$^2$. Dividing the total solar insolation by 12 hours gives a heat flux of (1474.7 Btu/ft$^2$) / (12 hr) = 122.9 Btu/hr-ft$^2$. This steady-state heat flux is applied to the curved surfaces of the transportation cask for Case 2. For the flat, vertical ends of the cask, a heat flux of 61.5 Btu/hr-ft$^2$ is applied, consistent with the value of 200 g-cal/cm$^2$ specified in §71.71 of Reference 7.1.

### 5.3.2 Natural Convection for Horizontal Cylindrical Surfaces

The laminar natural convection heat transfer coefficient associated with the RVTS outer surface is computed using Equation (7-27) of Reference 7.3, as shown below.

$$h = \frac{0.27}{D^{1/4}}\Delta T^{1/4} \qquad \text{(Eq. 5-4)}$$

For the RVTS diameter of 13 feet, the natural convection heat transfer coefficient is given as:

$$h = 0.142\Delta T^{1/4} \qquad \text{(Eq. 5-5a)}$$

where the temperature difference is the surface temperature minus the ambient temperature.

Per Assumption 3.8, a 25 percent reduction is taken to account for possible obstruction to heat transfer due to the RVTS support saddle. Therefore, the natural convection heat transfer coefficient for the RVTS cylindrical surface is taken as:

$$h = 0.107\Delta T^{1/4} \qquad \text{(Eq. 5-5b)}$$

### 5.3.3 Natural Convection for Vertical Surfaces

For the vertical end plates of the RVTS, the laminar natural convection heat transfer coefficient is determined using Equation (7-19b) of Reference 7.3.

$$h = 0.555\frac{k}{L}(Gr_L Pr)^{1/4} \qquad \text{(Eq. 5-6)}$$

The characteristic length, $L$, is taken as the RVTS diameter for the purposes of computing the heat transfer coefficient at the vertical end plates.

The Grashof number is defined as shown below, with the fluid properties evaluated at the film temperature, defined as the average of the surface and the ambient temperatures.

$$Gr_L = \frac{\rho^2 g\beta\Delta T L^3}{\mu^2} \qquad \text{(Eq. 5-7)}$$

Substituting the expression for the Grashof number into Equation 5-6 gives the following expression for the natural convection heat transfer coefficient for vertical plates.

$$h = 0.555\frac{k}{L^{1/4}}\left(\frac{\rho^2 g\beta}{\mu^2}Pr\right)^{1/4}\Delta T^{1/4} \qquad \text{(Eq. 5-8)}$$

It is convenient to form the temperature-dependent properties into a single grouping for ease of use in computations. The grouping has the form shown below, and is renamed $C_1$ for brevity.

$$C_1 = \frac{\rho^2 g\beta}{\mu^2} \qquad \text{(Eq. 5-9)}$$

Simplifying Equation 5-8 through the use of Equation 5-9 leads to the expression

$$h = 0.555\frac{k}{L^{1/4}}(C_1 Pr)^{1/4}\Delta T^{1/4} = C_2\Delta T^{1/4} \qquad \text{(Eq. 5-10)}$$

where $C_2$ is a function of the film temperature. The value of $C_2$ is evaluated below for use in the HEATING model, based on air property data obtained from Design Input 2.6.

| Temperature | Thermal Conductivity $k$ | Property Grouping $C_1$ | Prandtl Number $Pr$ | $C_2$ |
|---|---|---|---|---|
| (°F) | (Btu/hr-ft-°F) | (1/ft$^3$-°F) | (N/A) | (Btu/hr-ft$^2$-°F$^{5/4}$) |
| -100 | 0.01046 | 1.34E7 | 0.737 | 0.171 |
| 0 | 0.0133 | 4.20E6 | 0.73 | 0.163 |
| 100 | 0.0154 | 1.76E6 | 0.72 | 0.151 |
| 200 | 0.0174 | 8.50E5 | 0.72 | 0.142 |
| 400 | 0.0212 | 2.58E5 | 0.689 | 0.127 |
| 600 | 0.0250 | 1.06E5 | 0.685 | 0.120 |
| 800 | 0.0286 | 4.98E4 | 0.697 | 0.114 |

5.3.4 Radiation Heat Transfer from RVTS to Ambient

To model radiation from the surface of the RVTS to the ambient environment, an emissivity, $\varepsilon_s$, of 0.66 is employed per Design Input 2.7.

The total heat transfer rate from the RVTS surface to the ambient air is then calculated from the relation

$$q_{radiation} = \varepsilon_s \sigma A_s \left(T_s^4 - T_{air}^4\right) \quad \text{(Eq. 5-11)}$$

where the temperatures are in absolute units of °R.

5.3.5 Forced Convection Heat Transfer from Combustion Flames

Convective heat transfer from the combustion gases of the hypothetical accident fire to the RVTS are dominated by forced convection. Equation 18a of Reference 7.22, shown below, is based on measurements of turbulent, steady-state convection for flows parallel to flat plates. A turbulent forced convection heat transfer coefficient is conservatively employed for all ranges of Reynolds numbers. The length scale used in the correlation is the length of the surface in the direction of flow. For vertical flow, the length scale of interest in this analysis is the RVTS diameter, *D*.

$$Nu = 0.037 Re^{0.8} Pr^{0.6} \quad \text{(Eq. 5-12)}$$

$$h = \frac{kNu}{D} \quad \text{(Eq. 5-13)}$$

The Reynolds number is defined as shown below, where *V* is the flame velocity in feet/second.

$$Re = \frac{VD}{\nu} \quad \text{(Eq. 5-14)}$$

Figure 7.1.3 of Reference 7.23 reports a range of flame velocities for various hydrocarbons burned in air at atmospheric conditions. The maximum hydrocarbon flame velocity is approximately 5.0 feet/sec for $C_2H_2$ gas, although a flame velocity of approximately 8.0 feet/sec is shown for hydrogen, $H_2$. To envelop this data, a flame velocity of 10.0 feet/sec is chosen to conservatively estimate the forced convection heat transfer coefficient.

Gas properties for carbon dioxide ($CO_2$) and water vapor ($H_2O$) are taken from Table A-3 of Reference 7.3 at temperatures which are representative of the 1475 °F flame temperature specified in Reference 7.1. $CO_2$ and $H_2O$ are selected for evaluation as these are the primary gaseous products of a hydrocarbon/air combustion process.

| Gas | Thermal Conductivity | Kinematic Viscosity | Prandtl Number | Reynolds Number | Nusselt Number | Heat Transfer Coefficient |
|---|---|---|---|---|---|---|
| | (Btu/hr-ft-°F) | ($ft^2$/sec) | (N/A) | (N/A) | (N/A) | (Btu/hr-$ft^2$-°F) |
| $CO_2$@ 1500 °F | 0.0420 | 0.000925 | 0.73 | 140540.5 | 402.2 | 1.30 |
| $H_2O$@ 1400 °F | 0.053 | 0.00178 | 0.87 | 73033.7 | 264.7 | 1.08 |

To conservatively bound any uncertainties in the estimation of the heat transfer coefficient, a factor of two is applied to the maximum value computed in the above table. Therefore, a forced convection heat transfer coefficient of 2.6 Btu/hr-ft$^2$-°F is used for the hypothetical accident case. The PATRAM 1986 Symposium presentation, *Heat Transfer Boundary Conditions in Pool Fires* recommends an average heat transfer coefficient of 1.7 BTU/hr-ft$^2$-°F for HAC fire conditions. Therefore, the usage of a forced convection heat transfer coefficient of 2.6 BTU/hr-ft$^2$-°F is conservative.

### 5.3.6 Radiation Heat Transfer Across Gap Region

To model radiation heat transfer across the gap region shown in Figure 7, the methodology cited in Reference 7.2 is employed to approximate one-dimensional radiation exchange for narrow gaps. An effective heat transfer coefficient for radiation exchange, $h_r$, is provided as Equation 3.8 of Reference 7.2, shown below.

$$h_r = \frac{\sigma}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1)} \qquad \text{(Eq. 5-15)}$$

where
- $A_1$ = the surface area corresponding to the smaller radius
- $A_2$ = the surface area corresponding to the larger radius
- $\varepsilon_1$ = emissivity of surface corresponding to the smaller radius
- $\varepsilon_2$ = emissivity of surface corresponding to the larger radius

The numeric value of the surface area ratio $A_1/A_2$ equal to the ratio of radii $r_1/r_2$. This value is determined from a review of Figure 7, and is computed to be 74.875 / 75.0 = 0.9983. The emissivity values are the same for each surface, with $\varepsilon = 0.66$. Solving for $h_r$ gives:

$$h_r = \frac{0.1714E-8}{1/0.66 + (0.9983)(1/0.66 - 1)} = 8.446 \times 10^{-10} \text{ Btu/hr-ft}^2\text{-°R}$$

This heat transfer coefficient is applied to gap region number 51, as shown in Figure 7. The HEATING model is modified to per Figure 7 accommodate the gap region for Cases Gap1 and Gap2.

## 6.0 Results

The results of the HEATING analysis are summarized below, with computer code input and output files documented in Attachment A for the various cases examined in this calculation.

### 6.1 Maximum Accessible Surface Temperature

For the Case 1a analysis, the maximum accessible surface temperature of the RVTS is 101.2 °F. This surface temperature occurs on the top surface, at an elevation of $z$ = 24.94 feet. A sensitivity run is made with an RVTS surface emissivity value of $\varepsilon$ = 0.0. The maximum surface temperature computed for this scenario, Case 1b, is 103.8 °F, which is a 2.6 °F temperature increase over the Case 1a result. A plot of the radial temperature profile, at the top plate of the active region, is shown in Figure 8. The profile shown in Figure 8 is for the limiting azimuthal angle of $\theta$ = 90°, consistent with the location of the GBEP hot spot, as discussed on page 11. The peak in the radial profile of Figure 8 occurs at the modeled location of the GBEP hot spot.

The maximum RVTS surface temperature is below the acceptance criteria of 185 °F, therefore the requirements of 10 CRF 71.43 have been met.

Other results of this calculation are presented below, for use in structural analyses of the RVTS.

### 6.2 Normal Conditions of Transport

For the Case 2a scenario, NCT with applied solar insolation heat loads at an ambient temperature of 100 °F, the maximum temperature inside the RVTS is 191.18 °F. This point is located near the center of the active fuel region, at the elevation of $z$ = 11.91 feet. The maximum outer surface temperature of the RVTS is 191.2 °F. Plots of radial temperature profiles at various $z$ elevations are shown in Figure 9 and Figure 10.

The Case 2b sensitivity run models a crushed stainless steel insulation region, where the thermal conductivity of the insulation is replaced with that of 50 $lb_m/ft^3$ LDCC. The thermal gradient in the insulation region for Case 2b is approximately 1.5 °F, compared to 6.7 °F for Case 2a. The maximum outer surface temperature of the RVTS is 191.1 °F. The results of the Case 2b scenario indicate that the consequences of potentially crushed reactor vessel insulation are negligible in terms of RVTS thermal performance.

For the Case 3a scenario, NCT with no solar insolation and an ambient temperature of -40 °F, the maximum temperature inside the RVTS is –21.72 °F, occurring at the top plate at elevation 15.45 feet. The minimum RVTS surface temperature for the Case 3a analysis is –39.4 °F. The corresponding maximum internal temperature and minimum surface temperature for the Case 3b analysis are –1.81 °F and –19.45 °F respectively. Plots of radial temperature profiles at the active fuel region midpoint elevation are shown in Figure 11 for Cases 3a and 3b. The profile shown in Figure 11 is for the limiting azimuthal angle of $\theta$ = 90°, consistent with the location of the GBEP hot spot. The peak in the radial profile of Figure 11 occurs at the modeled location of the GBEP hot spot.

The effects of a postulated 0.125-inch gap between the 3-inch RVTS wall and the 4-inch shield plate are examined in sensitivity runs Case Gap1 (100 °F ambient air with no solar insolation) and Case Gap2 (100 °F ambient air with solar insolation). For Case Gap1, the temperature drop across the gap region is approximately 0.3 °F. For Case Gap2, the temperature drop across the gap region is approximately 0.5 °F. The change in RVTS surface temperature in the active region is less than 0.1 °F, when compared to the results of Cases 1a and 2a. Therefore, the effect of a postulated 0.125-inch gap between the RVTS wall and the shield plate is negligible in terms of RVTS thermal performance.

## 6.3 Hypothetical Accident Condition

For the Case 4a scenario, the maximum temperature is reached at 30 minutes after initiation of the postulated hydrocarbon fire. The maximum temperature is 1457.6 °F, located on the outer surface of the RVTS at $z = 0.0$ feet and $r = 6.5$ feet. Figure 12 shows time-dependent radial temperature profiles at the midpoint elevation of the active region for the Case 4a analysis. The temperature in the RVTS outer wall and the external grout are shown to increase sharply during the postulated hydrocarbon fire, with the maximum temperatures occurring at the RVTS outer surface. After the 30 minute fire, the RVTS outer wall begins to cool, however the peak RVTS wall temperature is still approximately 1100 °F 30 minutes after the postulated fire has been extinguished.

The results of Case 4b are similar to those of Case 4a, however the peak surface temperatures are slightly less than the Case 4a results. However, the temperature gradient in the RVTS wall is greater for the Case 4b scenario, due to the colder initial RVTS temperature distribution.

The temperature distribution for all cases analyzed in this calculation are tabulated in Table 4 for use in external structural analyses of the RVTS.

## 6.4 Other Considerations

The potential use of additional local shielding on the RVTS surface, nominally 0.5-inch thick steel plate, will have negligible impact on the thermal response of the RVTS documented in this calculation.

The thermal resistance (per unit area) to radial heat conduction of the RVTS wall and the 50 pcf LDCC in the active region, combined in series, is computed below based on the material thickness and thermal conductivity of the respective materials. See page 6 and page 39 for thermal conductivities and material thickness.

= (7"/12) / 23.6 Btu/hr-ft-F+ (9.53"/12) / 0.146 Btu/hr-ft-F

= 0.0247 hr-ft$^2$-F/Btu + 5.439 hr-ft$^2$-F/Btu

= 5.464 hr-ft$^2$-F/Btu

The thermal resistance of the 0.5 inch additional local shielding is equal to (0.5"/12) / 23.6 = 0.00177 ft$^2$-hr-F/Btu. Since this value is negligible compared to the thermal resistance of the LDCC and RVTS wall, the temperature gradients documented in this calculation will be essentially unaffected by the potential use of 0.5-inch additional local shielding on the RVTS surface.

## 7.0 References


7.1 United States Nuclear Regulatory Commission Rules and Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Materials", January 30, 1998.

7.2 HEATING 7.2f, Multidimensional, Finite-Difference Heat Conduction Analysis, Sargent & Lundy Program No. 03.7.564-7.2.

7.3 Principles of Heat Transfer, Frank Kreith, 3rd Edition, 1973.

7.4 Introduction to Heat Transfer, Frank P. Incropera & David P. DeWitt, Second Edition, 1990.

7.5 ASME Boiler and Pressure Vessel Code, Section II, Part D, "Properties", 1995 Edition, July 1, 1995.

7.6 SFPE Handbook of Fire Protection Engineering, Second Edition, 1995.

7.7 Thermal Radiation Heat Transfer, Siegel and Howell, 1972.

7.8 Flow of Fluids Through Valves, Fittings, and Pipe, Crane Technical Paper No. 410, Twenty Fifth Printing, 1991.

7.9 Sargent & Lundy Calculation No. N-10525-020-0001, Rev. 1, "Reactor Vessel Heat Rates and Shielding.

7.10 1997 ASHRAE Handbook, *Fundamentals*, Inch-Pound Edition.

7.11 WMG Inc. Report WMG-9902, Rev. 1, "Big Rock Point Reactor Vessel and Internals Characterization and Classification", June 1999.

7.12 Combustion Engineering Drawing No. F-230-791-2, Rev. 2, "General Arrangement – Reactor Vessel".

7.13 Combustion Engineering Drawing No. E-201-806-4, Rev. 4, "Closure Head Forming & Welding - Reactor Vessel".

7.14 General Electric Drawing No. 197E853, Rev. 2, “Vessel & Core Arrangement”.

7.15 General Electric Drawing No. 107C3539, Rev. 0, “Window”.

7.16 General Electric Drawing No. 141F797, Rev. 5, “Thermal Shield”.

7.17 Johns-Manville Co. Drawing No. BL-13954-1, Rev. 4, "Blanket Insulation".

7.18 General Electric Drawing No. 104R175, Sheet 4, Rev. 3, “Assembly Reactor Vessel”.

7.19 Determination of Thermal Transference of Metallic Pipe Insulation, Prepared for Johns-Manville Corporation by Colorado School of Mines Research Institute, January 26, 1973.

7.20 ACI Manual of Concrete Practice, Part 3 – 1998; ACI 216R-89 (Reapproved 1994), "Guide for Determining the Fire Endurance of Concrete Elements".

7.21 *Steels for Nuclear Applications*, Chapter 3: Mechanical and Physical Properties of Steels for Nuclear Applications, United States Steel Corporation, 1967.

7.22 NUREG/CR-3779, SAND83-2579, Vol. 2, "Hydrogen Burn – Equipment Response Algorithm (HYBER): Reference Manual", August, 1984.

7.23 Marks' Standard Handbook for Mechanical Engineers, Ninth Edition, Ed. Eugene A. Avallone, McGraw-Hill Book Company, New York, 1987.

7.24 Sargent & Lundy Calculation No. N-10525-020-0002, Rev. 1, "Transport Package Shielding Design".

7.25 Deleted

7.26 Sargent & Lundy Calculation No. N-10525-020-004, Rev. 1, "Reactor Vessel Transport System Radiation Source Term.

7.27 General Electric Drawing No. 104R175, Sheet 2, Rev. 6, "Assembly Reactor Vessel".

7.28 General Electric Drawing No. 197E861, Rev. 4, "Top Guide".

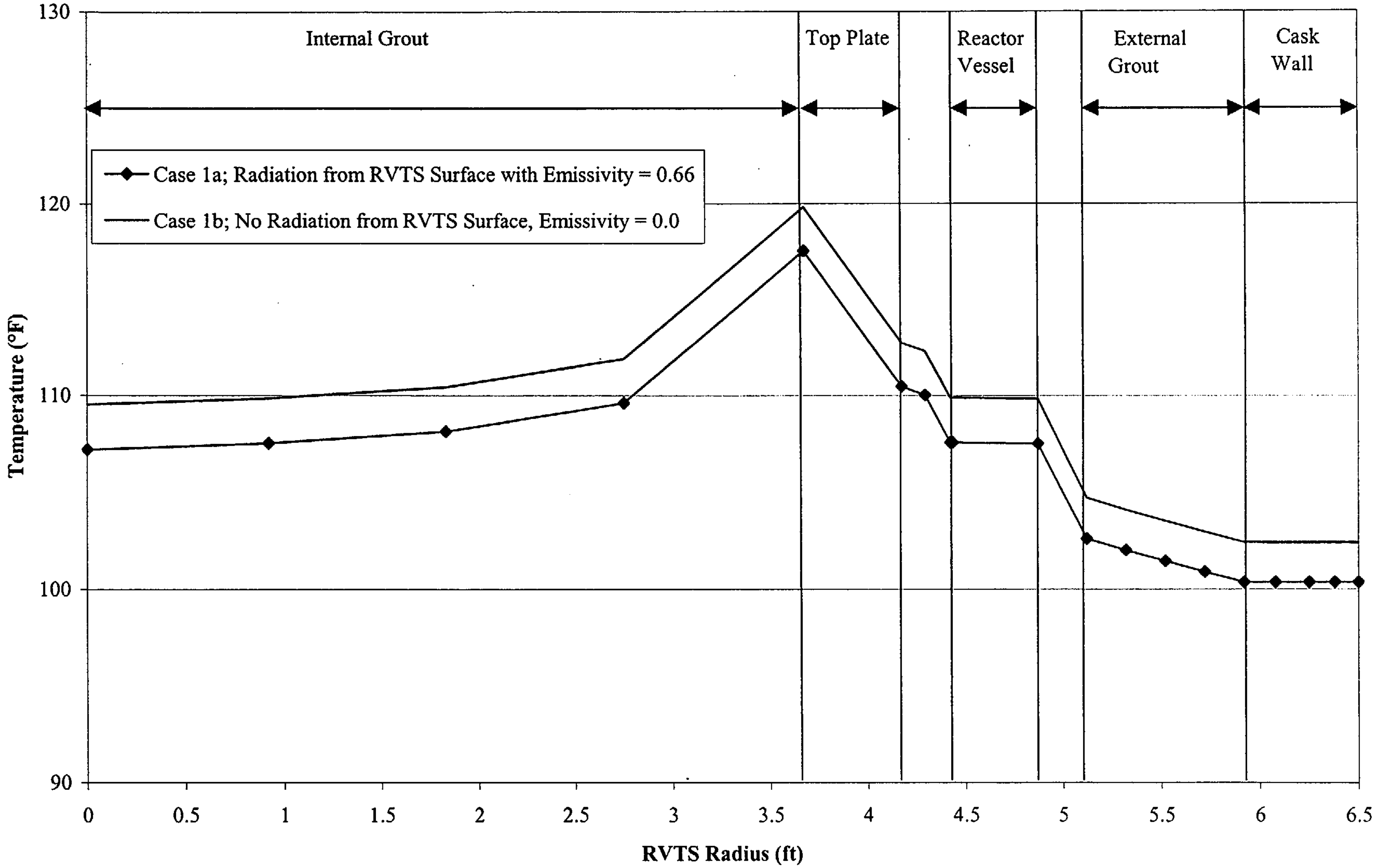
7.29 General Electric Drawing No. 198E118, Rev. 2, "Top Plate".

7.30 Sargent & Lundy Drawing No. SD-10525-020-001, Rev. 1, "RVTS Cask - Major Component Removal Big Rock Point Restoration", (See Attachment C, pages C1 – C2).

7.31 Sargent & Lundy Drawing No. SD-10525-020-002, Rev. 1, "RVTS Tie-Down System - Major Component Removal Big Rock Point Restoration", (See Attachment C, pages C3 – C4).

## Figure 8
### Case 1: Maximum Surface Temperature with No Insolation

### Temperature Profile at Top Plate in Active Region, θ = 90°, Z = 15.45 feet



## Figure 9
## Case 2a: Normal Conditions of Transport with Solar Insolation

**Radial Temperature Profiles at θ = 90°**

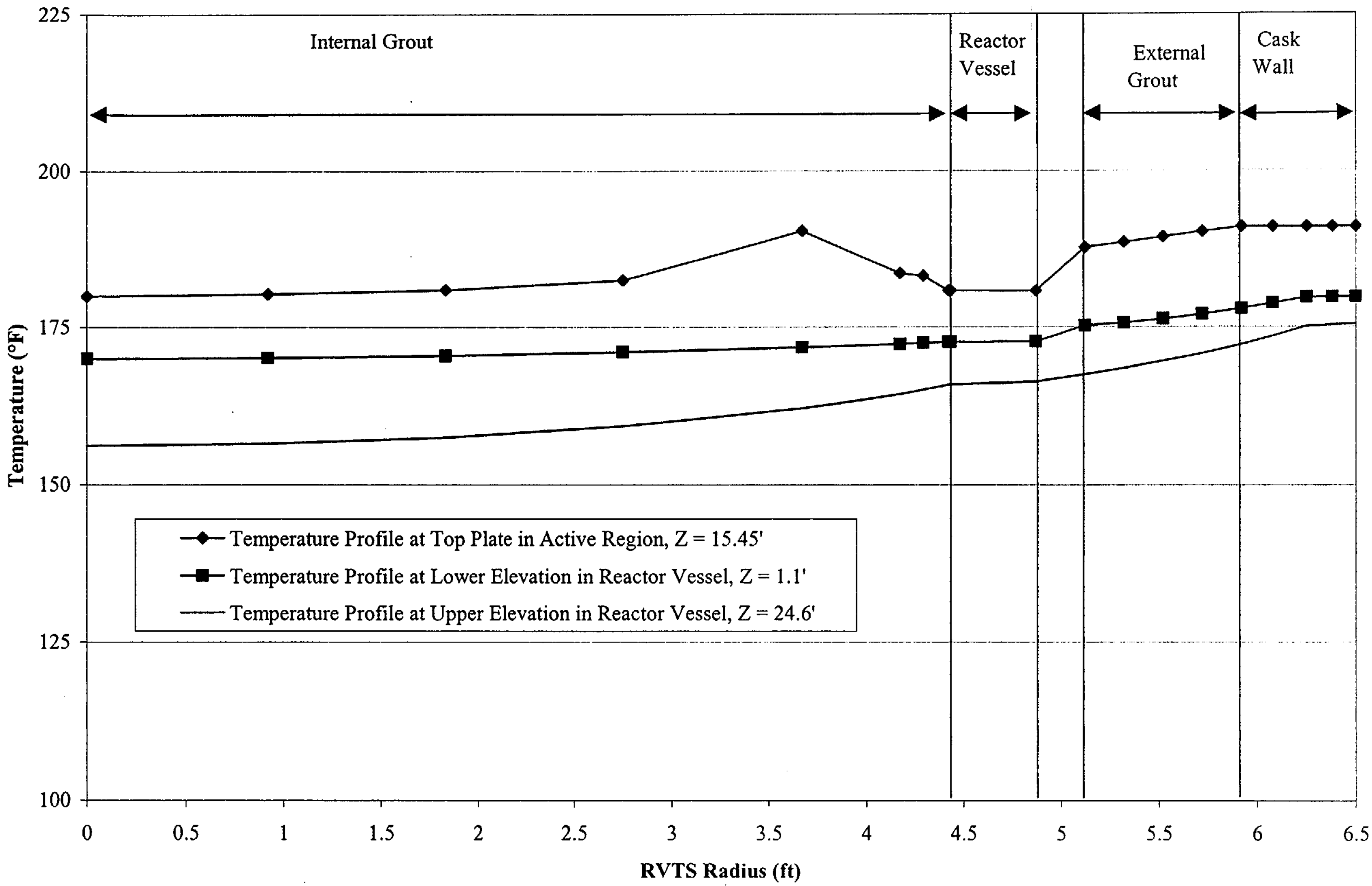


**Figure 10**

**Case 2a: Normal Conditions of Transport with Solar Insolation**

**Radial Temperature Profiles at θ = 90°**

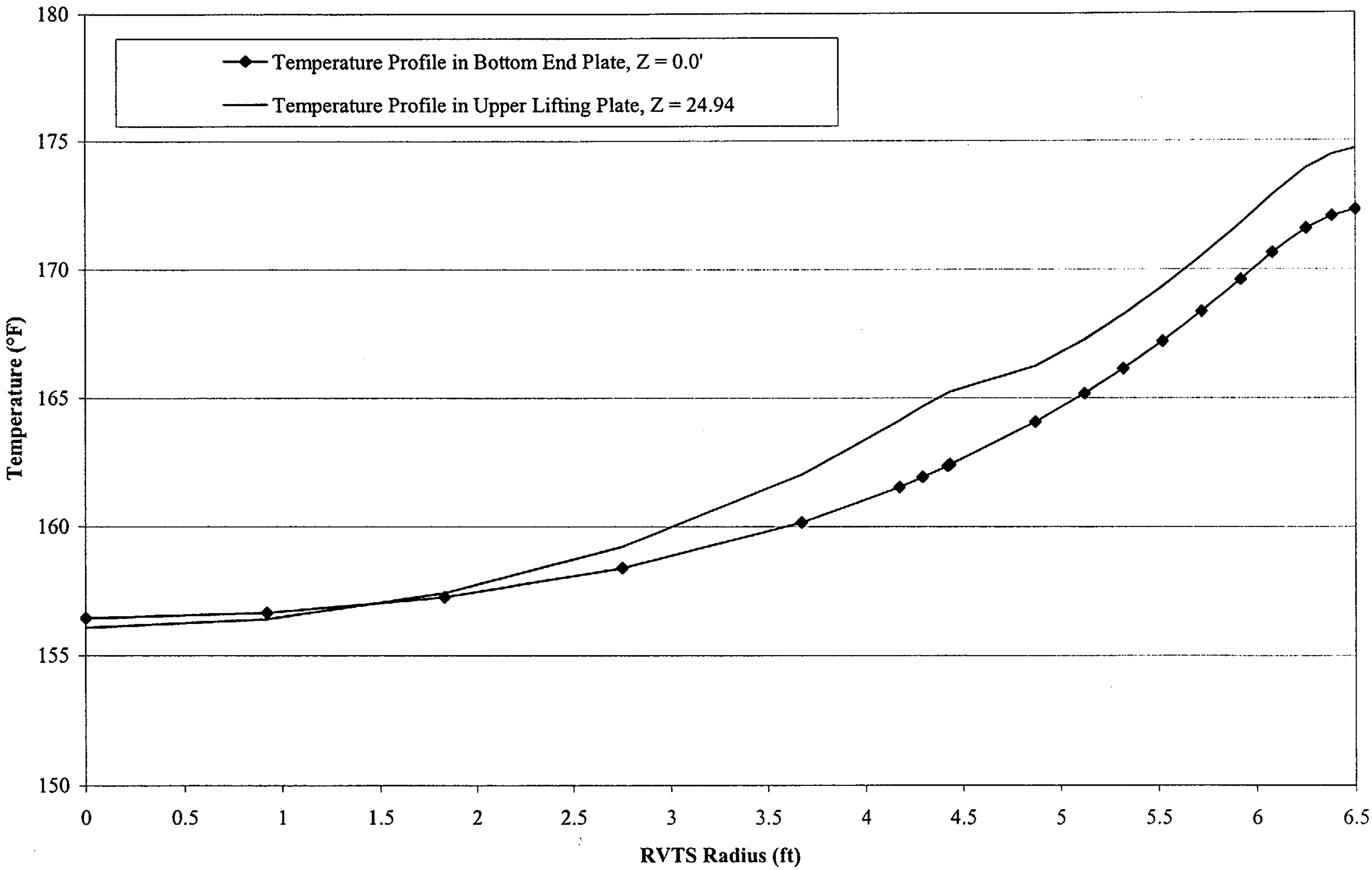
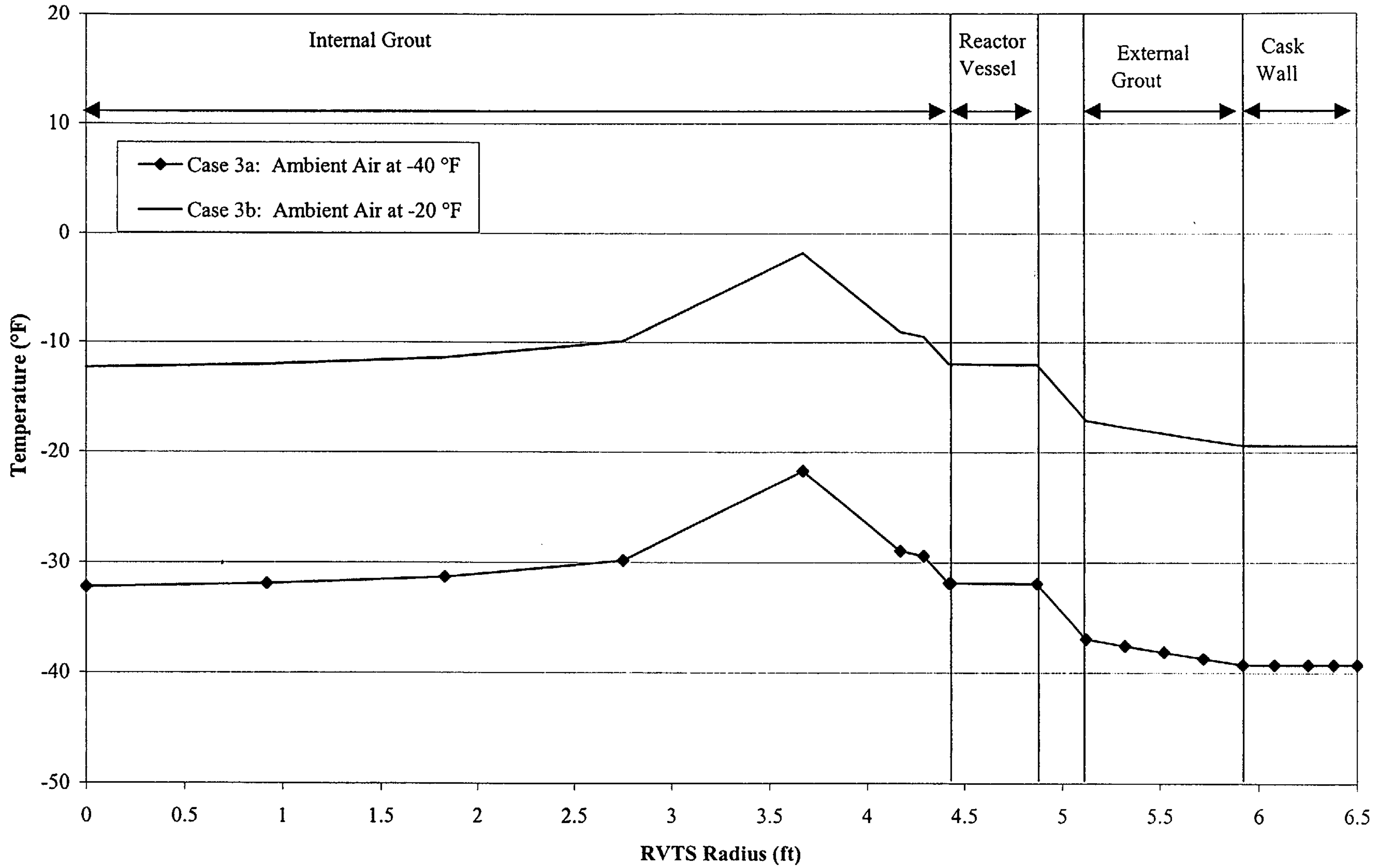


**Figure 11**

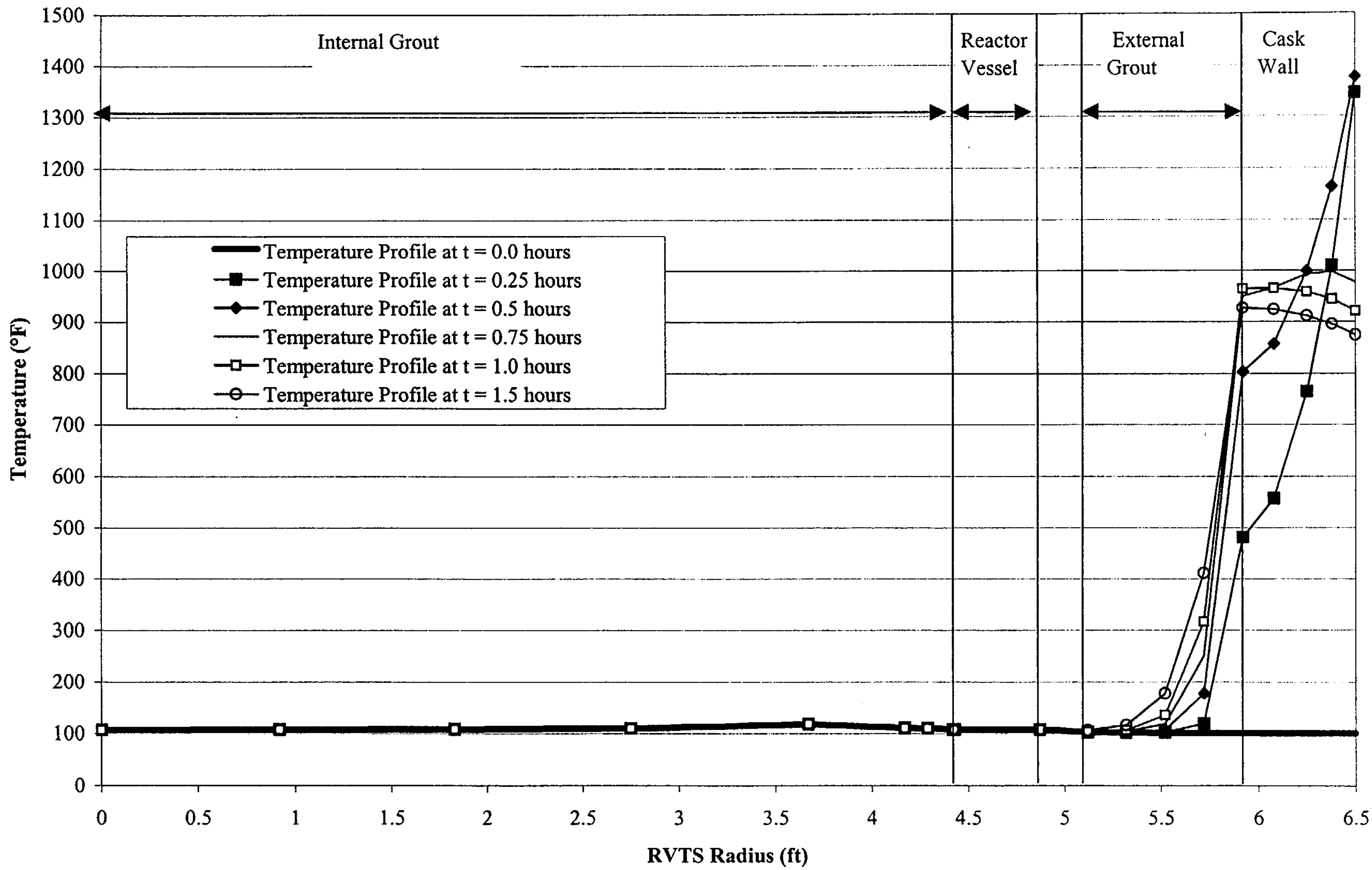
**Case 3: Normal Conditions of Transport without Solar Insolation**

**Temperature Profile at Top Plate in Active Region, θ = 90°, Z = 15.45**



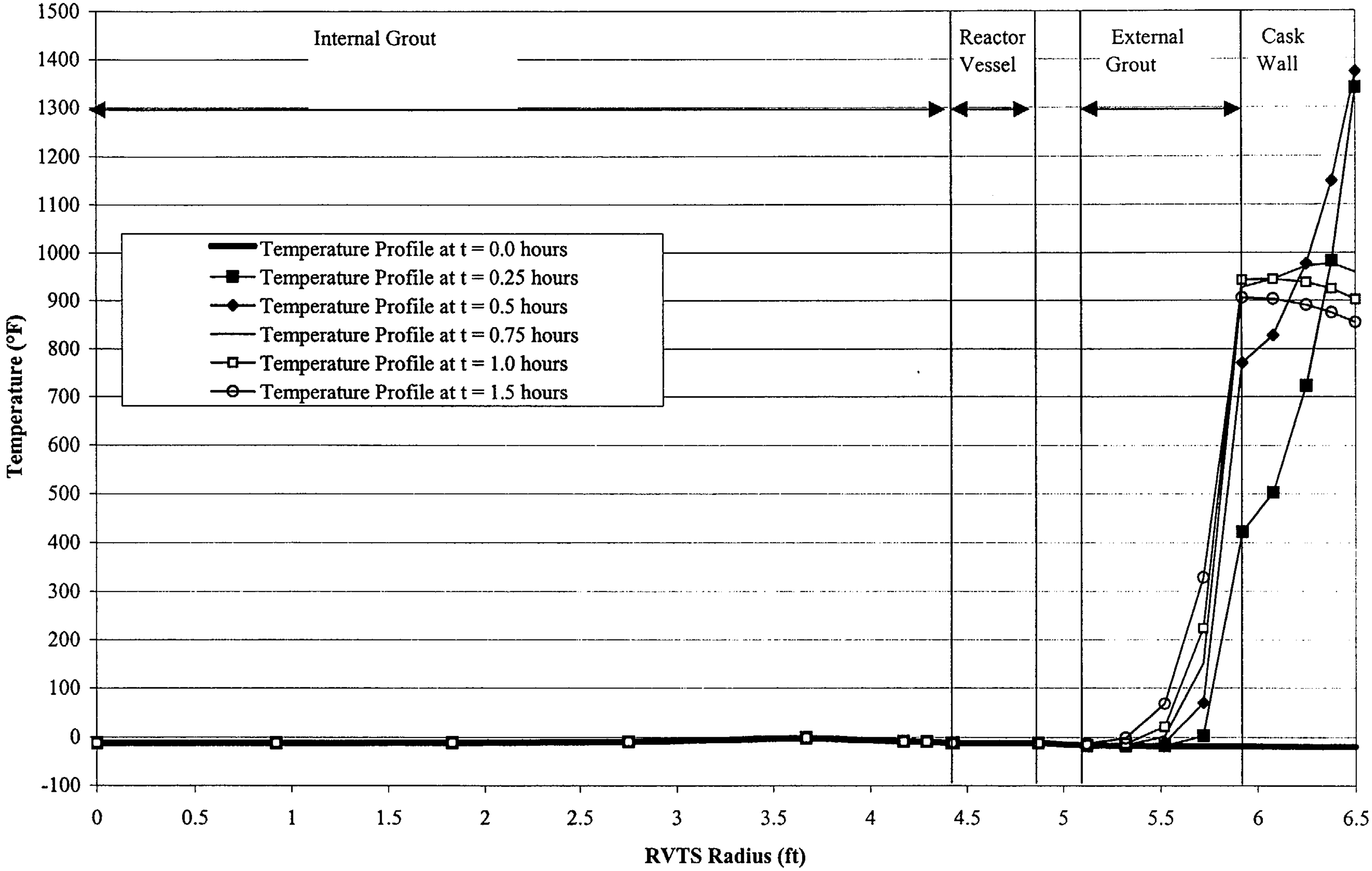
## Figure 12
## Case 4a: Hypothetical Accident Condition

**Temperature Profiles at Top Plate in Active Region, θ = 90°, Z = 15.45'**
**Ambient Air Temperature of 100 °F Before and After Fire**



## Figure 13
## Case 4b: Hypothetical Accident Condition

### Temperature Profiles at Top Plate in Active Region, θ = 90°, Z = 15.45'
### Ambient Air Temperature of -20 °F Before and After Fire



# Tab.. 1
## Summary of Regions for HEATING Model

| Region | Description | Min R (in) | Max R (in) | Min θ (°) | Max θ (°) | Min Z (in) | Max Z (in) | Material | Mat No. | Heat Load (Btu/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bottom of Cask | 0 | 78 | 0 | 360 | 0 | 4 | ASTM A516 Grade 70 | 1 | 0.0 |
| 2 | Side Wall of Cask Below Active Region | 75 | 78 | 0 | 360 | 4 | 101.375 | ASTM A516 Grade 70 | 1 | 0.0 |
| 3 | Side Wall of Cask in Active Region | 71 | 78 | 0 | 360 | 101.375 | 197.375 | ASTM A516 Grade 70 | 1 | 0.0 |
| 4 | Side Wall of Cask Above Active Region | 75 | 78 | 0 | 360 | 197.375 | 299.25 | ASTM A516 Grade 70 | 1 | 0.0 |
| 5 | Top Lifting Plate of Cask | 0 | 75 | 0 | 360 | 295.25 | 299.25 | ASTM A516 Grade 70 | 1 | 0.0 |
| 6 | External LDCC Below Vessel | 0 | 75 | 0 | 360 | 4 | 8 | Grout (50 $lb_m/ft^3$) | 2 | 0.0 |
| 7 | External LDCC Along Vessel Below Active Region | 61.46875 | 75 | 0 | 360 | 8 | 101.375 | Grout (50 $lb_m/ft^3$) | 2 | 0.0 |
| 8 | External LDCC Along Vessel in Active Region | 61.46875 | 71 | 0 | 360 | 101.375 | 197.375 | Grout (50 $lb_m/ft^3$) | 2 | 0.0 |
| 9 | External LDCC Along Vessel Above Active Region | 61.46875 | 75 | 0 | 360 | 197.375 | 295.25 | Grout (50 $lb_m/ft^3$) | 2 | 0.0 |
| 10 | SS Insulation on Reactor Vessel Exterior | 58.46875 | 61.46875 | 0 | 360 | 8 | 295.25 | SS 304 Folded Foil | 3 | 2.19 |
| 11 | Reactor Vessel Bottom | 0 | 58.46875 | 0 | 360 | 8 | 13.25 | SA-302 Grade B | 4 | 0.0 |
| 12 | Reactor Vessel Side Wall | 53.21875 | 58.46875 | 0 | 360 | 13.25 | 295.25 | SA-302 Grade B | 4 | 41.8 |
| 13 | SS Cladding on Reactor Vessel Interior | 53.0625 | 53.21875 | 0 | 360 | 13.25 | 295.25 | SS 304 | 5 | 9.23 |
| 14 | Interior LDCC Below Active Region | 0 | 53.0625 | 0 | 360 | 13.25 | 101.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.0 |
| 15 | Interior LDCC Above Active Region | 0 | 53.0625 | 0 | 360 | 193.375 | 295.25 | Grout (30 $lb_m/ft^3$) | 6 | 0.0 |
| 16 | Top Guide Plate with GBEP | 44 | 50 | 0 | 89 | 184.375 | 185.375 | SS 304 | 5 | 25.4 |
| 17 | Top Guide Plate with GBEP Hot Spot | 44 | 50 | 89 | 91 | 184.375 | 185.375 | SS 304 | 5 | 29.74 |
| 18 | Top Guide Plate with GBEP | 44 | 50 | 91 | 180 | 184.375 | 185.375 | SS 304 | 5 | 25.4 |
| 19 | Top Guide Plate without Top Guide End Stubs | 44 | 50 | 180 | 360 | 184.375 | 185.375 | SS 304 | 5 | 21.5 |
| 20 | Thermal Shield | 50 | 51.5 | 0 | 360 | 101.375 | 193.375 | SS 304 | 5 | 278.8 |
| 21 | Seal Weight | 51.5 | 53.0625 | 5 | 25 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 22 | Seal Weight | 51.5 | 53.0625 | 35 | 55 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 23 | Seal Weight | 51.5 | 53.0625 | 65 | 85 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 24 | Seal Weight | 51.5 | 53.0625 | 95 | 115 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 25 | Seal Weight | 51.5 | 53.0625 | 125 | 145 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |

# Table (
## Summary of Regions for HEATING Model

| Region | Description | Min R (in) | Max R (in) | Min θ (°) | Max θ (°) | Min Z (in) | Max Z (in) | Material | Mat No. | Heat Load (Btu/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 26 | Seal Weight | 51.5 | 53.0625 | 155 | 175 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 27 | Seal Weight | 51.5 | 53.0625 | 185 | 205 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 28 | Seal Weight | 51.5 | 53.0625 | 215 | 235 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 29 | Seal Weight | 51.5 | 53.0625 | 245 | 265 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 30 | Seal Weight | 51.5 | 53.0625 | 275 | 295 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 31 | Seal Weight | 51.5 | 53.0625 | 305 | 325 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 32 | Seal Weight | 51.5 | 53.0625 | 335 | 355 | 101.375 | 185.375 | SS 304 | 5 | 3.45 |
| 33 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 0 | 5 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 34 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 25 | 35 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 35 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 55 | 65 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 36 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 85 | 95 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 37 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 115 | 125 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 38 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 145 | 155 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 39 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 175 | 185 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 40 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 205 | 215 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 41 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 235 | 245 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 42 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 265 | 275 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 43 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 295 | 305 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 44 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 325 | 335 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 45 | LDCC Space between Seal Weights | 51.5 | 53.0625 | 355 | 360 | 101.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 46 | Interior LDCC in Active Region below Top Guide | 0 | 50 | 0 | 360 | 101.375 | 184.375 | Grout (30 $lb_m/ft^3$) | 6 | 9.64 |
| 47 | Interior LDCC within Top Guide Plate | 0 | 44 | 0 | 360 | 184.375 | 185.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 48 | Interior LDCC in Active Region above Top Guide | 0 | 50 | 0 | 360 | 185.375 | 193.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |
| 49 | LDCC Between RV Wall & Thermal Shield above Seal Weights | 51.5 | 53.0625 | 0 | 360 | 185.375 | 193.375 | Grout (30 $lb_m/ft^3$) | 6 | 0.00 |

## Table 2
## Dimensional Input Data for HEATING Model

| Region | Min R (in) | Max R (in) | Min θ (°) | Max θ (°) | Min Z (in) | Max Z (in) | Min R (feet) | Max R (feet) | Min θ (radians) | Max θ (radians) | Min Z (feet) | Max Z (feet) | Volume ($ft^3$) | Heat Load (Btu/hr) | Heat Source ($Btu/ft^3$-hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **0** | 78 | **0** | 360 | **0** | 4 | 0.0 | 6.5 | 0.0 | 6.2832 | 0.0 | 0.3333 | 44.24 | **0.0** | 0.0 |
| 2 | **75** | 78 | **0** | 360 | **4** | 101.375 | 6.25 | 6.5 | 0.0 | 6.2832 | 0.3333 | 8.4479 | 81.26 | **0.0** | 0.0 |
| 3 | **71** | 78 | **0** | 360 | **101.375** | 197.375 | 5.9167 | 6.5 | 0.0 | 6.2832 | 8.4479 | 16.4479 | 182.04 | **0.0** | 0.0 |
| 4 | **75** | 78 | **0** | 360 | **197.375** | 299.25 | 6.25 | 6.5 | 0.0 | 6.2832 | 16.4479 | 24.9375 | 85.01 | **0.0** | 0.0 |
| 5 | **0** | 75 | **0** | 360 | **295.25** | 299.25 | 0.0 | 6.25 | 0.0 | 6.2832 | 24.6042 | 24.9375 | 40.91 | **0.0** | 0.0 |
| 6 | **0** | 75 | **0** | 360 | **4** | 8 | 0.0 | 6.25 | 0.0 | 6.2832 | 0.3333 | 0.6667 | 40.91 | **0.0** | 0.0 |
| 7 | **61.46875** | 75 | **0** | 360 | **8** | 101.375 | 5.1224 | 6.25 | 0.0 | 6.2832 | 0.6667 | 8.4479 | 313.48 | **0.0** | 0.0 |
| 8 | **61.46875** | 71 | **0** | 360 | **101.375** | 197.375 | 5.1224 | 5.9167 | 0.0 | 6.2832 | 8.4479 | 16.4479 | 220.36 | **0.0** | 0.0 |
| 9 | **61.46875** | 75 | **0** | 360 | **197.375** | 295.25 | 5.1224 | 6.25 | 0.0 | 6.2832 | 16.4479 | 24.6042 | 328.59 | **0.0** | 0.0 |
| 10 | **58.46875** | 61.46875 | **0** | 360 | **8** | 295.25 | 4.8724 | 5.1224 | 0.0 | 6.2832 | 0.6667 | 24.6042 | 187.91 | **2.19** | 0.012 |
| 11 | **0** | 58.46875 | **0** | 360 | **8** | 13.25 | 0.0 | 4.8724 | 0.0 | 6.2832 | 0.6667 | 1.1042 | 32.63 | **0.0** | 0.0 |
| 12 | **53.21875** | 58.46875 | **0** | 360 | **13.25** | 295.25 | 4.4349 | 4.8724 | 0.0 | 6.2832 | 1.1042 | 24.6042 | 300.62 | **41.8** | 0.14 |
| 13 | **53.0625** | 53.21875 | **0** | 360 | **13.25** | 295.25 | 4.4219 | 4.4349 | 0.0 | 6.2832 | 1.1042 | 24.6042 | 8.51 | **9.23** | 1.08 |
| 14 | **0** | 53.0625 | **0** | 360 | **13.25** | 101.375 | 0.0 | 4.4219 | 0.0 | 6.2832 | 1.1042 | 8.4479 | 451.11 | **0.0** | 0.0 |
| 15 | **0** | 53.0625 | **0** | 360 | **193.375** | 295.25 | 0.0 | 4.4219 | 0.0 | 6.2832 | 16.1146 | 24.6042 | 521.49 | **0.0** | 0.0 |
| 16 | **44** | 50 | **0** | 89 | **184.375** | 185.375 | 3.6667 | 4.1667 | 0.0000 | 1.5533 | 15.3646 | 15.4479 | 0.253 | **25.38** | 100.12 |
| 17 | **44** | 50 | **89** | 91 | **184.375** | 185.375 | 3.6667 | 4.1667 | 1.5533 | 1.5882 | 15.3646 | 15.4479 | 0.006 | **29.74** | 5220.69 |
| 18 | **44** | 50 | **91** | 180 | **184.375** | 185.375 | 3.6667 | 4.1667 | 1.5882 | 3.1416 | 15.3646 | 15.4479 | 0.253 | **25.38** | 100.12 |
| 19 | **44** | 50 | **180** | 360 | **184.375** | 185.375 | 3.6667 | 4.1667 | 3.1416 | 6.2832 | 15.3646 | 15.4479 | 0.513 | **21.5** | 41.94 |
| 20 | **50** | 51.5 | **0** | 360 | **101.375** | 193.375 | 4.1667 | 4.2917 | 0.0 | 6.2832 | 8.4479 | 16.1146 | 25.47 | **278.8** | 10.95 |
| 21 | **51.5** | 53.0625 | **5** | 25 | **101.375** | 185.375 | 4.2917 | 4.4219 | 0.08727 | 0.4363 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 22 | **51.5** | 53.0625 | **35** | 55 | **101.375** | 185.375 | 4.2917 | 4.4219 | 0.6109 | 0.9599 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 23 | **51.5** | 53.0625 | **65** | 85 | **101.375** | 185.375 | 4.2917 | 4.4219 | 1.1345 | 1.4835 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 24 | **51.5** | 53.0625 | **95** | 115 | **101.375** | 185.375 | 4.2917 | 4.4219 | 1.6581 | 2.0071 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 25 | **51.5** | 53.0625 | **125** | 145 | **101.375** | 185.375 | 4.2917 | 4.4219 | 2.1817 | 2.5307 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |

## Table 2
## Dimensional Input Data for HEATING Model

| Region | Min R (in) | Max R (in) | Min θ (°) | Max θ (°) | Min Z (in) | Max Z (in) | Min R (feet) | Max R (feet) | Min θ (radians) | Max θ (radians) | Min Z (feet) | Max Z (feet) | Volume ($ft^3$) | Heat Load (Btu/hr) | Heat Source (Btu/$ft^3$-hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 51.5 | 53.0625 | 155 | 175 | 101.375 | 185.375 | 4.2917 | 4.4219 | 2.7053 | 3.0543 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 27 | 51.5 | 53.0625 | 185 | 205 | 101.375 | 185.375 | 4.2917 | 4.4219 | 3.2289 | 3.5779 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 28 | 51.5 | 53.0625 | 215 | 235 | 101.375 | 185.375 | 4.2917 | 4.4219 | 3.7525 | 4.1015 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 29 | 51.5 | 53.0625 | 245 | 265 | 101.375 | 185.375 | 4.2917 | 4.4219 | 4.2761 | 4.6251 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 30 | 51.5 | 53.0625 | 275 | 295 | 101.375 | 185.375 | 4.2917 | 4.4219 | 4.7997 | 5.1487 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 31 | 51.5 | 53.0625 | 305 | 325 | 101.375 | 185.375 | 4.2917 | 4.4219 | 5.3233 | 5.6723 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 32 | 51.5 | 53.0625 | 335 | 355 | 101.375 | 185.375 | 4.2917 | 4.4219 | 5.8469 | 6.1959 | 8.4479 | 15.4479 | 1.39 | **3.45** | 2.49 |
| 33 | 51.5 | 53.0625 | 0 | 5 | 101.375 | 185.375 | 4.2917 | 4.4219 | 0.00000 | 0.0873 | 8.4479 | 15.4479 | 0.35 | 0.0 | 0.0 |
| 34 | 51.5 | 53.0625 | 25 | 35 | 101.375 | 185.375 | 4.2917 | 4.4219 | 0.4363 | 0.6109 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 35 | 51.5 | 53.0625 | 55 | 65 | 101.375 | 185.375 | 4.2917 | 4.4219 | 0.9599 | 1.1345 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 36 | 51.5 | 53.0625 | 85 | 95 | 101.375 | 185.375 | 4.2917 | 4.4219 | 1.4835 | 1.6581 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 37 | 51.5 | 53.0625 | 115 | 125 | 101.375 | 185.375 | 4.2917 | 4.4219 | 2.0071 | 2.1817 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 38 | 51.5 | 53.0625 | 145 | 155 | 101.375 | 185.375 | 4.2917 | 4.4219 | 2.5307 | 2.7053 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 39 | 51.5 | 53.0625 | 175 | 185 | 101.375 | 185.375 | 4.2917 | 4.4219 | 3.0543 | 3.2289 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 40 | 51.5 | 53.0625 | 205 | 215 | 101.375 | 185.375 | 4.2917 | 4.4219 | 3.5779 | 3.7525 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 41 | 51.5 | 53.0625 | 235 | 245 | 101.375 | 185.375 | 4.2917 | 4.4219 | 4.1015 | 4.2761 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 42 | 51.5 | 53.0625 | 265 | 275 | 101.375 | 185.375 | 4.2917 | 4.4219 | 4.6251 | 4.7997 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 43 | 51.5 | 53.0625 | 295 | 305 | 101.375 | 185.375 | 4.2917 | 4.4219 | 5.1487 | 5.3233 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 44 | 51.5 | 53.0625 | 325 | 335 | 101.375 | 185.375 | 4.2917 | 4.4219 | 5.6723 | 5.8469 | 8.4479 | 15.4479 | 0.69 | 0.0 | 0.0 |
| 45 | 51.5 | 53.0625 | 355 | 360 | 101.375 | 185.375 | 4.2917 | 4.4219 | 6.1959 | 6.2832 | 8.4479 | 15.4479 | 0.35 | 0.0 | 0.0 |
| 46 | 0 | 50 | 0 | 360 | 101.375 | 184.375 | 0.0 | 4.1667 | 0.0 | 6.2832 | 8.4479 | 15.3646 | 377.25 | **9.64** | 0.026 |
| 47 | 0 | 44 | 0 | 360 | 184.375 | 185.375 | 0.0 | 3.6667 | 0.0 | 6.2832 | 15.3646 | 15.4479 | 3.52 | 0.0 | 0.0 |
| 48 | 0 | 50 | 0 | 360 | 185.375 | 193.375 | 0.0 | 4.1667 | 0.0 | 6.2832 | 15.4479 | 16.1146 | 36.36 | 0.0 | 0.0 |
| 49 | 51.5 | 53.0625 | 0 | 360 | 185.375 | 193.375 | 4.2917 | 4.4219 | 0.0 | 6.2832 | 15.4479 | 16.1146 | 2.38 | 0.0 | 0.0 |

# Table 3
# Thermal Property Data



**Material No. 1** — **Transport Cask**
A516 Grade 70 — (C-Mn-Si)
Density, $\rho$ ($lb_m/ft^3$) — 490.8

| Temperature $T$ (°F) | Thermal Conductivity $k$ (Btu/hr-ft-°F) | Thermal Diffusivity $\alpha$ ($ft^2/hr$) | Specific Heat $c_p$ ($Btu/lb_m$-°F) |
|---|---|---|---|
| 70 | 23.6 | 0.454 | 0.11 |
| 200 | 24.4 | 0.422 | 0.12 |
| 400 | 24.2 | 0.386 | 0.13 |
| 600 | 23.1 | 0.346 | 0.14 |
| 800 | 21.7 | 0.298 | 0.15 |
| 1200 | 18.2 | 0.197 | 0.19 |
| 1500 | 15.1 | 0.169 | 0.18 |

**Material No. 4** — **Reactor Vessel**
SA 302 Grade B — (Mn-1/2Mo)
Density, $\rho$ ($lb_m/ft^3$) — 489.0

| Temperature $T$ (°F) | Thermal Conductivity $k$ (Btu/hr-ft-°F) | Thermal Diffusivity $\alpha$ ($ft^2/hr$) | Specific Heat $c_p$ ($Btu/lb_m$-°F) |
|---|---|---|---|
| 70 | 23.3 | 0.455 | 0.10 |
| 200 | 24.4 | 0.437 | 0.11 |
| 400 | 24.6 | 0.398 | 0.13 |
| 600 | 23.5 | 0.353 | 0.14 |
| 800 | 22.0 | 0.300 | 0.15 |
| 1200 | 18.6 | 0.193 | 0.20 |
| 1500 | 15.5 | 0.164 | 0.19 |

**Material No. 5** — **Stainless Steel**
SS 304 — (18Cr-8Ni)
Density, $\rho$ ($lb_m/ft^3$) — 501.1

| Temperature $T$ (°F) | Thermal Conductivity $k$ (Btu/hr-ft-°F) | Thermal Diffusivity $\alpha$ ($ft^2/hr$) | Specific Heat $c_p$ ($Btu/lb_m$-°F) |
|---|---|---|---|
| 70 | 8.6 | 0.151 | 0.11 |
| 200 | 9.3 | 0.156 | 0.12 |
| 400 | 10.4 | 0.165 | 0.13 |
| 600 | 11.3 | 0.174 | 0.13 |
| 800 | 12.2 | 0.184 | 0.13 |
| 1200 | 14.0 | 0.203 | 0.14 |
| 1500 | 15.3 | 0.216 | 0.14 |

### Case 1a: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 100.73 | 100.76 | 100.81 | 100.91 | 101.05 | 101.14 | 101.17 | 101.18 | 101.19 | 101.16 | 101.07 | 101 | 100.94 | 100.87 | 100.82 | 100.78 | 100.75 | 100.74 | 100.73 |
| **24.6** | 100.74 | 100.76 | 100.82 | 100.91 | 101.05 | 101.16 | 101.19 | 101.24 | 101.24 | 101.23 | 101.1 | 101.01 | 100.94 | 100.88 | 100.82 | 100.78 | 100.73 | 100.72 | 100.72 |
| **22.57** | 102.22 | 102.25 | 102.29 | 102.34 | 102.4 | 102.43 | 102.44 | 102.45 | 102.45 | 102.44 | 101.23 | 101.08 | 100.94 | 100.79 | 100.65 | 100.54 | 100.42 | 100.42 | 100.42 |
| **20.53** | 103.58 | 103.63 | 103.67 | 103.7 | 103.71 | 103.71 | 103.71 | 103.7 | 103.7 | 103.7 | 101.64 | 101.39 | 101.15 | 100.91 | 100.68 | 100.5 | 100.32 | 100.32 | 100.32 |
| **18.49** | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.11 | 105.09 | 105.07 | 105.07 | 105.07 | 102.12 | 101.77 | 101.43 | 101.1 | 100.79 | 100.54 | 100.3 | 100.3 | 100.3 |
| **16.45** | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.37 | 101.84 | 101.34 | 100.85 | 100.37 | 100.35 | 100.34 | 100.34 | 100.34 |
| **16.11** | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 102.44 | 101.89 | 101.36 | 100.85 | 100.36 | 100.35 | 100.35 | 100.35 | 100.34 |
| **15.45** | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 102.59 | 102 | 101.43 | 100.88 | 100.36 | 100.36 | 100.35 | 100.35 | 100.35 |
| **15.36** | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.59 | 102.61 | 102.01 | 101.44 | 100.89 | 100.36 | 100.36 | 100.35 | 100.35 | 100.35 |
| **13.64** | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 102.62 | 102.02 | 101.45 | 100.9 | 100.36 | 100.36 | 100.36 | 100.36 | 100.35 |
| **11.91** | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 102.55 | 101.97 | 101.42 | 100.88 | 100.36 | 100.36 | 100.36 | 100.35 | 100.35 |
| **10.18** | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.96 | 106.95 | 102.43 | 101.88 | 101.35 | 100.84 | 100.35 | 100.35 | 100.35 | 100.35 | 100.34 |
| **8.45** | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.25 | 101.75 | 101.27 | 100.8 | 100.35 | 100.34 | 100.33 | 100.33 | 100.33 |
| **6** | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.2 | 101.83 | 101.47 | 101.13 | 100.8 | 100.54 | 100.29 | 100.28 | 100.28 |
| **3.55** | 104.24 | 104.26 | 104.28 | 104.3 | 104.33 | 104.35 | 104.35 | 104.35 | 104.35 | 104.35 | 101.86 | 101.56 | 101.26 | 100.98 | 100.71 | 100.49 | 100.28 | 100.27 | 100.27 |
| **1.1** | 103.02 | 103.04 | 103.1 | 103.2 | 103.35 | 103.45 | 103.49 | 103.53 | 103.53 | 103.54 | 101.53 | 101.28 | 101.05 | 100.83 | 100.64 | 100.48 | 100.33 | 100.32 | 100.32 |
| **0.67** | 103.01 | 103.03 | 103.09 | 103.19 | 103.34 | 103.43 | 103.45 | 103.47 | 103.47 | 103.47 | 101.54 | 101.11 | 100.86 | 100.68 | 100.54 | 100.44 | 100.35 | 100.35 | 100.35 |
| **0.33** | 100.81 | 100.81 | 100.79 | 100.76 | 100.7 | 100.65 | 100.64 | 100.63 | 100.62 | 100.57 | 100.52 | 100.49 | 100.47 | 100.44 | 100.42 | 100.4 | 100.38 | 100.37 | 100.37 |
| **0** | 100.8 | 100.8 | 100.78 | 100.75 | 100.69 | 100.64 | 100.63 | 100.61 | 100.61 | 100.55 | 100.52 | 100.49 | 100.46 | 100.44 | 100.42 | 100.4 | 100.39 | 100.38 | 100.38 |
| **Radius (feet)** | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |

### Case 1b: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 103.34 | 103.36 | 103.42 | 103.52 | 103.65 | 103.73 | 103.75 | 103.77 | 103.77 | 103.74 | 103.65 | 103.57 | 103.5 | 103.43 | 103.37 | 103.33 | 103.3 | 103.29 | 103.28 |
| **24.6** | 103.34 | 103.37 | 103.43 | 103.52 | 103.66 | 103.75 | 103.78 | 103.81 | 103.81 | 103.8 | 103.67 | 103.58 | 103.51 | 103.44 | 103.37 | 103.32 | 103.27 | 103.26 | 103.26 |
| **22.57** | 104.73 | 104.76 | 104.81 | 104.85 | 104.91 | 104.93 | 104.94 | 104.95 | 104.95 | 104.95 | 103.66 | 103.5 | 103.35 | 103.2 | 103.05 | 102.92 | 102.8 | 102.8 | 102.8 |
| **20.53** | 106.02 | 106.07 | 106.11 | 106.13 | 106.14 | 106.14 | 106.14 | 106.14 | 106.14 | 106.13 | 103.95 | 103.69 | 103.43 | 103.18 | 102.94 | 102.75 | 102.55 | 102.55 | 102.55 |
| **18.49** | 107.37 | 107.46 | 107.54 | 107.59 | 107.56 | 107.49 | 107.46 | 107.44 | 107.44 | 107.44 | 104.35 | 103.97 | 103.62 | 103.28 | 102.95 | 102.69 | 102.44 | 102.44 | 102.44 |
| **16.45** | 108.86 | 109.09 | 109.42 | 109.82 | 110.02 | 109.48 | 109.26 | 108.98 | 108.98 | 108.97 | 104.52 | 103.97 | 103.45 | 102.94 | 102.44 | 102.42 | 102.41 | 102.41 | 102.41 |
| **16.11** | 109.09 | 109.35 | 109.76 | 110.46 | 111.68 | 111.03 | 111.02 | 109.28 | 109.28 | 109.26 | 104.58 | 104.01 | 103.47 | 102.94 | 102.42 | 102.42 | 102.41 | 102.41 | 102.41 |
| **15.45** | 109.53 | 109.84 | 110.43 | 111.89 | 119.82 | 112.75 | 112.31 | 109.88 | 109.88 | 109.83 | 104.73 | 104.11 | 103.52 | 102.96 | 102.42 | 102.41 | 102.41 | 102.41 | 102.41 |
| **15.36** | 109.58 | 109.9 | 110.49 | 111.99 | 119.68 | 112.47 | 112.17 | 109.94 | 109.94 | 109.88 | 104.74 | 104.12 | 103.53 | 102.96 | 102.42 | 102.41 | 102.41 | 102.41 | 102.41 |
| **13.64** | 110.1 | 110.26 | 110.4 | 110.53 | 110.47 | 110 | 110 | 109.82 | 109.82 | 109.8 | 104.73 | 104.11 | 103.52 | 102.95 | 102.4 | 102.4 | 102.4 | 102.4 | 102.39 |
| **11.91** | 110.08 | 110.14 | 110.13 | 110.04 | 109.83 | 109.7 | 109.7 | 109.58 | 109.58 | 109.57 | 104.64 | 104.04 | 103.47 | 102.92 | 102.38 | 102.38 | 102.38 | 102.38 | 102.37 |
| **10.18** | 109.67 | 109.7 | 109.66 | 109.56 | 109.38 | 109.29 | 109.29 | 109.17 | 109.17 | 109.16 | 104.5 | 103.93 | 103.39 | 102.86 | 102.36 | 102.36 | 102.35 | 102.35 | 102.35 |
| **8.45** | 108.84 | 108.85 | 108.83 | 108.77 | 108.69 | 108.69 | 108.69 | 108.54 | 108.54 | 108.54 | 104.3 | 103.79 | 103.29 | 102.8 | 102.34 | 102.33 | 102.32 | 102.32 | 102.32 |
| **6** | 107.51 | 107.52 | 107.52 | 107.51 | 107.47 | 107.45 | 107.44 | 107.44 | 107.44 | 107.43 | 104.23 | 103.84 | 103.47 | 103.12 | 102.78 | 102.5 | 102.24 | 102.23 | 102.23 |
| **3.55** | 106.38 | 106.4 | 106.42 | 106.44 | 106.47 | 106.48 | 106.49 | 106.49 | 106.49 | 106.49 | 103.88 | 103.57 | 103.26 | 102.97 | 102.68 | 102.45 | 102.22 | 102.22 | 102.22 |
| **1.1** | 105.15 | 105.17 | 105.23 | 105.33 | 105.47 | 105.58 | 105.61 | 105.65 | 105.65 | 105.66 | 103.57 | 103.31 | 103.07 | 102.85 | 102.64 | 102.48 | 102.32 | 102.32 | 102.32 |
| **0.67** | 105.14 | 105.16 | 105.22 | 105.32 | 105.46 | 105.55 | 105.57 | 105.59 | 105.59 | 105.6 | 103.6 | 103.16 | 102.89 | 102.7 | 102.56 | 102.45 | 102.35 | 102.35 | 102.35 |
| **0.33** | 102.96 | 102.96 | 102.93 | 102.87 | 102.79 | 102.73 | 102.71 | 102.69 | 102.69 | 102.62 | 102.57 | 102.53 | 102.5 | 102.46 | 102.44 | 102.41 | 102.39 | 102.38 | 102.38 |
| **0** | 102.95 | 102.94 | 102.92 | 102.86 | 102.78 | 102.72 | 102.7 | 102.68 | 102.68 | 102.6 | 102.56 | 102.52 | 102.49 | 102.46 | 102.43 | 102.41 | 102.4 | 102.39 | 102.39 |
| **Radius (feet)** | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |

### Case 2a: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 156.09 | 156.41 | 157.42 | 159.22 | 162.04 | 164.12 | 164.67 | 165.2 | 165.25 | 166.26 | 167.29 | 168.25 | 169.33 | 170.51 | 171.79 | 172.9 | 173.95 | 174.45 | 174.69 |
| 24.6 | 156.18 | 156.51 | 157.52 | 159.34 | 162.2 | 164.39 | 165.08 | 165.88 | 165.91 | 166.33 | 167.49 | 168.48 | 169.58 | 170.81 | 172.2 | 173.53 | 175.11 | 175.3 | 175.45 |
| 22.57 | 165.74 | 165.96 | 166.55 | 167.5 | 168.76 | 169.51 | 169.7 | 169.89 | 169.89 | 169.91 | 178.76 | 179.87 | 181 | 182.17 | 183.36 | 184.38 | 185.42 | 185.44 | 185.48 |
| 20.53 | 171.5 | 171.64 | 171.94 | 172.39 | 172.92 | 173.22 | 173.29 | 173.36 | 173.36 | 173.37 | 182.85 | 184 | 185.13 | 186.24 | 187.33 | 188.24 | 189.13 | 189.14 | 189.16 |
| 18.49 | 175.51 | 175.65 | 175.87 | 176.14 | 176.38 | 176.47 | 176.49 | 176.51 | 176.51 | 176.52 | 185.1 | 186.13 | 187.13 | 188.09 | 189.02 | 189.78 | 190.51 | 190.52 | 190.52 |
| 16.45 | 178.7 | 178.97 | 179.39 | 179.95 | 180.37 | 179.93 | 179.72 | 179.44 | 179.44 | 179.45 | 187.28 | 188.23 | 189.17 | 190.09 | 191 | 191.03 | 191.04 | 191.04 | 191.04 |
| 16.11 | 179.15 | 179.44 | 179.94 | 180.79 | 182.24 | 181.9 | 181.88 | 179.92 | 179.92 | 179.91 | 187.49 | 188.41 | 189.31 | 190.19 | 191.05 | 191.05 | 191.06 | 191.06 | 191.07 |
| 15.45 | 179.96 | 180.29 | 180.96 | 182.54 | 190.48 | 183.64 | 183.22 | 180.84 | 180.84 | 180.8 | 187.82 | 188.67 | 189.5 | 190.31 | 191.09 | 191.1 | 191.1 | 191.11 | 191.11 |
| 15.36 | 180.05 | 180.39 | 181.06 | 182.67 | 190.35 | 183.38 | 183.09 | 180.93 | 180.93 | 180.89 | 187.85 | 188.7 | 189.52 | 190.32 | 191.1 | 191.1 | 191.11 | 191.11 | 191.12 |
| 13.64 | 181.21 | 181.38 | 181.59 | 181.82 | 181.91 | 181.53 | 181.53 | 181.37 | 181.37 | 181.37 | 188.08 | 188.89 | 189.67 | 190.43 | 191.17 | 191.17 | 191.17 | 191.18 | 191.18 |
| 11.91 | 181.48 | 181.56 | 181.61 | 181.63 | 181.56 | 181.51 | 181.51 | 181.4 | 181.4 | 181.41 | 188.1 | 188.91 | 189.69 | 190.44 | 191.17 | 191.18 | 191.18 | 191.18 | 191.19 |
| 10.18 | 181.07 | 181.11 | 181.14 | 181.15 | 181.12 | 181.12 | 181.12 | 181.01 | 181.01 | 181.01 | 187.94 | 188.78 | 189.58 | 190.37 | 191.12 | 191.13 | 191.13 | 191.14 | 191.14 |
| 8.45 | 179.91 | 179.95 | 180 | 180.07 | 180.16 | 180.28 | 180.28 | 180.13 | 180.13 | 180.13 | 187.53 | 188.43 | 189.3 | 190.16 | 191 | 191.01 | 191.02 | 191.02 | 191.03 |
| 6 | 177.52 | 177.56 | 177.64 | 177.76 | 177.92 | 178.01 | 178.03 | 178.06 | 178.06 | 178.06 | 185.5 | 186.4 | 187.27 | 188.12 | 188.94 | 189.61 | 190.27 | 190.27 | 190.28 |
| 3.55 | 174.49 | 174.55 | 174.71 | 174.96 | 175.27 | 175.46 | 175.51 | 175.56 | 175.56 | 175.56 | 182.74 | 183.62 | 184.51 | 185.4 | 186.29 | 187.05 | 187.81 | 187.82 | 187.85 |
| 1.1 | 170.02 | 170.14 | 170.47 | 171.02 | 171.78 | 172.28 | 172.43 | 172.61 | 172.62 | 172.67 | 175.2 | 175.63 | 176.23 | 177 | 177.91 | 178.77 | 179.71 | 179.74 | 179.82 |
| 0.67 | 169.97 | 170.08 | 170.42 | 170.97 | 171.72 | 172.19 | 172.29 | 172.38 | 172.39 | 172.47 | 170.62 | 171.02 | 171.74 | 172.7 | 173.87 | 175 | 176.29 | 176.34 | 176.45 |
| 0.33 | 156.58 | 156.78 | 157.41 | 158.54 | 160.34 | 161.72 | 162.12 | 162.56 | 162.6 | 164.28 | 165.39 | 166.38 | 167.46 | 168.65 | 169.99 | 171.27 | 172.81 | 173.33 | 173.59 |
| 0 | 156.45 | 156.65 | 157.26 | 158.39 | 160.17 | 161.54 | 161.94 | 162.37 | 162.42 | 164.07 | 165.18 | 166.16 | 167.22 | 168.37 | 169.6 | 170.64 | 171.59 | 172.07 | 172.33 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

Radius (feet)

### Case 2b: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 156.45 | 156.79 | 157.83 | 159.7 | 162.64 | 164.81 | 165.37 | 165.92 | 165.97 | 166.96 | 167.89 | 168.79 | 169.8 | 170.93 | 172.16 | 173.24 | 174.26 | 174.74 | 174.99 |
| 24.6 | 156.55 | 156.89 | 157.94 | 159.84 | 162.81 | 165.09 | 165.81 | 166.65 | 166.68 | 167.1 | 168.1 | 169.02 | 170.06 | 171.23 | 172.57 | 173.85 | 175.39 | 175.58 | 175.73 |
| 22.57 | 167.29 | 167.51 | 168.15 | 169.17 | 170.53 | 171.36 | 171.56 | 171.77 | 171.77 | 171.79 | 174.39 | 176.39 | 178.34 | 180.26 | 182.17 | 183.76 | 185.35 | 185.37 | 185.41 |
| 20.53 | 173.94 | 174.09 | 174.43 | 174.93 | 175.54 | 175.9 | 175.98 | 176.08 | 176.08 | 176.09 | 178.63 | 180.57 | 182.45 | 184.27 | 186.05 | 187.51 | 188.95 | 188.96 | 188.98 |
| 18.49 | 178.6 | 178.75 | 178.99 | 179.3 | 179.6 | 179.74 | 179.77 | 179.8 | 179.8 | 179.81 | 181.93 | 183.54 | 185.09 | 186.59 | 188.03 | 189.19 | 190.33 | 190.33 | 190.34 |
| 16.45 | 182.24 | 182.51 | 182.95 | 183.55 | 184.02 | 183.6 | 183.39 | 183.12 | 183.12 | 183.13 | 185.06 | 186.55 | 188 | 189.42 | 190.82 | 190.85 | 190.87 | 190.87 | 190.88 |
| 16.11 | 182.74 | 183.03 | 183.55 | 184.44 | 185.95 | 185.69 | 185.67 | 183.65 | 183.65 | 183.64 | 185.47 | 186.88 | 188.24 | 189.57 | 190.87 | 190.88 | 190.89 | 190.9 | 190.9 |
| 15.45 | 183.65 | 183.98 | 184.67 | 186.28 | 194.27 | 187.45 | 187.03 | 184.64 | 184.64 | 184.61 | 186.19 | 187.42 | 188.62 | 189.79 | 190.93 | 190.94 | 190.94 | 190.95 | 190.96 |
| 15.36 | 183.75 | 184.09 | 184.78 | 186.43 | 194.14 | 187.19 | 186.9 | 184.74 | 184.74 | 184.7 | 186.26 | 187.48 | 188.66 | 189.82 | 190.94 | 190.94 | 190.95 | 190.96 | 190.96 |
| 13.64 | 185.07 | 185.24 | 185.46 | 185.71 | 185.83 | 185.47 | 185.46 | 185.31 | 185.31 | 185.31 | 186.77 | 187.88 | 188.96 | 190.01 | 191.02 | 191.03 | 191.03 | 191.04 | 191.04 |
| 11.91 | 185.41 | 185.48 | 185.55 | 185.58 | 185.54 | 185.51 | 185.51 | 185.41 | 185.41 | 185.41 | 186.85 | 187.95 | 189.01 | 190.04 | 191.04 | 191.04 | 191.05 | 191.05 | 191.06 |
| 10.18 | 184.98 | 185.03 | 185.07 | 185.09 | 185.1 | 185.12 | 185.12 | 185.01 | 185.01 | 185.02 | 186.55 | 187.71 | 188.84 | 189.93 | 190.99 | 190.99 | 191 | 191 | 191.01 |
| 8.45 | 183.73 | 183.77 | 183.84 | 183.94 | 184.07 | 184.23 | 184.23 | 184.07 | 184.07 | 184.07 | 185.79 | 187.11 | 188.39 | 189.64 | 190.86 | 190.87 | 190.88 | 190.89 | 190.89 |
| 6 | 181.04 | 181.09 | 181.19 | 181.35 | 181.55 | 181.67 | 181.7 | 181.73 | 181.73 | 181.74 | 183.42 | 184.7 | 185.94 | 187.13 | 188.29 | 189.23 | 190.15 | 190.15 | 190.16 |
| 3.55 | 177.51 | 177.58 | 177.77 | 178.06 | 178.44 | 178.67 | 178.73 | 178.79 | 178.79 | 178.8 | 180.52 | 181.84 | 183.13 | 184.39 | 185.65 | 186.69 | 187.73 | 187.74 | 187.77 |
| 1.1 | 172.24 | 172.37 | 172.75 | 173.37 | 174.23 | 174.82 | 175 | 175.21 | 175.21 | 175.27 | 175.57 | 175.95 | 176.49 | 177.19 | 178.05 | 178.87 | 179.77 | 179.8 | 179.87 |
| 0.67 | 172.17 | 172.3 | 172.69 | 173.31 | 174.17 | 174.7 | 174.82 | 174.92 | 174.93 | 175.01 | 172.45 | 172.01 | 172.31 | 173.05 | 174.09 | 175.15 | 176.38 | 176.43 | 176.54 |
| 0.33 | 157.01 | 157.21 | 157.82 | 158.93 | 160.7 | 162.05 | 162.44 | 162.87 | 162.91 | 164.54 | 165.63 | 166.59 | 167.65 | 168.82 | 170.14 | 171.4 | 172.93 | 173.44 | 173.7 |
| 0 | 156.87 | 157.06 | 157.67 | 158.77 | 160.52 | 161.86 | 162.24 | 162.67 | 162.71 | 164.33 | 165.41 | 166.36 | 167.4 | 168.54 | 169.74 | 170.78 | 171.72 | 172.19 | 172.45 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

Radius (feet)

### Case 3a: Steady-State Temperature Distribution

| Elev. (ft) \ Radius (feet) | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | -38.66 | -38.64 | -38.58 | -38.48 | -38.35 | -38.25 | -38.23 | -38.22 | -38.22 | -38.24 | -38.34 | -38.41 | -38.48 | -38.55 | -38.6 | -38.65 | -38.68 | -38.69 | -38.7 |
| **24.6** | -38.66 | -38.63 | -38.57 | -38.48 | -38.34 | -38.24 | -38.21 | -38.17 | -38.17 | -38.18 | -38.32 | -38.4 | -38.47 | -38.54 | -38.6 | -38.65 | -38.71 | -38.71 | -38.72 |
| **22.57** | -37.2 | -37.17 | -37.13 | -37.08 | -37.03 | -37 | -36.99 | -36.98 | -36.98 | -36.99 | -38.25 | -38.41 | -38.56 | -38.71 | -38.85 | -38.98 | -39.09 | -39.1 | -39.1 |
| **20.53** | -35.86 | -35.82 | -35.77 | -35.75 | -35.74 | -35.74 | -35.74 | -35.74 | -35.74 | -35.75 | -37.89 | -38.15 | -38.4 | -38.64 | -38.88 | -39.07 | -39.26 | -39.26 | -39.26 |
| **18.49** | -34.47 | -34.37 | -34.29 | -34.24 | -34.27 | -34.34 | -34.37 | -34.39 | -34.39 | -34.39 | -37.43 | -37.8 | -38.15 | -38.49 | -38.8 | -39.06 | -39.31 | -39.31 | -39.31 |
| **16.45** | -32.93 | -32.69 | -32.36 | -31.94 | -31.73 | -32.29 | -32.52 | -32.8 | -32.8 | -32.81 | -37.21 | -37.74 | -38.26 | -38.77 | -39.26 | -39.27 | -39.29 | -39.29 | -39.29 |
| **16.11** | -32.69 | -32.42 | -32 | -31.29 | -30.04 | -30.7 | -30.72 | -32.49 | -32.49 | -32.51 | -37.14 | -37.7 | -38.24 | -38.76 | -39.27 | -39.27 | -39.28 | -39.28 | -39.28 |
| **15.45** | -32.24 | -31.92 | -31.32 | -29.82 | -21.72 | -28.94 | -29.39 | -31.87 | -31.88 | -31.92 | -36.98 | -37.59 | -38.17 | -38.73 | -39.27 | -39.27 | -39.28 | -39.28 | -39.28 |
| **15.36** | -32.18 | -31.86 | -31.25 | -29.72 | -21.87 | -29.23 | -29.53 | -31.81 | -31.82 | -31.87 | -36.97 | -37.58 | -38.17 | -38.73 | -39.27 | -39.27 | -39.28 | -39.28 | -39.28 |
| **13.64** | -31.64 | -31.48 | -31.33 | -31.2 | -31.25 | -31.73 | -31.73 | -31.92 | -31.92 | -31.93 | -36.97 | -37.57 | -38.16 | -38.72 | -39.27 | -39.27 | -39.27 | -39.28 | -39.28 |
| **11.91** | -31.65 | -31.59 | -31.59 | -31.68 | -31.89 | -32.02 | -32.02 | -32.15 | -32.15 | -32.16 | -37.04 | -37.63 | -38.2 | -38.75 | -39.28 | -39.28 | -39.28 | -39.28 | -39.28 |
| **10.18** | -32.04 | -32.02 | -32.05 | -32.16 | -32.33 | -32.42 | -32.42 | -32.54 | -32.54 | -32.55 | -37.17 | -37.73 | -38.27 | -38.79 | -39.29 | -39.29 | -39.29 | -39.29 | -39.3 |
| **8.45** | -32.87 | -32.86 | -32.88 | -32.93 | -33.01 | -33.01 | -33.01 | -33.16 | -33.16 | -33.17 | -37.36 | -37.87 | -38.36 | -38.84 | -39.3 | -39.31 | -39.31 | -39.31 | -39.31 |
| **6** | -34.19 | -34.18 | -34.18 | -34.2 | -34.23 | -34.25 | -34.26 | -34.26 | -34.26 | -34.27 | -37.41 | -37.79 | -38.16 | -38.51 | -38.84 | -39.11 | -39.37 | -39.37 | -39.38 |
| **3.55** | -35.31 | -35.3 | -35.28 | -35.25 | -35.22 | -35.21 | -35.21 | -35.21 | -35.21 | -35.21 | -37.76 | -38.07 | -38.36 | -38.65 | -38.93 | -39.16 | -39.38 | -39.38 | -39.38 |
| **1.1** | -36.55 | -36.52 | -36.46 | -36.36 | -36.22 | -36.11 | -36.08 | -36.04 | -36.04 | -36.03 | -38.07 | -38.32 | -38.56 | -38.78 | -38.98 | -39.14 | -39.3 | -39.3 | -39.3 |
| **0.67** | -36.56 | -36.53 | -36.47 | -36.37 | -36.23 | -36.14 | -36.12 | -36.1 | -36.1 | -36.09 | -38.05 | -38.48 | -38.75 | -38.93 | -39.07 | -39.17 | -39.27 | -39.27 | -39.27 |
| **0.33** | -38.71 | -38.72 | -38.74 | -38.79 | -38.86 | -38.91 | -38.93 | -38.95 | -38.95 | -39.02 | -39.06 | -39.1 | -39.13 | -39.16 | -39.19 | -39.21 | -39.23 | -39.24 | -39.24 |
| **0** | -38.72 | -38.73 | -38.75 | -38.8 | -38.87 | -38.93 | -38.94 | -38.96 | -38.96 | -39.03 | -39.07 | -39.1 | -39.13 | -39.16 | -39.19 | -39.21 | -39.22 | -39.23 | -39.23 |

### Case 3b: Steady-State Temperature Distribution

| Elev. (ft) \ Radius (feet) | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | -18.77 | -18.74 | -18.69 | -18.59 | -18.45 | -18.36 | -18.34 | -18.32 | -18.32 | -18.35 | -18.44 | -18.51 | -18.58 | -18.65 | -18.71 | -18.75 | -18.78 | -18.79 | -18.8 |
| **24.6** | -18.76 | -18.74 | -18.68 | -18.58 | -18.45 | -18.35 | -18.31 | -18.27 | -18.27 | -18.28 | -18.42 | -18.5 | -18.58 | -18.64 | -18.71 | -18.76 | -18.81 | -18.81 | -18.82 |
| **22.57** | -17.3 | -17.27 | -17.23 | -17.18 | -17.13 | -17.1 | -17.09 | -17.08 | -17.08 | -17.09 | -18.34 | -18.5 | -18.65 | -18.8 | -18.95 | -19.07 | -19.19 | -19.19 | -19.19 |
| **20.53** | -15.96 | -15.91 | -15.87 | -15.84 | -15.83 | -15.84 | -15.84 | -15.84 | -15.84 | -15.84 | -17.97 | -18.23 | -18.49 | -18.73 | -18.96 | -19.16 | -19.34 | -19.34 | -19.35 |
| **18.49** | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.46 | -14.48 | -14.48 | -14.48 | -17.51 | -17.88 | -18.23 | -18.56 | -18.88 | -19.14 | -19.39 | -19.39 | -19.39 |
| **16.45** | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.9 | -17.29 | -17.82 | -18.34 | -18.84 | -19.33 | -19.35 | -19.36 | -19.36 | -19.36 |
| **16.11** | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -17.22 | -17.77 | -18.32 | -18.84 | -19.34 | -19.35 | -19.35 | -19.35 | -19.36 |
| **15.45** | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -17.06 | -17.67 | -18.25 | -18.81 | -19.34 | -19.35 | -19.35 | -19.35 | -19.35 |
| **15.36** | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -17.05 | -17.66 | -18.24 | -18.8 | -19.34 | -19.35 | -19.35 | -19.35 | -19.35 |
| **13.64** | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -17.04 | -17.65 | -18.23 | -18.8 | -19.34 | -19.34 | -19.35 | -19.35 | -19.35 |
| **11.91** | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -17.11 | -17.7 | -18.27 | -18.82 | -19.35 | -19.35 | -19.35 | -19.35 | -19.36 |
| **10.18** | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -17.24 | -17.8 | -18.34 | -18.86 | -19.36 | -19.36 | -19.36 | -19.37 | -19.37 |
| **8.45** | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.25 | -13.25 | -17.43 | -17.94 | -18.43 | -18.91 | -19.37 | -19.38 | -19.38 | -19.38 | -19.38 |
| **6** | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.35 | -17.49 | -17.87 | -18.23 | -18.58 | -18.91 | -19.18 | -19.44 | -19.44 | -19.44 |
| **3.55** | -15.39 | -15.38 | -15.36 | -15.33 | -15.31 | -15.29 | -15.29 | -15.29 | -15.29 | -15.29 | -17.83 | -18.14 | -18.44 | -18.72 | -19 | -19.23 | -19.45 | -19.45 | -19.45 |
| **1.1** | -16.63 | -16.6 | -16.54 | -16.44 | -16.3 | -16.19 | -16.16 | -16.12 | -16.12 | -16.11 | -18.15 | -18.4 | -18.63 | -18.85 | -19.05 | -19.22 | -19.37 | -19.37 | -19.37 |
| **0.67** | -16.64 | -16.61 | -16.55 | -16.45 | -16.31 | -16.22 | -16.2 | -16.18 | -16.18 | -16.17 | -18.13 | -18.56 | -18.82 | -19 | -19.14 | -19.24 | -19.34 | -19.34 | -19.34 |
| **0.33** | -18.8 | -18.8 | -18.83 | -18.87 | -18.94 | -18.99 | -19.01 | -19.03 | -19.03 | -19.09 | -19.14 | -19.17 | -19.21 | -19.23 | -19.26 | -19.28 | -19.3 | -19.31 | -19.31 |
| **0** | -18.81 | -18.81 | -18.84 | -18.88 | -18.95 | -19.01 | -19.02 | -19.04 | -19.04 | -19.11 | -19.15 | -19.18 | -19.21 | -19.24 | -19.26 | -19.28 | -19.3 | -19.3 | -19.31 |

### Case 4a: Transient Temperature Distribution at Time Equal 0.00 Hours

Elev. (ft)

## Tabular Results of HEATING Model Temperature Distributions

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 100.73 | 100.76 | 100.81 | 100.91 | 101.05 | 101.14 | 101.17 | 101.18 | 101.19 | 101.16 | 101.07 | 101 | 100.94 | 100.87 | 100.82 | 100.78 | 100.75 | 100.74 | 100.73 |
| **24.6** | 100.74 | 100.76 | 100.82 | 100.91 | 101.05 | 101.16 | 101.19 | 101.24 | 101.24 | 101.23 | 101.1 | 101.01 | 100.94 | 100.88 | 100.82 | 100.78 | 100.73 | 100.72 | 100.72 |
| **22.57** | 102.22 | 102.25 | 102.29 | 102.34 | 102.4 | 102.43 | 102.44 | 102.45 | 102.45 | 102.44 | 101.23 | 101.08 | 100.94 | 100.79 | 100.65 | 100.54 | 100.42 | 100.42 | 100.42 |
| **20.53** | 103.58 | 103.63 | 103.67 | 103.7 | 103.71 | 103.71 | 103.71 | 103.7 | 103.7 | 103.7 | 101.64 | 101.39 | 101.15 | 100.91 | 100.68 | 100.5 | 100.32 | 100.32 | 100.32 |
| **18.49** | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.11 | 105.09 | 105.07 | 105.07 | 105.07 | 102.12 | 101.77 | 101.43 | 101.1 | 100.79 | 100.54 | 100.3 | 100.3 | 100.3 |
| **16.45** | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.37 | 101.84 | 101.34 | 100.85 | 100.37 | 100.35 | 100.34 | 100.34 | 100.34 |
| **16.11** | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 102.44 | 101.89 | 101.36 | 100.85 | 100.36 | 100.35 | 100.35 | 100.35 | 100.34 |
| **15.45** | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 102.59 | 102 | 101.43 | 100.88 | 100.36 | 100.36 | 100.35 | 100.35 | 100.35 |
| **15.36** | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.59 | 102.61 | 102.01 | 101.44 | 100.89 | 100.36 | 100.36 | 100.35 | 100.35 | 100.35 |
| **13.64** | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 102.62 | 102.02 | 101.45 | 100.9 | 100.36 | 100.36 | 100.36 | 100.36 | 100.35 |
| **11.91** | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 102.55 | 101.97 | 101.42 | 100.88 | 100.36 | 100.36 | 100.36 | 100.35 | 100.35 |
| **10.18** | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.96 | 106.95 | 102.43 | 101.88 | 101.35 | 100.84 | 100.35 | 100.35 | 100.35 | 100.35 | 100.34 |
| **8.45** | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.25 | 101.75 | 101.27 | 100.8 | 100.35 | 100.34 | 100.33 | 100.33 | 100.33 |
| **6** | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.2 | 101.83 | 101.47 | 101.13 | 100.8 | 100.54 | 100.29 | 100.28 | 100.28 |
| **3.55** | 104.24 | 104.26 | 104.28 | 104.3 | 104.33 | 104.35 | 104.35 | 104.35 | 104.35 | 104.35 | 101.86 | 101.56 | 101.26 | 100.98 | 100.71 | 100.49 | 100.28 | 100.27 | 100.27 |
| **1.1** | 103.02 | 103.04 | 103.1 | 103.2 | 103.35 | 103.45 | 103.49 | 103.53 | 103.53 | 103.54 | 101.53 | 101.28 | 101.05 | 100.83 | 100.64 | 100.48 | 100.33 | 100.32 | 100.32 |
| **0.67** | 103.01 | 103.03 | 103.09 | 103.19 | 103.34 | 103.43 | 103.45 | 103.47 | 103.47 | 103.47 | 101.54 | 101.11 | 100.86 | 100.68 | 100.54 | 100.44 | 100.35 | 100.35 | 100.35 |
| **0.33** | 100.81 | 100.81 | 100.79 | 100.76 | 100.7 | 100.65 | 100.64 | 100.63 | 100.62 | 100.57 | 100.52 | 100.49 | 100.47 | 100.44 | 100.42 | 100.4 | 100.38 | 100.37 | 100.37 |
| **0** | 100.8 | 100.8 | 100.78 | 100.75 | 100.69 | 100.64 | 100.63 | 100.61 | 100.61 | 100.55 | 100.52 | 100.49 | 100.46 | 100.44 | 100.42 | 100.4 | 100.39 | 100.38 | 100.38 |
| Radius (feet) | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |

### Case 4a: Transient Temperature Distribution at Time Equal 0.25 Hours

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 1372.21 | 1372.21 | 1372.21 | 1372.21 | 1371.81 | 1364.55 | 1353.18 | 1337.28 | 1336.19 | 1336.99 | 1359.8 | 1364.24 | 1365.41 | 1366.74 | 1370.76 | 1377.39 | 1371.1 | 1355.79 | 1421.06 |
| **24.6** | 862.62 | 862.62 | 862.64 | 862.59 | 858.79 | 787.94 | 667.13 | 464.07 | 456.89 | 469.47 | 739.76 | 781.85 | 793.08 | 806.12 | 847.43 | 941.34 | 1142.75 | 1221.88 | 1387.18 |
| **22.57** | 102.77 | 102.8 | 102.84 | 102.89 | 102.95 | 102.95 | 103.28 | 107.52 | 107.55 | 107.82 | 101.74 | 101.55 | 101.41 | 101.47 | 107.54 | 210.45 | 1167.46 | 1231.64 | 1389.17 |
| **20.53** | 103.58 | 103.63 | 103.67 | 103.7 | 103.71 | 103.71 | 103.71 | 103.75 | 103.75 | 103.75 | 101.64 | 101.39 | 101.15 | 101.12 | 107.09 | 209.95 | 1167.52 | 1231.68 | 1389.18 |
| **18.49** | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.11 | 105.09 | 105.07 | 105.07 | 105.07 | 102.12 | 101.77 | 101.43 | 101.32 | 107.33 | 210.17 | 1167.03 | 1231.32 | 1389.1 |
| **16.45** | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.37 | 101.85 | 101.77 | 115.06 | 429.13 | 601.54 | 1041.66 | 1162.95 | 1374.29 |
| **16.11** | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 102.44 | 101.91 | 101.96 | 119.28 | 488.45 | 572.8 | 792.87 | 1029.99 | 1348.14 |
| **15.45** | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 102.6 | 102.01 | 102.03 | 119.09 | 481.15 | 557.22 | 764.58 | 1009.59 | 1344.25 |
| **15.36** | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.59 | 102.61 | 102.02 | 102.03 | 119.06 | 480.44 | 556.23 | 763.27 | 1008.64 | 1344.07 |
| **13.64** | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 102.62 | 102.04 | 102.04 | 119.06 | 480.1 | 555.85 | 762.9 | 1008.39 | 1344.02 |
| **11.91** | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 102.55 | 101.99 | 102.01 | 119.05 | 480.11 | 555.86 | 762.91 | 1008.39 | 1344.02 |
| **10.18** | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.96 | 106.95 | 102.43 | 101.9 | 101.95 | 119.05 | 481.14 | 557.09 | 764.33 | 1009.35 | 1344.2 |
| **8.45** | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.25 | 101.77 | 101.89 | 120.26 | 516.77 | 633.88 | 935.68 | 1105.55 | 1362.59 |
| **6** | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.2 | 101.83 | 101.48 | 101.35 | 107.33 | 210.1 | 1166.84 | 1231.18 | 1389.07 |
| **3.55** | 104.24 | 104.26 | 104.28 | 104.3 | 104.33 | 104.35 | 104.35 | 104.35 | 104.35 | 104.35 | 101.86 | 101.56 | 101.27 | 101.19 | 107.11 | 209.94 | 1167.52 | 1231.68 | 1389.18 |
| **1.1** | 103.92 | 103.95 | 104.01 | 104.11 | 104.25 | 104.29 | 104.16 | 103.89 | 103.87 | 103.87 | 101.6 | 101.34 | 101.11 | 101.1 | 107.09 | 209.99 | 1167.63 | 1231.78 | 1389.21 |
| **0.67** | 106.46 | 106.49 | 106.55 | 106.65 | 106.79 | 106.89 | 106.93 | 107.01 | 107.02 | 108.12 | 126.61 | 120.71 | 120.26 | 120.44 | 126.99 | 229.16 | 1169.03 | 1233.62 | 1389.68 |
| **0.33** | 953.06 | 953.06 | 953.06 | 953.05 | 953.04 | 953.03 | 953.03 | 953.03 | 953.03 | 953.04 | 953.25 | 954 | 956.83 | 966.18 | 993.08 | 1047.14 | 1153.55 | 1241.48 | 1392.42 |
| **0** | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.56 | 1381.58 | 1381.66 | 1381.98 | 1383.04 | 1386.2 | 1392.84 | 1406.38 | 1421.82 | 1447.06 |
| Radius (feet) | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |

### Case 4a: Transient Temperature Distribution at Time Equal 0.50 Hours

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 1405.43 | 1405.43 | 1405.43 | 1405.38 | 1403.95 | 1389.9 | 1376.83 | 1360.62 | 1359.5 | 1360.13 | 1385.27 | 1393.83 | 1397.85 | 1401.18 | 1406.81 | 1414.55 | 1418.15 | 1418.14 | 1443.99 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.6 | 1136.76 | 1136.77 | 1136.76 | 1136.43 | 1125.75 | 1012.83 | 889.04 | 701.18 | 695.54 | 705.04 | 971.08 | 1043.46 | 1075.33 | 1100.89 | 1144.68 | 1215.49 | 1336.03 | 1368.82 | 1427.19 |
| 22.57 | 103.89 | 103.92 | 103.96 | 104.01 | 104.06 | 104.11 | 106.49 | 120.45 | 120.51 | 120.94 | 102.94 | 102.54 | 102.51 | 104.45 | 133.54 | 359.21 | 1354.91 | 1379.53 | 1430.51 |
| 20.53 | 103.58 | 103.63 | 103.67 | 103.7 | 103.71 | 103.71 | 103.75 | 104.04 | 104.04 | 104.05 | 101.65 | 101.4 | 101.26 | 103.08 | 132.06 | 357.92 | 1355.02 | 1379.62 | 1430.54 |
| 18.49 | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.11 | 105.09 | 105.08 | 105.08 | 105.07 | 102.12 | 101.77 | 101.55 | 103.36 | 132.85 | 358.53 | 1354.19 | 1378.98 | 1430.32 |
| 16.45 | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.38 | 102.1 | 106.23 | 171.05 | 783.1 | 916.82 | 1231.01 | 1302.06 | 1408.04 |
| 16.11 | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 102.46 | 102.21 | 107.13 | 179.61 | 821.26 | 881.67 | 1033.12 | 1187.92 | 1380.94 |
| 15.45 | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 102.62 | 102.32 | 107.12 | 178.14 | 803.15 | 856.92 | 999.68 | 1163.69 | 1375.49 |
| 15.36 | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.59 | 102.63 | 102.32 | 107.11 | 177.99 | 801.51 | 855.09 | 997.72 | 1162.29 | 1375.18 |
| 13.64 | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 102.64 | 102.34 | 107.12 | 177.89 | 800.18 | 853.78 | 996.62 | 1161.57 | 1375.02 |
| 11.91 | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 102.58 | 102.29 | 107.09 | 177.87 | 800.2 | 853.8 | 996.64 | 1161.58 | 1375.02 |
| 10.18 | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.96 | 106.95 | 102.45 | 102.2 | 107.04 | 178.08 | 802.71 | 856.34 | 998.96 | 1163.13 | 1375.36 |
| 8.45 | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.27 | 102.09 | 107.44 | 185.3 | 871.29 | 952.99 | 1152.84 | 1255.24 | 1396.27 |
| 6 | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.2 | 101.83 | 101.59 | 103.38 | 132.74 | 358.32 | 1354 | 1378.83 | 1430.27 |
| 3.55 | 104.24 | 104.26 | 104.28 | 104.31 | 104.33 | 104.35 | 104.35 | 104.37 | 104.37 | 104.37 | 101.86 | 101.56 | 101.38 | 103.15 | 132.09 | 357.92 | 1355.02 | 1379.62 | 1430.54 |
| 1.1 | 106.88 | 106.91 | 106.97 | 107.07 | 107.16 | 106.77 | 106.21 | 105.26 | 105.22 | 105.11 | 101.95 | 101.63 | 101.5 | 103.34 | 132.35 | 358.2 | 1355.07 | 1379.66 | 1430.55 |
| 0.67 | 111.32 | 111.34 | 111.4 | 111.5 | 111.61 | 111.54 | 111.52 | 111.55 | 111.57 | 113.4 | 170.05 | 157.09 | 155.99 | 158.29 | 187.37 | 403.98 | 1354.46 | 1379.41 | 1430.49 |
| 0.33 | 1202.15 | 1202.15 | 1202.15 | 1202.15 | 1202.14 | 1202.14 | 1202.15 | 1202.16 | 1202.16 | 1202.35 | 1203.15 | 1204.93 | 1209.47 | 1220.28 | 1243.91 | 1281.5 | 1341.28 | 1377.93 | 1430.65 |
| 0 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.13 | 1414.16 | 1414.27 | 1414.53 | 1415.2 | 1416.82 | 1420.46 | 1426.48 | 1436.37 | 1445.36 | 1457.55 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

Radius (feet)

**Case 4a: Transient Temperature Distribution at Time Equal 0.75 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1161.2 | 1161.2 | 1161.17 | 1160.53 | 1146.69 | 1051.27 | 998.76 | 946.01 | 942.09 | 940.16 | 1037.39 | 1092.19 | 1125.52 | 1150.48 | 1179.02 | 1209.7 | 1244.56 | 1247.03 | 1202.79 |
| 24.6 | 1187.6 | 1187.6 | 1187.57 | 1186.68 | 1166.91 | 1023.47 | 926.37 | 806.51 | 803.63 | 807.27 | 998.48 | 1085.21 | 1133.21 | 1168.42 | 1209.58 | 1250.49 | 1274.29 | 1256.46 | 1206.13 |
| 22.57 | 105.21 | 105.23 | 105.28 | 105.32 | 105.36 | 105.81 | 112.2 | 137.09 | 137.17 | 137.64 | 104.57 | 103.77 | 104.19 | 110.82 | 172.49 | 475.49 | 1280.33 | 1264.39 | 1213.38 |
| 20.53 | 103.59 | 103.63 | 103.67 | 103.7 | 103.71 | 103.73 | 103.89 | 104.72 | 104.72 | 104.74 | 101.67 | 101.43 | 101.75 | 108.24 | 169.87 | 473.49 | 1280.46 | 1264.52 | 1213.5 |
| 18.49 | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.11 | 105.1 | 105.09 | 105.09 | 105.09 | 102.13 | 101.81 | 102.06 | 108.73 | 171.36 | 474.48 | 1279 | 1263.12 | 1212.29 |
| 16.45 | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.51 | 103.17 | 117.25 | 244.67 | 964.15 | 1039.95 | 1162.29 | 1159.54 | 1123.69 |
| 16.11 | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 102.61 | 103.41 | 118.98 | 254.22 | 977.03 | 1001.1 | 1038.69 | 1044.87 | 1022.18 |
| 15.45 | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 102.76 | 103.5 | 118.75 | 250.88 | 949.52 | 966.76 | 993.34 | 997.84 | 978.17 |
| 15.36 | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.59 | 102.78 | 103.51 | 118.72 | 250.55 | 947.11 | 964.04 | 990.12 | 994.53 | 975.06 |
| 13.64 | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 102.79 | 103.52 | 118.71 | 250.25 | 944.6 | 961.45 | 987.48 | 991.98 | 972.69 |
| 11.91 | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 102.72 | 103.47 | 118.68 | 250.24 | 944.64 | 961.49 | 987.52 | 992.01 | 972.73 |
| 10.18 | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.96 | 106.95 | 102.6 | 103.38 | 118.67 | 250.75 | 948.33 | 965.32 | 991.44 | 995.78 | 976.2 |
| 8.45 | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.43 | 103.38 | 120.16 | 264.74 | 1031.53 | 1066.83 | 1118.17 | 1116.27 | 1085.07 |
| 6 | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.2 | 101.87 | 102.1 | 108.7 | 171.07 | 474.13 | 1278.82 | 1262.95 | 1212.14 |
| 3.55 | 104.25 | 104.26 | 104.28 | 104.31 | 104.34 | 104.35 | 104.36 | 104.42 | 104.42 | 104.41 | 101.86 | 101.6 | 101.87 | 108.31 | 169.9 | 473.49 | 1280.47 | 1264.53 | 1213.51 |
| 1.1 | 110.85 | 110.88 | 110.93 | 111.02 | 110.96 | 109.83 | 108.85 | 107.32 | 107.25 | 107 | 102.64 | 102.26 | 102.55 | 109.07 | 170.7 | 474.14 | 1280.45 | 1264.51 | 1213.49 |
| 0.67 | 115.94 | 115.96 | 116.02 | 116.11 | 116.08 | 115.53 | 115.34 | 115.24 | 115.24 | 117.28 | 213.8 | 196.64 | 194.88 | 201.65 | 260.35 | 541.29 | 1279.21 | 1262.81 | 1211.85 |
| 0.33 | 1229.65 | 1229.65 | 1229.65 | 1229.65 | 1229.65 | 1229.66 | 1229.68 | 1229.73 | 1229.74 | 1230.24 | 1231.85 | 1234.6 | 1240.27 | 1250.8 | 1266.75 | 1278.74 | 1275.04 | 1252.41 | 1201.28 |
| 0 | 1189.55 | 1189.55 | 1189.55 | 1189.55 | 1189.55 | 1189.56 | 1189.58 | 1189.6 | 1189.61 | 1189.93 | 1190.89 | 1192.68 | 1196.32 | 1202.81 | 1211.72 | 1216.01 | 1206.64 | 1181.26 | 1136.86 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

Radius (feet)

**Case 4a: Transient Temperature Distribution at Time Equal 1.00 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1081.93 | 1081.92 | 1081.82 | 1079.9 | 1050.98 | 928.86 | 889.9 | 854.14 | 851.48 | 851.69 | 929.13 | 987.81 | 1033.95 | 1069.63 | 1099.53 | 1121.03 | 1140 | 1138.57 | 1104.46 |
| 24.6 | 1148.89 | 1148.89 | 1148.78 | 1146.65 | 1112.75 | 958.34 | 897.19 | 829.13 | 827.59 | 829.04 | 955.34 | 1035.35 | 1092.91 | 1135.62 | 1169.87 | 1187.17 | 1179.45 | 1163.21 | 1122.9 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22.57 | 106.51 | 106.54 | 106.58 | 106.62 | 106.64 | 108.07 | 119.63 | 153.98 | 154.06 | 154.53 | 106.44 | 105.12 | 106.54 | 120.65 | 215.36 | 547.49 | 1177.13 | 1164.71 | 1125.22 |
| 20.53 | 103.59 | 103.64 | 103.68 | 103.71 | 103.72 | 103.77 | 104.19 | 105.8 | 105.81 | 105.84 | 101.72 | 101.56 | 102.92 | 116.89 | 211.72 | 544.94 | 1177.23 | 1164.82 | 1125.33 |
| 18.49 | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.12 | 105.11 | 105.13 | 105.13 | 105.13 | 102.14 | 101.94 | 103.29 | 117.68 | 213.86 | 546.15 | 1174.92 | 1162.57 | 1123.31 |
| 16.45 | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.94 | 106.67 | 106.67 | 106.66 | 102.93 | 105.63 | 134.21 | 315.11 | 1007.41 | 1039.14 | 1067.61 | 1058.85 | 1029.69 |
| 16.11 | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.97 | 106.96 | 103.07 | 106.05 | 136.54 | 322.99 | 1004.11 | 1009.27 | 1008.06 | 994.82 | 969.13 |
| 15.45 | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.54 | 103.22 | 106.1 | 135.9 | 316.82 | 964.65 | 965.73 | 958.66 | 944.47 | 921.53 |
| 15.36 | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.6 | 103.23 | 106.1 | 135.82 | 316.22 | 961.12 | 961.97 | 954.6 | 940.38 | 917.66 |
| 13.64 | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 103.24 | 106.1 | 135.76 | 315.55 | 956.21 | 956.94 | 949.49 | 935.39 | 912.98 |
| 11.91 | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 103.17 | 106.06 | 135.73 | 315.55 | 956.26 | 956.99 | 949.54 | 935.44 | 913.03 |
| 10.18 | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.97 | 106.96 | 103.05 | 105.98 | 135.8 | 316.49 | 961.74 | 962.55 | 955.07 | 940.79 | 918.02 |
| 8.45 | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.35 | 102.93 | 106.21 | 138.9 | 337.34 | 1052.43 | 1059.6 | 1053.43 | 1039.77 | 1010.72 |
| 6 | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.28 | 105.28 | 105.28 | 102.22 | 102 | 103.32 | 117.58 | 213.37 | 545.67 | 1174.89 | 1162.53 | 1123.28 |
| 3.55 | 104.26 | 104.27 | 104.29 | 104.32 | 104.35 | 104.36 | 104.39 | 104.5 | 104.5 | 104.5 | 101.88 | 101.72 | 103.03 | 116.95 | 211.74 | 544.95 | 1177.24 | 1164.83 | 1125.34 |
| 1.1 | 115.01 | 115.03 | 115.08 | 115.14 | 114.78 | 112.85 | 111.54 | 109.63 | 109.56 | 109.18 | 103.65 | 103.26 | 104.57 | 118.55 | 213.3 | 546.05 | 1177.07 | 1164.65 | 1125.18 |
| 0.67 | 120.01 | 120.03 | 120.09 | 120.14 | 119.83 | 118.63 | 118.27 | 118.01 | 118 | 119.94 | 250.79 | 232.98 | 231.13 | 244.34 | 330.54 | 626.53 | 1174 | 1160.94 | 1121.55 |
| 0.33 | 1173.53 | 1173.53 | 1173.53 | 1173.53 | 1173.53 | 1173.58 | 1173.65 | 1173.77 | 1173.78 | 1174.88 | 1177.45 | 1180.83 | 1185.92 | 1191.86 | 1194.89 | 1188.86 | 1168.37 | 1146.81 | 1106.48 |
| 0 | 1106.75 | 1106.75 | 1106.75 | 1106.75 | 1106.76 | 1106.8 | 1106.85 | 1106.95 | 1106.96 | 1107.83 | 1109.7 | 1112.35 | 1116.2 | 1120.33 | 1121.34 | 1114.48 | 1095.6 | 1071.27 | 1036.75 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

**Case 4a: Transient Temperature Distribution at Time Equal 1.50 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 991.88 | 991.83 | 991.29 | 985.28 | 936.05 | 839.99 | 820.38 | 804.29 | 803.13 | 808.43 | 855.02 | 896.64 | 934.93 | 965.6 | 986.42 | 996.35 | 1002.81 | 999.26 | 975.68 |
| 24.6 | 1050.39 | 1050.35 | 1049.77 | 1043.16 | 986.88 | 871.79 | 844.35 | 817.01 | 816.41 | 818.93 | 887.66 | 941.14 | 987.86 | 1024.02 | 1045.58 | 1047.82 | 1029.61 | 1017.84 | 990.75 |
| 22.57 | 108.93 | 108.96 | 109 | 109.03 | 109.03 | 114.41 | 136.67 | 184.71 | 184.79 | 185.29 | 110.74 | 108.42 | 113.88 | 147.75 | 292.79 | 613.83 | 1016.38 | 1008.34 | 982.97 |
| 20.53 | 103.61 | 103.65 | 103.69 | 103.72 | 103.73 | 104.01 | 105.35 | 109.06 | 109.07 | 109.13 | 102.02 | 102.38 | 108.06 | 141.91 | 287.58 | 610.56 | 1016.21 | 1008.19 | 982.83 |
| 18.49 | 104.99 | 105.09 | 105.17 | 105.22 | 105.19 | 105.12 | 105.16 | 105.31 | 105.31 | 105.31 | 102.32 | 102.79 | 108.69 | 143.45 | 290.58 | 611.71 | 1012.59 | 1004.64 | 979.53 |
| 16.45 | 106.54 | 106.77 | 107.1 | 107.51 | 107.71 | 107.16 | 106.95 | 106.68 | 106.68 | 106.68 | 105.49 | 115.51 | 177.29 | 417.59 | 960.89 | 965.19 | 945.21 | 935.23 | 913.85 |
| 16.11 | 106.78 | 107.04 | 107.45 | 108.16 | 109.38 | 108.74 | 108.73 | 106.98 | 106.98 | 106.97 | 105.79 | 116.31 | 180 | 422.72 | 963.2 | 960.69 | 946.85 | 929.75 | 906.66 |
| 15.45 | 107.23 | 107.55 | 108.14 | 109.6 | 117.54 | 110.46 | 110.02 | 107.59 | 107.59 | 107.55 | 105.89 | 116.12 | 177.91 | 411.29 | 927.13 | 924.42 | 911.48 | 895.45 | 874.45 |
| 15.36 | 107.29 | 107.6 | 108.2 | 109.7 | 117.4 | 110.18 | 109.88 | 107.65 | 107.65 | 107.6 | 105.9 | 116.09 | 177.7 | 410.17 | 923.61 | 920.91 | 908.05 | 892.15 | 871.36 |
| 13.64 | 107.84 | 108 | 108.14 | 108.27 | 108.22 | 107.74 | 107.74 | 107.56 | 107.56 | 107.55 | 105.9 | 116.06 | 177.37 | 408.08 | 913.44 | 910.77 | 898.21 | 882.73 | 862.53 |
| 11.91 | 107.85 | 107.9 | 107.9 | 107.81 | 107.6 | 107.47 | 107.47 | 107.35 | 107.35 | 107.34 | 105.84 | 116.01 | 177.34 | 408.08 | 913.45 | 910.78 | 898.22 | 882.74 | 862.53 |
| 10.18 | 107.47 | 107.49 | 107.45 | 107.35 | 107.18 | 107.09 | 107.09 | 106.97 | 106.97 | 106.96 | 105.73 | 115.98 | 177.69 | 410.13 | 921.36 | 918.63 | 905.76 | 889.93 | 869.26 |
| 8.45 | 106.65 | 106.67 | 106.65 | 106.59 | 106.51 | 106.51 | 106.51 | 106.36 | 106.36 | 106.36 | 105.84 | 117.15 | 184.78 | 439.18 | 988.22 | 984.58 | 962.34 | 947.81 | 924.38 |
| 6 | 105.35 | 105.36 | 105.36 | 105.35 | 105.32 | 105.29 | 105.29 | 105.29 | 105.29 | 105.29 | 102.39 | 102.83 | 108.65 | 143.15 | 289.79 | 611.2 | 1013.18 | 1005.21 | 980.07 |
| 3.55 | 104.29 | 104.3 | 104.32 | 104.35 | 104.37 | 104.4 | 104.49 | 104.78 | 104.78 | 104.78 | 102.06 | 102.51 | 108.17 | 141.97 | 287.6 | 610.57 | 1016.23 | 1008.21 | 982.85 |
| 1.1 | 122.72 | 122.74 | 122.77 | 122.65 | 121.42 | 118.16 | 116.5 | 114.23 | 114.14 | 113.64 | 106.47 | 106.56 | 112.1 | 145.84 | 291.01 | 612.59 | 1015.4 | 1007.38 | 982.07 |
| 0.67 | 127.14 | 127.16 | 127.19 | 127.07 | 125.88 | 123.49 | 122.87 | 122.37 | 122.34 | 124.01 | 304.53 | 292.09 | 292.6 | 320.68 | 441.74 | 703.76 | 1009.75 | 1001.16 | 976.02 |
| 0.33 | 1051.31 | 1051.31 | 1051.31 | 1051.32 | 1051.35 | 1051.62 | 1051.85 | 1052.19 | 1052.23 | 1054.36 | 1056.77 | 1057.97 | 1057.57 | 1053.69 | 1043.81 | 1028.69 | 1005.74 | 989.81 | 963.36 |
| 0 | 999.05 | 999.05 | 999.05 | 999.05 | 999.09 | 999.33 | 999.53 | 999.82 | 999.85 | 1001.59 | 1003.27 | 1004.12 | 1003.55 | 999.87 | 990.84 | 977.28 | 957.3 | 938.07 | 913.92 |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

**Case 4b: Transient Temperature Distribution at Time Equal 0.00 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | -18.77 | -18.74 | -18.69 | -18.59 | -18.45 | -18.36 | -18.34 | -18.32 | -18.32 | -18.35 | -18.44 | -18.51 | -18.58 | -18.65 | -18.71 | -18.75 | -18.78 | -18.79 | -18.8 |
| 24.6 | -18.76 | -18.74 | -18.68 | -18.58 | -18.45 | -18.35 | -18.31 | -18.27 | -18.27 | -18.28 | -18.42 | -18.5 | -18.58 | -18.64 | -18.71 | -18.76 | -18.81 | -18.81 | -18.82 |
| 22.57 | -17.3 | -17.27 | -17.23 | -17.18 | -17.13 | -17.1 | -17.09 | -17.08 | -17.08 | -17.09 | -18.34 | -18.5 | -18.65 | -18.8 | -18.95 | -19.07 | -19.19 | -19.19 | -19.19 |

## Tabular Results of HEATING Model Temperature Distributions

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20.53 | -15.96 | -15.91 | -15.87 | -15.84 | -15.83 | -15.84 | -15.84 | -15.84 | -15.84 | -15.84 | -17.97 | -18.23 | -18.49 | -18.73 | -18.96 | -19.16 | -19.34 | -19.34 | -19.35 |
| 18.49 | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.46 | -14.48 | -14.48 | -14.48 | -17.51 | -17.88 | -18.23 | -18.56 | -18.88 | -19.14 | -19.39 | -19.39 | -19.39 |
| 16.45 | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.9 | -17.29 | -17.82 | -18.34 | -18.84 | -19.33 | -19.35 | -19.36 | -19.36 | -19.36 |
| 16.11 | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -17.22 | -17.77 | -18.32 | -18.84 | -19.34 | -19.35 | -19.35 | -19.35 | -19.36 |
| 15.45 | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -17.06 | -17.67 | -18.25 | -18.81 | -19.34 | -19.35 | -19.35 | -19.35 | -19.35 |
| 15.36 | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -17.05 | -17.66 | -18.24 | -18.8 | -19.34 | -19.35 | -19.35 | -19.35 | -19.35 |
| 13.64 | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -17.04 | -17.65 | -18.23 | -18.8 | -19.34 | -19.34 | -19.35 | -19.35 | -19.35 |
| 11.91 | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -17.11 | -17.7 | -18.27 | -18.82 | -19.35 | -19.35 | -19.35 | -19.35 | -19.36 |
| 10.18 | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -17.24 | -17.8 | -18.34 | -18.86 | -19.36 | -19.36 | -19.36 | -19.37 | -19.37 |
| 8.45 | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.25 | -13.25 | -17.43 | -17.94 | -18.43 | -18.91 | -19.37 | -19.38 | -19.38 | -19.38 | -19.38 |
| 6 | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.35 | -17.49 | -17.87 | -18.23 | -18.58 | -18.91 | -19.18 | -19.44 | -19.44 | -19.44 |
| 3.55 | -15.39 | -15.38 | -15.36 | -15.33 | -15.31 | -15.29 | -15.29 | -15.29 | -15.29 | -15.29 | -17.83 | -18.14 | -18.44 | -18.72 | -19 | -19.23 | -19.45 | -19.45 | -19.45 |
| 1.1 | -16.63 | -16.6 | -16.54 | -16.44 | -16.3 | -16.19 | -16.16 | -16.12 | -16.12 | -16.11 | -18.15 | -18.4 | -18.63 | -18.85 | -19.05 | -19.22 | -19.37 | -19.37 | -19.37 |
| 0.67 | -16.64 | -16.61 | -16.55 | -16.45 | -16.31 | -16.22 | -16.2 | -16.18 | -16.18 | -16.17 | -18.13 | -18.56 | -18.82 | -19 | -19.14 | -19.24 | -19.34 | -19.34 | -19.34 |
| 0.33 | -18.8 | -18.8 | -18.83 | -18.87 | -18.94 | -18.99 | -19.01 | -19.03 | -19.03 | -19.09 | -19.14 | -19.17 | -19.21 | -19.23 | -19.26 | -19.28 | -19.3 | -19.31 | -19.31 |
| 0 | -18.81 | -18.81 | -18.84 | -18.88 | -18.95 | -19.01 | -19.02 | -19.04 | -19.04 | -19.11 | -19.15 | -19.18 | -19.21 | -19.24 | -19.26 | -19.28 | -19.3 | -19.3 | -19.31 |
| Radius (feet) | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

### Case 4b: Transient Temperature Distribution at Time Equal 0.25 Hours

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1368.65 | 1368.65 | 1368.65 | 1368.65 | 1368.2 | 1360.35 | 1348.34 | 1331.55 | 1330.4 | 1331.28 | 1355.31 | 1360.01 | 1361.27 | 1362.75 | 1367.16 | 1374.44 | 1368.42 | 1352.26 | 1419.93 |
| 24.6 | 830.2 | 830.2 | 830.22 | 830.16 | 825.83 | 747.81 | 618.7 | 402.49 | 394.63 | 408.22 | 696.02 | 741.28 | 753.68 | 768.38 | 814.2 | 915.84 | 1130.26 | 1212.81 | 1385.06 |
| 22.57 | -16.68 | -16.65 | -16.61 | -16.56 | -16.51 | -16.51 | -16.12 | -11.12 | -11.08 | -10.76 | -17.78 | -17.98 | -18.12 | -18.03 | -11.19 | 103.64 | 1157.07 | 1223.66 | 1387.28 |
| 20.53 | -15.96 | -15.91 | -15.87 | -15.84 | -15.83 | -15.84 | -15.83 | -15.79 | -15.79 | -15.78 | -17.97 | -18.23 | -18.48 | -18.49 | -11.75 | 103.03 | 1157.14 | 1223.7 | 1387.29 |
| 18.49 | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.46 | -14.48 | -14.48 | -14.48 | -17.51 | -17.88 | -18.22 | -18.32 | -11.51 | 103.25 | 1156.6 | 1223.31 | 1387.19 |
| 16.45 | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.9 | -17.29 | -17.81 | -17.83 | -2.28 | 359.92 | 547.91 | 1020.58 | 1148.82 | 1371.24 |
| 16.11 | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -17.21 | -17.76 | -17.6 | 2.83 | 428.92 | 519.51 | 753.96 | 1005.34 | 1343.5 |
| 15.45 | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -17.06 | -17.65 | -17.54 | 2.64 | 421.26 | 502.71 | 723.28 | 983.08 | 1339.33 |
| 15.36 | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -17.05 | -17.64 | -17.53 | 2.61 | 420.48 | 501.61 | 721.84 | 982.03 | 1339.13 |
| 13.64 | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -17.04 | -17.63 | -17.53 | 2.6 | 420.09 | 501.18 | 721.42 | 981.74 | 1339.08 |
| 11.91 | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -17.11 | -17.69 | -17.56 | 2.58 | 420.1 | 501.19 | 721.43 | 981.75 | 1339.08 |
| 10.18 | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -17.24 | -17.79 | -17.63 | 2.59 | 421.27 | 502.57 | 723 | 982.81 | 1339.27 |
| 8.45 | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.25 | -13.25 | -17.43 | -17.92 | -17.69 | 3.85 | 459.91 | 585.75 | 907.51 | 1087.09 | 1358.82 |
| 6 | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.35 | -17.49 | -17.87 | -18.22 | -18.33 | -11.55 | 103.14 | 1156.39 | 1223.15 | 1387.16 |
| 3.55 | -15.39 | -15.38 | -15.36 | -15.33 | -15.31 | -15.29 | -15.29 | -15.28 | -15.28 | -15.29 | -17.83 | -18.14 | -18.43 | -18.49 | -11.79 | 102.97 | 1157.14 | 1223.7 | 1387.28 |
| 1.1 | -15.58 | -15.56 | -15.5 | -15.4 | -15.25 | -15.23 | -15.37 | -15.7 | -15.72 | -15.72 | -18.07 | -18.34 | -18.57 | -18.55 | -11.78 | 103.05 | 1157.26 | 1223.8 | 1387.31 |
| 0.67 | -12.67 | -12.65 | -12.59 | -12.49 | -12.35 | -12.25 | -12.2 | -12.11 | -12.1 | -10.85 | 10.17 | 3.52 | 3.04 | 3.27 | 10.64 | 124.56 | 1158.59 | 1225.61 | 1387.77 |
| 0.33 | 929.55 | 929.54 | 929.54 | 929.53 | 929.52 | 929.51 | 929.51 | 929.51 | 929.51 | 929.53 | 929.77 | 930.65 | 933.85 | 944.14 | 973.09 | 1030.27 | 1141.73 | 1233.16 | 1390.43 |
| 0 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.81 | 1378.83 | 1378.93 | 1379.28 | 1380.43 | 1383.79 | 1390.71 | 1404.71 | 1420.56 | 1446.55 |
| Radius (feet) | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |

### Case 4b: Transient Temperature Distribution at Time Equal 0.50 Hours

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1403.57 | 1403.57 | 1403.57 | 1403.52 | 1401.98 | 1387.18 | 1373.55 | 1356.59 | 1355.43 | 1356.1 | 1382.36 | 1391.3 | 1395.55 | 1399.08 | 1404.99 | 1413.06 | 1416.84 | 1416.74 | 1443.41 |
| 24.6 | 1122.94 | 1122.94 | 1122.94 | 1122.56 | 1110.87 | 989.81 | 858.92 | 660.39 | 654.31 | 664.41 | 945.7 | 1022.77 | 1057.08 | 1084.63 | 1131.13 | 1205.44 | 1331.37 | 1365.48 | 1426.12 |
| 22.57 | -15.44 | -15.41 | -15.37 | -15.32 | -15.28 | -15.21 | -12.38 | 4.06 | 4.14 | 4.64 | -16.44 | -16.88 | -16.89 | -14.72 | 17.56 | 266.02 | 1351 | 1376.71 | 1429.57 |
| 20.53 | -15.96 | -15.91 | -15.87 | -15.84 | -15.83 | -15.83 | -15.78 | -15.44 | -15.44 | -15.43 | -17.97 | -18.23 | -18.35 | -16.31 | 15.86 | 264.55 | 1351.12 | 1376.81 | 1429.6 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18.49 | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.46 | -14.47 | -14.47 | -14.48 | -17.51 | -17.87 | -18.09 | -16.04 | 16.71 | 265.22 | 1350.22 | 1376.12 | 1429.37 |
| 16.45 | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.9 | -17.27 | -17.52 | -12.72 | 61.07 | 746.96 | 888.82 | 1219.69 | 1294.45 | 1406.02 |
| 16.11 | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -17.19 | -17.4 | -11.66 | 71.03 | 789.76 | 853.5 | 1012.26 | 1174.74 | 1378.02 |
| 15.45 | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -17.03 | -17.3 | -11.67 | 69.51 | 770.78 | 827.54 | 977.07 | 1149.22 | 1372.36 |
| 15.36 | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -17.02 | -17.29 | -11.68 | 69.35 | 769.05 | 825.6 | 975 | 1147.74 | 1372.04 |
| 13.64 | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -17.02 | -17.28 | -11.68 | 69.23 | 767.57 | 824.15 | 973.79 | 1146.95 | 1371.87 |
| 11.91 | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -17.09 | -17.34 | -11.71 | 69.21 | 767.6 | 824.18 | 973.82 | 1146.96 | 1371.87 |
| 10.18 | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -17.22 | -17.43 | -11.76 | 69.45 | 770.36 | 826.96 | 976.34 | 1148.63 | 1372.23 |
| 8.45 | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.25 | -13.25 | -17.4 | -17.55 | -11.34 | 77.17 | 843.52 | 929.33 | 1138.43 | 1245.7 | 1393.94 |
| 6 | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.35 | -17.49 | -17.86 | -18.09 | -16.07 | 16.54 | 264.95 | 1350.02 | 1375.96 | 1429.32 |
| 3.55 | -15.39 | -15.38 | -15.36 | -15.33 | -15.3 | -15.29 | -15.29 | -15.26 | -15.26 | -15.27 | -17.83 | -18.13 | -18.31 | -16.3 | 15.82 | 264.5 | 1351.11 | 1376.81 | 1429.6 |
| 1.1 | -12.21 | -12.19 | -12.13 | -12.03 | -11.94 | -12.41 | -13.04 | -14.12 | -14.17 | -14.3 | -17.67 | -18.01 | -18.13 | -16.05 | 16.15 | 264.83 | 1351.16 | 1376.85 | 1429.61 |
| 0.67 | -7.22 | -7.19 | -7.13 | -7.04 | -6.93 | -7.02 | -7.06 | -7.02 | -7.01 | -4.95 | 58.28 | 43.73 | 42.5 | 45.06 | 77.25 | 315.51 | 1350.51 | 1376.55 | 1429.54 |
| 0.33 | 1192.54 | 1192.54 | 1192.54 | 1192.54 | 1192.53 | 1192.53 | 1192.54 | 1192.55 | 1192.55 | 1192.76 | 1193.65 | 1195.57 | 1200.37 | 1211.65 | 1236.15 | 1275.09 | 1337.06 | 1375.05 | 1429.7 |
| 0 | 1412.73 | 1412.73 | 1412.73 | 1412.73 | 1412.73 | 1412.73 | 1412.73 | 1412.73 | 1412.74 | 1412.76 | 1412.89 | 1413.17 | 1413.87 | 1415.55 | 1419.28 | 1425.44 | 1435.57 | 1444.76 | 1457.26 |
| | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | ------- |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

**Case 4b: Transient Temperature Distribution at Time Equal 0.75 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1152.14 | 1152.15 | 1152.12 | 1151.41 | 1136.31 | 1033.28 | 977.11 | 920.83 | 916.65 | 914.55 | 1018.56 | 1077.55 | 1113.54 | 1140.33 | 1170.59 | 1202.88 | 1239.34 | 1242.52 | 1198.29 |
| 24.6 | 1177.47 | 1177.47 | 1177.44 | 1176.46 | 1155.06 | 1001.93 | 899.34 | 772.9 | 769.79 | 773.61 | 975.68 | 1067.87 | 1119.16 | 1156.67 | 1200.09 | 1243.27 | 1269.65 | 1251.98 | 1201.52 |
| 22.57 | -14 | -13.97 | -13.93 | -13.88 | -13.85 | -13.29 | -5.72 | 23.73 | 23.82 | 24.4 | -14.59 | -15.51 | -15.04 | -7.69 | 60.29 | 392.7 | 1275.77 | 1260.09 | 1208.97 |
| 20.53 | -15.95 | -15.91 | -15.87 | -15.84 | -15.83 | -15.81 | -15.61 | -14.64 | -14.64 | -14.61 | -17.94 | -18.18 | -17.81 | -10.6 | 57.34 | 390.45 | 1275.9 | 1260.23 | 1209.1 |
| 18.49 | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.45 | -14.45 | -14.45 | -14.46 | -17.51 | -17.83 | -17.52 | -10.11 | 58.98 | 391.55 | 1274.34 | 1258.74 | 1207.81 |
| 16.45 | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.9 | -17.12 | -16.3 | -0.29 | 142.85 | 940.26 | 1020.59 | 1150.45 | 1148.65 | 1113.44 |
| 16.11 | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -17.02 | -16.03 | 1.73 | 153.87 | 955.37 | 980.62 | 1020.19 | 1027.69 | 1006.03 |
| 15.45 | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -16.87 | -15.94 | 1.49 | 150.43 | 926.7 | 944.66 | 972.37 | 977.89 | 959.22 |
| 15.36 | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -16.85 | -15.93 | 1.46 | 150.08 | 924.18 | 941.8 | 968.97 | 974.38 | 955.9 |
| 13.64 | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -16.85 | -15.93 | 1.44 | 149.75 | 921.46 | 938.99 | 966.11 | 971.59 | 953.32 |
| 11.91 | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -16.92 | -15.98 | 1.4 | 149.74 | 921.51 | 939.04 | 966.15 | 971.63 | 953.36 |
| 10.18 | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -17.05 | -16.08 | 1.4 | 150.3 | 925.49 | 943.17 | 970.39 | 975.72 | 957.13 |
| 8.45 | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.24 | -13.25 | -17.22 | -16.07 | 2.98 | 165.12 | 1012.9 | 1050.11 | 1104.42 | 1103.48 | 1073 |
| 6 | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.35 | -17.48 | -17.82 | -17.53 | -10.18 | 58.61 | 391.13 | 1274.16 | 1258.56 | 1207.65 |
| 3.55 | -15.39 | -15.37 | -15.35 | -15.33 | -15.3 | -15.28 | -15.27 | -15.21 | -15.21 | -15.21 | -17.82 | -18.09 | -17.77 | -10.6 | 57.31 | 390.41 | 1275.91 | 1260.24 | 1209.1 |
| 1.1 | -7.73 | -7.71 | -7.65 | -7.57 | -7.66 | -8.95 | -10.07 | -11.79 | -11.86 | -12.15 | -16.9 | -17.31 | -16.96 | -9.72 | 58.23 | 391.15 | 1275.89 | 1260.22 | 1209.08 |
| 0.67 | -2.03 | -2.01 | -1.95 | -1.87 | -1.92 | -2.57 | -2.78 | -2.91 | -2.9 | -0.64 | 106.43 | 87.16 | 85.16 | 92.62 | 157.21 | 465.15 | 1274.69 | 1258.52 | 1207.43 |
| 0.33 | 1221.84 | 1221.84 | 1221.84 | 1221.84 | 1221.84 | 1221.85 | 1221.88 | 1221.93 | 1221.93 | 1222.49 | 1224.2 | 1227.09 | 1233.01 | 1243.98 | 1260.61 | 1273.39 | 1270.53 | 1248.03 | 1196.75 |
| 0 | 1182.33 | 1182.33 | 1182.33 | 1182.33 | 1182.33 | 1182.34 | 1182.35 | 1182.39 | 1182.39 | 1182.74 | 1183.77 | 1185.66 | 1189.48 | 1196.28 | 1205.62 | 1210.31 | 1201.24 | 1175.83 | 1131.24 |
| | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | ------- |
| | 0 | 0.92 | 1.83 | 2.75 | 3.67 | 4.17 | 4.29 | 4.42 | 4.43 | 4.87 | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | 6.38 | 6.5 |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

**Case 4b: Transient Temperature Distribution at Time Equal 1.00 Hours**

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.94 | 1071.1 | 1071.09 | 1070.98 | 1068.86 | 1037.33 | 905.78 | 864.23 | 826.15 | 823.32 | 823.64 | 906.37 | 969.28 | 1018.9 | 1057.24 | 1089.28 | 1112.39 | 1132.81 | 1132.05 | 1098.03 |
| 24.6 | 1138.42 | 1138.42 | 1138.3 | 1135.96 | 1099.22 | 934 | 869.1 | 796.67 | 794.99 | 796.56 | 931.07 | 1016.24 | 1077.76 | 1123.45 | 1160.17 | 1179.48 | 1173.7 | 1157.56 | 1117.13 |
| 22.57 | -12.56 | -12.53 | -12.49 | -12.44 | -12.44 | -10.69 | 3.03 | 43.93 | 44.03 | 44.62 | -12.44 | -14.01 | -12.45 | 3.13 | 107.33 | 472.42 | 1171.22 | 1159.02 | 1119.45 |
| 20.53 | -15.95 | -15.9 | -15.86 | -15.83 | -15.82 | -15.76 | -15.26 | -13.35 | -13.34 | -13.3 | -17.88 | -18.04 | -16.52 | -1.1 | 103.26 | 469.57 | 1171.32 | 1159.13 | 1119.56 |
| 18.49 | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.44 | -14.44 | -14.41 | -14.41 | -14.41 | -17.49 | -17.69 | -16.16 | -0.26 | 105.62 | 470.92 | 1168.84 | 1156.71 | 1117.39 |

## Tabular Results of HEATING Model Temperature Distributions

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **16.45** | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.61 | -12.89 | -12.89 | -12.89 | -16.65 | -13.54 | 18.66 | 220.57 | 986.45 | 1021.27 | 1053.91 | 1045.71 | 1017.05 |
| **16.11** | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.58 | -12.58 | -12.6 | -16.49 | -13.05 | 21.36 | 229.78 | 984.22 | 990.16 | 990.06 | 977.59 | 952.6 |
| **15.45** | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -16.34 | -13 | 20.71 | 223.39 | 942.73 | 944.26 | 937.79 | 924.19 | 901.95 |
| **15.36** | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.32 | -9.62 | -11.9 | -11.9 | -11.96 | -16.33 | -13 | 20.64 | 222.76 | 939.01 | 940.29 | 933.48 | 919.84 | 897.83 |
| **13.64** | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.02 | -16.33 | -13 | 20.56 | 222.03 | 933.7 | 934.85 | 927.96 | 914.43 | 892.73 |
| **11.91** | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -16.4 | -13.06 | 20.52 | 222.02 | 933.76 | 934.91 | 928.02 | 914.48 | 892.79 |
| **10.18** | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.63 | -12.63 | -12.64 | -16.53 | -13.14 | 20.6 | 223.05 | 939.68 | 940.92 | 934 | 920.28 | 898.22 |
| **8.45** | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.24 | -13.25 | -16.66 | -12.89 | 23.89 | 245.05 | 1035.23 | 1043.59 | 1038.89 | 1025.74 | 997.2 |
| **6** | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.34 | -14.34 | -14.34 | -14.34 | -17.46 | -17.68 | -16.18 | -0.41 | 105.03 | 470.37 | 1168.81 | 1156.69 | 1117.37 |
| **3.55** | -15.38 | -15.36 | -15.34 | -15.32 | -15.29 | -15.27 | -15.24 | -15.11 | -15.11 | -15.12 | -17.8 | -17.96 | -16.48 | -1.1 | 103.22 | 469.54 | 1171.32 | 1159.14 | 1119.57 |
| **1.1** | -3.05 | -3.03 | -2.97 | -2.93 | -3.35 | -5.55 | -7.03 | -9.17 | -9.25 | -9.67 | -15.78 | -16.2 | -14.73 | 0.71 | 104.97 | 470.78 | 1171.16 | 1158.96 | 1119.41 |
| **0.67** | 2.58 | 2.6 | 2.65 | 2.7 | 2.32 | 0.94 | 0.53 | 0.22 | 0.21 | 2.39 | 147.19 | 127.17 | 125.04 | 139.55 | 234.26 | 559.51 | 1168.1 | 1155.22 | 1115.74 |
| **0.33** | 1164.64 | 1164.64 | 1164.64 | 1164.64 | 1164.64 | 1164.69 | 1164.76 | 1164.89 | 1164.91 | 1166.09 | 1168.83 | 1172.41 | 1177.78 | 1184.14 | 1187.71 | 1182.19 | 1162.23 | 1140.75 | 1100.32 |
| **0** | 1097.52 | 1097.52 | 1097.52 | 1097.52 | 1097.52 | 1097.57 | 1097.63 | 1097.74 | 1097.75 | 1098.69 | 1100.68 | 1103.48 | 1107.56 | 1111.99 | 1113.35 | 1106.78 | 1088.08 | 1063.78 | 1029.17 |
| | -------- | -------- | --------- | -------- | ------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | --------- | -------- | ------- |
| | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

### Case 4b: Transient Temperature Distribution at Time Equal 1.50 Hours

| Elev. (ft) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 979.22 | 979.17 | 978.56 | 971.93 | 918.12 | 814.16 | 792.74 | 775.05 | 773.78 | 779.52 | 830.31 | 875.42 | 916.91 | 950.35 | 973.5 | 985.08 | 992.93 | 990.01 | 966.58 |
| **24.6** | 1038.15 | 1038.1 | 1037.46 | 1030.19 | 968.91 | 844.83 | 814.59 | 783.87 | 783.16 | 785.94 | 861.6 | 919.35 | 969.74 | 1009.04 | 1033.29 | 1037.54 | 1021.21 | 1009.57 | 982.45 |
| **22.57** | -9.88 | -9.85 | -9.81 | -9.78 | -9.77 | -3.29 | 23.33 | 81.05 | 81.16 | 81.78 | -7.46 | -10.31 | -4.34 | 32.98 | 192.9 | 549.08 | 1007.71 | 999.86 | 974.47 |
| **20.53** | -15.93 | -15.89 | -15.85 | -15.82 | -15.8 | -15.48 | -13.88 | -9.47 | -9.45 | -9.39 | -17.53 | -17.13 | -10.86 | 26.45 | 187.09 | 545.43 | 1007.52 | 999.69 | 974.32 |
| **18.49** | -14.56 | -14.46 | -14.38 | -14.33 | -14.36 | -14.43 | -14.38 | -14.19 | -14.19 | -14.19 | -17.29 | -16.75 | -10.21 | 28.13 | 190.42 | 546.74 | 1003.59 | 995.83 | 970.74 |
| **16.45** | -13.02 | -12.78 | -12.45 | -12.03 | -11.82 | -12.38 | -12.6 | -12.87 | -12.87 | -12.88 | -13.75 | -2.48 | 66.57 | 334.1 | 940.25 | 946.8 | 929.4 | 919.76 | 898.74 |
| **16.11** | -12.78 | -12.51 | -12.09 | -11.38 | -10.13 | -10.79 | -10.81 | -12.57 | -12.57 | -12.59 | -13.41 | -1.56 | 69.76 | 340.34 | 943.59 | 941.69 | 928.69 | 912.16 | 889.59 |
| **15.45** | -12.32 | -12.01 | -11.4 | -9.91 | -1.81 | -9.03 | -9.48 | -11.96 | -11.96 | -12.01 | -13.31 | -1.75 | 67.61 | 328.39 | 905.45 | 903.18 | 890.84 | 875.33 | 854.89 |
| **15.36** | -12.27 | -11.95 | -11.34 | -9.81 | -1.96 | -9.31 | -9.62 | -11.9 | -11.9 | -11.95 | -13.3 | -1.77 | 67.38 | 327.21 | 901.72 | 899.45 | 887.18 | 871.8 | 851.57 |
| **13.64** | -11.72 | -11.57 | -11.42 | -11.29 | -11.34 | -11.82 | -11.82 | -12 | -12 | -12.01 | -13.31 | -1.82 | 67.02 | 324.95 | 890.73 | 888.48 | 876.51 | 861.57 | 841.95 |
| **11.91** | -11.73 | -11.68 | -11.68 | -11.77 | -11.97 | -12.1 | -12.1 | -12.23 | -12.23 | -12.24 | -13.38 | -1.87 | 66.99 | 324.95 | 890.74 | 888.49 | 876.52 | 861.57 | 841.95 |
| **10.18** | -12.13 | -12.1 | -12.14 | -12.24 | -12.41 | -12.5 | -12.5 | -12.62 | -12.62 | -12.63 | -13.5 | -1.9 | 67.36 | 327.17 | 899.32 | 897 | 884.72 | 869.41 | 849.32 |
| **8.45** | -12.95 | -12.94 | -12.96 | -13.02 | -13.1 | -13.09 | -13.09 | -13.24 | -13.24 | -13.25 | -13.37 | -0.66 | 74.85 | 357.86 | 970.53 | 967.84 | 946.72 | 932.56 | 909.49 |
| **6** | -14.27 | -14.26 | -14.26 | -14.28 | -14.31 | -14.33 | -14.33 | -14.33 | -14.33 | -14.33 | -17.28 | -16.76 | -10.3 | 27.75 | 189.49 | 546.14 | 1004.23 | 996.46 | 971.32 |
| **3.55** | -15.35 | -15.33 | -15.31 | -15.29 | -15.26 | -15.23 | -15.12 | -14.79 | -14.79 | -14.79 | -17.61 | -17.08 | -10.82 | 26.44 | 187.05 | 545.4 | 1007.54 | 999.71 | 974.34 |
| **1.1** | 5.72 | 5.74 | 5.76 | 5.62 | 4.18 | 0.48 | -1.39 | -3.94 | -4.04 | -4.6 | -12.64 | -12.55 | -6.43 | 30.76 | 190.85 | 547.67 | 1006.7 | 998.86 | 973.54 |
| **0.67** | 10.75 | 10.77 | 10.79 | 10.63 | 9.25 | 6.53 | 5.82 | 5.25 | 5.22 | 7.11 | 206.91 | 192.76 | 193.19 | 224.07 | 357.58 | 648.79 | 1000.89 | 992.45 | 967.3 |
| **0.33** | 1039.35 | 1039.35 | 1039.35 | 1039.35 | 1039.39 | 1039.69 | 1039.94 | 1040.3 | 1040.35 | 1042.65 | 1045.29 | 1046.69 | 1046.51 | 1042.93 | 1033.44 | 1018.75 | 996.33 | 980.54 | 954.08 |
| **0** | 986.96 | 986.96 | 986.96 | 986.96 | 987 | 987.27 | 987.49 | 987.79 | 987.83 | 989.72 | 991.56 | 992.58 | 992.19 | 988.72 | 979.94 | 966.61 | 946.82 | 927.64 | 903.47 |
| | -------- | -------- | --------- | -------- | ------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | -------- | --------- | -------- | ------- |
| | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.25** | **6.38** | **6.5** |
| | Radius (feet) | | | | | | | | | | | | | | | | | | |

### Case Gap1: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 100.74 | 100.76 | 100.82 | 100.91 | 101.06 | 101.15 | 101.18 | 101.19 | 101.2 | 101.17 | 101.08 | 101.01 | 100.94 | 100.88 | 100.83 | 100.79 | 100.76 | 100.76 | 100.75 | 100.74 |
| **24.6** | 100.74 | 100.77 | 100.82 | 100.92 | 101.06 | 101.17 | 101.2 | 101.25 | 101.25 | 101.24 | 101.1 | 101.02 | 100.95 | 100.89 | 100.83 | 100.78 | 100.74 | 100.73 | 100.73 | 100.72 |
| **22.57** | 102.24 | 102.27 | 102.31 | 102.36 | 102.42 | 102.45 | 102.46 | 102.47 | 102.47 | 102.46 | 101.24 | 101.09 | 100.95 | 100.8 | 100.66 | 100.55 | 100.44 | 100.43 | 100.43 | 100.43 |
| **20.53** | 103.61 | 103.66 | 103.7 | 103.73 | 103.74 | 103.74 | 103.73 | 103.73 | 103.73 | 103.73 | 101.66 | 101.41 | 101.16 | 100.93 | 100.7 | 100.52 | 100.34 | 100.33 | 100.33 | 100.33 |
| **18.49** | 105.03 | 105.13 | 105.21 | 105.26 | 105.23 | 105.15 | 105.13 | 105.11 | 105.11 | 105.11 | 102.16 | 101.8 | 101.46 | 101.13 | 100.82 | 100.58 | 100.34 | 100.33 | 100.32 | 100.32 |
| **16.45** | 106.59 | 106.82 | 107.15 | 107.56 | 107.76 | 107.21 | 106.99 | 106.72 | 106.72 | 106.71 | 102.47 | 101.96 | 101.46 | 100.98 | 100.5 | 100.48 | 100.45 | 100.38 | 100.38 | 100.38 |

FINAL

## Tabular Results of HEATING Model Temperature Distributions

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **16.11** | 106.82 | 107.09 | 107.5 | 108.21 | 109.43 | 108.8 | 108.78 | 107.03 | 107.03 | 107.01 | 102.56 | 102.02 | 101.5 | 101 | 100.51 | 100.51 | 100.51 | 100.36 | 100.36 | 100.36 |
| **15.45** | 107.28 | 107.6 | 108.19 | 109.65 | 117.59 | 110.52 | 110.08 | 107.65 | 107.64 | 107.6 | 102.75 | 102.16 | 101.6 | 101.07 | 100.56 | 100.56 | 100.55 | 100.32 | 100.32 | 100.32 |
| **15.36** | 107.34 | 107.65 | 108.26 | 109.76 | 117.45 | 110.24 | 109.94 | 107.71 | 107.7 | 107.65 | 102.76 | 102.17 | 101.61 | 101.08 | 100.56 | 100.56 | 100.56 | 100.32 | 100.32 | 100.32 |
| **13.64** | 107.9 | 108.05 | 108.2 | 108.32 | 108.28 | 107.8 | 107.8 | 107.62 | 107.62 | 107.61 | 102.81 | 102.23 | 101.67 | 101.14 | 100.62 | 100.62 | 100.62 | 100.28 | 100.28 | 100.28 |
| **11.91** | 107.9 | 107.96 | 107.96 | 107.87 | 107.66 | 107.53 | 107.53 | 107.41 | 107.41 | 107.4 | 102.75 | 102.19 | 101.65 | 101.13 | 100.62 | 100.62 | 100.62 | 100.28 | 100.28 | 100.28 |
| **10.18** | 107.52 | 107.55 | 107.51 | 107.41 | 107.23 | 107.15 | 107.15 | 107.02 | 107.02 | 107.01 | 102.59 | 102.06 | 101.54 | 101.05 | 100.57 | 100.57 | 100.57 | 100.3 | 100.3 | 100.3 |
| **8.45** | 106.71 | 106.72 | 106.7 | 106.64 | 106.56 | 106.56 | 106.56 | 106.42 | 106.42 | 106.41 | 102.34 | 101.85 | 101.37 | 100.91 | 100.46 | 100.45 | 100.44 | 100.38 | 100.37 | 100.37 |
| **6** | 105.4 | 105.41 | 105.41 | 105.39 | 105.36 | 105.34 | 105.33 | 105.33 | 105.33 | 105.32 | 102.23 | 101.86 | 101.5 | 101.16 | 100.83 | 100.57 | 100.32 | 100.3 | 100.3 | 100.3 |
| **3.55** | 104.28 | 104.29 | 104.31 | 104.34 | 104.37 | 104.38 | 104.39 | 104.39 | 104.39 | 104.39 | 101.88 | 101.57 | 101.28 | 101 | 100.72 | 100.51 | 100.3 | 100.28 | 100.28 | 100.28 |
| **1.1** | 103.05 | 103.07 | 103.13 | 103.23 | 103.38 | 103.48 | 103.52 | 103.56 | 103.56 | 103.57 | 101.54 | 101.29 | 101.06 | 100.84 | 100.64 | 100.49 | 100.34 | 100.33 | 100.33 | 100.33 |
| **0.67** | 103.04 | 103.06 | 103.12 | 103.22 | 103.37 | 103.46 | 103.48 | 103.5 | 103.5 | 103.51 | 101.55 | 101.13 | 100.86 | 100.69 | 100.55 | 100.45 | 100.36 | 100.36 | 100.36 | 100.35 |
| **0.33** | 100.82 | 100.82 | 100.8 | 100.77 | 100.71 | 100.66 | 100.65 | 100.63 | 100.63 | 100.57 | 100.53 | 100.5 | 100.47 | 100.45 | 100.42 | 100.4 | 100.39 | 100.39 | 100.38 | 100.38 |
| **0** | 100.81 | 100.8 | 100.79 | 100.75 | 100.7 | 100.65 | 100.64 | 100.62 | 100.62 | 100.56 | 100.52 | 100.49 | 100.47 | 100.44 | 100.42 | 100.4 | 100.39 | 100.39 | 100.39 | 100.38 |
| | -------- | -------- | ---------- | ------ | -------- | -------- | ---------- | -------- | ------ | -------- | -------- | -------- | -------- | -------- | -------- | -------- | ---------- | ------ | -------- | -------- |
| | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.24** | **6.25** | **6.38** | **6.5** |
| | Radius (feet) | | | | | | | | | | | | | | | | | | | |

### Case Gap2: Steady-State Temperature Distribution

| Elev. (ft) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.94** | 156.08 | 156.41 | 157.41 | 159.21 | 162.03 | 164.11 | 164.65 | 165.19 | 165.23 | 166.25 | 167.28 | 168.24 | 169.32 | 170.5 | 171.79 | 172.86 | 173.88 | 173.94 | 174.44 | 174.68 |
| **24.6** | 156.18 | 156.5 | 157.52 | 159.34 | 162.19 | 164.38 | 165.06 | 165.87 | 165.9 | 166.32 | 167.48 | 168.47 | 169.57 | 170.81 | 172.19 | 173.47 | 174.99 | 175.1 | 175.29 | 175.45 |
| **22.57** | 165.72 | 165.93 | 166.53 | 167.48 | 168.74 | 169.49 | 169.67 | 169.87 | 169.87 | 169.88 | 178.75 | 179.86 | 180.99 | 182.16 | 183.35 | 184.34 | 185.35 | 185.41 | 185.43 | 185.47 |
| **20.53** | 171.47 | 171.6 | 171.91 | 172.35 | 172.88 | 173.17 | 173.25 | 173.32 | 173.32 | 173.33 | 182.82 | 183.98 | 185.11 | 186.22 | 187.32 | 188.2 | 189.07 | 189.12 | 189.13 | 189.15 |
| **18.49** | 175.47 | 175.61 | 175.82 | 176.08 | 176.32 | 176.41 | 176.43 | 176.45 | 176.45 | 176.46 | 185.05 | 186.09 | 187.09 | 188.05 | 188.99 | 189.72 | 190.44 | 190.49 | 190.49 | 190.5 |
| **16.45** | 178.67 | 178.94 | 179.35 | 179.88 | 180.25 | 179.82 | 179.62 | 179.36 | 179.36 | 179.37 | 187.12 | 188.06 | 188.99 | 189.9 | 190.81 | 190.84 | 190.87 | 190.96 | 190.97 | 190.97 |
| **16.11** | 179.12 | 179.42 | 179.91 | 180.72 | 182.03 | 181.67 | 181.66 | 179.84 | 179.84 | 179.83 | 187.31 | 188.21 | 189.1 | 189.97 | 190.81 | 190.82 | 190.82 | 191.04 | 191.04 | 191.05 |
| **15.45** | 179.95 | 180.3 | 180.97 | 182.5 | 189.88 | 183.22 | 182.83 | 180.75 | 180.75 | 180.72 | 187.59 | 188.43 | 189.24 | 190.02 | 190.79 | 190.79 | 190.79 | 191.15 | 191.15 | 191.16 |
| **15.36** | 180.05 | 180.4 | 181.09 | 182.65 | 189.69 | 182.89 | 182.66 | 180.85 | 180.85 | 180.81 | 187.62 | 188.45 | 189.25 | 190.03 | 190.78 | 190.79 | 190.79 | 191.16 | 191.16 | 191.17 |
| **13.06** | 181.31 | 181.45 | 181.59 | 181.71 | 181.7 | 181.47 | 181.47 | 181.33 | 181.33 | 181.33 | 187.8 | 188.59 | 189.34 | 190.07 | 190.77 | 190.77 | 190.78 | 191.27 | 191.27 | 191.27 |
| **10.75** | 181.21 | 181.26 | 181.29 | 181.29 | 181.24 | 181.22 | 181.22 | 181.11 | 181.11 | 181.11 | 187.74 | 188.54 | 189.32 | 190.06 | 190.78 | 190.79 | 190.79 | 191.23 | 191.23 | 191.24 |
| **8.45** | 179.86 | 179.89 | 179.94 | 180.01 | 180.09 | 180.2 | 180.2 | 180.05 | 180.05 | 180.05 | 187.4 | 188.3 | 189.17 | 190.02 | 190.85 | 190.86 | 190.87 | 190.96 | 190.96 | 190.97 |
| **6** | 177.46 | 177.5 | 177.58 | 177.7 | 177.86 | 177.95 | 177.97 | 177.99 | 177.99 | 178 | 185.46 | 186.36 | 187.24 | 188.09 | 188.91 | 189.57 | 190.21 | 190.25 | 190.25 | 190.26 |
| **3.55** | 174.45 | 174.51 | 174.66 | 174.91 | 175.22 | 175.41 | 175.46 | 175.51 | 175.51 | 175.51 | 182.72 | 183.6 | 184.49 | 185.38 | 186.28 | 187.02 | 187.76 | 187.81 | 187.82 | 187.84 |
| **1.1** | 169.99 | 170.1 | 170.44 | 170.99 | 171.74 | 172.24 | 172.39 | 172.57 | 172.58 | 172.63 | 175.19 | 175.61 | 176.22 | 176.99 | 177.9 | 178.74 | 179.65 | 179.71 | 179.74 | 179.81 |
| **0.67** | 169.93 | 170.05 | 170.38 | 170.94 | 171.69 | 172.15 | 172.25 | 172.34 | 172.35 | 172.43 | 170.6 | 171 | 171.73 | 172.7 | 173.86 | 174.96 | 176.2 | 176.28 | 176.34 | 176.45 |
| **0.33** | 156.58 | 156.78 | 157.4 | 158.53 | 160.33 | 161.71 | 162.11 | 162.55 | 162.6 | 164.27 | 165.38 | 166.37 | 167.45 | 168.65 | 169.98 | 171.22 | 172.69 | 172.81 | 173.32 | 173.59 |
| **0** | 156.44 | 156.64 | 157.26 | 158.38 | 160.17 | 161.53 | 161.93 | 162.36 | 162.41 | 164.07 | 165.18 | 166.15 | 167.21 | 168.36 | 169.59 | 170.6 | 171.53 | 171.58 | 172.06 | 172.32 |
| | ------- | -------- | ---------- | ------ | -------- | -------- | ---------- | -------- | ------ | -------- | -------- | -------- | -------- | -------- | ------- | -------- | ---------- | ------ | -------- | -------- |
| | **0** | **0.92** | **1.83** | **2.75** | **3.67** | **4.17** | **4.29** | **4.42** | **4.43** | **4.87** | **5.12** | **5.32** | **5.52** | **5.72** | **5.92** | **6.08** | **6.24** | **6.25** | **6.38** | **6.5** |
| | Radius (feet) | | | | | | | | | | | | | | | | | | | |

# Attachment A
# HEATING 7.2f Input/Output Files and Audit Trail Listing

```
HEATING72 Version 7.2f  -  Sargent & Lundy Program No. 03.7.564-7.2F
User 0K0212 on PC5765     Thursday, December 14, 2000     Time: 17:56:06
Controlled Files:

Drive V: = SNL4A_SYS3: \

 Volume in drive V is SYS3

[Base]\H72.EXE                                       03-29-1995 09:18
[Base]\H7LINE.EXE                                    01-25-1995 11:32
[Base]\H7MAP.EXE                                     03-31-1995 11:19
[Base]\H7MONITO.EXE                                  03-21-1995 10:37
[Base]\H7TECPLO.EXE                                  01-24-1995 16:54
[Base]\CONCVR.EXE                                    01-26-1995 12:04
[Base]\H7MATLIB                                      10-22-1992 15:44
[Base]\F77L3.EER                                     08-27-1993 11:03
[Base]\HEATING$.BAT                                  06-27-1996 16:00
[Base]\H7.BAT                                        06-27-1996 16:02

Active Data Directory:

 Volume in drive C is PC5765
 Volume Serial Number is 36A5-AE37
 Directory of C:\WORK\BIG-ROCK\CASK\REV1\MODEL

.            <DIR>            12-14-00  10:34a
..           <DIR>            12-14-00  10:34a
case1a   inp         8,041 12-14-00   2:31p
case1a   map       217,186 12-14-00   3:12p
case1a   out       103,532 12-14-00   2:42p
case1b   inp         8,066 12-14-00   2:31p
case1b   map       217,186 12-14-00   3:12p
case1b   out       104,202 12-14-00   3:02p
case2a   inp         8,122 12-14-00   2:08p
case2a   map       217,186 12-14-00   3:03p
case2a   out       104,738 12-14-00   2:29p
case2b   inp         8,214 12-14-00   2:30p
case2b   map       217,186 12-14-00   3:33p
case2b   out       104,202 12-14-00   3:33p
case3a   inp         8,072 12-14-00   3:04p
case3a   map       217,186 12-14-00   3:44p
case3a   out       103,532 12-14-00   3:43p
case3b   inp         8,072 12-14-00   3:04p
case3b   map       217,186 12-14-00   3:54p
case3b   out       103,532 12-14-00   3:53p
case4a   inp         8,328 12-14-00   3:04p
case4a   map     1,303,116 12-14-00   4:32p
case4a   out       129,510 12-14-00   4:31p
case4b   inp         8,328 12-14-00   3:05p
```

| Sargent & Lundy LLC | Calc For Thermal Response of Reactor Vessel Transport System | Calc No. M-10525-020-001 |
|---|---|---|
| | | Rev. 1 / Date |
| | X Important to Safety - Category A / Non-Safety Related | Page A2 |

| | | | |
|---|---|---|---|
| Client | BNFL, Inc. | Prepared by | Mark C. Handrick / Date |
| Project | Big Rock Point Major Component Removal | Reviewed by | Michael E. Duffy / Date |
| Proj. No | 10525-020 Equip. No. | Approved by | Robert J. Peterson / Date |

```
case4b   map    1,303,116 12-14-00   5:17p
case4b   out      129,510 12-14-00   5:15p
casegap1 inp        8,309 12-14-00   5:16p
casegap1 map      217,186 12-14-00   5:27p
casegap1 out      106,212 12-14-00   5:27p
casegap2 inp        8,389 12-14-00   5:33p
casegap2 map      208,816 12-14-00   5:54p
casegap2 out      107,418 12-14-00   5:53p
h72f     $cr       48,987 12-14-00   5:53p
nodemap           194,674 12-14-00   3:03p
plot0000          667,900 12-14-00   2:39p
plot0001          667,900 12-14-00   3:00p
plot0002          667,900 12-14-00   2:28p
plot0003          667,900 12-14-00   3:32p
plot0004          667,900 12-14-00   3:42p
plot0005          667,900 12-14-00   3:52p
plot0006        1,115,825 12-14-00   4:30p
plot0007        1,115,825 12-14-00   5:14p
plot0008          695,582 12-14-00   5:25p
plot0009          658,554 12-14-00   5:53p
print000          103,532 12-14-00   2:39p
print001          104,202 12-14-00   3:00p
print002          104,738 12-14-00   2:28p
print003          104,202 12-14-00   3:32p
print004          103,532 12-14-00   3:42p
print005          103,532 12-14-00   3:52p
print006          129,510 12-14-00   4:30p
print007          129,510 12-14-00   5:14p
print008          106,212 12-14-00   5:25p
print009          107,418 12-14-00   5:54p
         54 file(s)     14,446,914 bytes
                       159,694,848 bytes free

End of Controlled File Information scope
```

HEATING 7.2f Input/Output Files on CD ROM

This calculation is classified as Important to Safety – Category A

# Table B1
## Spreadsheet Cell Formulas and Computations for Table 2

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | |
| 2 | Region | Min R | Max R | Min θ | Max θ | Min Z | Max Z | Min R | Max R | Min θ | Max θ | Min Z | Max Z | Volume | Heat Load | Heat Source |
| 3 | | (in) | (in) | (°) | (°) | (in) | (in) | (feet) | (feet) | (radians) | (radians) | (feet) | (feet) | ($ft^3$) | (Btu/hr) | (Btu/ft$^3$-hr) |
| 4 | 1 | 0 | 78 | 0 | 360 | 0 | 4 | =B4/12 | =C4/12 | =RADIANS(0) | =RADIANS(E4) | =F4/12 | =G4/12 | =0.5*(I4^2-H4^2)*(K4-J4)*(M4-L4) | 0 | =O4/N4 |
| 5 | 2 | 75 | 78 | 0 | 360 | 4 | 101.375 | =B5/12 | =C5/12 | =RADIANS(D5) | =RADIANS(E5) | =F5/12 | =G5/12 | =0.5*(I5^2-H5^2)*(K5-J5)*(M5-L5) | 0 | =O5/N5 |
| 6 | 3 | 71 | 78 | 0 | 360 | 101.375 | 197.375 | =B6/12 | =C6/12 | =RADIANS(D6) | =RADIANS(E6) | =F6/12 | =G6/12 | =0.5*(I6^2-H6^2)*(K6-J6)*(M6-L6) | 0 | =O6/N6 |
| 7 | 4 | 75 | 78 | 0 | 360 | 197.375 | 299.25 | =B7/12 | =C7/12 | =RADIANS(D7) | =RADIANS(E7) | =F7/12 | =G7/12 | =0.5*(I7^2-H7^2)*(K7-J7)*(M7-L7) | 0 | =O7/N7 |
| 8 | 5 | 0 | 75 | 0 | 360 | 295.25 | 299.25 | =B8/12 | =C8/12 | =RADIANS(D8) | =RADIANS(E8) | =F8/12 | =G8/12 | =0.5*(I8^2-H8^2)*(K8-J8)*(M8-L8) | 0 | =O8/N8 |
| 9 | 6 | 0 | 75 | 0 | 360 | 4 | 8 | =B9/12 | =C9/12 | =RADIANS(D9) | =RADIANS(E9) | =F9/12 | =G9/12 | =0.5*(I9^2-H9^2)*(K9-J9)*(M9-L9) | 0 | =O9/N9 |
| 10 | 7 | 61.46875 | 75 | 0 | 360 | 8 | 101.375 | =B10/12 | =C10/12 | =RADIANS(D10) | =RADIANS(E10) | =F10/12 | =G10/12 | =0.5*(I10^2-H10^2)*(K10-J10)*(M10-L10) | 0 | =O10/N10 |
| 11 | 8 | 61.46875 | 71 | 0 | 360 | 101.375 | 197.375 | =B11/12 | =C11/12 | =RADIANS(D11) | =RADIANS(E11) | =F11/12 | =G11/12 | =0.5*(I11^2-H11^2)*(K11-J11)*(M11-L11) | 0 | =O11/N11 |
| 12 | 9 | 61.46875 | 75 | 0 | 360 | 197.375 | 295.25 | =B12/12 | =C12/12 | =RADIANS(D12) | =RADIANS(E12) | =F12/12 | =G12/12 | =0.5*(I12^2-H12^2)*(K12-J12)*(M12-L12) | 0 | =O12/N12 |
| 13 | 10 | 58.46875 | 61.46875 | 0 | 360 | 8 | 295.25 | =B13/12 | =C13/12 | =RADIANS(D13) | =RADIANS(E13) | =F13/12 | =G13/12 | =0.5*(I13^2-H13^2)*(K13-J13)*(M13-L13) | 2.19 | =O13/N13 |
| 14 | 11 | 0 | 58.46875 | 0 | 360 | 8 | 13.25 | =B14/12 | =C14/12 | =RADIANS(D14) | =RADIANS(E14) | =F14/12 | =G14/12 | =0.5*(I14^2-H14^2)*(K14-J14)*(M14-L14) | 0 | =O14/N14 |
| 15 | 12 | 53.21875 | 58.46875 | 0 | 360 | 13.25 | 295.25 | =B15/12 | =C15/12 | =RADIANS(D15) | =RADIANS(E15) | =F15/12 | =G15/12 | =0.5*(I15^2-H15^2)*(K15-J15)*(M15-L15) | 41.8 | =O15/N15 |
| 16 | 13 | 53.0625 | 53.21875 | 0 | 360 | 13.25 | 295.25 | =B16/12 | =C16/12 | =RADIANS(D16) | =RADIANS(E16) | =F16/12 | =G16/12 | =0.5*(I16^2-H16^2)*(K16-J16)*(M16-L16) | 9.23 | =O16/N16 |
| 17 | 14 | 0 | 53.0625 | 0 | 360 | 13.25 | 101.375 | =B17/12 | =C17/12 | =RADIANS(D17) | =RADIANS(E17) | =F17/12 | =G17/12 | =0.5*(I17^2-H17^2)*(K17-J17)*(M17-L17) | 0 | =O17/N17 |
| 18 | 15 | 0 | 53.0625 | 0 | 360 | 193.375 | 295.25 | =B18/12 | =C18/12 | =RADIANS(D18) | =RADIANS(E18) | =F18/12 | =G18/12 | =0.5*(I18^2-H18^2)*(K18-J18)*(M18-L18) | 0 | =O18/N18 |
| 19 | 16 | 44 | 50 | 0 | 89 | 184.375 | 185.375 | =B19/12 | =C19/12 | =RADIANS(D19) | =RADIANS(E19) | =F19/12 | =G19/12 | =0.5*(I19^2-H19^2)*(K19-J19)*(M19-L19) | 25.38 | =O19/N19 |
| 20 | 17 | 44 | 50 | 89 | 91 | 184.375 | 185.375 | =B20/12 | =C20/12 | =RADIANS(D20) | =RADIANS(E20) | =F20/12 | =G20/12 | =0.5*(I20^2-H20^2)*(K20-J20)*(M20-L20) | 29.74 | =O20/N20 |
| 21 | 18 | 44 | 50 | 91 | 180 | 184.375 | 185.375 | =B21/12 | =C21/12 | =RADIANS(D21) | =RADIANS(E21) | =F21/12 | =G21/12 | =0.5*(I21^2-H21^2)*(K21-J21)*(M21-L21) | 25.38 | =O21/N21 |
| 22 | 19 | 44 | 50 | 180 | 360 | 184.375 | 185.375 | =B22/12 | =C22/12 | =RADIANS(D22) | =RADIANS(E22) | =F22/12 | =G22/12 | =0.5*(I22^2-H22^2)*(K22-J22)*(M22-L22) | 21.5 | =O22/N22 |
| 23 | 20 | 50 | 51.5 | 0 | 360 | 101.375 | 193.375 | =B23/12 | =C23/12 | =RADIANS(D23) | =RADIANS(E23) | =F23/12 | =G23/12 | =0.5*(I23^2-H23^2)*(K23-J23)*(M23-L23) | 278.8 | =O23/N23 |
| 24 | 21 | 51.5 | 53.0625 | 5 | 25 | 101.375 | 185.375 | =B24/12 | =C24/12 | =RADIANS(D24) | =RADIANS(E24) | =F24/12 | =G24/12 | =0.5*(I24^2-H24^2)*(K24-J24)*(M24-L24) | 3.45 | =O24/N24 |
| 25 | 22 | 51.5 | 53.0625 | 35 | 55 | 101.375 | 185.375 | =B25/12 | =C25/12 | =RADIANS(D25) | =RADIANS(E25) | =F25/12 | =G25/12 | =0.5*(I25^2-H25^2)*(K25-J25)*(M25-L25) | 3.45 | =O25/N25 |
| 26 | 23 | 51.5 | 53.0625 | 65 | 85 | 101.375 | 185.375 | =B26/12 | =C26/12 | =RADIANS(D26) | =RADIANS(E26) | =F26/12 | =G26/12 | =0.5*(I26^2-H26^2)*(K26-J26)*(M26-L26) | 3.45 | =O26/N26 |
| 27 | 24 | 51.5 | 53.0625 | 95 | 115 | 101.375 | 185.375 | =B27/12 | =C27/12 | =RADIANS(D27) | =RADIANS(E27) | =F27/12 | =G27/12 | =0.5*(I27^2-H27^2)*(K27-J27)*(M27-L27) | 3.45 | =O27/N27 |
| 28 | 25 | 51.5 | 53.0625 | 125 | 145 | 101.375 | 185.375 | =B28/12 | =C28/12 | =RADIANS(D28) | =RADIANS(E28) | =F28/12 | =G28/12 | =0.5*(I28^2-H28^2)*(K28-J28)*(M28-L28) | 3.45 | =O28/N28 |
| 29 | 26 | 51.5 | 53.0625 | 155 | 175 | 101.375 | 185.375 | =B29/12 | =C29/12 | =RADIANS(D29) | =RADIANS(E29) | =F29/12 | =G29/12 | =0.5*(I29^2-H29^2)*(K29-J29)*(M29-L29) | 3.45 | =O29/N29 |
| 30 | 27 | 51.5 | 53.0625 | 185 | 205 | 101.375 | 185.375 | =B30/12 | =C30/12 | =RADIANS(D30) | =RADIANS(E30) | =F30/12 | =G30/12 | =0.5*(I30^2-H30^2)*(K30-J30)*(M30-L30) | 3.45 | =O30/N30 |
| 31 | 28 | 51.5 | 53.0625 | 215 | 235 | 101.375 | 185.375 | =B31/12 | =C31/12 | =RADIANS(D31) | =RADIANS(E31) | =F31/12 | =G31/12 | =0.5*(I31^2-H31^2)*(K31-J31)*(M31-L31) | 3.45 | =O31/N31 |
| 32 | 29 | 51.5 | 53.0625 | 245 | 265 | 101.375 | 185.375 | =B32/12 | =C32/12 | =RADIANS(D32) | =RADIANS(E32) | =F32/12 | =G32/12 | =0.5*(I32^2-H32^2)*(K32-J32)*(M32-L32) | 3.45 | =O32/N32 |
| 33 | 30 | 51.5 | 53.0625 | 275 | 295 | 101.375 | 185.375 | =B33/12 | =C33/12 | =RADIANS(D33) | =RADIANS(E33) | =F33/12 | =G33/12 | =0.5*(I33^2-H33^2)*(K33-J33)*(M33-L33) | 3.45 | =O33/N33 |

**Table B1**

**Spreadsheet Cell Formulas and Computations for Table 2**

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | |
| 2 | Region | Min R | Max R | Min θ | Max θ | Min Z | Max Z | Min R | Max R | Min θ | Max θ | Min Z | Max Z | Volume | Heat Load | Heat Source |
| 3 | | (in) | (in) | (°) | (°) | (in) | (in) | (feet) | (feet) | (radians) | (radians) | (feet) | (feet) | ($ft^3$) | (Btu/hr) | (Btu/$ft^3$-hr) |
| 34 | 31 | 51.5 | 53.0625 | 305 | 325 | 101.375 | 185.375 | =B34/12 | =C34/12 | =RADIANS(D34) | =RADIANS(E34) | =F34/12 | =G34/12 | =0.5*(I34^2-H34^2)*(K34-J34)*(M34-L34) | 3.45 | =O34/N34 |
| 35 | 32 | 51.5 | 53.0625 | 325 | 355 | 101.375 | 185.375 | =B35/12 | =C35/12 | =RADIANS(D35) | =RADIANS(E35) | =F35/12 | =G35/12 | =0.5*(I35^2-H35^2)*(K35-J35)*(M35-L35) | 3.45 | =O35/N35 |
| 36 | 33 | 51.5 | 53.0625 | 0 | 5 | 101.375 | 185.375 | =B36/12 | =C36/12 | =RADIANS(D36) | =RADIANS(E36) | =F36/12 | =G36/12 | =0.5*(I36^2-H36^2)*(K36-J36)*(M36-L36) | 0 | =O36/N36 |
| 37 | 34 | 51.5 | 53.0625 | 25 | 35 | 101.375 | 185.375 | =B37/12 | =C37/12 | =RADIANS(D37) | =RADIANS(E37) | =F37/12 | =G37/12 | =0.5*(I37^2-H37^2)*(K37-J37)*(M37-L37) | 0 | =O37/N37 |
| 38 | 35 | 51.5 | 53.0625 | 55 | 65 | 101.375 | 185.375 | =B38/12 | =C38/12 | =RADIANS(D38) | =RADIANS(E38) | =F38/12 | =G38/12 | =0.5*(I38^2-H38^2)*(K38-J38)*(M38-L38) | 0 | =O38/N38 |
| 39 | 36 | 51.5 | 53.0625 | 85 | 95 | 101.375 | 185.375 | =B39/12 | =C39/12 | =RADIANS(D39) | =RADIANS(E39) | =F39/12 | =G39/12 | =0.5*(I39^2-H39^2)*(K39-J39)*(M39-L39) | 0 | =O39/N39 |
| 40 | 37 | 51.5 | 53.0625 | 115 | 125 | 101.375 | 185.375 | =B40/12 | =C40/12 | =RADIANS(D40) | =RADIANS(E40) | =F40/12 | =G40/12 | =0.5*(I40^2-H40^2)*(K40-J40)*(M40-L40) | 0 | =O40/N40 |
| 41 | 38 | 51.5 | 53.0625 | 145 | 155 | 101.375 | 185.375 | =B41/12 | =C41/12 | =RADIANS(D41) | =RADIANS(E41) | =F41/12 | =G41/12 | =0.5*(I41^2-H41^2)*(K41-J41)*(M41-L41) | 0 | =O41/N41 |
| 42 | 39 | 51.5 | 53.0625 | 175 | 185 | 101.375 | 185.375 | =B42/12 | =C42/12 | =RADIANS(D42) | =RADIANS(E42) | =F42/12 | =G42/12 | =0.5*(I42^2-H42^2)*(K42-J42)*(M42-L42) | 0 | =O42/N42 |
| 43 | 40 | 51.5 | 53.0625 | 205 | 215 | 101.375 | 185.375 | =B43/12 | =C43/12 | =RADIANS(D43) | =RADIANS(E43) | =F43/12 | =G43/12 | =0.5*(I43^2-H43^2)*(K43-J43)*(M43-L43) | 0 | =O43/N43 |
| 44 | 41 | 51.5 | 53.0625 | 235 | 245 | 101.375 | 185.375 | =B44/12 | =C44/12 | =RADIANS(D44) | =RADIANS(E44) | =F44/12 | =G44/12 | =0.5*(I44^2-H44^2)*(K44-J44)*(M44-L44) | 0 | =O44/N44 |
| 45 | 42 | 51.5 | 53.0625 | 265 | 275 | 101.375 | 185.375 | =B45/12 | =C45/12 | =RADIANS(D45) | =RADIANS(E45) | =F45/12 | =G45/12 | =0.5*(I45^2-H45^2)*(K45-J45)*(M45-L45) | 0 | =O45/N45 |
| 46 | 43 | 51.5 | 53.0625 | 295 | 305 | 101.375 | 185.375 | =B46/12 | =C46/12 | =RADIANS(D46) | =RADIANS(E46) | =F46/12 | =G46/12 | =0.5*(I46^2-H46^2)*(K46-J46)*(M46-L46) | 0 | =O46/N46 |
| 47 | 44 | 51.5 | 53.0625 | 325 | 335 | 101.375 | 185.375 | =B47/12 | =C47/12 | =RADIANS(D47) | =RADIANS(E47) | =F47/12 | =G47/12 | =0.5*(I47^2-H47^2)*(K47-J47)*(M47-L47) | 0 | =O47/N47 |
| 48 | 45 | 51.5 | 53.0625 | 355 | 360 | 101.375 | 185.375 | =B48/12 | =C48/12 | =RADIANS(D48) | =RADIANS(E48) | =F48/12 | =G48/12 | =0.5*(I48^2-H48^2)*(K48-J48)*(M48-L48) | 0 | =O48/N48 |
| 49 | 46 | 0 | 50 | 0 | 360 | 101.375 | 184.375 | =B49/12 | =C49/12 | =RADIANS(D49) | =RADIANS(E49) | =F49/12 | =G49/12 | =0.5*(I49^2-H49^2)*(K49-J49)*(M49-L49) | 9.64 | =O49/N49 |
| 50 | 47 | 0 | 44 | 0 | 360 | 184.375 | 185.375 | =B50/12 | =C50/12 | =RADIANS(D50) | =RADIANS(E50) | =F50/12 | =G50/12 | =0.5*(I50^2-H50^2)*(K50-J50)*(M50-L50) | 0 | =O50/N50 |
| 51 | 48 | 0 | 50 | 0 | 360 | 185.375 | 193.375 | =B51/12 | =C51/12 | =RADIANS(D51) | =RADIANS(E51) | =F51/12 | =G51/12 | =0.5*(I51^2-H51^2)*(K51-J51)*(M51-L51) | 0 | =O51/N51 |
| 52 | 49 | 51.5 | 53.0625 | 0 | 360 | 185.375 | 193.375 | =B52/12 | =C52/12 | =RADIANS(D52) | =RADIANS(E52) | =F52/12 | =G52/12 | =0.5*(I52^2-H52^2)*(K52-J52)*(M52-L52) | 0 | =O52/N52 |

# Table B2
## Spreadsheet Cell Formulas and Computations for Table 3

| | A | B | C | D |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | **Material No. 1** | **Transport Cask** | | |
| 4 | A516 Grade 70 | (C-Mn-Si) | | |
| 5 | Density, $\rho$ ($lb_m/ft^3$) | 490.8 | | |
| 6 | Temperature | Thermal Conductivity | Thermal Diffusivity | Specific Heat |
| 7 | $T$ | $k$ | $\alpha$ | $c_p$ |
| 8 | (°F) | (Btu/hr-ft-°F) | ($ft^2$/hr) | (Btu/$lb_m$-°F) |
| 9 | 70 | 23.6 | 0.454 | =B9/($B$5*C9) |
| 10 | 200 | 24.4 | 0.422 | =B10/($B$5*C10) |
| 11 | 400 | 24.2 | 0.386 | =B11/($B$5*C11) |
| 12 | 600 | 23.1 | 0.346 | =B12/($B$5*C12) |
| 13 | 800 | 21.7 | 0.298 | =B13/($B$5*C13) |
| 14 | 1200 | 18.2 | 0.197 | =B14/($B$5*C14) |
| 15 | 1500 | 15.1 | 0.169 | =B15/($B$5*C15) |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | **Material No. 4** | **Reactor Vessel** | | |
| 20 | SA 302 Grade B | (Mn-1/2Mo) | | |
| 21 | Density, $\rho$ ($lb_m/ft^3$) | 489 | | |
| 22 | Temperature | Thermal Conductivity | Thermal Diffusivity | Specific Heat |
| 23 | $T$ | $k$ | $\alpha$ | $c_p$ |
| 24 | (°F) | (Btu/hr-ft-°F) | ($ft^2$/hr) | (Btu/$lb_m$-°F) |
| 25 | 70 | 23.3 | 0.455 | =B25/($B$21*C25) |
| 26 | 200 | 24.4 | 0.437 | =B26/($B$21*C26) |
| 27 | 400 | 24.6 | 0.398 | =B27/($B$21*C27) |
| 28 | 600 | 23.5 | 0.353 | =B28/($B$21*C28) |
| 29 | 800 | 22 | 0.3 | =B29/($B$21*C29) |
| 30 | 1200 | 18.6 | 0.193 | =B30/($B$21*C30) |
| 31 | 1500 | 15.5 | 0.164 | =B31/($B$21*C31) |
| 32 | | | | |
| 33 | | | | |
| 34 | | | | |
| 35 | **Material No. 5** | **Stainless Steel** | | |
| 36 | SS 304 | (18Cr-8Ni) | | |
| 37 | Density, $\rho$ ($lb_m/ft^3$) | 501.1 | | |
| 38 | Temperature | Thermal Conductivity | Thermal Diffusivity | Specific Heat |
| 39 | $T$ | $k$ | $\alpha$ | $c_p$ |
| 40 | (°F) | (Btu/hr-ft-°F) | ($ft^2$/hr) | (Btu/$lb_m$-°F) |
| 41 | 70 | 8.6 | 0.151 | =B41/($B$37*C41) |
| 42 | 200 | 9.3 | 0.156 | =B42/($B$37*C42) |
| 43 | 400 | 10.4 | 0.165 | =B43/($B$37*C43) |
| 44 | 600 | 11.3 | 0.174 | =B44/($B$37*C44) |
| 45 | 800 | 12.2 | 0.184 | =B45/($B$37*C45) |
| 46 | 1200 | 14 | 0.203 | =B46/($B$37*C46) |
| 47 | 1500 | 15.3 | 0.216 | =B47/($B$37*C47) |

FIGURE WITHHELD UNDER 10 CFR 2.390

| By | Date | | | | |
|---|---|---|---|---|---|
| | | BNFL Inc.<br>Big Rock Point<br>10269 US 31 North<br>Charlevoix, MI<br>49720-9436<br>Sargent & Lundy | Project No. | 10525-020 | RVTS CASK<br>MAJOR COMPONENT REMOVAL<br>BIG ROCK POINT RESTORATION |
| | | | Site/Area | N/A | |
| | | | Building No. | N/A | |
| | | | Size/Scale | D/1/4"-1'-0"UN | |
| | | | Codfile | 10525020-001 | Drawing Number: SD-10525-020-001 |
| | | | Preparing Organization | | Revision: 1<br>Sheet of |

A

Calc. No. M-10525-0020-001 Rev. 1

FIGURE WITHHELD UNDER 10 CFR 2.390

ELEVATION

DETAIL 2

SCALE: 1"=1'-0"

SECTIONAL PLAN

TYPICAL

| Rev. | Date | Description | Prepared | Reviewed | Approved |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| 1 | 10/24/00 | FOR CLIENT COMMENT | [illegible] | — | — |
| 0 | 06/12/00 | FOR CLIENT COMMENT | PC | BBS | SRR |

BNFL Inc. Proprietary

[illegible]

Pre

Rev

App

FIGURE WITHHELD UNDER 10 CFR 2.390

| By | Date |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |

BNFL Inc.

Big Rock Point
10269 US 31 North
Charlevoix, MI
49720-9436

Sargent & Lundy

| | |
|---|---|
| Project No. | 10525-020 |
| Site/Area | N/A |
| Building No. | N/A |
| Size/Scale | D/$^1/_4$"-1'-0"UN |
| Cadfile | 10525020-002 |
| Preparing Organization | |

RVTS TIE-DOWN SYSTEM
MAJOR COMPONENT REMOVAL
BIG ROCK POINT RESTORATION

| Drawing Number | Revision |
|---|---|
| SD-10525-020-002 | 1 |
| | Sheet of |

A

Calc. No. M-10525-0020-001 Rev. 1
Project No. 10525-020
Attachment C Page C3

FIGURE WITHHELD UNDER 10 CFR 2.390

| Rev. | Date | | Rev. 1 | Date 09/20/00 | | Rev. 0 | Date 06/12/00 | | BNFL Inc. Proprietary |
|---|---|---|---|---|---|---|---|---|---|
| | | | FOR BDS SPEC BRP-MCR-SPEC-001 | | | FOR CLIENT COMMENT | | | |
| Prepared | Reviewed | Approved | Prepared | Reviewed | Approved | Prepared | Reviewed | Approved | |
| | | | | | | | | | |

# FAX FROM CARBOLINE COMPANY

carboline.

350 Hanley Industrial Court • St. Louis, Missouri 63144

**To:** Bart Slimp

**Company:** Sargent + Lundy

**FAX #:** 312/269-7313 / ph - 7002

**From:** Kirt Smith

**Date:** 9/19/00 **Time:** 11:30 AM

**# of Pages:** **Doc. #:**

*If you do not receive all the pages indicated please call: (314) 644-1000*

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| | Color Lab | (314) 644-1080 Ext. 1-2468 |
| | New Orleans | (504) 734-9120 |

A white epoxy is reported to have a thermal emittance of 0.91. This certainly relates to thermal emissivity, but I am not sure if it is identical.

Kirt Smith



**CC:**

# APPENDIX 3-3

# ISSUE SUMMARY
## Form SOP-0402-03, Revision 3B



DESIGN CONTROL SUMMARY

| | | | |
|---|---|---|---|
| CLIENT: | **BNFL Inc.** | UNIT NO.: N/A | QA SERIAL NO. |
| PROJECT NAME: | **Big Rock Point Major Component Removal** | | |
| PROJECT NO.: | **10525-020** | ☐ NUCLEAR SAFETY-RELATED | |
| CALC. NO.: | **M-10525-020-002** | ☐ NOT NUCLEAR SAFETY-RELATED | |
| TITLE: | **Pressure Response of Reactor Vessel Transport System** | ☒ IMPORTANT TO SAFETY - CATEGORY A | |
| EQUIPMENT NO.: | | | |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Initial Issue: 17 pages issued as Revision 0.

INPUTS/ ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

| | | |
|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 0 |
| STATUS: | Approved | DATE FOR REV.: 06/08/2000 |
| PREPARER | Helmut R. Kopke - signature on file | DATE: |
| REVIEWER * | Jack F. Wakeland (Sections 1.0, 4.0, Tbls. 1, 2) - signature on file | DATE: |
| REVIEWER * | Mark C. Handrick (All Other Sections) - signature on file | DATE: |
| APPROVER | Robert J. Peterson - signature on file | DATE: |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Revised to address modified RVTS temperature profile as described in Calculation No. M-10525-020-001, Revision 1.
Revision 1: All pages superseded.
18 pages issued as Revision 1.

INPUTS/ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

| | | |
|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 1 |
| STATUS: | Approved | DATE FOR REV.: 02/12/01 |
| PREPARER | Mark C. Handrick - signature on file | DATE: |
| REVIEWER* | Helmut R. Kopke - signature on file | DATE: |
| APPROVER | Robert J. Peterson - signature on file | DATE: |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Revised to incorporate client comments and add case 2b.
Revision 2: All pages superseded.
19 pages issued as Revision 2.

INPUTS/ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

| | | |
|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 2 |
| STATUS: | Approved | DATE FOR REV.: 6-4-01 |
| PREPARER | Frank A. Nezrick *Frank A. Nezrick* | DATE: 5-21-01 |
| REVIEWER* | Daniel A. Tallitsch *Dan Tallitsch* | DATE: 5-21-01 |
| APPROVER | Robert J. Peterson *Robert J. Peterson* | DATE: 6-4-01 |

* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

**NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS**

| Sargent & Lundy LLC | Calc For Pressure Response of Reactor Vessel Transport System | | | Calc No. M-10525-020-002 | |
|---|---|---|---|---|---|
| | | | | Rev. 2 | Date |
| | X | Important to Safety - Category A | | Non-Safety Related | Page 2 |

| | | | | |
|---|---|---|---|---|
| Client | BNFL, Inc. | | Prepared by | Frank A. Nezrick | Date |
| Project | Big Rock Point Major Component Removal | | Reviewed by | Daniel A. Tallitsch | Date |
| Proj. No | 10525-020 | Equip. No. | Approved by | Robert J. Peterson | Date |

## TABLE OF CONTENTS

## 1.0 Purpose and Scope

One of the tasks associated with the decommissioning of Big Rock Point Nuclear Plant is removal and transportation of the Reactor Vessel to its final disposal site. A Reactor Vessel Transport System (RVTS) has been specifically designed for transportation and disposal of the Big Rock Point Nuclear Plant Reactor Vessel. The purpose of this calculation is to determine the internal pressure of the RVTS under design conditions prescribed in Title 10 of the Code of Federal Regulations (CFR), Part 71, "Packaging and Transportation of Radioactive Material." The RVTS bounding normal operating pressures and the maximum pressure during hypothetical accident conditions will be evaluated to ensure compliance with 10 CFR 71.

The transport package maximum normal operating pressure is defined in 10 CFR 71.4 and is given below. The heat condition specified in 10 CFR 71.71(c)(1) is also given.

> "*Maximum normal operating pressure* means the maximum gauge pressure that would develop in the containment system in a period of 1 year under the heat condition specified in §71.71(c)(1), in the absence of venting, external cooling by an ancillary system, or operational controls during transport."

Package approval standards are identified in 10 CFR 71 Subpart E. Demonstration of compliance with these standards is specified in 10 CFR 71.41(a), repeated below.

> "The effects on a package of the tests specified in §71.71 ("Normal conditions of transport"), and the tests specified in §71.73 ("Hypothetical accident conditions"), and §71.61 (Special requirements for irradiated nuclear fuel shipments"), must be evaluated by subjecting a specimen or scale model to a specific test, or by another method of demonstration acceptable to the Commission, as appropriate for the particular feature being considered."

The general standards for all transportation packages are identified in 10 CFR 71.43. The standard applicable to the finding the bounding normal operating pressures of the RVTS, paragraph 10 CFR 71.43(f), is listed below.

> "A package must be designed, constructed, and prepared for shipment so that under the tests specified in §71.71 ("Normal conditions of transport") there would be no loss or dispersal of radioactive contents, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging."

The RVTS pressure results of this calculation will be used in external analyses to assess the structural integrity of the RVTS under the Normal Conditions of Transport (NCT) and the Hypothetical Accident Conditions (HAC).

Specifically, this calculation will document the bounding pressures of the RVTS under the four conditions outlined below. The basis for the selection of these scenarios is given in 10 CFR 71.71(b), 10 CFR 71.71(c)(1), 10 CFR 71.71(c)(2), and 10 CFR 71.73(c)(4) and is documented in Section 4.1.

Case 1: Under NCT with an ambient temperature of 100 °F in still air, and with a solar insolation of 400 g-cal/cm$^2$ (for curved surfaces) for a 12-hour period. (Maximum Initial and Heat Condition)

Case 2a: Under NCT with an ambient temperature of -20 °F in still air, and without solar insolation. (Minimum Initial Condition)

Case 2b: Under NCT with an ambient temperature of -40 °F in still air, and without solar insolation. (Cold Condition)

Case 3: Under HAC where the RVTS is fully engulfed in a hydrocarbon fuel/air fire, with an average flame temperature of at least 800 °C (approximately 1475 °F) for a period of 30 minutes.

Case 1 will be used to determine the maximum normal operating pressure and Cases 2a and 2b will be used to determine the minimum normal operating pressure. Case 3 will be used to determine the maximum pressure during the HAC.

## 2.0 Design Inputs

2.1 The concentration of radiolysis products inside the RVTS after one year is given below (Ref. 7.4):

$[H_2]$ = 3.7% by volume

Note that the hydrogen concentration given in Reference 7.4 is for the Low Density Cellular Concrete (LDCC) surrounding the reactor vessel; therefore, it is conservative to apply this concentration to the entire RVTS.

2.2 The highest point in the Appalachian Mountains is Mount Mitchell in North Carolina which has a peak elevation of 6684 feet (Ref. 7.5).

2.3 The maximum and minimum temperatures in the LDCC for Cases 1, 2a, and 2b are taken from Calculation M-10525-020-001 (Ref. 7.3) and are given below.

| Case No. | Case Description | Bounding Temperature in LDCC |
|---|---|---|
| Case 1 | NCT with Solar Insolation (Maximum Initial Condition) | 191.17 °F at Elevation 11.91 ft, Radius 5.92 ft. (Case 2a in Ref. 7.3) |
| Case 2a | NCT without Solar Insolation (Minimum Initial and Heat Condition) | -19.45 °F at Elevation 3.55 ft, Radius 6.25 ft. (Case 3b in Ref. 7.3) |
| Case 2b | NCT without Solar Insolation (Cold Condition) | -39.4 °F at Elevation 3.55 ft, Radius 6.25 ft. (Case 3a in Ref. 7.3) |

Note that the temperature profile for the LDCC in the outer region of the RVTS at 0.5 hours from Case 4a of Reference 7.3 is also used but is not presented here as Design Input. It is given in Table 1 (see page 16).

2.4 The saturation pressure of water at various temperatures is given below (Ref. 7.2).

$P_{saturation}$ = 9.58 psia at 191.17 °F
$P_{saturation}$ = 79.6 psia at 311.70 °F

2.5 The elevation of the Reactor Building centerline at Big Rock Point Plant is 591 feet (Ref. 7.6).

2.6 The atmospheric pressure is taken from Table 13.37 of the Compressed Air and Gas Handbook (Ref. 7.7).

At Elevation 0 feet: 14.69 psia
At Elevation 500 feet: 14.42 psia
At Elevation 1000 feet: 14.16 psia
At Elevation 6500 feet: 11.55 psia
At Elevation 7000 feet: 11.33 psia
At Elevation 591 feet: 14.37 psia (interpolated)
At Elevation 6684 feet: 11.47 psia (interpolated)

## 3.0 Assumptions

3.1 The initial relative humidity of the gas trapped inside of the porous concrete is taken as 0% (dry air) and at 1 year the relative humidity is taken as 100%. This assumption is conservative since it will result in the greatest increase in the amount of water in the pores, thus leading to largest pressure increase from initial to final conditions.

3.2 The heat of curing of the LDCC is considered negligible. This is conservative when calculating maximum operating pressures and is considered acceptable when calculating the minimum normal operating pressure.

3.3 For this analysis, the RVTS is assumed to have a tight seal; i.e. there will be no leakage of gases to the atmosphere from the RVTS or from the atmosphere to the RVTS. This seal also makes the inside of the RVTS impervious to changes in elevation which may be encountered during transport. This is conservative since it will lead to higher pressures. However, it should be noted that, in reality, some leakage from the RVTS to the atmosphere may be permissible.

3.4 Reference 7.10 states that due to interconnectivity of air voids within concrete, the concrete is inherently pervious to water. Therefore, a pressure applied to a portion of the RVTS (constructed of low density concrete) allows equal pressurization to occur throughout. Because of this, localized high pressures will not exist in the RVTS.

3.5 It is assumed that no chemical decomposition of the LDCC will occur at high temperatures. This is reasonable since the LDCC does not contain limestone aggregate (Ref. 7.8).

3.6 The LDCC is assumed to be poured when the ambient temperature is between 60 °F and 85 °F. This is consistent with Note 5d of Reference 7.9.

## 4.0 Methodology and Acceptance Criteria

### 4.1 Model Development

In order to determine the maximum RVTS internal pressure, the following components must be considered: initial gas trapped inside the RVTS, the vapor pressure from the moisture within the LDCC matrix, and the gas pressure from radiolysis for the duration of transport.

The initial conditions for all cases are taken as the conditions which exist when the LDCC is poured into the cask. The relative humidity at this time is conservatively taken as 0% (see Assumption 3.1). In addition, at this time radiolysis has not begun. Thus, the only gas trapped inside the RVTS initially is air at the ambient temperature and pressure.

In order to determine the bounding normal operating pressures, three scenarios are considered: one in which the RVTS is exposed to 100 °F still air and insolation for a 12 hour period (Case 1), another in which the RVTS is exposed to –20 °F still air and shade without insolation (Case 2a), and another in which the RVTS is exposed to –40 °F still air and shade without insolation (Case 2b). These three conditions are outlined in 10 CFR 71.71(b), (c)(1) and (c)(2). Case 1 is used to determine the maximum normal operating pressure under maximum initial and heat conditions within the RVTS and Cases 2a and 2b will be used to determine the minimum normal operating pressure within the RVTS under minimum initial and cold conditions, respectively. Cases 2a and 2b are of interest since the gases trapped within the RVTS may "shrink," thus leading to slightly negative pressures.

In addition, one scenario is analyzed to determine the maximum pressure during HAC (Case 3). Under HAC, the RVTS is fully engulfed in a hydrocarbon fuel/air fire, with an average flame temperature of at least 800 °C (approximately 1475 °F) for a period of 30 minutes.

#### 4.1.1 Case 1 – Maximum Normal Operating Pressure for NCT

The maximum normal operating pressure will be calculated at one year per Reference 7.1. At this point in time, there are four species of gas present within the RVTS: air, water vapor, hydrogen, and oxygen. The hydrogen and oxygen are the products of radiolysis. The temperature used for this case is the maximum steady state temperature attained when the RVTS is exposed to 100 °F still air and insolation for a 12 hour period since this temperature will lead to the highest pressure increase in the air pressure and vapor pressure. The total pressure of gases within the RVTS can be broken down as follows:

$$P_{total} = P_{air} + P_{vapor} + P_{H2} + P_{O2} \qquad \text{(Eq. 4.1)}$$

where:

$P_{total}$ total pressure in the RVTS [psia]
$P_{air}$ partial pressure of air in the RVTS [psia]
$P_{vapor}$ partial pressure of water vapor in the RVTS [psia]
$P_{H2}$ partial pressure of hydrogen from radiolysis in the RVTS [psia]
$P_{O2}$ partial pressure of oxygen from radiolysis in the RVTS [psia]

The partial pressure of air in the RVTS ($P_{air}$) can be calculated using the ideal gas law (Ref. 7.2), given below:

$$PV=mRT \qquad \text{(Eq. 4.2)}$$

where:

$P$ pressure of the gas [psfa]

$V$ volume of the gas [ft$^3$]
$m$ mass of the gas [lbm]
$R$ gas constant [(ft-lbf)/(lbm-°R)]
$T$ temperature of the gas [°R]

Since the volume inside of the RVTS ($V_{air}$) and the amount of air within the RVTS ($m_{air}$) are constant, the ideal gas law can be rearranged as follows:

$$\frac{P_{air}}{T_{air}} = \frac{m_{air} \cdot R}{V_{air}} = constant \quad (4.3a)$$

$$\frac{P_{1\_air}}{T_{1\_air}} = \frac{P_{2\_air}}{T_{2\_air}} \quad (4.3b)$$

$$P_{2\_air} = P_{1\_air} \cdot \frac{T_{2\_air}}{T_{1\_air}} \quad (4.3c)$$

where:
$P_{1\_air}$ initial air pressure [psfa, psia]
$P_{2\_air}$ maximum air pressure attained within the RVTS [psfa, psia]
$T_{1\_air}$ initial air temperature [°R]
$T_{2\_air}$ maximum air temperature attained within the RVTS [°R]

Note that to conservatively maximize the pressure increase, the lower bound LDCC pour temperature is used for the air's initial temperature. This gives the greatest change in temperature. The initial air pressure is taken as 14.37 psia, which is the atmospheric pressure for an elevation of 591 feet (Design Input 2.6).

The partial pressure of water vapor in the RVTS ($P_{vapor}$) can also be found since the relative humidity is conservatively assumed to be 100% (see Assumption 3.1). At 100% relative humidity, the vapor pressure is equal to the saturation pressure.

Reference 7.4 gives the hydrogen concentration (from radiolysis) at one year from the time the vessel is closed as a percentage by volume. From this, the oxygen concentration can be deduced since one mole of oxygen is produced for every two moles of hydrogen produced per the equation below:

$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{(Eq. 4.4)}$$

The partial pressures of the hydrogen and oxygen can be found using the Amagat-Leduc Law of Additive Volumes (Ref. 7.2), which shows that the mole fraction of a component in a mixture is equal to its volume fraction. However, the mole fraction of a component in a mixture is also equal to its partial pressure. This is demonstrated by Dalton's Law of Additive Pressures (Ref. 7.2). This leads to the following:

$$\frac{V_i}{V_{total}} = \frac{P_i}{P_{total}} = \frac{n_i}{n_{total}} = y_i \quad \text{(Eq. 4.5)}$$

where:
$V_i$ volume of component gas
$P_i$ pressure of component gas
$n_i$ number of moles of component gas

$V_{total}$ total mixture volume
$P_{total}$ total mixture pressure
$n_{total}$ total number of moles in the mixture
$y_i$ mole fraction of component gas

Thus, the partial pressures of hydrogen ($P_{H2}$) and oxygen ($P_{O2}$) from radiolysis can be found in terms of the total pressure as follows:

$$P_{H2} = P_{total} \cdot \frac{V_{H2}}{V_{total}} = P_{total} \cdot \frac{(\% H_2 \text{ by volume})}{100} \qquad \text{(Eq. 4.6a)}$$

$$P_{O2} = P_{total} \cdot \frac{V_{O2}}{V_{total}} = P_{total} \cdot \frac{(\% O_2 \text{ by volume})}{100} \qquad \text{(Eq. 4.6b)}$$

With the partial pressures of air and water vapor known and the partial pressures of hydrogen and oxygen given in terms of the total pressure, equation 4.1 can be solved to find the maximum pressure.

4.1.2 Cases 2a/2b – Minimum Normal Operating Pressure for NCT

The minimum pressure is calculated in order to provide a lower bound for normal operating pressures. The temperatures used for these cases are the minimum steady state temperature attained when the RVTS is exposed to -20 °F and -40 °F still air and shade since these temperatures will lead to the greatest decrease in the air pressure. However, it should also be noted that water vapor will not be present at these temperatures. In order to be conservative, the effects of radiolysis are also neglected.

Since a conservative lower bound pressure is being calculated, the total pressure within the RVTS is only a function of the air pressure. The pressure within the RVTS will decrease since the temperature decreases. Equation 4.3c will be used to calculate the pressure decrease. However, the initial temperature used will be the upper bound LDCC pour temperature since this will give the largest temperature differential.

4.1.3 Case 3 – Maximum Pressure During Hypothetical Accident Conditions (HAC)

The maximum pressure which will occur during HAC will be calculated using the same methodology as that for the maximum normal operating pressure (Case 1). The accident will be assumed to occur after radiolysis has been occurring within the cask for a period of one year. However, the temperature which will be used to determine this pressure will *not* be the maximum attained within the LDCC in the cask during accident conditions. Using the maximum temperature would lead to artificially high, localized pressures within the cask, which would not exist due to pressure equalization via concrete porosity (see Assumption 3.4). Therefore, a volume average temperature will be used. In addition, the temperatures from Reference 7.3 conservatively ignore the latent heat of vaporization of water within the cask. In order to convert water to vapor, energy is consumed, therefore neglecting this phenomenon results in more energy being applied to the air, and higher temperatures.

The analysis in Reference 7.3 shows that the only portion of the cask internals that are subject to significant heating is the annular region between the RPV and the cask walls, which is the region filled with LDCC. Although the LDCC inside the RPV is also subject to heating, it is not as great as that experienced by the LDCC in the annular region. The volume average LDCC temperature in the annular region at the end of the half hour fire specified in 10 CFR 71.73(c)(4) will be used to determine the volume average temperature. To compute the volume average temperature, the annular region is divided into concentric rings using the divisions of Reference 7.3. The concentric rings are stacked to form the annular LDCC region.

The temperature assigned to each ring is found by first taking the average of the temperature on the top of the ring and the temperature on the bottom of the ring and then by taking the average of the temperature at the outer radius of the ring and the temperature at the inner radius of the ring. The volume average temperature is then defined as follows:

$$T_{volume\_average} = \frac{\sum_{i=1}^{n}\left(T_{i\_ring} \cdot V_{i\_ring}\right)}{\sum_{i=1}^{n} V_{i\_ring}} \qquad \text{(Eq. 4.7)}$$

where:

| | |
|---|---|
| $T_{volume\_average}$ | volume average temperature |
| $T_{i\_ring}$ | temperature of ring i |
| $V_{i\_ring}$ | volume of ring i |
| $i$ | ring element subscript |
| $n$ | total number of ring elements |

Once the volume average temperature is known, the total pressure can be found using the equations developed for Case 1 (Section 4.1.1).

## 4.2 Acceptance Criteria

The acceptance criteria for the thermal analysis of the RVTS is provided by Reference 7.1. For this analysis, Reference 7.1, §71.4, specifies that the maximum pressure in the RVTS must be less than 100 psig in order to be classified as a *Type B Package*.

In addition to the specific acceptance criteria for maximum normal operating pressure, general approval standards for all radioactive material transportation packages are specified in 10 CFR 71.41(a) and 10 CFR 71.43(f), repeated below respectively.

> "The effects on a package of the tests specified in §71.71 ("Normal conditions of transport"), and the tests specified in §71.73 ("Hypothetical accident conditions"), and §71.61 (Special requirements for irradiated nuclear fuel shipments"), must be evaluated by subjecting a specimen or scale model to a specific test, or by another method of demonstration acceptable to the Commission, as appropriate for the particular feature being considered."

> "A package must be designed, constructed, and prepared for shipment so that under the tests specified in §71.71 ("Normal conditions of transport") there would be no loss or dispersal of radioactive contents, no significant increase in external surface radiation levels, and no substantial reduction in the effectiveness of the packaging."

Compliance with 10 CFR 71.43(f) will be ensured in external structural analyses of the RVTS, based on the pressures documented in this calculation.

The pressure in the RVTS following the HAC, Case 3, can be used to ensure that the RVTS design meets the requirements given in 10 CFR 71.51(a)(2).

## 5.0 Calculations

The bounding pressures within the RVTS are calculated below. Note that all gauge pressures calculated below are with regard to the atmospheric pressure at 591 feet above sea level which is 14.37 psia.

However, it should be noted that in transport from Big Rock Point to the storage facility in South Carolina, higher elevations may be encountered in the Appalachian Mountains. Mount Mitchell in North Carolina is the highest point in the Appalachians with an elevation of 6684 feet. The atmospheric pressure at this elevation is 11.47 psia. Thus, at these high elevations, the gauge pressure will be higher than when using 14.37 psia as a basis. Lower elevations may also be encountered, but they will not adversely affect maximum pressure calculations.

### 5.1 Case 1 – Maximum Pressure for NCT

The maximum pressure is calculated using the lowest initial temperature and the highest temperature attained in the RVTS when subjected to 100 °F still air and 12 hours of 400 g-cal/cm$^2$ insolation. The minimum initial temperature is the lower bound of the LDCC pour temperature, which is 60 °F (Assumption 3.6), and the maximum temperature within the RVTS after 12 hours of the prescribed insolation is 191.17 °F (Design Input 2.3).

The total pressure is given by equation 4.1, repeated below:

$$P_{total} = P_{air} + P_{vapor} + P_{H2} + P_{O2}$$

For the maximum partial pressure of air, equation 4.3c is used.

$$P_{air} = P_{2\_air} = P_{1\_air} \cdot \frac{T_{2\_air}}{T_{1\_air}} = 14.37[psia] \cdot \frac{(191.17 + 459.67)°R}{(60 + 459.67)°R} = 18.00\ psia$$

The partial pressure of water vapor is conservatively taken as the saturation pressure of water at 191.17 °F (relative humidity=100%). Thus,

$$P_{vapor} = P_{sat\_191.17°F} = 9.58\ psia$$

Design Input 2.1 states that the hydrogen concentration after one year is 3.7% by volume. For conservatism, this concentration is taken as 4% by volume. Thus, the oxygen concentration is 2% by volume. The partial pressures of hydrogen and oxygen resulting from radiolysis are given in terms of the total pressure per equations 4.6a and 4.6b.

$$P_{H2} = P_{total} \cdot \frac{(\%H_2\ by\ volume)}{100} = P_{total} \cdot \frac{4}{100} = 0.04 \cdot P_{total}$$

$$P_{O2} = P_{total} \cdot \frac{(\%O_2\ by\ volume)}{100} = P_{total} \cdot \frac{2}{100} = 0.02 \cdot P_{total}$$

The above partial pressures can now be substituted into equation 4.1 to solve for the total pressure.

$$P_{total} = 18.00 + 9.58 + 0.04P_{total} + 0.02P_{total}$$

$$P_{total} = 29.34\ psia = 15.0\ psig$$

Thus, the maximum normal operating pressure within the RVTS is 15.0 psig at elevation 591 feet. At elevation 6684 feet, the maximum normal operating pressure within the RVTS is 17.9 psig. The partial pressures are summarized below.

$P_{air} = 18.00\ psia$
$P_{vapor} = 9.58\ psia$
$P_{H2} = 1.17\ psia$
$P_{O2} = 0.59\ psia$

5.2 Case 2a – Minimum Pressure for NCT Based on Minimum Initial Condition

The minimum pressure is calculated using the highest initial temperature and the lowest temperature attained in the RVTS when subjected to -20 °F still air and shade. The maximum initial temperature is the upper bound of the LDCC pour temperature, which is 85 °F (Assumption 3.6), and the minimum temperature within the RVTS is –19.45 °F (Design Input 2.3).

The total pressure is given by equation 4.1, repeated below:

$$P_{total} = P_{air} + P_{vapor} + P_{H2} + P_{O2}$$

However, as is discussed in Section 4.1.2, at a temperature of –19.45 °F, water vapor will not exist and, to be conservative, radiolysis is neglected. Therefore, the total pressure is only dependent on the air component. For the minimum pressure of air (total pressure), equation 4.3c is used.

$$P_{total} = P_{air} = P_{2\_air} = P_{1\_air} \cdot \frac{T_{2\_air}}{T_{1\_air}} = 14.37[psia] \cdot \frac{(-19.45 + 459.67)°R}{(85 + 459.67)°R} = 11.61\ psia = -2.8\ psig$$

Thus, the minimum normal operating pressure within the RVTS is –2.8 psig at an elevation 591 feet and a still air temperature of -20 °F. The partial pressures are summarized below.

$P_{air} = 11.61\ psia$
$P_{vapor} = 0.0\ psia$
$P_{H2} = 0.0\ psia$
$P_{O2} = 0.0\ psia$

5.3 Case 2b - Minimum Pressure for NCT Based on Cold Condition

The minimum pressure is calculated using the highest initial temperature and the lowest temperature attained in the RVTS when subjected to -40 °F still air and shade. The maximum initial temperature is the upper bound of the LDCC pour temperature, which is 85 °F (Assumption 3.6), and the minimum temperature within the RVTS is –39.4 °F (Design Input 2.3).

The total pressure is given by equation 4.1, repeated below:

$$P_{total} = P_{air} + P_{vapor} + P_{H2} + P_{O2}$$

However, as is discussed in Section 4.1.2, at a temperature of –39.4 °F, water vapor will not exist and, to be conservative, radiolysis is neglected. Therefore, the total pressure is only dependent on the air component. For the minimum pressure of air (total pressure), equation 4.3c is used.

$$P_{total} = P_{air} = P_{2\_air} = P_{1\_air} \cdot \frac{T_{2\_air}}{T_{1\_air}} = 14.37\,[\text{psia}] \cdot \frac{(-39.4 + 459.67)°R}{(85 + 459.67)°R} = 11.09 \text{ psia} = -3.3 \text{ psig}$$

Thus, the minimum normal operating pressure within the RVTS is –3.3 psig at an elevation 591 feet and a still air temperature of -40 °F

$P_{air} = 11.09\ psia$
$P_{vapor} = 0.0\ psia$
$P_{H2} = 0.0\ psia$
$P_{O2} = 0.0\ psia$

5.4 Case 3 – Maximum Pressure for HAC

The maximum pressure is calculated using the lowest initial temperature and the volume average temperature, which is computed in Table 1 (attached). The minimum initial temperature is the lower bound of the LDCC pour temperature, which is 60 °F (Assumption 3.6), and the volume average temperature is 311.70 °F (see Table 1).

The total pressure is given by equation 4.1, repeated below:

$$P_{total} = P_{air} + P_{vapor} + P_{H2} + P_{O2}$$

For the maximum partial pressure of air, equation 4.3c is used.

$$P_{air} = P_{2\_air} = P_{1\_air} \cdot \frac{T_{2\_air}}{T_{1\_air}} = 14.37\,[psia] \cdot \frac{(311.70 + 459.67)°R}{(60 + 459.67)°R} = 21.33\ psia$$

The partial pressure of water vapor is conservatively taken as the saturation pressure of water at 311.70 °F (relative humidity=100%). Thus,

$$P_{vapor} = P_{sat\_311.70°F} = 79.6\ psia$$

Design Input 2.1 states that the hydrogen concentration after one year is 3.7% by volume. For conservatism, this concentration is taken as 4% by volume. Thus, the oxygen concentration is 2% by volume. The partial pressures of hydrogen and oxygen resulting from radiolysis are given in terms of the total pressure per equations 4.6a and 4.6b.

$$P_{H2} = P_{total} \cdot \frac{(\%H_2\ by\,volume)}{100} = P_{total} \cdot \frac{4}{100} = 0.04 \cdot P_{total}$$

$$P_{O2} = P_{total} \cdot \frac{(\%O_2\ by\,volume)}{100} = P_{total} \cdot \frac{2}{100} = 0.02 \cdot P_{total}$$

The above partial pressures can now be substituted into equation 4.1 to solve for the total pressure.

$$P_{total} = 21.33 + 79.6 + 0.04P_{total} + 0.02P_{total}$$

$$P_{total} = 107.37\ psia = 93.0\ psig$$

Thus, the maximum pressure within the RVTS due to HAC is 93.0 psig at elevation 591 feet. At elevation 6684 feet, the maximum pressure within the RVTS is 95.9 psig. The partial pressures are summarized below.

$P_{air} = 21.33\ psia$
$P_{vapor} = 79.6\ psia$
$P_{H2} = 4.29\ psia$
$P_{O2} = 2.15\ psia$

## 6.0 Results

### 6.1 Conclusions

For Case 1, which has Normal Conditions of Transport with applied solar insolation heat loads at an ambient temperature of 100 °F corresponding to the maximum initial and heat conditions, the maximum LDCC steady state temperature inside the RVTS is 191.17 °F. Using this maximum temperature with a hydrogen concentration of 4% at one year gives a maximum normal operating pressure within the RVTS of 15.0 psig at elevation 591 feet. At elevation 6684 feet, the maximum normal operating pressure within the RVTS is 17.9 psig. This pressure is below the 100 psig limit for Type B Packages.

For Case 2a, which has Normal Conditions of Transport with an ambient temperature of –20 °F corresponding to the minimum initial condition, the minimum LDCC steady state temperature inside the RVTS is –19.45 °F. Using this minimum temperature gives a minimum normal operating pressure within the RVTS of –2.8 psig.

For Case 2b, which has Normal Conditions of Transport with an ambient temperature of –40 °F corresponding to the cold condition, the minimum LDCC steady state temperature inside the RVTS is –39.4 °F. Using this minimum temperature gives a minimum normal operating pressure within the RVTS of –3.3 psig.

For Case 3, which has Hypothetical Accident Conditions with a 1475 °F flame applied to the RVTS, the volume average temperature of the LDCC in the annular region is 311.70 °F. Using this temperature gives a maximum pressure within the RVTS of 93.0 psig at elevation 591 feet. At elevation 6684 feet, the maximum pressure within the RVTS is 95.9 psig. This pressure is below the 100 psig limit for Type B Packages.

The results of the analysis are summarized below.

| | Case 1 (Maximum Pressure for NCT) under Maximum Initial and Heat Condition | Case 2a (Minimum Pressure for NCT) under Minimum Initial Condition | Case 2b (Minimum Pressure for NCT) under Cold Condition | Case 3 (Maximum Pressure for HAC |
|---|---|---|---|---|
| Pressure | 15.0 psig at el. 591 feet (17.9 psig at el. 6684 feet) | -2.8 psig at el. 591 feet | -3.3 psig at el. 591 feet | 93.0 psig at el. 591 feet (95.9 psig at el. 6684 feet) |

It should be noted that since the initial pressure in all cases is taken as 14.37 psia (0 psig), the gauge pressures are the pressure differentials from the initial LDCC pour.

### 6.2 Recommendations

It is recommended that the LDCC inside the RVTS be poured when the ambient temperature is between 60 °F and 85 °F. This is assumed in this calculation (Assumption 3.6).

## 7.0 References


7.1 United States Nuclear Regulatory Commission Rules and Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Material," March 31, 1999.

7.2 Fundamentals of Engineering Thermodynamics, John R. Howell & Richard O. Buckius, Second Edition, 1992.

7.3 Sargent & Lundy Calculation No. M-10525-020-001, Rev. 1, "Thermal Response of Reactor Vessel Transport System."

7.4 Sargent & Lundy Calculation No. N-10525-042-001, Rev. 1, "Reactor Vessel Transport System Hydrogen Gas Generation."

7.5 Encyclopedia.com (http://encyclopedia.com) by Electronic Library, "Appalachian Mountains."

7.6 Big Rock Point Plant Drawing No. C-3, Rev. AC, "Site Plan."

7.7 *Compressed Air and Gas Handbook*, Rollins, J. P. Editor, 5th Edition, Compressed Air and Gas Institute, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1989.

7.8 Pan Pacific Engineering Pty. Ltd. Technical Information (LITEBUILT® Aerated Concrete).

7.9 Sargent & Lundy Drawing No. SD-10525-020-001, Rev. 0, "RVTS Cask - Major Component Removal Big Rock Point Restoration".

7.10 "Composition and Properties of Concrete", 2nd Edition, Troxell, Davis, Kelly, McGraw-Hill Civil Engineering Series.

# Table 1
## Calculation of Volume Average Temperature

**Temperature Distribution in Annular LDCC Region at t=0.5 hours (°F) (Ref. 7.3)**

| Elev. (ft) | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 |
|---|---|---|---|---|---|---|---|
| 24.6 | 971.08 | 1043.46 | 1075.33 | 1100.89 | 1144.68 | 1215.49 | 1336.03 |
| 22.57 | 102.94 | 102.54 | 102.51 | 104.45 | 133.54 | 359.21 | 1354.91 |
| 20.53 | 101.65 | 101.4 | 101.26 | 103.08 | 132.06 | 357.92 | 1355.02 |
| 18.49 | 102.12 | 101.77 | 101.55 | 103.36 | 132.85 | 358.53 | 1354.19 |
| 16.45 | 102.38 | 102.1 | 106.23 | 171.05 | 783.1 | 916.82 | 1231.01 |
| 16.11 | 102.46 | 102.21 | 107.13 | 179.61 | 821.26 | | |
| 15.45 | 102.62 | 102.32 | 107.12 | 178.14 | 803.15 | | |
| 15.36 | 102.63 | 102.32 | 107.11 | 177.99 | 801.51 | | |
| 13.64 | 102.64 | 402.34 | 107.12 | 177.89 | 800.18 | | |
| 11.91 | 102.58 | 102.29 | 107.09 | 177.87 | 800.2 | | |
| 10.18 | 102.45 | 102.2 | 107.04 | 178.08 | 802.71 | | |
| 8.45 | 102.27 | 102.09 | 107.44 | 185.3 | 871.29 | 952.99 | 1152.84 |
| 6.0 | 102.2 | 101.83 | 101.59 | 103.38 | 132.74 | 358.32 | 1354 |
| 3.55 | 101.86 | 101.56 | 101.38 | 103.15 | 132.09 | 357.92 | 1355.02 |
| 1.1 | 101.95 | 101.63 | 101.5 | 103.34 | 132.35 | 358.2 | 1355.07 |
| 0.67 | 170.05 | 157.09 | 155.99 | 158.29 | 187.37 | 403.98 | 1354.46 |
| 0.33 | 1203.15 | 1204.93 | 1209.47 | 1220.28 | 1243.91 | 1281.5 | 1341.28 |

Radius (ft)

**Average Temperatures in Vertical Direction (°F)**

| | | | | | | |
|---|---|---|---|---|---|---|
| 537.01 | 573.00 | 588.92 | 602.67 | 639.11 | 787.35 | 1345.47 |
| 102.30 | 101.97 | 101.89 | 103.77 | 132.80 | 358.57 | 1354.97 |
| 101.89 | 101.59 | 101.41 | 103.22 | 132.46 | 358.23 | 1354.61 |
| 102.25 | 101.94 | 103.89 | 137.21 | 457.98 | 637.68 | 1292.60 |
| 102.42 | 102.16 | 106.68 | 175.33 | 802.18 | | |
| 102.54 | 102.27 | 107.13 | 178.88 | 812.21 | | |
| 102.63 | 102.32 | 107.12 | 178.07 | 802.33 | | |
| 102.64 | 102.33 | 107.12 | 177.94 | 800.85 | | |
| | | | | | | |
| 102.61 | 102.32 | 107.11 | 177.88 | 800.19 | | |
| 102.52 | 102.25 | 107.07 | 177.98 | 801.46 | | |
| 102.36 | 102.15 | 107.24 | 181.69 | 837.00 | | |
| 102.24 | 101.96 | 104.52 | 144.34 | 502.02 | 655.66 | 1253.42 |
| 102.03 | 101.70 | 101.49 | 103.27 | 132.42 | 358.12 | 1354.51 |
| 101.91 | 101.60 | 101.44 | 103.25 | 132.22 | 358.06 | 1355.05 |
| 136.00 | 129.36 | 128.75 | 130.82 | 159.86 | 381.09 | 1354.77 |
| 686.60 | 681.01 | 682.73 | 689.29 | 715.64 | 842.74 | 1347.87 |

**Average Temperatures in Radial Direction (°F)**

| | | | | | |
|---|---|---|---|---|---|
| 555.01 | 580.96 | 595.80 | 620.89 | 713.23 | 1066.41 |
| 102.13 | 101.93 | 102.83 | 118.28 | 245.68 | 856.77 |
| 101.74 | 101.50 | 102.31 | 117.84 | 245.34 | 856.42 |
| 102.09 | 102.91 | 120.55 | 297.59 | 547.83 | 965.14 |
| 102.29 | 104.42 | 141.01 | 488.76 | | |
| 102.40 | 104.70 | 143.00 | 495.54 | | |
| 102.47 | 104.72 | 142.59 | 490.20 | | |
| 102.48 | 104.72 | 142.53 | 489.39 | | |
| | | | | | |
| 102.46 | 104.71 | 142.49 | 489.04 | | |
| 102.38 | 104.66 | 142.52 | 489.72 | | |
| 102.25 | 104.69 | 144.47 | 509.35 | | |
| 102.10 | 103.24 | 124.43 | 323.18 | 578.84 | 954.54 |
| 101.86 | 101.59 | 102.38 | 117.84 | 245.27 | 856.32 |
| 101.75 | 101.52 | 102.34 | 117.73 | 245.14 | 856.55 |
| 132.68 | 129.05 | 129.78 | 145.34 | 270.48 | 867.93 |
| 683.81 | 681.87 | 686.01 | 702.46 | 779.19 | 1095.31 |

**Volumes ($ft^3$)**

| | | | | | |
|---|---|---|---|---|---|
| 13.32 | 13.83 | 14.34 | 14.85 | 12.24 | 13.37 |
| 13.38 | 13.89 | 14.41 | 14.92 | 12.30 | 13.43 |
| 13.38 | 13.89 | 14.41 | 14.92 | 12.30 | 13.43 |
| 13.38 | 13.89 | 14.41 | 14.92 | 12.30 | 13.43 |
| 2.23 | 2.32 | 2.40 | 2.49 | | |
| 4.33 | 4.50 | 4.66 | 4.83 | | |
| 0.59 | 0.61 | 0.64 | 0.66 | | |
| 11.28 | 11.71 | 12.15 | 12.58 | | |
| | | | | | |
| 11.35 | 11.78 | 12.22 | 12.65 | | |
| 11.35 | 11.78 | 12.22 | 12.65 | | |
| 11.35 | 11.78 | 12.22 | 12.65 | | |
| 16.07 | 16.69 | 17.30 | 17.92 | 14.78 | 16.13 |
| 16.07 | 16.69 | 17.30 | 17.92 | 14.78 | 16.13 |
| 16.07 | 16.69 | 17.30 | 17.92 | 14.78 | 16.13 |
| 2.82 | 2.93 | 3.04 | 3.14 | 2.59 | 2.83 |
| 2.23 | 2.32 | 2.40 | 2.49 | 2.05 | 2.24 |
| Sub-Totals | | | | | |
| 159.20 | 165.30 | 171.40 | 177.50 | 98.14 | 107.14 |
| Total Vol. | 878.69 | $ft^3$ | | | |

**Average Temperature*Volume (°F-$ft^3$)**

| | | | | | |
|---|---|---|---|---|---|
| 7390.49 | 8032.51 | 8541.60 | 9218.15 | 8733.27 | 14255.49 |
| 1366.70 | 1416.22 | 1481.41 | 1764.75 | 3023.12 | 11509.43 |
| 1361.38 | 1410.21 | 1474.03 | 1758.11 | 3018.91 | 11504.73 |
| 1366.17 | 1429.91 | 1736.74 | 4439.98 | 6740.98 | 12965.26 |
| 228.13 | 241.80 | 338.58 | 1215.35 | | |
| 443.34 | 470.63 | 666.54 | 2391.97 | | |
| 60.50 | 64.19 | 90.63 | 322.66 | | |
| 1156.27 | 1226.81 | 1731.30 | 6156.28 | | |
| | | | | | |
| 1162.76 | 1233.80 | 1740.94 | 6187.55 | | |
| 1161.83 | 1233.15 | 1741.28 | 6196.16 | | |
| 1160.38 | 1233.59 | 1765.04 | 6444.53 | | |
| 1640.82 | 1722.71 | 2152.92 | 5790.82 | 8554.05 | 15400.01 |
| 1637.05 | 1695.22 | 1771.36 | 2111.50 | 3624.58 | 13815.34 |
| 1635.24 | 1694.01 | 1770.79 | 2109.58 | 3622.69 | 13819.17 |
| 374.24 | 377.96 | 394.11 | 457.07 | 701.53 | 2457.61 |
| 1525.08 | 1579.03 | 1647.23 | 1746.77 | 1597.99 | 2452.31 |
| Sub-Totals | | | | | |
| 23670.4 | 25061.7 | 29044.5 | 58311.2 | 39617.1 | 98179.3 |
| Total | 273884.3 | °F-$ft^3$ | | | |

| Volume Average Temperature | 311.70 | °F |
|---|---|---|

## Table
## Equations for Table 1



| | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | |
| 2 | Elev. (ft) | Temperature Distribu | | | | | | | | | | |
| 3 | 24.6 | 971.08 | 1043.46 | 1075.33 | 1100.89 | 1144.68 | 1215.49 | 1336.03 | | | =(B3+B4)/2 | =(C3+C4)/2 |
| 4 | 22.57 | 102.94 | 102.54 | 102.51 | 104.45 | 133.54 | 359.21 | 1354.91 | | | =(B4+B5)/2 | =(C4+C5)/2 |
| 5 | 20.53 | 101.65 | 101.4 | 101.26 | 103.08 | 132.06 | 357.92 | 1355.02 | | | =(B5+B6)/2 | =(C5+C6)/2 |
| 6 | 18.49 | 102.12 | 101.77 | 101.55 | 103.36 | 132.85 | 358.53 | 1354.19 | | | =(B6+B7)/2 | =(C6+C7)/2 |
| 7 | 16.45 | 102.38 | 102.1 | 106.23 | 171.05 | 783.1 | 916.82 | 1231.01 | | | =(B7+B8)/2 | =(C7+C8)/2 |
| 8 | 16.11 | 102.46 | 102.21 | 107.13 | 179.61 | 821.26 | | | | | =(B8+B9)/2 | =(C8+C9)/2 |
| 9 | 15.45 | 102.62 | 102.32 | 107.12 | 178.14 | 803.15 | | | | | =(B9+B10)/2 | =(C9+C10)/2 |
| 10 | 15.36 | 102.63 | 102.32 | 107.11 | 177.99 | 801.51 | | | | | =(B10+B11)/2 | =(C10+C11)/2 |
| 11 | 13.64 | 102.64 | 102.34 | 107.12 | 177.89 | 800.18 | | | | | | |
| 12 | 11.91 | 102.58 | 102.29 | 107.09 | 177.87 | 800.2 | | | | | =(B12+B11)/2 | =(C12+C11)/2 |
| 13 | 10.18 | 102.45 | 102.2 | 107.04 | 178.08 | 802.71 | | | | | =(B13+B12)/2 | =(C13+C12)/2 |
| 14 | 8.45 | 102.27 | 102.09 | 107.44 | 185.3 | 871.29 | 952.99 | 1152.84 | | | =(B14+B13)/2 | =(C14+C13)/2 |
| 15 | 6 | 102.2 | 101.83 | 101.59 | 103.38 | 132.74 | 358.32 | 1354 | | | =(B15+B14)/2 | =(C15+C14)/2 |
| 16 | 3.55 | 101.86 | 101.56 | 101.38 | 103.15 | 132.09 | 357.92 | 1355.02 | | | =(B16+B15)/2 | =(C16+C15)/2 |
| 17 | 1.1 | 101.95 | 101.63 | 101.5 | 103.34 | 132.35 | 358.2 | 1355.07 | | | =(B17+B16)/2 | =(C17+C16)/2 |
| 18 | 0.67 | 170.05 | 157.09 | 155.99 | 158.29 | 187.37 | 403.98 | 1354.46 | | | =(B18+B17)/2 | =(C18+C17)/2 |
| 19 | 0.33 | 1203.15 | 1204.93 | 1209.47 | 1220.28 | 1243.91 | 1281.5 | 1341.28 | | | =(B19+B18)/2 | =(C19+C18)/2 |
| 20 | | -------- | -------- | -------- | -------- | -------- | -------- | -------- | | | | |
| 21 | | 5.12 | 5.32 | 5.52 | 5.72 | 5.92 | 6.08 | 6.25 | | | | |
| 22 | | | | | Radius (ft) | | | | | | | |
| 23 | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | =(K3+L3)/2 | =(L3+M3)/2 | =(M3+N3)/2 | =(N3+O3)/2 | =(O3+P3)/2 | =(P3+Q3)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A3-$A4) | =PI()*(D$21^2-C$21^2)*ABS($A3-$A4) |
| 26 | =(K4+L4)/2 | =(L4+M4)/2 | =(M4+N4)/2 | =(N4+O4)/2 | =(O4+P4)/2 | =(P4+Q4)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A4-$A5) | =PI()*(D$21^2-C$21^2)*ABS($A4-$A5) |
| 27 | =(K5+L5)/2 | =(L5+M5)/2 | =(M5+N5)/2 | =(N5+O5)/2 | =(O5+P5)/2 | =(P5+Q5)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A5-$A6) | =PI()*(D$21^2-C$21^2)*ABS($A5-$A6) |
| 28 | =(K6+L6)/2 | =(L6+M6)/2 | =(M6+N6)/2 | =(N6+O6)/2 | =(O6+P6)/2 | =(P6+Q6)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A6-$A7) | =PI()*(D$21^2-C$21^2)*ABS($A6-$A7) |
| 29 | =(K7+L7)/2 | =(L7+M7)/2 | =(M7+N7)/2 | =(N7+O7)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A7-$A8) | =PI()*(D$21^2-C$21^2)*ABS($A7-$A8) |
| 30 | =(K8+L8)/2 | =(L8+M8)/2 | =(M8+N8)/2 | =(N8+O8)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A8-$A9) | =PI()*(D$21^2-C$21^2)*ABS($A8-$A9) |
| 31 | =(K9+L9)/2 | =(L9+M9)/2 | =(M9+N9)/2 | =(N9+O9)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A9-$A10) | =PI()*(D$21^2-C$21^2)*ABS($A9-$A10) |
| 32 | =(K10+L10)/2 | =(L10+M10)/2 | =(M10+N10)/2 | =(N10+O10)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A10-$A11) | =PI()*(D$21^2-C$21^2)*ABS($A10-$A11) |
| 33 | | | | | | | | | | | | |
| 34 | =(K12+L12)/2 | =(L12+M12)/2 | =(M12+N12)/2 | =(N12+O12)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A12-$A11) | =PI()*(D$21^2-C$21^2)*ABS($A12-$A11) |
| 35 | =(K13+L13)/2 | =(L13+M13)/2 | =(M13+N13)/2 | =(N13+O13)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A13-$A12) | =PI()*(D$21^2-C$21^2)*ABS($A13-$A12) |
| 36 | =(K14+L14)/2 | =(L14+M14)/2 | =(M14+N14)/2 | =(N14+O14)/2 | | | | | | | =PI()*(C$21^2-B$21^2)*ABS($A14-$A13) | =PI()*(D$21^2-C$21^2)*ABS($A14-$A13) |
| 37 | =(K15+L15)/2 | =(L15+M15)/2 | =(M15+N15)/2 | =(N15+O15)/2 | =(O15+P15)/2 | =(P15+Q15)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A15-$A14) | =PI()*(D$21^2-C$21^2)*ABS($A15-$A14) |
| 38 | =(K16+L16)/2 | =(L16+M16)/2 | =(M16+N16)/2 | =(N16+O16)/2 | =(O16+P16)/2 | =(P16+Q16)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A16-$A15) | =PI()*(D$21^2-C$21^2)*ABS($A16-$A15) |
| 39 | =(K17+L17)/2 | =(L17+M17)/2 | =(M17+N17)/2 | =(N17+O17)/2 | =(O17+P17)/2 | =(P17+Q17)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A17-$A16) | =PI()*(D$21^2-C$21^2)*ABS($A17-$A16) |
| 40 | =(K18+L18)/2 | =(L18+M18)/2 | =(M18+N18)/2 | =(N18+O18)/2 | =(O18+P18)/2 | =(P18+Q18)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A18-$A17) | =PI()*(D$21^2-C$21^2)*ABS($A18-$A17) |
| 41 | =(K19+L19)/2 | =(L19+M19)/2 | =(M19+N19)/2 | =(N19+O19)/2 | =(O19+P19)/2 | =(P19+Q19)/2 | | | | | =PI()*(C$21^2-B$21^2)*ABS($A19-$A18) | =PI()*(D$21^2-C$21^2)*ABS($A19-$A18) |
| 42 | | | | | | | | | | | Sub-Totals | |
| 43 | | | | | | | | | | | =SUM(K25:K41) | =SUM(L25:L41) |
| 44 | | | | | | | | | | | Total Vol. | =SUM(K43:P43) |
| 45 | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | |
| 47 | =A25*K25 | =B25*L25 | =C25*M25 | =D25*N25 | =E25*O25 | =F25*P25 | | | | | | |
| 48 | =A26*K26 | =B26*L26 | =C26*M26 | =D26*N26 | =E26*O26 | =F26*P26 | | | | | | |
| 49 | =A27*K27 | =B27*L27 | =C27*M27 | =D27*N27 | =E27*O27 | =F27*P27 | | | | | | |
| 50 | =A28*K28 | =B28*L28 | =C28*M28 | =D28*N28 | =E28*O28 | =F28*P28 | | | | | | |
| 51 | =A29*K29 | =B29*L29 | =C29*M29 | =D29*N29 | | | | | | | | |
| 52 | =A30*K30 | =B30*L30 | =C30*M30 | =D30*N30 | | | | | | | | |
| 53 | =A31*K31 | =B31*L31 | =C31*M31 | =D31*N31 | | | | | | | | |
| 54 | =A32*K32 | =B32*L32 | =C32*M32 | =D32*N32 | | | | | | | | |
| 55 | | | | | | | | | | | | |
| 56 | =A34*K34 | =B34*L34 | =C34*M34 | =D34*N34 | | | | | | | | |
| 57 | =A35*K35 | =B35*L35 | =C35*M35 | =D35*N35 | | | | | | | | |
| 58 | =A36*K36 | =B36*L36 | =C36*M36 | =D36*N36 | | | | | | | | |
| 59 | =A37*K37 | =B37*L37 | =C37*M37 | =D37*N37 | =E37*O37 | =F37*P37 | | | | | | |
| 60 | =A38*K38 | =B38*L38 | =C38*M38 | =D38*N38 | =E38*O38 | =F38*P38 | | | | | | |
| 61 | =A39*K39 | =B39*L39 | =C39*M39 | =D39*N39 | =E39*O39 | =F39*P39 | | | | | | |
| 62 | =A40*K40 | =B40*L40 | =C40*M40 | =D40*N40 | =E40*O40 | =F40*P40 | | | | | | |
| 63 | =A41*K41 | =B41*L41 | =C41*M41 | =D41*N41 | =E41*O41 | =F41*P41 | | | | | | |
| 64 | Sub-Totals | | | | | | | | | | | |
| 65 | =SUM(A47:A63) | =SUM(B47:B63) | =SUM(C47:C63) | =SUM(D47:D63) | =SUM(E47:E63) | =SUM(F47:F63) | | | | | | |
| 66 | Total | =SUM(A65:F65) | °F-ft³ | | | | | | | | | |
| 67 | | | | | | | | | | | | |
| 68 | Volume Average Tem | | | =B66/L44 | °F | | | | | | | |

| | M | N | O | P | Q |
|---|---|---|---|---|---|
| 1 | | | | | |
| 2 | | | | | |
| 3 | =(D3+D4)/2 | =(E3+E4)/2 | =(F3+F4)/2 | =(G3+G4)/2 | =(H3+H4)/2 |
| 4 | =(D4+D5)/2 | =(E4+E5)/2 | =(F4+F5)/2 | =(G4+G5)/2 | =(H4+H5)/2 |
| 5 | =(D5+D6)/2 | =(E5+E6)/2 | =(F5+F6)/2 | =(G5+G6)/2 | =(H5+H6)/2 |
| 6 | =(D6+D7)/2 | =(E6+E7)/2 | =(F6+F7)/2 | =(G6+G7)/2 | =(H6+H7)/2 |
| 7 | =(D7+D8)/2 | =(E7+E8)/2 | =(F7+F8)/2 | | |
| 8 | =(D8+D9)/2 | =(E8+E9)/2 | =(F8+F9)/2 | | |
| 9 | =(D9+D10)/2 | =(E9+E10)/2 | =(F9+F10)/2 | | |
| 10 | =(D10+D11)/2 | =(E10+E11)/2 | =(F10+F11)/2 | | |
| 11 | | | | | |
| 12 | =(D12+D11)/2 | =(E12+E11)/2 | =(F12+F11)/2 | | |
| 13 | =(D13+D12)/2 | =(E13+E12)/2 | =(F13+F12)/2 | | |
| 14 | =(D14+D13)/2 | =(E14+E13)/2 | =(F14+F13)/2 | | |
| 15 | =(D15+D14)/2 | =(E15+E14)/2 | =(F15+F14)/2 | =(G15+G14)/2 | =(H15+H14)/2 |
| 16 | =(D16+D15)/2 | =(E16+E15)/2 | =(F16+F15)/2 | =(G16+G15)/2 | =(H16+H15)/2 |
| 17 | =(D17+D16)/2 | =(E17+E16)/2 | =(F17+F16)/2 | =(G17+G16)/2 | =(H17+H16)/2 |
| 18 | =(D18+D17)/2 | =(E18+E17)/2 | =(F18+F17)/2 | =(G18+G17)/2 | =(H18+H17)/2 |
| 19 | =(D19+D18)/2 | =(E19+E18)/2 | =(F19+F18)/2 | =(G19+G18)/2 | =(H19+H18)/2 |
| 20 | | | | | |
| 21 | | | | | |
| 22 | | | | | |
| 23 | | | | | |
| 24 | | | | | |
| 25 | =PI()*(E$21^2-D$21^2)*ABS($A3-$A4) | =PI()*(F$21^2-E$21^2)*ABS($A3-$A4) | =PI()*(G$21^2-F$21^2)*ABS($A3-$A4) | =PI()*(H$21^2-G$21^2)*ABS($A3-$A4) | |
| 26 | =PI()*(E$21^2-D$21^2)*ABS($A4-$A5) | =PI()*(F$21^2-E$21^2)*ABS($A4-$A5) | =PI()*(G$21^2-F$21^2)*ABS($A4-$A5) | =PI()*(H$21^2-G$21^2)*ABS($A4-$A5) | |
| 27 | =PI()*(E$21^2-D$21^2)*ABS($A5-$A6) | =PI()*(F$21^2-E$21^2)*ABS($A5-$A6) | =PI()*(G$21^2-F$21^2)*ABS($A5-$A6) | =PI()*(H$21^2-G$21^2)*ABS($A5-$A6) | |
| 28 | =PI()*(E$21^2-D$21^2)*ABS($A6-$A7) | =PI()*(F$21^2-E$21^2)*ABS($A6-$A7) | =PI()*(G$21^2-F$21^2)*ABS($A6-$A7) | =PI()*(H$21^2-G$21^2)*ABS($A6-$A7) | |
| 29 | =PI()*(E$21^2-D$21^2)*ABS($A7-$A8) | =PI()*(F$21^2-E$21^2)*ABS($A7-$A8) | | | |
| 30 | =PI()*(E$21^2-D$21^2)*ABS($A8-$A9) | =PI()*(F$21^2-E$21^2)*ABS($A8-$A9) | | | |
| 31 | =PI()*(E$21^2-D$21^2)*ABS($A9-$A10) | =PI()*(F$21^2-E$21^2)*ABS($A9-$A10) | | | |
| 32 | =PI()*(E$21^2-D$21^2)*ABS($A10-$A11) | =PI()*(F$21^2-E$21^2)*ABS($A10-$A11) | | | |
| 33 | | | | | |
| 34 | =PI()*(E$21^2-D$21^2)*ABS($A12-$A11) | =PI()*(F$21^2-E$21^2)*ABS($A12-$A11) | | | |
| 35 | =PI()*(E$21^2-D$21^2)*ABS($A13-$A12) | =PI()*(F$21^2-E$21^2)*ABS($A13-$A12) | | | |
| 36 | =PI()*(E$21^2-D$21^2)*ABS($A14-$A13) | =PI()*(F$21^2-E$21^2)*ABS($A14-$A13) | | | |
| 37 | =PI()*(E$21^2-D$21^2)*ABS($A15-$A14) | =PI()*(F$21^2-E$21^2)*ABS($A15-$A14) | =PI()*(G$21^2-F$21^2)*ABS($A15-$A14) | =PI()*(H$21^2-G$21^2)*ABS($A15-$A14) | |
| 38 | =PI()*(E$21^2-D$21^2)*ABS($A16-$A15) | =PI()*(F$21^2-E$21^2)*ABS($A16-$A15) | =PI()*(G$21^2-F$21^2)*ABS($A16-$A15) | =PI()*(H$21^2-G$21^2)*ABS($A16-$A15) | |
| 39 | =PI()*(E$21^2-D$21^2)*ABS($A17-$A16) | =PI()*(F$21^2-E$21^2)*ABS($A17-$A16) | =PI()*(G$21^2-F$21^2)*ABS($A17-$A16) | =PI()*(H$21^2-G$21^2)*ABS($A17-$A16) | |
| 40 | =PI()*(E$21^2-D$21^2)*ABS($A18-$A17) | =PI()*(F$21^2-E$21^2)*ABS($A18-$A17) | =PI()*(G$21^2-F$21^2)*ABS($A18-$A17) | =PI()*(H$21^2-G$21^2)*ABS($A18-$A17) | |
| 41 | =PI()*(E$21^2-D$21^2)*ABS($A19-$A18) | =PI()*(F$21^2-E$21^2)*ABS($A19-$A18) | =PI()*(G$21^2-F$21^2)*ABS($A19-$A18) | =PI()*(H$21^2-G$21^2)*ABS($A19-$A18) | |
| 42 | | | | | |
| 43 | =SUM(M25:M41) | =SUM(N25:N41) | =SUM(O25:O41) | =SUM(P25:P41) | |
| 44 | $ft^3$ | | | | |
| 45 | | | | | |
| 46 | | | | | |
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# APPENDIX 4-1

# ISSUE SUMMARY
## Form SOP-0402-03, Revision 2



**DESIGN CONTROL SUMMARY**

| | | | |
|---|---|---|---|
| CLIENT: | **BNFL Inc.** | UNIT NO.: **N/A** | QA SERIAL NO. |
| PROJECT NAME: | **Big Rock Point Major Component Removal** | | |
| PROJECT NO.: | **10525-042** | ☐ NUCLEAR SAFETY-RELATED | |
| CALC. NO.: | **N-10525-042-001** | ☐ NOT NUCLEAR SAFETY-RELATED | |
| TITLE: | **Reactor Vessel Transport System Hydrogen Gas Generation** | ☒ IMPORTANT TO SAFETY - CATEGORY A | |
| EQUIPMENT NO.: | **N/A** | | |

**IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD**

Initial Issue: 15 pages issued as Revision 0.

INPUTS/ ASSUMPTIONS
☒ VERIFIED
☐ UNVERIFIED

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|---|---|---|
| REVIEW METHOD: | Detailed Review | REV. 0 |
| STATUS: | | DATE FOR REV.: June 2, 2000 |
| PREPARER | G. Douglas Cole | DATE: |
| REVIEWER * | Roman Kahn | DATE: |
| APPROVER | William J. Johnson | DATE: |

**IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD**

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☐ UNVERIFIED

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|---|---|---|---|
| REVIEW METHOD: | Detailed | | REV. 1 |
| STATUS: | | | DATE FOR REV.: January 31, 2001 |
| PREPARER | G. Douglas Cole | G. Douglas Cole | DATE: 31 Jan. 2001 |
| REVIEWER* | Roman Kahn | Roman Kahn | DATE: 31 Jan 2001 |
| APPROVER | William J. Johnson | William J. Johnson | DATE: 2/21/01 |

**IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD**

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☐ VERIFIED
☐ UNVERIFIED

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| REVIEW METHOD: | | REV. |
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| APPROVER | | DATE: |

* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

**NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS**

## 1.0 Purpose and Scope

1.1 Purpose

The purpose of this calculation is to evaluate the extent to which hydrogen gas may be present in the Big Rock Point's Reactor Vessel Transport System (RVTS). Molecular hydrogen gas ($H_2$) may be produced by radiolysis which would originate with the radioactivity in and on the Reactor Vessel Assembly and Internals (RVAI). Molecular hydrogen can explosively recombine with oxygen if present in sufficient fraction of a defined volume. This revision will also include the contribution from the radioactivity in and on the Grid Bar End Pieces (GBEP) which will add to the amount of molecular hydrogen production.

1.2 Scope

The scope of this calculation is directed to the determination of the amount of hydrogen gas that could be present in the partially-free RVTS volume otherwise comprised of the low density cellular concrete (LDCC). The LDCC will fill the interstices between the RVAI and the integrated structural steel shielding of the RVTS package. The rate of gas production will be related to restrictions from the Nuclear Regulatory Commission based on a fractional limit after one year of the sealing of the RVTS package.

1.3 Background

The RVAI will be physically processed to obtain an integrated unit. The RV Internals are already fixed in position, but LDCC will be pumped into the RV to surround the remaining internals. This operation serves to prevent the movement of superficial radioactive contaminants. The LDCC will also contribute to the formation of a readily identifiable boundary at the RV's nozzles and orifices. It is expected that the RV Head will not be a part of the RV integrated unit. Some other enclosure, like a steel plate, will be attached to the remaining RV Assembly and Internals in place of the RV Head.

The RVAI unit will be packaged for the purposes of transport to and near surface burial at the Barnwell, South Carolina Waste Management Facility. The packaged RVAI is the essential item that is a part of the Reactor Vessel Transportation System (RVTS). To create the RVTS package, the RVAI unit will be positioned in the package and surrounded by low density cellular concrete. The LDCC will help maintain the RVAI's optimal position, and also serve to insulate and radiologically shield the RVAI. The package itself will provide additional radiological shielding and be of sufficient construction to withstand the expected rigors of handling, transport and burial.

Federal regulations with regard to low-level radioactive waste, especially in Chapter 10 of the Code of Federal Regulations, Parts 20, 61 and 71, are accommodated in this calculation. The general standards for all packages specified in Part 71 (71.43 and .71) receive primary consideration in this calculation with respect to the RVTS' capability to retain its radioactive contents due to internal gaseous pressure.

## 2.0 References


2.1 "Reactor Vessel Heat Rates and Shielding", Calculation No. N-10525-020-0001, Rev.1, Big Rock Point Major Component Removal, December 2000, Sargent & Lundy LLC ;

2.2 "Handbook of Chemistry and Physics", Edited by D.R. Lide, et al., 78th Edition, 1997-98, CRC Press LLC;

2.3 "Radiolytic and thermal generation of gases from Hanford grout samples", D. Meisel, et al., Argonne National Laboratory, IL (USA), October 1993, DOE Contract W31109DNG38, Sup. Document #E 1.99:DE94005377;

2.4 Code of Federal Regulations, Title 10, Volume 2, Part 71, Revised January 1, 1999, U.S. Government Printing Office via GPO Access; Table A-1, Appendix A;

2.5 "Clarification of Conditions for Waste Shipments Subject to Hydrogen Gas Generation", Information Notice No. 84-72, U.S. Nuclear Regulatory Commission, September 10, 1984, Washington, D.C.;

2.6 "Methodology for Calculating Combustible Gas Concentration in Radwaste Containers", NP-4938, Research Project 2558, March 1987, Electric Power Research Institute, California (USA);

2.7 "RVTS Component Weights", DIT No. DIT-BNFL-MCR-001-01, S. Reed--Preparer, Issue Date 5/5/2000, Sargent & Lundy LLC;

2.8 "Reactor Vessel Transport System Radiation Source Term", Calculation No. N-10525-020-004, Rev.1, Big Rock Point Major Component Removal, December 2000, Sargent & Lundy LLC ;

2.9 "RVTS Cask", Drawing No. SD-10525-020-001, Rev. A, General Note 5.a, Big Rock Point Major Component Removal, December 11, 2000, BNFL, Inc., Sargent & Lundy LLC .


## 3.0 Design Input

3.1 Conversion Factors (Reference 2.2, pgs. 1-24 – 1-31; 1-19):

a. 1 pound = 0.4536 kilograms (kg) ;

b. 1 kg = 1000 grams (g);

c. 1 Curie (Ci) = 3.7 E+10 Bequerels = 3.7 E+10 disintegration (dis.)/second;

d. 1 MeV = 1 E+6 eV;

e. 1 Liter (L) = 1000 milliliter = 1000 $cm^3$;

f. 1 hour (hr) = 3600 second (sec);

g. 1 day = 24 hour;

h. 1 year = 365.25 day;

i. 1 mole = 6.022 E+23 units of a specie (in this case, $H_2$ molecules).

3.2 Reactor Component Activation Activties (Reference 2.1, Section 6.6) by radionuclide. These data are excerpted from the cited calculation step and have been decayed to a date of September 1, 2002.

Table 3-1. RVAI Activation Activities

| Nuclide | Activity, Curies |
| --- | --- |
| H-3 | 4.83 E+0 |
| C-14 | 1.60 E+0 |
| Sb-125 | 2.98 E-3 |
| Mn-54 | 1.59 E+1 |
| Eu-152 | 1.87 E-1 |
| Fe-55 | 5.61 E+3 |
| Co-60 | 8.00 E+3 |
| Ni-59 | 7.02 E+0 |
| Ni-63 | 1.16 E+3 |
| Nb-94 | 2.43 E-2 |
| Tc-99 | 4.88 E-3 |
| Total | 1.48 E+4 |

3.3 For the radionuclides given in Table 3-1, Total Disintegration Energies are obtained from Reference 2.2, "Table of the Isotopes", pgs, **11**-41—**11**-146. Only beta and beta-gamma radioactive nuclides have an associated energy listing.

Table 3-2. Radionuclide Decay Energy Characteristics

| Nuclide | Total Disintegration Energy, MeV/dis |
|---|---|
| H-3 | 0.01859 |
| C-14 | 0.1565 |
| Sb-125 | 0.767 |
| Mn-54 | 1.377 |
| Ce-144 | 0.319 |
| Eu-152 | 1.86 |
| Fe-55 | 0.2316 |
| Co-60 | 2.824 |
| Ni-59 | (no entry) |
| Ni-63 | 0.06 |
| Zn-65 | 1.3514 |
| Sr-90 | 0.546 |
| Nb-94 | 2.045 |
| Tc-99 | 0.294 |
| I-129 | 0.194 |
| Pu-238 | (alpha) |
| Pu-239/240 | (alpha) |
| Pu-241 | 0.021 |
| Pu-242 | (alpha) |
| Cm-242 | (alpha) |
| Cm-243 | (alpha) |
| Cm-244 | (alpha) |
| Am-241 | (alpha) |

3.4 Reactor Component Surface Contamination Activation Activties (Reference 2.8, Table 6.2.3-1) by radionuclide. These data are excerpted from the Table and include only the radionuclides that will contribute beta and beta-gamma decay energy to the cellular concrete layer of the RVTS. The activities are decayed to a date of September 1, 2002.

Table 3-3. RVAI Surface Contamination Activities

| Nuclide | Activity, Curies |
|---|---|
| H-3 | 5.30 E-4 |
| C-14 | 7.51 E-4 |
| Sb-125 | 1.09 E-2 |
| Mn-54 | 8.22 E-3 |
| Fe-55 | 1.99 E-1 |
| Co-60 | 2.49 E+0 |
| Ni-63 | 1.42 E-1 |
| Zn-65 | 1.36 E-3 |
| Sr-90 | 6.04 E-3 |
| Tc-99 | 6.07 E-4 |
| I-129 | 1.53 E-3 |
| Ce-144 | 3.03 E-4 |
| Pu-241 | 3.31 E-2 |
| Total | 2.90 E+0 |

3.5 Average radiolytic generation rate of hydrogen gas in concrete by virtue of deposition of beta-gamma energy, independent of dose rate, from Reference 2.3:

$$G(H_2) = 0.047 \text{ molecules} / 100 \text{ eV}.$$

3.6 Physical constants for $H_2$ (Reference 2.2, pg. 4-61).

a. Molecular weight: 2.016 grams per mole;

b. Density: 0.088 g/L, at 25°C and 101.325 kPascal (Standard Temperature and Pressure).

3.7 The annulus region between the RVAI and the RVTS steel shielding will be filled with cellular concrete with a density range of 50 – 60 lbs/ft$^3$ (see Reference 2.9). Within the RVAI, the cellular concrete employed will have a density range of 30 – 36 lbs/ft$^3$. This less dense concrete will also span the baffle-sparger component layer near the top of the RV up to the RVTS package's top plate.

## 4.0 Assumptions

4.1 The radionuclides in Table 3-2 have associated Total Disintegration Energies only if they are beta and beta-gamma decay types. The nuclides that are listed as "alpha" emitters are taken to deposit no energy in the LDCC layer. See Reference 2.2.

a. The alpha particles that result from the indicated nuclides have considerable energies (from 4-6 MeV/dis) but very short mean free paths; the resultant associated gamma decays have generally low energies (< 500 keV), which are considered to remain completely in the RVAI metal layers;

b. The beta and gamma-ray energies are assumed to be completely deposited in the LDCC. This will translate later to a fractional energy conversion of unity (100%).

4.2 The hydrogen gas of interest in this calculation is assumed to be generated in the LDCC between the RVAI's exterior and the RVTS steel walls by the deposition of beta- and gamma-particle energies in the LDCC layer.

4.3 Organic compounds are assumed to not be present to the extent that they can contribute no hydrogen gas to that created in the LDCC. Neither surface contaminant radioactive materials nor entrained radioactivity are considered to be present in the LDCC.

## 5.0 Methodology and Acceptance Criteria

5.1 This calculation's methodology will utilize the references, design input, and assumptions to provide an evaluation of the potential accumulation of hydrogen gas in the air volume comprising a portion of the RVTS' LDCC layer. The model is related to that from Reference 2.6 (page 2-8), which allows the determination of a gas production rate by employing the simple product of the absorbed energy with the gas production rate per unit of absorbed energy. Additional factors may be employed which account for the difference between the available energy and the absorbed energy, and allow conversion to the desired rate-dependent quantitiy, e.g. volume of gas after a set period of time.

5.2 The primary acceptance criteria are based on the dictates of 10 CFR 71 (71.43 and .71) with respect to the RVTS' capability to retain its radioactive contents due to internal gaseous pressure. The presence of hydrogen gas in sufficient quantity to cause an explosion may reasonably also need to be considered.

5.3 Strictly, the explosion-potential considerations from Reference 2.5 do not apply to radioactive waste comprised of solidified activated reactor components. However, the informal criteria related, if not completely applicable, to the Information Notice is that the radiolytically-produced hydrogen gas in the RVTS be less than 5% by volume after a period of time that is twice the expected shipment time. Such criteria conservatively suggest consideration of a completely packaged and sealed RVAI in the RVTS awaiting transport and/or in transit for one year prior to receipt at the RVTS package's disposal site.

## 6.0 Calculations

6.1 Table 6-1 combines the design input from Tables 3-1 and 3-3 to allow calculation of the the beta-gamma energy deposition rate shown in the last column of the table. The calculation requires the conversion of Curies to disintegrations/second, then to energy deposition rate in MeV/sec. The following uses Co-60 as an example:

$$8.00\text{ E+3 Curies} \times 3.7\text{ E+10 dis sec}^{-1}\text{/Curie} \times 2.824\text{ MeV/dis} =$$

$$8.36\text{ E+14 MeV/sec}.$$

Table 6-1. RVAI Activation and Contamination Activities

| Nuclide | Activity, Curies | Total Disintegration Energy, MeV/dis | Disintegration Energy rate, MeV/sec |
|---|---|---|---|
| H-3 | 4.83 E+0 | 0.01859 | 3.32 E+9 |
| C-14 | 1.60 E+0 | 0.1565 | 9.27 E+9 |
| Sb-125 | 1.39 E-2 | 0.767 | 3.94 E+8 |
| Mn-54 | 1.59 E+1 | 1.377 | 8.10 E+11 |
| Ce-144 | 3.03 E-4 | 0.319 | 3.58 E+6 |
| Eu-152 | 1.87 E-1 | 1.86 | 1.28 E+10 |
| Fe-55 | 5.61 E+3 | 0.2316 | 4.81 E+13 |
| Co-60 | 8.00 E+3 | 2.824 | 8.36 E+14 |
| Ni-59 | --- | --- | 0 |
| Ni-63 | 1.16 E+3 | 0.06 | 2.58 E+12 |
| Sr-90 | 6.07 E-4 | 0.546 | 1.23 E+7 |
| Nb-94 | 2.43 E-2 | 2.045 | 1.84 E+9 |
| Tc-99 | 5.49 E-3 | 0.294 | 5.97 E+7 |
| Pu-238 | --- | (alpha) | 0 |
| Pu-239/240 | --- | (alpha) | 0 |
| Pu-241 | 3.31 E-2 | 0.021 | 2.57 E+7 |
| Pu-242 | --- | (alpha) | 0 |
| Cm-242 | --- | (alpha) | 0 |
| Cm-243 | --- | (alpha) | 0 |
| Cm-244 | --- | (alpha) | 0 |
| Am-241 | --- | (alpha) | 0 |
| I-129 | 1.53 E-3 | 0.194 | 1.10 E+7 |
| Zn-65 | 1.36 E-3 | 1.3514 | 6.80 E+7 |
| Total | 1.48 E+4 | | 8.88 E+14 |

6.2 The total beta-gamma energy depositon rate may be converted to a rate of hydrogen gas production using Reference 2.3:

8.88 E+14 MeV/sec x 1 E+6 eV/ MeV x 0.047 $H_2$ molecules / 100 eV =

4.17 E+17 $H_2$ molecules /sec .

6.3 This production rate may be re-calculated as an annual rate, as follows:

4.17 E+17 $H_2$ molecules /sec x 3600 sec/hr x 24 hr/day x 365.25 day/year =

1.32 E+25 $H_2$ molecules /year .

6.4 The annual hydrogen gas production rate may be converted to moles:

1.32 E+25 $H_2$ molecules /year x ( 6.022 E+23 $H_2$ molecules/mole )$^{-1}$ =

21.9 mole $H_2$ gas /year .

6.5 This production rate may be converted to gas volume produced annually:

21.9 mole $H_2$ /year x 2.016 g/mole x ( 0.088 g/L )$^{-1}$ =

502 L /year of $H_2$ gas .

6.6 Compare this annual production rate to the LDCC available volume in the RVTS. That volume may be calculated by using the weight of the "RV External Cellular Concrete" from Attachment B, as follows:

LDCC Volume = 47,770 lbs / (50 lbs/ ft$^3$ ) = 955.4 ft$^3$ ;

LDCC Volume = 955.4 ft$^3$ x (12 in/ft x 2.54 cm/in )$^3$ x 1 L /1000 cm$^3$ =

2.705 E+4 L ;

6.7 This RVTS inner volume must be adjusted for the fact that only 50% of the volume is available for the hydrogen gas to occupy. The 50% factor is a conservative interpretation of the proportionality of the outer annulus cellular concrete with that for regular concrete (see Reference 2.1, Attachment F) . In this case the more conservative value of the range, i.e. 60 lbs/ft$^3$ , is used.

Void Fraction = 1.0 - ( 60 lbs /ft$^3$ ) / (147 lbs /ft$^3$ ) = 0.59 > **0.5** (used) .

6.8 The 50% factor may then be applied to the result of Step 6.6, as follows:

2.705 E+4 L x 0.5 = 1.35 E+4 L .

6.9 Thus, after one year, the amount of hydrogen gas present in the LDCC layer of the RVTS is:

$H_2$ (RVTS) = 502 L hydrogen / 1.35 E+4 L = 0.037 or 3.7% .

## 7.0 Summary and Conclusions

This calculation provides an evaluation of the potential for hydrogen gas production due to radiolysis in the cellular concrete between the RVAI and the interior surfaces of the RVTS. The production rate of 501 L/year of molecular hydrogen gas may be used with other input to assess the integrity of the sealed RVTS package in terms of the package's ability to withstand internal pressure.

A number of assumptions and calculation steps allows the comparison of this hydrogen production rate to the available void volume in the LDCC. This provides a comparison akin to that called for in the previously cited NRC Information Notice (Reference 2.5). That notice indicated that "...over a period of time that is twice the expected shipment time," the hydrogen gas shall be limited to no more than 5% by volume in the available secondary container gas void. This calculation suggests that the volume limit would not be exceeded over the period of one year, as the resultant level is 3.7% hydrogen by volume in the Big Rock RVTS.

## 8.0 Attachments

A. (REPORT RECORD), "Radiolytic and thermal generation of gases from Hanford grout samples," D. Meisel, et al., Argonne National Laboratory, IL (USA), October 1993, 1 page;

B. "RVTS Component Weights", DIT No. DIT-BNFL-MCR-001-01, S. Reed –Preparer, Issue Date 5/5/2000, Sargent & Lundy[LLC] , 1 page;

C. "Clarification of Conditions for Waste Shipments Subject to Hydrogen Gas Generation", NRC Information Notice No. 84-72, U.S. Nuclear Regulatory Commission, September 10, 1984, Washington D.C., 2 pages .

# REPORT RECORD

*See Bottom of Page for Report Location Information*

**Radiolytic and thermal generation of gases from Hanford grout samples** . Meisel, D.; Jonah, C.D.; Kapoor, S.;Matheson, M.S.; Mulac, W.A. . Argonne National Lab., IL (United States) . Oct 1993 . 45p . DOE Contract W31109ENG38 . Sup.Doc.Num. E 1.99:DE94005377. NTIS Order Number DE94005377 . Primary Report Number: ANL--93/42 . Source: OSTI (DOE and DOE contractors only); NTIS (Public Sales); GPO Dep. (Depository Libraries)

Gamma irradiation of WHC-supplied samples of grouted Tank 102-AP simulated nonradioactive waste has been carried out at three dose rates, 0.25, 0.63, and 130 krad/hr. The low dose rate corresponds to that in the actual grout vaults; with the high dose rate, doses equivalent to more than 40 years in the grout vault were achieved. An average G(H{sub 2}) = 0.047 molecules/100 eV was found, independent of dose rate. The rate of H2 production decreases above 80 Mrad. For other gases, G(N{sub 2}) = 0.12, G(O{sub 2}) = 0.026, G(N{sub 2}O) = 0.011 and G(CO) = 0.0042 at 130 krad/hr were determined. At lower dose rates, N{sub 2} and O{sub 2} could not be measured because of interference by trapped air. The value of G(H{sub 2}) is higher than expected, suggesting segregation of water from nitrate and nitrite salts in the grout. The total pressure generated by the radiolysis at 130 krad/h has been independently measured, and total amounts of gases generated were calculated from this measurement. Good agreement between this measurement and the sum of all the gases that were independently determined was obtained. Therefore, the individual gas measurements account for most of the major components that are generated by the radiolysis. At 90 {degree}C, H{sub 2}, N{sub 2}, and N{sub 2}O were generated at a rate that could be described by exponential formation of each of the gases. Gases measured at the lower temperatures were probably residual trapped gases. An as yet unknown product interfered with oxygen determinations at temperatures above ambient. The thermal results do not affect the radiolytic findings.

**KEYWORDS:**
HANFORD RESERVATION/tanks;GROUTING/irradiation;GROUTING/radiolysis; TANKS;RADIOACTIVE WASTES;GROUTING;IRRADIATION;RADIOLYSIS;RADIATION DOSES; THERMAL ANALYSIS;GAS ANALYSIS;RADIOACTIVE WASTE STORAGE

**GPO SUBJECT CATEGORIES TEXT:**
NUCLEAR FUELS

**GPO SUBJECT CATEGORY NUMBERS:**
0430-M-05

**GPO SUBJECT CATEGORY NUMBERS - PACKED:**
0430M05

**DOE/EDB SUBJECT CATEGORY TEXT:**
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DESIGN INFORMATION TRANSMITTAL - FIRST PAGE
Form SOP-0403-01-02, Revision 2

Sargent & Lundy

# DESIGN INFORMATION TRANSMITTAL

☒ ~~Safety Related~~ ☐ Non-Safety-Related

IMPORTANT TO SAFETY - CATEGORY A

DIT No. DIT-BNFL-MCR-001-01

Page 1 of 1

Client: BNFL, Inc.

Project No.: 10525-020

Station: Big Rock

Unit(s): 1

To: Janusz W. Kot

Subject: RVTS Component Weights

MODIFICATION OR DESIGN CHANGE NUMBERS

| Preparer (Print name) | Process Group | Preparer's Signature | Issue Date |
|---|---|---|---|
| Shannon Reed | NPT | Shannon Reed | 5/05/00 |

STATUS OF INFORMATION (This information is approved for use. Design information, approved for use, that contains assumptions or is preliminary or requires further verification shall be so identified).

All information transmitted in the DIT is approved for use.

This transmittal supercedes DIT No. DIT-BNFL-MCR-001.

IDENTIFICATION OF THE SPECIFIC DESIGN INFORMATION TRANSMITTED AND PURPOSE OF ISSUE
(List any supporting documents attached to DIT by its title, revision and/or issue date, and total number of pages for each supporting document.)

e purpose of this DIT is to issue the individual component weights that comprise part of the Reactor Vessel Transport System (..VTS) that are needed for the hydrogen generation calculation. The necessary component weights are as follows:

1. Reactor Vessel Shell = 183,665 lbs.
2. Reactor Vessel Internals = 27,343 lbs.
3. Reactor Vessel Insulation = 3,300 lbs. (This value does not include the weight of the insulation covering the RV base because it will be removed.)
4. Reactor Vessel Internal Cellular Concrete (30 pcf) = 38,985 lbs.
5. Reactor Vessel External Cellular Concrete (50 pcf) = 47,770 lbs.

SOURCE OF INFORMATION

| | Rev. | Date |
|---|---|---|
| Calc No. S-10525-020-002 | 0 | 4/25/00 |
| Report No. NA | | |
| Other NA | | |

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Kot, J. W.
Cole, G. D.
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SSINS No.: 6835
IN 84-72

UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF INSPECTION AND ENFORCEMENT
WASHINGTON, D. C. 20555

September 10, 1984

IE INFORMATION NOTICE NO. 84-72: CLARIFICATION OF CONDITIONS FOR WASTE SHIPMENTS SUBJECT TO HYDROGEN GAS GENERATION

Addressees:

All nuclear power reactor facilities holding an operating license (OL) or construction permit (CP) and certain registered users of NRC Certificates of Compliance for transport packages.

Purpose:

The NRC's Office of Nuclear Materials Safety and Safeguards (NMSS) has identified a need to clarify conditions relating to the use of NRC-certified packages for shipment of wastes.

Discussion:

A potential exists for the generation of combustible quantities of hydrogen for certain waste forms containing radioactive material. This is pertinent to shipments of resins, binders, waste sludge, and wet filters. It is not pertinent to dry compacted or uncompacted waste and irradiated hardware.

In general, applications for waste package certificates of compliance have not addressed the potential for generation of combustible gas mixtures. Generic requirements have recently been included in certain NRC Certificates of Compliance to preclude the possibility of significantly reducing packaging effectiveness in use. These conditions are typically stated as follows:

(1) For any package containing water and/or organic substances that could radiolytically generate combustible gases, it must be determined by tests and measurements of a representative package whether or not the following criteria are met over a period of time that is twice the expected shipment time:

(a) The hydrogen generated must be limited to a molar quantity that would be no more than 5% by volume (or equivalent limits for other inflammable gases) of the secondary container gas void, if present, at STP (i.e., no more than 0.063 g-moles/ft-3 at 14.7 psia and 70<deg>F) or

(b) The secondary container and cask cavity must be inerted with a diluent to ensure that oxygen must be limited to 5% by volume in those portions of the package that could have hydrogen greater than 5%.

For any package delivered to a carrier for transport, the secondary container must be prepared for shipment in the same manner in which determination for gas generation is made. The shipment period begins when the package is prepared (sealed) and must be completed within twice the expected shipment time.

(2) For any package containing materials with radioactivity concentration not exceeding that for low specific activity (LSA) material, and shipped within 10 days of preparation, or within 10 days after venting of drums or other secondary containers, the determination in (1) above need not be made, and the time restriction in (1) above does not apply.

The generation of combustible gases is dependent on the waste form, radioactive concentration and isotope, free volume, total mass and accumulated dose in the waste. In addition, packaging limitations such as effective shielding provided may preclude the radioactive concentrations and hence the generation of combustible gases.

It is believed, in most cases, that the above combustible gas criteria for waste not exceeding LSA concentrations will be met by ensuring that waste packages are shipped within 10 days of preparation. However, in those cases where this is not feasible, licensees may request a specific approval for their proposed shipment. The application should address those factors that would preclude the generation of combustible gases over at least twice the expected shipment time. Such applications should be directed to NMSS.

In all other cases, a determination must be made in accordance with the provisions of the certificate that the requirements of (1) above are met. Any tests and measurements that are representative of the waste to be shipped and address the factors that affect gas generation may be used. The determination should be documented and retained as part of the records for the shipment.

Recipients of this notice should review the information discussed for possible applicability to their waste shipments. No written response to this information notice is required. If you have any questions regarding this matter, please contact NMSS.

Edward L. Jordan, Director
Division of Emergency Preparedness
and Engineering Response
Office of Inspection and Enforcement

Technical Contact: C. E. MacDonald, NMSS
301-427-4122

Attachment:
List of Recently Issued IE Information Notices

# APPENDIX 4-2

ISSUE SUMMARY
Form SOP-0402-03, Revision 2



DESIGN CONTROL SUMMARY

| | | |
|---|---|---|
| CLIENT: **BNFL Inc.** | UNIT NO.: N/A | QA SERIAL NO. |
| PROJECT NAME: **Big Rock Point Major Component Removal** | | |
| PROJECT NO.: **10525-043** | ☐ NUCLEAR SAFETY-RELATED | |
| CALC. NO.: **N-10525-043-001** | ☐ NOT NUCLEAR SAFETY-RELATED | |
| TITLE: **Leakage Test Qualification of the Reactor Vessel Transportation System** | ☒ IMPORTANT TO SAFETY - CATEGORY A | |
| EQUIPMENT NO.: **N/A** | | |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Initial Issue: 16 pages issued as Revision 0.

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| REVIEW METHOD: | Detailed Review | REV. 0 |
| STATUS: | | DATE FOR REV.: September 13, 2000 |
| PREPARER | G. Douglas Cole | DATE: |
| REVIEWER * | Anthony G. Klazura | DATE: |
| APPROVER | | DATE: |

IDENTIFICATION OF PAGES ADDED/REVISED/SUPERSEDED/VOIDED & REVIEW METHOD

Revised Issue: All pages superceded;
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**NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS**

# Table of Contents

## 1.0 Purpose and Scope

### 1.1 Purpose

The purpose of this calculation is to evaluate Big Rock Point's Reactor Vessel Transportation System (RVTS) package for compliance with the containment requirements of 10 CFR 71. As the RVTS will be designed and designated for transport of normal form ("$A_2$" values) radioactive material, Type B package allowable release limits for the RVTS will be determined. This revision also includes the contribution from the Grid Bar End Pieces (GBEP).

### 1.2 Scope

The scope of this calculation is primarily directed to the determination of the $A_2$ value for the mixture of surface contamination radioactive materials in the RVTS package using the 10 CFR 71 Appendix A methodology. The package's release limits are based on the estimated total surface contamination activity, the $A_2$ (mix), and the formulations described in the American National Standard Institute's (ANSI) N14.5-1997 .

### 1.3 Background

The Reactor Vessel Assembly and Internals (RVAI) will be physically processed to obtain an integrated unit. The RV Internals are already fixed in position, but a low-density cellular concrete (LDCC) will be pumped into the RV to surround the remaining internals. This operation serves to prevent the movement of superficial radioactive contaminants. The LDCC will also contribute to the formation of a readily identifiable boundary at the RV's nozzles and orifices. The RV Head will not be a part of the RV integrated unit. Some other enclosure, like a steel plate, will be attached to the remaining RVAI in place of the RV Head.

The RVAI unit will be packaged for the purposes of transport to and near surface burial at the Barnwell, South Carolina Waste Management Facility. The packaged RVAI is the essential item that is a part of the RVTS. To create the RVTS package, the RVAI unit will be positioned in the package and surrounded by LDCC. The LDCC will help maintain the RVAI's optimal position, and also serve to insulate and radiologically shield the RVAI. The package itself will provide additional radiological shielding and be of sufficient construction to exceed the expected rigors of handling, transport and burial.

Federal regulations with regard to low-level radioactive waste, especially in Chapter 10 of the Code of Federal Regulations, Parts 20, 61 and 71, are accommodated in this calculation. The normal form radioactive material quantities specified in Part 71 receive primary consideration in this calculation with respect to their contribution to the RVTS' leakage characteristics.

## 2.0 References


2.1 "Leakage Tests on Packages [for Radioactive Materials -- ] for Shipment", ANSI N14.5-1997, February 5, 1998, American National Standards Institute, Inc., New York;

2.2 "LSA Evaluation of the Unpackaged Object", Calculation No. N-10525-020-003, Rev. 1, Big Rock Point Major Component Removal, December 2000, Sargent & Lundy[LLC] ;

2.3 "Big Rock Point Reactor Vessel and Internals Characterization and Classification", Report WMG-9902, Rev. 1, June 1999, WMG Project 8057;

2.4 Code of Federal Regulations, Title 10, Volume 2, Part 71, Revised January 1, 1999, U.S. Government Printing Office via GPO Access, Table A-1, Appendix A;

2.5 Not used;

2.6 Not used;

2.7 "Handbook of Chemistry and Physics", Edited by D.R. Lide, et al., 78th Edition, 1997-98, CRC Press[LLC];

2.8 "Reactor Vessel Transport System Radiation Source Term", Calculation No. N-10525-020-004, Rev. 1, Big Rock Point Major Component Removal, December 2000, Sargent & Lundy[LLC] ;

2.9 "Dose Projections due to Hypothetical Drops of the Reactor Vessel", Calculation No. RPC 97-007 Rev. 2, Trojan Nuclear Plant, 8/4/1998, Portland General Electric Company;

2.10 "Calculation of Allowable Test Leakage Rate for Reactor Vessel Package per ANSI 14.5", Calculation No. 97-006, Trojan Nuclear Plant, 2/25/1997, Portland General Electric Company.

## 3.0 Design Input

3.1 Conversion Factors (Reference 2.7, pgs. 1-24 – 1-31, 1-38) :

a. 1 Curie (Ci) = 3.7 E+10 Bequerels = 3.7 E+10 disintegrations (dis.) /second;

b. 1 hour (hr) = 3.600 E+3 seconds (sec);

c. 1 day = 24 hours;

d. 1 week (wk) = 7 days;

e. 1 inch (in) = 0.0254 meter (m) = 2.54 centimeter (cm);

f. 1 liter (L) = 1000 milliliter = 1000 $cm^3$ .

3.2 Physical measurements of the RV Wall (Tables 2-1 and 4-1, Reference 2.3):

a. Wetted (outer) Surface Area = 7.69 E+2 $ft^2$ ;

b. Outer Diameter = 116.938 inches;

c. Height = 287.625 inches;

d. Volume = 4.14 E+2 $ft^3$ .

3.3 Normal Form A Values ("$A_2$") from Reference 2.4, Appendix A, Table A-1:

Table 3-1. $A_2$ Values

| Nuclide | $A_2$, Curies |
|---|---|
| H-3 | 1080 |
| C-14 | 54.1 |
| Sb-125 | 24.3 |
| Mn-54 | 27.0 |
| Ce-144 | 5.41 |
| Eu-152 | 24.3 |
| Fe-55 | 1080 |
| Co-60 | 10.8 |
| Ni-59 | 1080 |
| Ni-63 | 811 |
| Zn-65 | 54.1 |
| Sr-90 | 2.70 |
| Nb-94 | 16.2 |
| Tc-99 | 24.3 |
| I-129 | unlimited |
| Pu-238 | 0.00541 |
| Pu-239/240 | 0.00541 |
| Pu-241 | 0.270 |
| Pu-242 | 0.00541 |
| Cm-242 | 0.270 |
| Cm-243 | 0.00811 |
| Cm-244 | 0.0108 |
| Am-241 | 0.00541 |

3.4 Reactor Component Surface Contamination Activation Activities (Reference 2.2, Table 3-3) by radionuclide. These data are excerpted from the Table and the activities are decayed to a date of September 1, 2002.

Table 3-2. RVAI Surface Contamination Activities

| Nuclide | Activities, Curies | Fraction |
|---|---|---|
| H-3 | 5.30 E-4 | 1.83 E-3 |
| C-14 | 7.51 E-4 | 2.59 E-4 |
| Sb-125 | 1.09 E-2 | 3.76 E-3 |
| Mn-54 | 8.22 E-3 | 2.84 E-3 |
| Ce-144 | 3.03 E-4 | 1.05 E-4 |
| Fe-55 | 1.99 E-1 | 6.87 E-2 |
| Co-60 | 2.49 E+0 | 8.60 E-1 |
| Sr-90 | 6.04 E-3 | 2.08 E-3 |
| Ni-63 | 1.42 E-1 | 4.90 E-2 |
| Zn-65 | 1.36 E-3 | 4.70 E-4 |
| Tc-99 | 6.07 E-4 | 2.10 E-4 |
| I-129 | 1.53 E-3 | 5.28 E-4 |
| Pu-238 | 5.83 E-4 | 2.01 E-4 |
| Pu-239/240 | 6.93 E-4 | 2.39 E-4 |
| Pu-241 | 3.31 E-2 | 1.14 E-2 |
| Pu-242 | 3.07 E-6 | 1.06 E-6 |
| Cm-242 | 3.79 E-7 | 1.31 E-7 |
| Cm-243 | 2.35 E-4 | 8.11 E-5 |
| Cm-244 | 2.23 E-4 | 7.70 E-5 |
| Am-241 | 8.81 E-4 | 3.04 E-4 |
| Total | 2.90 E+0 | 1.0 |

## 4.0 Assumptions

4.1 The component of interest is the RV Wall to the extent that it is assumed to be the only significant containment structure other than the RVTS. This affects the inputs to the normal transport conditions allowable release rate calculations. In addition, the volume of the RV Wall is assumed to satisfy the definitions in Reference 2.1, Section 2.2 ("$C_A$" and "$C_N$") as the medium's volume from which the average activity of radioactive material could escape. This approach is similar to that documented in Reference 2.10.

A conceptual model featuring the primacy of the RV Wall starts with an assumption that all of the contamination activity is located on the inner surface of the RV Wall or coats the reactor internals inside the RV. Employing the RV Wall's entire volume to determine the "$C_A$" and "$C_N$" values logically follows as all of the contamination would necessarily have to escape from or through the RV Wall.

4.2 The nature of the normal or hypothetical accident release is that 1% of the surface contamination activity is assumed to become airborne (Reference 2.9, Section 5.6) and respirable. The amount of airborne activity must be known to calculate the quantity of radioactive material that could escape from the RVTS containment system.

4.3 The normal and accident leakage rates are strictly those at standard temperature and pressure. Those conditions are: 1 atmosphere absolute, ambient pressure; and 25 °C temperature in surrounding air. The RVTS package will be assumed to be at standard conditions during the design, fabrication, maintenance, periodic and pre-shipment testing phases.

4.4 Applicability of the ANSI Standard assumes that a Type B package is being evaluated. This calculation must therefore assume that the RVTS package is Type B (Reference 2.1).

## 5.0 Methodology and Acceptance Criteria

5.1 This calculation's methodology will utilize the references, design input, and assumptions to provide an evaluation of the RVTS package's leakage characteristics according to ANSI Standard N14.5-1997.

The radioactive material to be considered is the surface contamination present on the RVAI. It is the radioactivity potentially releasable during either normal or hypothetical accident situations. The total surface contamination activity is conservatively estimated and will also be distributed by radionuclide in order to obtain the normal form, $A_2$, value for the mixture.

<u>If the total releasable contents are less than the $A_2$ (mix) quantity, then there is no limit on the release rate of radioactive material from the package under hypothetical accident conditions.</u> The ANSI Standard also explicitly gives formulations for calculating the release limits, if required, under normal conditions of transport and under hypothetical accident conditions. Less explicitly described are the determinations related to the activity per unit volume in the containment system, i.e., the RVTS package, or within the containment system. Both the release limits and the activity densities are necessary to determine the allowable leakage rates.

5.2 Two allowable leakage rates will be calculated; that for conditions normally incident to transport, and for hypothetical accident conditions. The two leakage rates are compared and the more restrictive value is then taken to be the reference air leakage rate, $L_R$ . The normal and accident leakage rates are determined at standard temperature and pressure, while $L_R$ is the more restrictive of the two rates. The utility of $L_R$ is to dictate in what manner actual design, fabrication, maintenance, periodic and pre-shipment leakage rate tests on the Type B package will be conducted.

5.3 No acceptance criteria are strictly applicable. However, to the extent that the calculated $L_R$ exceeds 0.1 $cm^3/sec_{|ref}$ , $L_R$ becomes 0.1 $cm^3/sec_{|ref}$ when the container's test requirements from ANSI N14.5 are considered and eventually employed.

## 6.0 Calculations

6.1 The following regulatory elements are listed and calculated to demonstrate adherence to the $A_2$ (mix) formulation. Table 6-1 combines the information from Tables 3-1 and 3-2. The final column is the result of dividing the fraction for each radionuclide by the corresponding $A_2$ value:

Table 6-1. RVTS Surface Contamination Regulatory Elements

| Nuclide | Activity, Curies | Fraction | $A_2$ , Curies | Fraction/$A_2$ , Curies $^{-1}$ |
|---|---|---|---|---|
| H-3 | 5.30 E-4 | 1.83 E-4 | 1080 | 1.69 E-7 |
| C-14 | 7.51 E-4 | 2.59 E-4 | 54.1 | 4.79 E-6 |
| Sb-125 | 1.09 E-2 | 3.76 E-3 | 24.3 | 1.55 E-4 |
| Mn-54 | 8.22 E-3 | 2.84 E-3 | 27.0 | 1.05 E-4 |
| Ce-144 | 3.03 E-4 | 1.05 E-4 | 5.41 | 1.94 E-5 |
| Fe-55 | 1.99 E-1 | 6.87 E-2 | 1080 | 6.36 E-5 |
| Co-60 | 2.49 E+0 | 8.60 E-1 | 10.8 | 7.96 E-2 |
| Sr-90 | 6.04 E-3 | 2.08 E-3 | 2.70 | 7.70 E-4 |
| Ni-63 | 1.42 E-1 | 4.90 E-2 | 811 | 6.04 E-5 |
| Zn-65 | 1.36 E-3 | 4.70 E-4 | 54.1 | 8.69 E-6 |
| Tc-99 | 6.07 E-4 | 2.10 E-4 | 24.3 | 8.64 E-6 |
| I-129 | 1.53 E-3 | 5.28 E-4 | unlimited | 0 |
| Pu-238 | 5.83 E-4 | 2.01 E-4 | 0.00541 | 3.72 E-2 |
| Pu-239/240 | 6.93 E-4 | 2.39 E-4 | 0.00541 | 4.42 E-2 |
| Pu-241 | 3.31 E-2 | 1.14 E-2 | 0.270 | 4.13 E-2 |
| Pu-242 | 3.07 E-6 | 1.06 E-6 | 0.00541 | 1.96 E-4 |
| Cm-242 | 3.79 E-7 | 1.31 E-7 | 0.270 | 4.85 E-7 |
| Cm-243 | 2.35 E-4 | 8.11 E-5 | 0.00811 | 1.00 E-2 |
| Cm-244 | 2.23 E-4 | 7.70 E-5 | 0.0108 | 7.13 E-3 |
| Am-241 | 8.81 E-4 | 3.04 E-4 | 0.00541 | 5.62 E-2 |
| Total | 2.90 E+0 | 1.0 | | 2.76 E-1 |

6.2 The $A_2$ value for the mixture of "i" radionuclides is obtained using the formulation from Reference 2.4, as follows:

$$A_2\,(\text{mix}) = (\text{SUM}_i[\,\text{Fraction}_i / A_{2,i}\,])^{-1} = (\,2.76\text{ E-1 Curies}^{-1}\,)^{-1} =$$

**3.62 Curies** .

6.3 The release limits for normal conditions of transport and under hypothetical accident conditions employ the ANSI N14.5, Section 5.4, formulations, as follows:

$$R_N = 10^{-6} A_2\,(\text{mix}) \text{ per hour} = 2.78\text{ E-10 } A_2\,(\text{mix}) \text{ per second ;}$$

$$R_N = 10^{-6} \times 3.62 \text{ Curies per hour} = 3.62\text{ E-6 Curies /hour}$$

$$= 3.62\text{ E-6 Curies /hr} \times 1\text{ hr /3600 sec} = 1.01\text{ E-9 Curies /sec .}$$

6.4 The release limits under hypothetical accident conditions are calculated, as follows:

$$R_A = A_2\,(\text{mix}) \text{ per week} = 1.65\text{ E-6 } A_2\,(\text{mix}) \text{ per second ;}$$

$$R_A = 3.62 \text{ Curies per week} = 3.62 \text{ Curies /week} \times 1 \text{ week /7 days} \times$$

$$1 \text{ day /24 hours} \times 1\text{ hr /3600 sec} = 5.99\text{ E-6 Curies /sec .}$$

6.5 The average activity of radioactive material per unit volume that could escape under normal conditions of transport shall be based on 1% of the available surface contamination activity becoming airborne and thus available for leakage from the RVTS (Section 4.4). The total activity is also reduced by a factor that is the RV Wall's surface area fraction from Table 6.2.1-1 of Reference 2.8. The volume is that for the RV Wall.

$$C_N = \frac{2.90\text{ Ci} \times (7.69\text{ E+2 ft}^2 / 2.09\text{ E+3 ft}^2) \times 0.01}{4.14\text{ E+2 ft}^3 \times (12\text{ in/ft} \times 2.54\text{ cm/in})^3} = 9.10\text{ E-10 Ci/cm}^3 \text{ .}$$

6.6 The average activity of radioactive material per unit volume for accident conditions shall be based on 1% of the available surface contamination activity becoming airborne and thus available for leakage from the RVTS. The activity is the entire surface contamination inventory.

$$C_A = \frac{2.90\text{ Ci} \times 0.01}{4.14\text{ E+2 ft}^3 \times (12\text{ in/ft} \times 2.54\text{ cm/in})^3} = 2.47\text{ E-09 Ci/cm}^3 \text{ .}$$

6.7 The maximum permissible leakage rate from the package during transport under normal conditions of transport is calculated using the formulation in Reference 2.1, Section 6, as follows:

$$L_N = R_N / C_N = 1.01 \text{ E-9 Ci sec}^{-1} / 9.10 \text{ E-10 Ci cm}^{-3}$$

$$= 1.11 \text{ cm}^3 / \text{sec} .$$

6.8 The maximum permissible leakage rate from the package during transport under accident conditions is calculated as follows:

$$L_A = R_A / C_A = 5.99 \text{ E-6 Ci sec}^{-1} / 2.47 \text{ E-9 Ci cm}^{-3}$$

$$= 2.42 \text{ E+3 cm}^3 / \text{sec} .$$

## 7.0 Summary and Conclusions

This calculation's methodology utilizes the references, design input, and assumptions to provide an evaluation of the RVTS package's leakage characteristics according to ANSI Standard N14.5-1997. Employing the standard assumes the RVTS package must be a Type B containment system.

With the package's contents estimated at 2.90 Curies, its comparison to the $A_2$ (mix) value of 3.62 Curies indicates that release rate limits under hypothetical accident conditions do not need to be determined. Even so, two allowable leakage rates are calculated for the surface contamination contained in the RVTS. The rate for conditions considered normal for transport is estimated to be 1.11 cm$^3$/sec; that for hypothetical accident conditions is 2.42 E+3 cm$^3$/sec . The dictates of the ANSI Standard associate the reference leakage rate, $L_R$, to the lower value. The value of $L_R$ is thus 1.10 cm$^3$/sec .

Further application of the standard states that since $L_R$ exceeds 0.1 cm$^3$/sec$_{|ref}$ , $L_R$ becomes 0.1 cm$^3$/sec$_{|ref}$ when the test requirements of ANSI N14.5 are considered and eventually employed. The utility of this $L_R$ value is to dictate in what manner actual design, fabrication, maintenance, periodic and pre-shipment leakage rate tests on the Type B package will be conducted. The reference value is in units of one cm$^3$ of dry air volume per second at 1 atmosphere absolute pressure and 25°C .

## 8.0 Attachments

(none)

# APPENDIX 4-3

# ISSUE SUMMARY
Form SOP-0402-03, Revision 2



| DESIGN CONTROL SUMMARY | | | |
|---|---|---|---|
| CLIENT: | BNFL Inc. | UNIT NO.: | |
| PROJECT NAME: | **Big Rock Point Major Component Removal** | | |
| PROJECT NO.: | **10525-041** | ☐ NUCLEAR SAFETY-RELATED | |
| CALC. NO.: | **N-10525-041-001** | ☐ NOT NUCLEAR SAFETY-RELATED | QA |
| TITLE: | **Breach Of Containment** | ☒ IMPORTANT TO SAFETY - CATEGORY A | SERIAL |
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| APPROVER | W. J. Johnson (See Rev. 1 for signature) | DATE: 2/23/2001 |

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| APPROVER | W. J. Johnson *[signature]* | DATE: 6/04/01 |

* The reviewer's signature indicates compliance with S&L procedure SOP-0402 and the verification of, as a minimum, the following items: correctness of mathematics for manual calculations, appropriateness of input data, appropriateness of assumptions, and appropriateness of the calculation method.

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|---|---|---|---|---|---|
| | | | | Rev. 2 | Date 03/22/01 |
| | X | Important To Safety - Category A | | Non-Safety Related | Page 2 |

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|---|---|---|---|---|---|
| Client | BNFL, Inc. | | Prepared by | John Rich | Date |
| Project | Big Rock Point Major Component Removal | | Reviewed by | Roman Kahn | Date |
| Proj. No | 10525-041 | Equip. No. | Approved by | W. J. Johnson | Date |

## TABLE OF CONTENTS

## 1 Purpose and Scope

Definitions are presented first in this section because they are key to the calculation write-up.

### 1.1 Definitions

HAC –Hypothetical Accident Conditions

Hypothetical Accident Conditions are defined in 10 CFR 71.73 as a set of tests and test conditions to be applied to the package. In this calculation, the assumed damage is greater than the damage that could result from these tests and test conditions.

LDCC – Low Density Cellular Concrete (LDCC)

Low density cellular concrete is concrete which has entrained air to decrease the density. Two densities are used; 30-36 $lb/ft^3$ inside the reactor vessel and 50-60 $lb/ft^3$ in the annular space between the reactor vessel insulation and the outermost steel shell of the containment. The minimum densities are assumed in this calculation.

RV – Reactor Vessel

In this calculation, the reactor vessel does not include the head.

RVAI – Reactor Vessel And Internals (RVAI)

In this calculation the RVAI includes the Reactor Vessel (RV), RV insulation, RV clad, Seal Weights (SW), Thermal Shield and Thermal Shield retainer (TS), steam baffle, sparger, top guide plate, seal housing and LDCC inside the RV.

RVTS – Reactor Vessel Transport System (RVTS)

In this calculation the RVTS includes the RVAI and steel shell and LDCC surrounding the RVAI.

Containment

In this calculation the containment is the outer steel container, not the RV. The outer steel container is the outermost cylindrical steel shell plus the top and bottom covers.

Leaching

In this calculation leaching is the process of radioactivity being released to <u>water</u>. All of the radioactivity in the RVAI is available for leaching. Therefore $A_2$ for <u>leaching</u> is based on the entire radioactive content of the RVAI.

Leaking

In this calculation leaking is the process of radioactivity being released to <u>air</u>. Only the surface contamination is available for leaking, because the activation products are bound in the steel matrix. Therefore $A_2$ for <u>leaking</u> is based only on the radioactivity in the surface contamination.

DDE – Deep Dose Equivalent

This is the dose which applies to external whole body exposure as defined in 10 CFR 20.1003 [Ref. 8.28]. It is the dose equivalent at a tissue depth of 1 cm (1000 $mg/cm^2$).

Wetted Surface Area

This is the area of the surfaces inside the RV that have been in contact with reactor water. It includes the entire inner surface of the RV clad and the surfaces of the components that are still in the RV, such as the thermal shield and support plates. It excludes the outer surfaces of the RV because these surfaces were not in continuous contact with reactor water under operating conditions.

### 1.2 Purpose

The purpose of this calculation is to determine the upper bound radiological consequences from hypothetical accident conditions (HAC) postulated for the RVAI/RVTS. These consequences, dose rates and releases, will then be compared with the criteria in 10CFR 71.51 [Ref. 8.27].

### 1.3 Scope

The scope of this calculation includes radiation dose, leach rate (due to immersion in water) , and leak rate (airborne release).

### 1.4 Background

The doses in this calculation are intentionally greater than the doses that could reasonably be expected to result from an accident, and therefore should not be interpreted as being the expected consequence. They are values that will not be exceeded, and are to be used for comparison with appropriate guidelines.

The potential accidents are undefined at the time of this calculation, so bounding assumptions are used to evaluate the radiological consequences. The assumptions include; (a) postulated gaps in the shielding, (b) a release of airborne radioactivity, and (c) a release of radioactivity into water. The gaps in the shielding and the releases are not to be interpreted as being the expected result of an accident. They are assumed solely for the purpose of ensuring that the calculated radiological consequences are bounding.

These assumptions do not depend on the transportation mode or transportation route. They are selected to ensure that any accident scenario is bounded. (For example, the effect of complete submersion following breach of containment is evaluated even though water transportation is not considered at this time. This scenario does, however, envelop the case where the RVAI/RVTS package is assumed to fall from a bridge into a river.)

## 2 Design Inputs

### 2.1 Source Term

The RVAI radionuclide inventories are obtained from Reference 8.24. The source terms for the accident releases are determined by applying reduction factors to the RVAI inventories. The reduction factors account for the fact that the radioactivity is bound in either (a) the steel matrix itself (activation products) or (b) between the steel and LDCC (surface contamination). Table 2.1-1 lists the activation inventory, Table 2.1-2 lists the surface contamination inventory, and Table 2.1-3 lists the total inventory.

Table 2.1-1. RVAI Activation Inventory [Ref. 8.24]

| Nuclide | Fraction | Activity |
|---|---|---|
| H-3 | 3.26 E -4 | 4.28 E+0 Curies |
| C-14 | 1.09 E -4 | 1.42 E+0 Curies |
| Sb-125 | 2.01 E -7 | 2.64 E-3 Curies |
| Mn-54 | 1.08 E -3 | 1.41 E+1 Curies |
| Eu-152 | 1.26 E -5 | 1.66 E-1 Curies |
| Fe-55 | 3.47 E -1 | 4.96 E+3 Curies |
| Co-60 | 5.73 E -1 | 7.11 E+3 Curies |
| Ni-59 | 4.75 E -4 | 6.23 E+0 Curies |
| Ni-63 | 7.82 E -2 | 1.03 E+3 Curies |
| Nb-94 | 1.64 E -6 | 2.15 E-2 Curies |
| Tc-99 | 3.52 E -7 | 4.61 E-3 Curies |
| Total | 1.0 | 1.31 E+4 Curies |

Table 2.1-2 RVAI Design Basis Surface Contamination Inventory [Ref. 8.24]

| Nuclide | (Ci) | Nuclide | (Ci) |
|---|---|---|---|
| C14 | 7.51E-04 | Ce144 | 3.03E-04 |
| Fe55 | 1.99E-01 | H3 | 5.30E-04 |
| I129 | 1.53E-03 | Am241 | 8.81E-04 |
| Ni63 | 1.42E-01 | Cm242 | 3.79E-07 |
| Sr90 | 6.04E-03 | Cm243 | 2.35E-04 |
| Tc99 | 6.07E-04 | Cm244 | 2.23E-04 |
| Mn54 | 8.22E-03 | Pu238 | 5.83E-04 |
| Co60 | 2.49E+00 | Pu239/240 | 6.93E-04 |
| Zn65 | 1.36E-03 | Pu241 | 3.31E-02 |
| Sb125 | 1.09E-02 | Pu242 | 3.07E-06 |
| | | Total | 2.89E+00 |

Table 2.1-3 RVAI Design Basis Total Inventory [Ref. 8.24]

| Nuclide | (Ci) | Nuclide | (Ci) |
|---|---|---|---|
| C14 | 1.42E+00 | Ce144 | 3.03E-04 |
| Fe55 | 4.96E+03 | Eu152 | 1.66E-01 |
| I129 | 1.53E-03 | H3 | 4.28E+00 |
| Ni59 | 6.23E+00 | Am241 | 8.81E-04 |
| Ni63 | 1.03E+03 | Cm242 | 3.79E-07 |
| Sr90 | 6.04E-03 | Cm243 | 2.35E-04 |
| Tc99 | 5.22E-03 | Cm244 | 2.23E-04 |
| Mn54 | 1.41E+01 | Pu238 | 5.83E-04 |
| Co60 | 7.11E+03 | Pu239/240 | 6.93E-04 |
| Zn65 | 1.36E-03 | Pu241 | 3.31E-02 |
| Nb94 | 2.15E-02 | Pu242 | 3.07E-06 |
| Sb125 | 1.35E-02 | Total | 1.31E+04 |

## 2.2 RV (Reactor Vessel) Dimensions

For the purposes of this calculation, the required information is only diameters, heights, an estimate of the total surface area, and thicknesses for selected components. Therefore, these dimensions do not reflect the nozzles, penetrations, or other surface features of the RV and insulation. All RV heights are measured from lowest point on the inside (wetted) surface of the RV.

Table 2.2-1 RVAI Dimensions

| Dimension | Value | Reference |
|---|---|---|
| Total Vessel Height | 344 13/32 in. | DWG F-230-791-2 [Ref. 8.4] |
| Vessel Head Height | 62 13/32 in. | DWG F-230-791-2 [Ref. 8.4] |
| Vessel Height to Flange | 282 in. | DWG F-230-791-2 [Ref. 8.4] |
| Vessel Inner Diameter | 106 7/16 in. | DWG F-230-791-2 [Ref. 8.4] |
| Vessel Base Metal Thickness | 5 ¼ in. | DWG F-230-791-2 [Ref. 8.4] |
| Vessel Clad Thickness | 5/32 in. | DWG F-230-791-2 [Ref. 8.4] |
| Height to Tangent Line | 52 27/32 in. | DWG F-230-791-2 [Ref. 8.4] |
| Insulation Thickness | 3 in. | DWG 198E79 [Ref. 8.5] |
| Active Fuel Height | 70 in. | DWG 197E853 [Ref. 8.7] |
| Thermal Shield Inner Radius | 50 in. | Calc. N-10525-020-0002 [Ref. 8.1] |
| Thermal Shield Thickness | 1.5 in. | Calc. N-10525-020-0002 [Ref. 8.1] |
| Seal Weight Inner Radius | 51.5 in. | Calc. N-10525-020-0002 [Ref. 8.1] |
| Seal Weight Thickness | 1.0 in. | Calc. N-10525-020-0002 [Ref. 8.1] |
| Seal Weight Height | 27 in. | Calc. N-10525-020-0002 [Ref. 8.1] |
| Seal Weight Width | 18 in. | Calc. N-10525-020-0002 [Ref. 8.1] |

## 2.3 LDCC (Low Density Cellular Concrete)

The LDCC has a permissible range as shown in the table below. The minimum density is used in this calculation because it yields the highest dose rates, and is therefore conservative and bounding.

| Parameter | Value | Reference |
|---|---|---|
| Density Inside RV | 30 - 36 pcf | [Ref. 8.8] |
| Density Outside RV | 50 - 60 pcf | [Ref. 8.8] |

## 2.4 Transport Cask Dimensions

| | | |
|---|---|---|
| Outside Diameter | 13 ft - 0 in. | [Ref. 8.8] |
| Height | 24 ft - 11 ½ in. | [Ref. 8.8] |
| Steel thickness over active core region | 7 in. | [Ref. 8.8] |

## 2.5 Corrosion Rates

In order to bound the leach rates, salt water corrosion rates are used for the activity bound in the steel matrix.

| Salt Water Corrosion Rate | Value | Reference |
|---|---|---|
| Stainless Steel | 3.34 MDD* | Corrosion Handbook [Ref. 8.15] |
| Mild Steel | 18.6 MDD* | Corrosion Handbook [Ref. 8.15] |

MDD ≡ milligrams per day per square decimeter

## 3 Assumptions and Limitations

There are no limitations associated with this calculation. The following assumptions are used in this calculation.

### 3.1 Radioactive Source Term

The source term has been decay corrected to 9/1/2002. It is assumed that the hypothetical accident takes place on 9/1/2002. No credit is taken for further radiodecay.

### 3.2 Breach Of Containment Due To Post-HAC Damage

Four openings are conservatively assumed for the breach of containment. It is assumed that these openings bound the post-HAC damage. This assumption is supported by calculation S-10525-020-012 [Ref. 8.29, Sections 5.2 and 8].

a) A horizontal 1 inch wide segment of the RV and insulation are unshielded around the circumference of the vessel at the core midplane.
b) A vertical 1 inch wide by 48 inch long segment of the RV and insulation are unshielded, centered on the core midplane.
c) A 6 inch diameter segment of the RV and insulation are unshielded, centered on the core midplane.
d) The entire top shield plate is removed.

In addition, to bound the release of radioactivity to water, it is non-mechanistically assumed that the entire outer surface of the RV and all surfaces of the mirror insulation are exposed to water. To bound the release of radioactivity to air, it is non-mechanistically assumed that the entire inventory of surface contamination is available for release.

For cases a, b, and c, this is equivalent to completely removing the 7 inch thick steel shell, and ~ 9 inch thick LDCC over the segment. For case d the entire 4 inch thick plate is removed.

The core midplane has the highest flux, and therefore the highest concentration of activation products. It is assumed that the axial peaking factor is 1.2, so a factor of 1.2 is applied to account for the increased dose rates at the core mid-plane.

### 3.3 Liquid Release (Leached Activity)

At the time of this calculation, the transportation route and accident scenarios have not yet been developed. These assumptions below are judged to bound the leached activity for possible accidents.

It is assumed that 50% of the surface contamination is leached out of the RVAI in 7 days. It is also assumed that sea water corrosion rates are applicable. The assumption that 50% of the surface contamination leaches out in 7 days is consistent with half of the wetted surface area being completely exposed. Since the reactor vessel is filled with LDCC which fixes the surface contamination, and the vessel is robust (5 ¼ in. thick steel) it is not considered credible that this much of the surface area could be exposed. Nevertheless, these assumptions are used to demonstrate that even under worst case conditions, the leach rate will be less than $A_2$ / week.

### 3.4 Source Term

For the purposes of this calculation it is assumed that the source term is distributed over a 70 inch height, regardless of the actual geometry. This is the length of the active fuel, and is, in general, conservative. For example, the entire reactor vessel source is concentrated in a 70 inch long cylinder, even though the vessel itself is 282 inches long.

# 4 Methodology

## 4.1 Direct Dose

Direct dose rates are calculated using MicroShield [Ref. 8.14]. The geometries, activities, and materials are taken from References 8.1 and 8.24. The MicroShield dose rates are benchmarked to the QAD dose rates in Reference 8.1. MicroShield has been qualified under S&L's Quality Assurance Program. The file listings are contained in Attachment A.

## 4.2 Airborne Release

Airborne releases are calculated using a non-mechanistic model that assumes all of the surface contamination is released, regardless of the accident scenario or location.

## 4.3 Leach Rates

Leach rates are calculated using salt-water corrosion rates for stainless and carbon steel and a non-mechanistic release of 50% of the surface contamination (Assumption 3.3).

# 5 Acceptance Criteria

The purpose of this calculation is to determine the radiological consequences of an accident. Therefore, the acceptance criteria are taken from the 10 CFR 71 limits for hypothetical accident conditions. They are:

1. No escape of krypton exceeding $A_2$ in 1 week (10 CFR 71.51(a) (2));
2. No escape of other radioactive material exceeding a total amount $A_2$ in 1 week (10 CFR 71.51 (a) (2));
3. No external, radiation dose rate exceeding 10 mSv/h (1 rem/h) at 1 m (40 in) from the external surface of the package (10 CFR 71.51(a) (2)).

# 6 Calculations

## 6.1 RVAI $A_2$, Leachable Activity (All Radionuclides)

The value of $A_2$ for all radionuclides in the RVAI is calculated using the formula in 10CFR71, APP A for a mixture [Ref. 8.23]. This formula is:

$$A_2 = 1/\{\Sigma f(i) / A_2(i)\}$$

Where: $A_2$ = $A_2$ value for the mixture
$f(i)$ = fraction of activity of nuclide i in the mixture
$A_2(i)$ = appropriate $A_2$ value for nuclide i from 10CFR71, Table A-1.

The RVAI radioactivity is the sum of 1.31E4 Ci of activation products that are bound in the steel matrix, and 2.89 Ci of surface contamination that is bound between the LDCC and steel surfaces. The value of $A_2$ for the RVIA is calculated in Table 6.1-1 below.

Table 6.1-1; RVAI $A_2$ Limit , Leachable Activity

| Nuclide | Activity (Ci) | Fraction (f) | A2 (Ci) | f/A2 (1/Ci) |
|---|---|---|---|---|
| H3 | 4.28E+00 | 3.262E-04 | 1.080E+03 | 3.020E-07 |
| C14 | 1.42E+00 | 1.086E-04 | 5.410E+01 | 2.007E-06 |
| Sb125 | 1.35E-02 | 1.033E-06 | 2.430E+01 | 4.250E-08 |
| Mn54 | 1.41E+01 | 1.076E-03 | 2.700E+01 | 3.985E-05 |
| Ce144 | 3.03E-04 | 2.310E-08 | 5.410E+00 | 4.270E-09 |
| Eu152 | 1.66E-01 | 1.265E-05 | 2.430E+01 | 5.204E-07 |
| Fe55 | 4.96E+03 | 3.779E-01 | 1.080E+03 | 3.499E-04 |
| Co60 | 7.11E+03 | 5.419E-01 | 1.080E+01 | 5.018E-02 |
| Ni59 | 6.23E+00 | 4.745E-04 | 1.080E+03 | 4.393E-07 |
| Ni63 | 1.03E+03 | 7.818E-02 | 8.110E+02 | 9.640E-05 |
| Sr90 | 6.04E-03 | 4.601E-07 | 2.700E+00 | 1.704E-07 |
| Nb94 | 2.15E-02 | 1.638E-06 | 1.620E+01 | 1.011E-07 |
| Tc99 | 5.22E-03 | 3.978E-07 | 2.430E+01 | 1.637E-08 |
| Pu238 | 5.83E-04 | 4.442E-08 | 5.410E-03 | 8.210E-06 |
| Pu239/240 | 6.93E-04 | 5.279E-08 | 5.410E-03 | 9.757E-06 |
| Pu241 | 3.31E-02 | 2.524E-06 | 2.700E-01 | 9.349E-06 |
| Pu242 | 3.07E-06 | 2.340E-10 | 5.410E-03 | 4.326E-08 |
| Cm242 | 3.79E-07 | 2.892E-11 | 2.700E-01 | 1.071E-10 |
| Cm243 | 2.35E-04 | 1.792E-08 | 8.110E-03 | 2.210E-06 |
| Cm244 | 2.23E-04 | 1.698E-08 | 1.080E-02 | 1.572E-06 |
| Am241 | 8.81E-04 | 6.712E-08 | 5.410E-03 | 1.241E-05 |
| I129 | 1.53E-03 | 1.169E-07 | Unlimited | |
| Zn65 | 1.36E-03 | 1.037E-07 | 5.410E+01 | 1.916E-09 |
| SUM | 1.31E+04 | 1.000E+00 | | 5.071E-02 |

$A_2 = 1/\{\Sigma f(i) / A_2(i)\}$
$A_2 = 1/ 5.071E\text{-}2$
$A_2 = 19.72$ Ci

### 6.2 RVAI $A_2$, Potentially Airborne Nuclides (Surface Contamination)

One of the requirements of 10CFR71.51(a)(2) is "... there would be no escape of krypton-85 exceeding 10 $A_2$ in one week, no escape of other radioactive material exceeding a total amount $A_2$ in one week ..." [Ref. 8.27]. The only radioactive material available for escape via pathways other than dissolution (leaching) is the surface contamination because all other activity is bound in the steel matrix of large components. Therefore the $A_2$ is calculated for the surface contamination.

The value of $A_2$ for the RVAI surface contamination is calculated using the formula in 10CFR71, APP A for a mixture [Ref. 8.23]. This formula is given below.

$A_2 = 1/\{\Sigma f(i) / A_2(i)\}$

Where: $A_2$ = $A_2$ value for the mixture
f(i) = fraction of activity of nuclide i in the mixture
$A_2$ (i) = appropriate $A_2$ value for nuclide i from 10CFR71, Table A-1.

The RVAI surface contamination radioactivity is 2.89 Ci, which is bound between the LDCC and steel surfaces. The value of $A_2$ for the RVAI is calculated in Table 6.2-1 below.

As can be seen from Table 6.2-1, the total quantity of activity available for airborne release, 2.89 Ci, is less than $A_2$, 3.59 Ci. Therefore, the quantity of radioactivity that could leak from the package will always be less than $A_2$, and meet this acceptance criterion.

Table 6.2-1; RVAI $A_2$ Limit, Releasable Activity (Other Than Leaching)

| Nuclide | Activity (Ci) | Fraction (f) | A2 (Ci) | f/A2 (1/Ci) |
|---|---|---|---|---|
| H3 | 5.30E-04 | 1.83E-04 | 1.08E+03 | 1.69E-07 |
| C14 | 7.51E-04 | 2.60E-04 | 5.41E+01 | 4.80E-06 |
| Sb125 | 1.09E-02 | 3.77E-03 | 2.43E+01 | 1.55E-04 |
| Mn54 | 8.22E-03 | 2.84E-03 | 2.70E+01 | 1.05E-04 |
| Ce144 | 3.03E-04 | 1.05E-04 | 5.41E+00 | 1.94E-05 |
| Eu152 | 0.00E+00 | 0.00E+00 | 2.43E+01 | 0.00E+00 |
| Fe55 | 1.99E-01 | 6.88E-02 | 1.08E+03 | 6.37E-05 |
| Co60 | 2.49E+00 | 8.60E-01 | 1.08E+01 | 7.96E-02 |
| Ni59 | 0.00E+00 | 0.00E+00 | 1.08E+03 | 0.00E+00 |
| Ni63 | 1.42E-01 | 4.92E-02 | 8.11E+02 | 6.07E-05 |
| Sr90 | 6.04E-03 | 2.09E-03 | 2.70E+00 | 7.72E-04 |
| Nb94 | 0.00E+00 | 0.00E+00 | 1.62E+01 | 0.00E+00 |
| Tc99 | 6.07E-04 | 2.10E-04 | 2.43E+01 | 8.63E-06 |
| Pu238 | 5.83E-04 | 2.01E-04 | 5.41E-03 | 3.72E-02 |
| Pu239/240 | 6.93E-04 | 2.39E-04 | 5.41E-03 | 4.42E-02 |
| Pu241 | 3.31E-02 | 1.14E-02 | 2.70E-01 | 4.24E-02 |
| Pu242 | 3.07E-06 | 1.06E-06 | 5.41E-03 | 1.96E-04 |
| Cm242 | 3.79E-07 | 1.31E-07 | 2.70E-01 | 4.86E-07 |
| Cm243 | 2.35E-04 | 8.12E-05 | 8.11E-03 | 1.00E-02 |
| Cm244 | 2.23E-04 | 7.70E-05 | 1.08E-02 | 7.13E-03 |
| Am241 | 8.81E-04 | 3.04E-04 | 5.41E-03 | 5.62E-02 |
| I129 | 0.00E+00 | 0.00E+00 | Unlimited | |
| Zn65 | 1.36E-03 | 4.70E-04 | 5.41E+01 | 8.69E-06 |
| SUM | 2.89E+00 | 1.00E+00 | | 2.78E-01 |

$A_2 = 1/\{\Sigma f(i) / A_2(i)\}$
$A_2 = 1/ 2.78E-1$
$A_2 = 3.59$ Ci

### 6.3 Direct Dose

There is no fuel and less than 0.05 gram of fissile material [Ref. 8.24]. Therefore, the neutron source is negligible and only gamma dose rates are considered.

The gamma dose rates are calculated using MicroShield [Ref. 8.14]. The input for the MicroShield runs is developed below. MicroShield has been validated and verified under S&L's QA program for computer applications.

The total direct dose rate at 1 meter from the package is the sum of two dose rates:

(a) The dose rate from the fully shielded RVAI, and
(b) The dose rate from the unshielded segment of the RVAI.

The unshielded segments that are considered are:

(a) A horizontal 1 inch wide segment of the RV and insulation are unshielded around the circumference of the vessel at the core midplane.
(b) A vertical 1 inch wide by 48 inch long segment of the RV and insulation are unshielded, centered on the core midplane.
(c) A 6 inch diameter segment of the RV and insulation are unshielded, centered on the core midplane.
(d) The entire top shield plate is removed (dose rate taken from reference 8.1).

The 7 in. thick steel shield and ~ 9 in. thick LDCC shield are assumed to be completely removed from unshielded segments in cases a, b, and c. The segments are centered on the core midplane because the midplane has the highest concentration of activation products, and is therefore conservative. A factor of 1.2 is applied to the core midplane dose rates to account for the increased activation product inventory. (See Assumption 3.2)

The MicroShield model does not include components that are above and below the active core region (grid bar stubs, etc.) The shielding calculation, N-10525-020-0002 [Ref. 8.1], does include these components. Therefore, the MicroShield model is benchmarked against Reference 8.1 to determine correction factors that incorporate the contributions from the segments above and below the active fuel region. (This is discussed in more detail where the factors are calculated below.)

#### 6.3.1 Component And Source Descriptions

The sources are calculated using the nuclide ratios and total activities from Reference 8.24. They are calculated in Table 6.3.1-1 below .

Table 6.3.1-1 RV Sources

| Nuclide | Fraction | Thermal Shield (Ci) | Thermal Shield Ret. (Ci) | Seal Weights (Ci) | RV Wall (Ci) | RV Clad (Ci) | RV Insulation (Ci) |
|---|---|---|---|---|---|---|---|
| Total | | 7.40E+03 | 1.14E+02 | 1.10E+03 | 1.11E+03 | 2.45E+02 | 5.81E+01 |
| H3 | 3.26E-04 | 2.41E+00 | 3.72E-02 | 3.59E-01 | 3.62E-01 | 7.99E-02 | 1.90E-02 |
| C14 | 1.09E-04 | 8.03E-01 | 1.24E-02 | 1.19E-01 | 1.21E-01 | 2.66E-02 | 6.31E-03 |
| Sb125 | 2.01E-07 | 1.49E-03 | 2.29E-05 | 2.21E-04 | 2.23E-04 | 4.93E-05 | 1.17E-05 |
| Mn54 | 1.08E-03 | 7.96E+00 | 1.23E-01 | 1.18E+00 | 1.19E+00 | 2.64E-01 | 6.25E-02 |
| Eu152 | 1.26E-05 | 9.36E-02 | 1.44E-03 | 1.39E-02 | 1.40E-02 | 3.10E-03 | 7.35E-04 |
| Fe55 | 3.47E-01 | 2.57E+03 | 3.96E+01 | 3.82E+02 | 7.90E+02 | 8.50E+01 | 2.02E+01 |
| Co60 | 5.73E-01 | 4.24E+03 | 6.53E+01 | 6.30E+02 | 2.31E+02 | 1.40E+02 | 3.33E+01 |
| Ni59 | 4.75E-04 | 3.51E+00 | 5.41E-02 | 5.22E-01 | 5.27E-01 | 1.16E-01 | 2.76E-02 |
| Ni63 | 7.82E-02 | 5.79E+02 | 8.91E+00 | 8.60E+01 | 8.68E+01 | 1.92E+01 | 4.54E+00 |
| Nb94 | 1.64E-06 | 1.21E-02 | 1.87E-04 | 1.80E-03 | 1.82E-03 | 4.01E-04 | 9.52E-05 |
| Tc99 | 3.52E-07 | 2.60E-03 | 4.01E-05 | 3.87E-04 | 3.90E-04 | 8.61E-05 | 2.04E-05 |

In the MicroShield model, the thermal shield and thermal shield retainer are combined for convenience. The total is shown in Table 6.3.1-2 below.

Table 6.3.1-2 Thermal Shield + Thermal Shield Retainer

| Nuclide | Thermal Shield (Ci) | Thermal Shield Ret. (Ci) | TS + TS Ret. (Ci) |
|---|---|---|---|
| Total | 7.40E+03 | 1.14E+02 | 7.51E+03 |
| H3 | 2.41E+00 | 3.72E-02 | 2.45E+00 |
| C14 | 8.03E-01 | 1.24E-02 | 8.16E-01 |
| Sb125 | 1.49E-03 | 2.29E-05 | 1.51E-03 |
| Mn54 | 7.96E+00 | 1.23E-01 | 8.08E+00 |
| Eu152 | 9.36E-02 | 1.44E-03 | 9.50E-02 |
| Fe55 | 2.57E+03 | 3.96E+01 | 2.61E+03 |
| Co60 | 4.24E+03 | 6.53E+01 | 4.30E+03 |
| Ni59 | 3.51E+00 | 5.41E-02 | 3.57E+00 |
| Ni63 | 5.79E+02 | 8.91E+00 | 5.87E+02 |
| Nb94 | 1.21E-02 | 1.87E-04 | 1.23E-02 |
| Tc99 | 2.60E-03 | 4.01E-05 | 2.64E-03 |

### 6.3.2 RV Insulation Equivalent Thickness and Density

The insulation equivalent thickness is the sum of the thicknesses of the corrugated spacers and separation sheets. From Drawing BL-13954-2 [Ref. 8.12] there are 6 corrugated spacers, and 6 separator sheets in a 1½ inch section. Each of these is 0.009 in. thick. The insulation is 3 inches thick (two 1½ inch thick sections). The total equivalent metal thickness is calculated below.

$T_{EQ} = 2 \times (6 \times 0.009 + 6 \times 0.009)$
$T_{EQ} = 0.216$ in.

The actual thickness is 3 in., and the insulation is made of stainless steel. The equivalent density is:

$D_{EQ} = (0.216 / 3.0) \times \rho_{SS}$
$D_{EQ} = 0.566$ gm/cc

Where: 0.216 = total thickness of stainless steel in insulation
3.0 = thickness of insulation (including air between corrugations)
$\rho_{SS}$ = density of stainless steel, 7.86 gm/cc

**6.3.3 Intact Containment (Shielded) Dose Rates**

Shielded dose rates are calculated as a function of distance from the outer surface of the RVTS package for each component (RV wall, RV insulation, etc.). These are then summed to yield the total shielded dose rates. (The RVTS is the reference surface because these dose rates are for an intact RVTS.)

The dose rates that are calculated in the MicroShield runs do not include the radiation from above and below the active core region. (The MicroShield runs only cover the active core region, which is ~70 inches tall.) Correction factors are calculated to include the radiation from above and below the active core region. The correction factors are the ratio of the dose rate in Reference 8.1 to the dose rate from the MicroShield runs at; (a) contact (1 inch from the RVTS) and (b) 2 meters. This is because the dose rates in Reference 8.1 do include the dose rate contributions from above and below the active core region. Note however, that Reference 8.1 uses mrem/hr – tissue, and the doses in this calculation are mrem/hr - DDE. For the purposes of calculating the correction factor, 1 R/hr = 1 rem/hr. Therefore the ratio is calculated using mR/hr from the MicroShield runs, and then applied to the DDE dose rates.

The source terms are from Tables 6.3.1-1 and 6.3.1-2. The geometric input is derived from the input data in Section 2.2. The geometric input is summarized in Tables 6.3.3-1 and 6.3.3-2 below. The MicroShield file listing is in Attachment A.

Table 6.3.3-1, Thicknesses For Fully Shielded Case

| Source Comp. | 30 pcf LDCC Thck. (in.) | Thermal Shield Thck. (in.) | Seal Weight Thck. (in.) | Seal Weight to RV Clad (in.) | RV Clad Thck. (in.) | RV Wall Thck. (in.) | RV Insulation Thck. (in.) | 50 pcf LDCC Thck. (in.) | Shield Steel Thck. (in.) | Total Radial Distance (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| Th. Shld | 50.000 | 1.500 | 1.000 | 0.5625 | 0.156 | 5.250 | 3.000 | 9.531 | 7.000 | 78.000 |
| Seal Wt. | 51.500 | | 1.000 | 0.5625 | 0.156 | 5.250 | 3.000 | 9.531 | 7.000 | 78.000 |
| RV Clad | 53.063 | | | | 0.156 | 5.250 | 3.000 | 9.531 | 7.000 | 78.000 |
| RV Wall | 53.219 | | | | | 5.250 | 3.000 | 9.531 | 7.000 | 78.000 |
| RV Ins. | 53.219 | | | | | 5.250 | 3.000 | 9.531 | 7.000 | 78.000 |

Table 6.3.3-2, Shielded Case Dose Point Distances

| Distance From RVTS Surface | RVTS Radius (in.) | Distance To RV Center (in.) |
|---|---|---|
| Comp. Thk | N/A | N/A |
| 1 in. | 78.00 | 79.00 |
| 1 m | 78.00 | 117.37 |
| 2 m | 78.00 | 156.74 |

The 1 inch (contact) and 2 meter dose rates (mR/hr) from MicroShield and Calculation N-10525-020-0002 (mrem/hr) [Ref. 8.1] are shown in Table 6.3.3-3 below. The correction factor is the ratio of "Calculation N-10525-020-0002" dose rate to the "Total Shielded Dose Rate." The 1 meter correction factor is a linear interpolation between the 1" and 2 m correction factors.

Table 6.3.3-3, Shielded Dose Rate Correction Factor

| | Distance | Thermal Shield (mR/hr) | Seal Weight (mR/hr.) | RV Clad (mR/hr) | RV Wall (mR/hr) | RV Insulation (mR/hr) | Total Shielded (mR/hr) | Calc. N-10525-020-0002 (mrem/hr) | Calculated Dose Correction Factor |
|---|---|---|---|---|---|---|---|---|---|
| Shielded | Contact | 5.55E-01 | 2.57E-01 | 9.49E-02 | 5.67E+00 | 4.56E+00 | 1.11E+01 | 1.11E+01 | 9.96E-01 |
| Shielded | 1 meter | 3.49E-01 | 1.61E-01 | 5.92E-01 | 3.36E+00 | 2.67E+00 | 7.13E+00 | N/A | 1.08E+00 |
| Shielded | 2 meters | 2.16E-01 | 9.83E-02 | 3.60E-02 | 1.93E+00 | 1.51E+00 | 3.79E+00 | 4.39E+00 | 1.16E+00 |

The corrected DDE dose rates (mrem/hr) for the shielded RVTS are shown in Table 6.3.3-4 below.

Table 6.3.3-4, DDE for Shielded RVTS (mrem/hr)

| Distance | Thermal Shield DDE (mSv/hr) | Seal Weight DDE (mSv/hr.) | RV Clad DDE (mSv/hr) | RV Wall DDE (mSv/hr) | RV Insulation DDE (mSv/hr) | Total Shielded DDE (mSv/hr) | Total Shielded DDE (mrem/hr) | Shielded Dose Correction Factor | Corrected Shielded DDE (mrem/hr) |
|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 5.476E-03 | 2.541E-03 | 9.375E-04 | 5.609E-02 | 4.514E-02 | 1.10E-01 | 1.10E+01 | 9.96E-01 | 1.10E+01 |
| 1 m | 3.443E-03 | 1.586E-03 | 5.843E-04 | 3.324E-02 | 2.641E-02 | 6.53E-02 | 6.53E+00 | 1.08E+00 | 7.03E+00 |
| 2 m | 2.129E-03 | 9.705E-04 | 3.560E-04 | 1.911E-02 | 1.493E-02 | 3.75E-02 | 3.75E+00 | 1.16E+00 | 4.34E+00 |

### 6.3.4 Breach Of Containment Dose Rates

The dose rates for the breach of containment are the sum of the dose rates from the unshielded segment plus the dose rate from the fully shielded RVTS. The dose rates for the unshielded segments are calculated for 4 configurations.

a) A horizontal 1 inch wide band of the RV and insulation are unshielded around the circumference of the vessel at the core midplane.
b) A vertical 1 inch wide by 48 inch long band of the RV and insulation are unshielded, centered on the core midplane.
c) A 6 inch diameter hole goes through the shielding and exposes a 6 inch diameter segment of the RV and insulation at the core midplane.
d) The entire top shield plate is removed.

Cases a, b, and c are calculated below. Case d is calculated in Reference 8.1 and the dose rate is included in this calculation for completeness.

The unshielded segments are centered on the core midplane because it has the highest flux, and therefore the highest concentration of activation products. It is assumed that the axial peaking factor is 1.2, so a factor of 1.2 is applied to the unshielded segment dose rates (Assumption 3.2). The dose rate contributions from above and below the shielding gaps are taken into account in the dose rates from the shielded RVTS (Section 6.3.3) which is added to gap dose rates.

The total component source terms are from Table 6.2.1-1. They are modified by correction factors. The correction factors reduce the source term so that it is correct for the volume of metal in the MicroShield model. The MicroShield models and the correct source term are calculated below for each case.

Case a, horizontal 1 inch unshielded segment

The MicroShield model is a 1 inch high cylinder. As stated in Assumption 3.4, the entire RVTS is modeled as a 70 inch tall cylinder. Therefore the 1 inch band has 1/70 of the total source for each component, and the correction factor is 1.429E-2. The source term for case a is calculated below.

Table 6.3.4-1, 1 inch Horizontal Segment Source

| Nuclide | Fraction | Thermal Shield (Ci) | Seal Weights (Ci) | RV Clad (Ci) | RV Wall (Ci) | RV Insulation (Ci) |
|---|---|---|---|---|---|---|
| Corr. Fctr. | 1.00E+00 | 1.43E-02 | 1.43E-02 | 1.43E-02 | 1.43E-02 | 1.43E-02 |
| Total | 1.00E+00 | 1.07E+02 | 1.57E+01 | 3.50E+00 | 1.59E+01 | 8.30E-01 |
| H-3 | 3.26E-04 | 3.50E-02 | 5.13E-03 | 1.14E-03 | 5.17E-03 | 2.71E-04 |
| C-14 | 1.09E-04 | 1.17E-02 | 1.71E-03 | 3.80E-04 | 1.72E-03 | 9.01E-05 |
| Sb-125 | 2.01E-07 | 2.16E-05 | 3.16E-06 | 7.04E-07 | 3.19E-06 | 1.67E-07 |
| Mn-54 | 1.08E-03 | 1.15E-01 | 1.69E-02 | 3.76E-03 | 1.71E-02 | 8.93E-04 |
| Eu-152 | 1.26E-05 | 1.36E-03 | 1.99E-04 | 4.43E-05 | 2.01E-04 | 1.05E-05 |
| Fe-55 | 3.47E-01 | 3.73E+01 | 5.45E+00 | 1.21E+00 | 1.13E+01 | 2.88E-01 |
| Co-60 | 5.73E-01 | 6.15E+01 | 9.00E+00 | 2.00E+00 | 3.30E+00 | 4.75E-01 |
| Ni-59 | 4.75E-04 | 5.09E-02 | 7.46E-03 | 1.66E-03 | 7.53E-03 | 3.94E-04 |
| Ni-63 | 7.82E-02 | 8.39E+00 | 1.23E+00 | 2.74E-01 | 1.24E+00 | 6.49E-02 |
| Nb-94 | 1.64E-06 | 1.76E-04 | 2.57E-05 | 5.73E-06 | 2.60E-05 | 1.36E-06 |
| Tc-99 | 3.52E-07 | 3.77E-05 | 5.52E-06 | 1.23E-06 | 5.58E-06 | 2.92E-07 |

Case b, vertical 1 inch wide, 48 inch long unshielded segment

The MicroShield model is a rectangular piece, 1 inch wide, 48 inches long, and as thick as the component, e.g., 5 ¼ inches thick for the RV wall. The correction factor is the ratio of the volume of the model to the volume of the component.

$R = V_{MODEL} / V_{COMP}$

Where; $V_{MODEL}$ = source volume in MicroShield model

$V_{COMP}$ = component volume

$V_{MODEL} = L \times W \times T$

Where; L = MicroShield source volume height

= 48 inch

W = MicroShield source volume width

= 1 inch

T = MicroShield source volume thickness

= component thickness (e.g., 5 ¼ in for RV wall)

$V_{COMP} = \pi \times (r_2^2 - r_1^2) \times L$

Where; $r_1$ = inner radius of component

$r_2$ = outer radius of component

$= r_1 + T$

The correction factors and source terms for case b are calculated in the tables below.

Table 6.3.4-2, 1 Inch Vertical Segment Correction Factors

| Component | Component Thickness (in) | Component Inner Radius (in) | Component Height (in) | Component Volume (in) | Source Area (in) | Source Volume (in) | Source Fraction (in) |
|---|---|---|---|---|---|---|---|
| Therm. Shld | 1.500E+00 | 50.000 | 70 | 3.348E+04 | 4.800E+01 | 7.200E+01 | 2.150E-03 |
| Seal Weight | 1.000E+00 | 51.500 | 70 | 2.287E+04 | 4.800E+01 | 4.800E+01 | 2.099E-03 |
| RV Clad | 1.560E-01 | 53.063 | 70 | 3.646E+03 | 4.800E+01 | 7.488E+00 | 2.054E-03 |
| RV Wall | 5.250E+00 | 53.219 | 70 | 1.289E+05 | 4.800E+01 | 2.520E+02 | 1.954E-03 |
| RV Ins. | 3.000E+00 | 58.469 | 70 | 7.913E+04 | 4.800E+01 | 1.440E+02 | 1.820E-03 |

Table 6.3.4-3, 1 Inch Vertical Segment Source Terms

| Nuclide | Fraction | Therm. Shld (Ci) | Seal Weight (Ci) | RV Clad (Ci) | RV Wall (Ci) | RV Ins. (Ci) |
|---|---|---|---|---|---|---|
| Corr. Factor | 1.00E+00 | 2.15E-03 | 2.10E-03 | 2.05E-03 | 1.95E-03 | 1.82E-03 |
| Total | 1.00E+00 | 1.62E+01 | 2.31E+00 | 5.03E-01 | 2.17E+00 | 1.06E-01 |
| H-3 | 3.26E-04 | 5.27E-03 | 7.53E-04 | 1.64E-04 | 7.08E-04 | 3.45E-05 |
| C-14 | 1.09E-04 | 1.75E-03 | 2.51E-04 | 5.46E-05 | 2.36E-04 | 1.15E-05 |
| Sb-125 | 2.01E-07 | 3.25E-06 | 4.64E-07 | 1.01E-07 | 4.36E-07 | 2.13E-08 |
| Mn-54 | 1.08E-03 | 1.74E-02 | 2.48E-03 | 5.41E-04 | 2.33E-03 | 1.14E-04 |
| Eu-152 | 1.26E-05 | 2.04E-04 | 2.92E-05 | 6.36E-06 | 2.74E-05 | 1.34E-06 |
| Fe-55 | 3.47E-01 | 5.61E+00 | 8.01E-01 | 1.75E-01 | 1.54E+00 | 3.67E-02 |
| Co-60 | 5.73E-01 | 9.25E+00 | 1.32E+00 | 2.88E-01 | 4.52E-01 | 6.06E-02 |
| Ni-59 | 4.75E-04 | 7.67E-03 | 1.10E-03 | 2.39E-04 | 1.03E-03 | 5.02E-05 |
| Ni-63 | 7.82E-02 | 1.26E+00 | 1.81E-01 | 3.93E-02 | 1.70E-01 | 8.27E-03 |
| Nb-94 | 1.64E-06 | 2.65E-05 | 3.78E-06 | 8.24E-07 | 3.55E-06 | 1.73E-07 |
| Tc-99 | 3.52E-07 | 5.68E-06 | 8.12E-07 | 1.77E-07 | 7.63E-07 | 3.72E-08 |

Case c, 6 inch diameter unshielded segment

The MicroShield model is a solid cylinder, 6 inches in diameter and as thick as the component, e.g., 5 ¼ inches thick for the RV wall. The correction factor is the ratio of the volume of the model to the volume of the component.

$R = V_{MODEL} / V_{COMP}$

Where; $V_{MODEL}$ = source volume in MicroShield model

$V_{COMP}$ = component volume

$V_{MODEL} = \pi \times 3^2 \times T$

Where; 3 = MicroShield source volume radius

T = MicroShield source volume thickness

= component thickness (e.g., 5 ¼ in for RV Wall)

$V_{COMP} = \pi \times (r_2^2 - r_1^2) \times L$

Where; $r_1$ = inner radius of component

$r_2$ = outer radius of component

$= r_1 + T$

The correction factors and source terms for case c are calculated in the tables below.

Table 6.3.4-4, 6 inch Diameter Segment Correction Factors

| Comp. | Comp. Thk. (in) | Comp. IR (in) | Comp. Hgt (in) | Comp. Vol. (in) | Src. Area. (in) | Src. Vol. (in) | Src. Frctn. (in) |
|---|---|---|---|---|---|---|---|
| Ther. Shld | 1.500E+00 | 50.000 | 70 | 3.348E+04 | 6.000E+00 | 4.241E+01 | 1.267E-03 |
| Seal Weight | 1.000E+00 | 51.500 | 70 | 2.287E+04 | 6.000E+00 | 2.827E+01 | 1.236E-03 |
| RV Clad | 1.560E-01 | 53.063 | 70 | 3.646E+03 | 6.000E+00 | 4.411E+00 | 1.210E-03 |
| RV Wall | 5.250E+00 | 53.219 | 70 | 1.289E+05 | 6.000E+00 | 1.484E+02 | 1.151E-03 |
| RV Ins. | 3.000E+00 | 58.469 | 70 | 7.913E+04 | 6.000E+00 | 8.482E+01 | 1.072E-03 |

Table 6.3.4-5, 6 Inch Diameter Segment Source Terms

| Nuclide | Fraction | Thermal Shield (Ci) | Seal Weights (Ci) | RV Clad (Ci) | RV Wall (Ci) | RV Insulation (Ci) |
|---|---|---|---|---|---|---|
| Corr. Fctr. | 1.00E+00 | 1.27E-03 | 1.24E-03 | 1.21E-03 | 1.15E-03 | 1.07E-03 |
| Total | 1.00E+00 | 9.52E+00 | 1.36E+00 | 2.96E-01 | 1.28E+00 | 6.23E-02 |
| H-3 | 3.26E-04 | 3.10E-03 | 4.44E-04 | 9.67E-05 | 4.17E-04 | 2.03E-05 |
| C-14 | 1.09E-04 | 1.03E-03 | 1.48E-04 | 3.22E-05 | 1.39E-04 | 6.76E-06 |
| Sb-125 | 2.01E-07 | 1.91E-06 | 2.74E-07 | 5.96E-08 | 2.57E-07 | 1.25E-08 |
| Mn-54 | 1.08E-03 | 1.02E-02 | 1.46E-03 | 3.19E-04 | 1.37E-03 | 6.70E-05 |
| Eu-152 | 1.26E-05 | 1.20E-04 | 1.72E-05 | 3.75E-06 | 1.62E-05 | 7.88E-07 |
| Fe-55 | 3.47E-01 | 3.30E+00 | 4.72E-01 | 1.03E-01 | 9.09E-01 | 2.16E-02 |
| Co-60 | 5.73E-01 | 5.45E+00 | 7.79E-01 | 1.70E-01 | 2.66E-01 | 3.57E-02 |
| Ni-59 | 4.75E-04 | 4.52E-03 | 6.45E-04 | 1.41E-04 | 6.06E-04 | 2.96E-05 |
| Ni-63 | 7.82E-02 | 7.44E-01 | 1.06E-01 | 2.32E-02 | 9.99E-02 | 4.87E-03 |
| Nb-94 | 1.64E-06 | 1.56E-05 | 2.23E-06 | 4.86E-07 | 2.09E-06 | 1.02E-07 |
| Tc-99 | 3.52E-07 | 3.35E-06 | 4.78E-07 | 1.04E-07 | 4.49E-07 | 2.19E-08 |

The MicroShield geometry input consists of the source volume geometry, shield thicknesses, and dose point distances. The thicknesses and dose point distances are calculated below. The source area dimensions are predefined but are reproduced below for completeness. The source thicknesses are the same as the component., e.g. 5 ¼ in. for the RV wall.

Table 6.3.4-6, Source Volume Dimensions

| Case | Length (in) | Width (in) | Radius (in) |
|---|---|---|---|
| a | N/A | 1 | N/A |
| b | 48 | 1 | N/A |
| c | N/A | N/A | 3 |

In the table below, a single air shield replaces the LDCC and outer steel shield. This is the only difference between the fully shielded case and the unshielded source cases.

Table 6.3.4-7, Thicknesses For Unshielded Source Cases

| Source Comp. | 30 pcf LDCC Thck. (in.) | Thermal Shield Thck. (in.) | Seal Weight Thck. (in.) | Seal Weight to RV Clad (in.) | RV Clad Thck. (in.) | RV Wall Thck. (in.) | RV Insulation Thck. (in.) | Air Thck. (in.) | Total Radial Distance (in.) |
|---|---|---|---|---|---|---|---|---|---|
| Th. Shld | 50.000 | 1.500 | 1.000 | 0.5625 | 0.156 | 5.250 | 3.000 | 16.531 | 78.000 |
| Seal Wt. | 51.500 | | 1.000 | 0.5625 | 0.156 | 5.250 | 3.000 | 16.531 | 78.000 |
| RV Clad | 53.063 | | | | 0.156 | 5.250 | 3.000 | 16.531 | 78.000 |
| RV Wall | 53.219 | | | | | 5.250 | 3.000 | 16.531 | 78.000 |
| RV Ins. | 53.219 | | | | | 5.250 | 3.000 | 16.531 | 78.000 |

The distances to the dose points are calculated from the center of the RVTS for cylindrical geometry (case a) and from the 'back' of the source for the other geometries (cases b and c).

Table 6.3.4-8, Dose Points For Unshielded Source Cases

| | | Case a | Cases b and c | | | | |
|---|---|---|---|---|---|---|---|
| Distance From RVTS Surface | RVTS Radius (in.) | Distance RV Cente (in.) | Thermal Shield (in.) | Seal Weights (in.) | RV Clad (in.) | RV Wall (in.) | RV Insulation (in.) |
| Comp. Thk | N/A | N/A | 1.500 | 1.000 | 0.156 | 5.250 | 3.000 |
| 1 in. | 78.00 | 79.00 | 29.00 | 27.50 | 25.94 | 25.78 | 20.531 |
| 1 m | 78.00 | 117.37 | 67.37 | 65.87 | 64.31 | 64.15 | 58.90 |
| 2 m | 78.00 | 156.74 | 106.74 | 105.24 | 103.68 | 103.52 | 98.27 |

The DDE dose rates (mrem/hr) for the unshielded segments are shown in Tables 6.3.4-9 through 11.

Table 6.3.4-9, DDE For 1 Inch Horizontal Gap (mrem/hr)

| Distance | Thermal Shield DDE (mSv/hr) | Seal Weight DDE (mSv/hr.) | RV Clad DDE (mSv/hr) | RV Wall DDE (mSv/hr) | RV Insulation DDE (mSv/hr) | 1 inch Gap DDE (mSv/hr) | 1 inch Gap DDE (mrem/hr) | Core Midplane Dose Correction Factor | Corrected 1 inch Gap DDE (mrem/hr) | Total Dose Rate (mrem/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 4.330E-01 | 1.967E-01 | 7.321E-02 | 3.342E+00 | 2.709E+00 | 6.75E+00 | 6.75E+02 | 1.20 | 8.10E+02 | 8.21E+02 |
| 1 m | 1.226E-01 | 5.431E-02 | 1.974E-02 | 8.071E-01 | 6.125E-01 | 1.62E+00 | 1.62E+02 | 1.20 | 1.94E+02 | 2.01E+02 |
| 2 m | 5.745E-02 | 2.530E-02 | 9.143E-03 | 3.654E-01 | 2.786E-01 | 7.36E-01 | 7.36E+01 | 1.20 | 8.83E+01 | 9.26E+01 |

Table 6.3.4-10, DDE For 1 Inch Vertical Gap (mrem/hr)

| Distance | Thermal Shield DDE (mSv/hr) | Seal Weight DDE (mSv/hr.) | RV Clad DDE (mSv/hr) | RV Wall DDE (mSv/hr) | RV Insulation DDE (mSv/hr) | 1 inch Gap DDE (mSv/hr) | 1 inch Gap DDE (mrem/hr) | Core Midplane Dose Correction Factor | Corrected 1 inch Gap DDE (mrem/hr) | Total Dose Rate (mrem/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 6.073E-01 | 2.697E-01 | 1.003E-01 | 3.674E+00 | 2.269E+00 | 6.92E+00 | 6.92E+02 | 1.20 | 8.30E+02 | 8.41E+02 |
| 1 m | 1.754E-01 | 7.316E-02 | 2.612E-02 | 6.623E-01 | 3.308E-01 | 1.27E+00 | 1.27E+02 | 1.20 | 1.52E+02 | 1.59E+02 |
| 2 m | 7.562E-02 | 3.088E-02 | 1.087E-02 | 2.523E-01 | 1.202E-01 | 4.90E-01 | 4.90E+01 | 1.20 | 5.88E+01 | 6.31E+01 |

Table 6.3.4-11, DDE For 6 inch Diameter Gap (mrem/hr)

| Distance | Thermal Shield DDE (mSv/hr) | Seal Weight DDE (mSv/hr.) | RV Clad DDE (mSv/hr) | RV Wall DDE (mSv/hr) | RV Insulation DDE (mSv/hr) | 6 inch Dia. Gap DDE (mSv/hr) | 6 inch Dia. Gap DDE (mrem/hr) | Core Midplane Dose Correction Factor | Corrected 6 inch dia Gap DDE (mrem/hr) | Total Dose Rate (mrem/hr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 in. | 6.687E-01 | 2.891E-01 | 1.076E-01 | 3.129E+00 | 1.865E+00 | 6.06E+00 | 6.06E+02 | 1.20 | 7.27E+02 | 7.38E+02 |
| 1 m | 1.211E-01 | 4.985E-02 | 1.775E-02 | 4.130E-01 | 2.057E-01 | 8.07E-01 | 8.07E+01 | 1.20 | 9.69E+01 | 1.04E+02 |
| 2 m | 4.759E-02 | 1.930E-02 | 6.793E-03 | 1.505E-01 | 7.210E-02 | 2.96E-01 | 2.96E+01 | 1.20 | 3.56E+01 | 3.99E+01 |

## 6.4 Leached Activity

The activity that is leached from the RVAI comes from two sources; (a) the surface contamination and, (b) the activation products which are bound in the steel matrix.

Released Surface Contamination

For the purpose of determining an upper bound leach rate, it is conservatively assumed that 50% of the surface contamination is leached out in 7 days. This is equivalent to completely uncovering half of the wetted surface area that has been covered with LDCC inside the reactor vessel (including the thermal shield, seal weights, etc.). This is assumed even though a breach of the RV itself is not considered credible because of the innate strength of the vessel combined with the protection afforded by the outer steel and LDCC shielding.

Released Bound Activation Products

The majority of the radioactivity is bound in the steel matrix (RV walls, RV clad, RV insulation, etc.). The quantity of radioactivity that is leached from the steel matrix over a 7day period is:

$$A = (SA_I \times L_{SS} + SA_{RV} \times L_{MS}) \times t$$

Where: $A$ = total leached radioactivity (Ci)
$SA_I$ = RV insulation specific activity (Ci/gm)
$SA_{RV}$ = RV wall specific activity (Ci/gm)
$L_{SS}$ = mass leach rate for stainless steel insulation (gm/day)
$L_{MS}$ = mass leach rate for mild steel RV wall (gm/day)
$t$ = time (days)

Specific Activity, SA

For activity bound in the steel matrix, the outer vessel wall and mirror insulation are assumed (non-mechanistically) to be entirely and directly exposed to the water (Assumption 3.2). The specific activities are:

SA = A/M

Where: SA = specific activity (Ci/gm)
A = component activity (Ci)
M = component mass (gm)

RV Insulation Activity = 58.1 Ci
RV insulation mass = 3300 lbs (1.50E6 gm) [Ref. 8.8]
RV Wall Activity = 1110 Ci
RV Wall mass = 183,665 lbs (8.35E7 gms) [Ref. 8.8]

$SA_I$ = 58.1 Ci / 1.50E6 gm
$SA_I$ = 3.87E-5 Ci/gm
$SA_{RV}$ = 1110 Ci / 8.35E7 gm
$SA_{RV}$ = 1.33E-5 Ci/gm

Leach Rate, *L*

$L$ = S x CR x 0.01
Where: $L$ = mass leach rate (gm/day)
S = surface area ($cm^2$)
CR = corrosion rate ($mg/dm^2$)
0.01 = conversion from $dm^2$ to $cm^2$

$S_{SS}$ = surface area of insulation stainless steel = 3.29E7 $cm^2$ (See below.)
$S_{MS}$ =surface area of RV mild steel = 8.07E5 $cm^2$ (See below.)

CR for stainless steel insulation (salt water) = 3.34 $mg/dm^2$ per day [Ref. 8.15]
CR for mild steel RV (salt water) = 18.6 $mg/dm^2$ per day [Ref. 8.15]
Corrosion rates for salt water are used because this is conservative.

$L$ = S x CR x 0.01

$L_{SS}$ = 3.29E7 $cm^2$ x 3.34 $mg/dm^2$ per day x 0.01
$L_{SS}$ = 1.10E6 mg/day (1.1 kg/day)

$L_{MS}$ = 8.07E5 $cm^2$ x 18.6 $mg/dm^2$ per day x 0.01
$L_{MS}$ = 1.50 E5 mg/day (150 gm/day)

**Surface Area, $S_{SS}$, For Stainless Steel**

The only stainless steel accessible to water following an accident is the stainless steel insulation outside the RV. As discussed above, this is because the RV itself will not be breached. Per Reference 8.8, the insulation on the bottom of the vessel will be removed, so only the cylindrical portion of the insulation remains. Per Reference 8.12, the 1.5 inch thick insulation has 12 layers, so the 3 inch thick insulation has 24 layers. |

$S_{SS} = 2 \times \pi \times r \times h \times 2n \times 2.54^2$

Where; r = nominal insulation radius

= RV radius + ½ insulation thickness

= 58.469 in. + ½ x 3.0 in.

= 59.969 in.

h = nominal insulation height (cylindrical RV section height to flange)

= 282 in. [Ref. 8.4]

n = number of layers in insulation

= 24 [Ref. 8.12] (12 layers per each 1½ inch thickness, 3 inch total)

$2.54^2$ = conversion from inch$^2$ to cm$^2$

$S_{SS} = 2 \times \pi \times 59.969 \times 282 \times 2 \times 24 \times 2.54^2$

$S_{SS} = 3.29E7 \text{ cm}^2$

**Surface Area, $S_{MS}$, For Mild Steel**

The only mild steel accessible to water following an accident is the outside surface of the RV. As, discussed above, this is because the RV itself will not be breached.

$S_{MS} = (2 \times \pi \times r \times h + 2 \times \pi \times r^2) \times 2.54^2$

Where; r = RV outside radius

= 58.469 in.

h = nominal RV height (cylindrical section)

= 282 in. (Section 2.3)

$2.54^2$ = conversion from inch$^2$ to cm$^2$

$S_{MS} = (2 \times \pi \times 58.469 \times 282 + 2 \times \pi \times 58.469^2) \times 2.54^2$

$S_{MS} = 8.07E5 \text{ cm}^2$

Released Bound Activation Products

The activity released from the activated metal is now calculated as:

$A = (SA_I \times L_{SS} + SA_{RV} \times L_{MS}) \times t$

$A = (3.87E\text{-}5 \times 1.10E3 + 1.33E\text{-}5 \times 1.50E2) \times 7$

$A = 0.312$ Ci

Total Released Activity

The total radioactivity that is released over 7 days is thus:

$A_{TOTAL} = A_{SC} + A_{AM}$

Where: $A_{TOTAL}$ = total released activity (Ci)

$A_{SC}$ = surface contamination activity that is released (Ci)

$A_{AM}$ = activated metal contamination activity that is released (Ci)

$A_{TOTAL} = A_{SC} + A_{AM}$

$A_{TOTAL} = 50\% \times 2.89 \text{ (Ci)} + 0.312 \text{ (Ci)}$

$A_{TOTAL} = 1.76$ Ci

Thus, the total activity that is expected to be leached in a period of 1 week is less than 1.76 Ci. The $A_2$ value is 19.72 Ci (Section 6.1). Therefore, using conservative assumptions and data it has been shown that leaching from the RVAI/RVTS is within the requirement of 10 CFR 71.51(a)(2).

# 7 Summary And Conclusions

## 7.1 Summary

Conservative data and assumptions have been used to calculate radiological consequences that bound those that could result from potential land and/or water based accidents regardless of location or scenario. The radiological consequences are well within the acceptance criteria set forth in 10CFR71.

### 7.1.1 Direct Dose Rate

The acceptance criterion for accident conditions is from 10CFR71.51(a)(2). The external radiation dose rate shall not exceed "... 10 mSv/h (1 rem/h) at 1 m (40 in) from the external surface of the package." Dose rates for 4 damage conditions have been calculated. These four (4) damage conditions bound possible accident damage to the RVTS, and in all 4 cases the dose rates are much less than 1 rem/hr at 1 meter. This is summarized below.

| Damage | Dose Rate | Reference |
|---|---|---|
| 1 inch horizontal gap around vessel at core midplane | 0.20 rem/hr | Table 6.3.4-9 |
| 1 inch by 48 inch vertical gap at core midplane | 0.16 rem/hr | Table 6.3.4-10 |
| 6 inch diameter hole through shielding | 0.10 rem/hr | Table 6.3.4-11 |
| loss of top cover plate | 0.79 rem/hr | Ref. 8.1 |

### 7.1.2 Leak Rate Into Air

The acceptance criteria for accident conditions are from 10CFR71.51(a)(2). "...there would be no escape of krypton-85 exceeding 10 $A_2$ in 1 week, no escape of other radioactive material exceeding a total amount $A_2$ in 1 week, ..."

There is no krypton-85 in the package so the krypton criterion is met regardless of accident scenario or location.

The RVTS is a monolithic package in which the radioactive material is either bound in the matrix of steel components (activation products) or is in the form of surface contamination that is fixed in place by LDCC. The activation products are not available for release, but it is conservatively assumed that <u>all</u> of the surface contamination <u>is</u> available for release. Under this assumption the total quantity of radioactive material available for release is 2.89 Ci (Section 6.2). The $A_2$ value for the releasable radioactivity is 3.59 Ci (section 6.2). Therefore the total quantity available for release is less than $A_2$ so this criterion is met regardless of accident scenario or location.

### 7.1.3 Leach Rate Into Water

The acceptance criterion for leaching is from 10CFR71.51 (a)(2):

> "... there would be no escape of krypton-85 exceeding 10 $A_2$ in 1 week and no escape of <u>other</u> radioactive material exceeding a total amount $A_2$ in 1 week." (10CFR71.51(a)(2))

The upper bound leach rate has been calculated using salt water corrosion rates. Under these conditions the total activity that could be leached out in 1 week is less than 1.76 Ci (Section 6.4). The $A_2$ value is 19.72 Ci (Section 6.1). Therefore the quantity of radioactivity that could be leached out of the package is less than $A_2$ and is well within the criterion stated above.

## 7.2 Conclusions

The radiological consequences of possible post-HAC damage from the tests and conditions specified in 10 CFR 71.73 have been conservatively calculated. It has been shown that the calculated radiological consequences are bounding and well within the criteria stated in 10 CFR 71.51.

# 8 References


8.1 Calculation N-10525-020-0002, "Transport Package Shielding Design," Rev. 1.

8.2 Not Used

8.3 Not Used

8.4 CE Drawing, F-230-791-2, "General Arrangement, Reactor Vessel," 8/17/61.

8.5 GE Drawing, 198E179, "Reactor Vessel Insulation," 1/13/61.

8.6 Not Used

8.7 GE Drawing 197E853, Rev. 2, 6/30/61.

8.8 Dwg. SD-10525-020-001, Rev. B, "RVTS Cask"

8.9 Not Used

8.10 Not Used

8.11 Not Used

8.12 Johns-Manville Drawing BL-13954-2, 4/23/62.

8.13 Not Used

8.14 MicroShield 5.05, S&L Program No. 03.7.508-5.05.

8.15 Corrosion Handbook, Uhlig, H.H. Ed., John Wiley & Sons, (Attachment B).

8.16 Not Used

8.17 Not Used

8.18 Not Used

8.19 Not Used

8.20 Not Used

8.21 Not Used

8.22 Not Used

8.23 10CFR71, App. A, "Determination of $A_1$ and $A_2$.

8.24 "Reactor Vessel Transport System Radiation Source Term," Calculation N-10525-020-004, Rev. 1.

8.25 Not Used

8.26 Not Used

8.27 10CFR71.51(a)(2), "Additional Requirements for Type B Packages."

8.28 10CFR20.1003, "Definitions."

8.29 Calculation S-10525-020-012, "Reactor Vessel Transport Cask Stress Analysis," Rev. 0, Sections 5.2 and 8.


## 9 Attachments

| | | |
|---|---|---|
| Attachment A | MicroShield Files And Listings | Pages A1 – A121 |
| Attachment B | Corrosion Handbook (Selected Pages) | Pages B1 – B3 |

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REVIEW COMMENT
Form SOP-0402-02, Revision 3B

| | | | | | |
|---|---|---|---|---|---|
| Project: | Big Rock Point Major Component Removal | | | Unit: | |
| Project No.: | 10525-041 | Calc. No. | N-10525-041-001 | Calc. Rev. | 2 |
| Calc. Title: | Breach of Containment | | | | |

| # | Comment | Resolution |
|---|---|---|
| 1 | Reference 8.29 (Calc S-10525-020-012): Calc number begins with an N instead of an S and the word "Stress" is omitted from the calculation's title. Change the N to an S and correct the title to read "Reactor Vessel Transport Cask Stress Analysis." | Incorporated |

Reviewed by: Anthony G. Klazura / Anthony G. Klazura    Date: 03/22/01

CALCULATION N-10525-041-001

REVISION 2

ATTACHMENT "A" NOT INCLUDED

ATTACHMENT B
Calc. No.: N-10525-041-001
Proj. No.: 10525-041
Rev.: 1
Page B1

# THE CORRODION HANDBOOK

*edited by*

HERBERT H. UHLIG, PH.D.

PROFESSOR OF METALLURGY IN CHARGE OF THE CORROSION LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASSACHUSETTS

*and sponsored by*

THE ELECTROCHEMICAL SOCIETY, INC.

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New York • Chichester • Brisbane • Toronto • Singapore

ATTACHMENT B
Calc. No.: N-10525-041-001
Proj. No.: 10525-041
Rev.: 1
Page B2



TABLE 2. CORROSION RATES OF VARIOUS STAINLESS STEELS IN LABORATORY TESTS AND SEA-WATER EXPOSURE*

MDD
(Mill Surface. Pitting Occurs in All Specimens Except as Noted)

| Stainless Steel | Sea-Water Immersion, 1 Year, Boston Harbor. Spec.: 7.7 × 12.8 × 0.35 cm (3 × 5 × 1/8 in.). Badly fouled at end of test. (Av. of 5 Spec.) | 4% NaCl, 90° C ± 0.1. 24-hour Immersion. Aerated: 40–75 ml air per min, 3½ L. soln. Spec.: 2.5 × 12.8 × 0.35 cm (1 × 5 × 1/8 in.). (Av. of 2 or 3 Spec.) | 10% $FeCl_3 \cdot 6H_2O$.† 4-Hour Contact, Room Temp. Area of Spec. Exposed: 5.74 sq cm (0.89 sq in.). (Av. of 2 or more spec.) |
|---|---|---|---|
| 18-8, 3% Mo | 0.013 (no pits) | 2.54 (no pits) | 2.1 (no pits) |
| 18-8: | | | |
| Manufacturer A | 2.08 | 4.83 | 570 |
| " B | 1.84 | .... | 820 |
| " C (Steckel mill, cold-rolled) | 2.76 | 28.2 | 5,620 |
| 18% Cr | 3.34 | 38.3 (1 spec.) | 6,120 |
| 18-8, 0.2% Ti | 0.78 | 4.4 | 8,540 |
| 18-8, 0.4% Ti | | 3.55 | 16,000 |
| 18-8, 0.9% Cb | | 7.45 | 4,200 |
| Mild steel (abraded #180 emery) | 18.6 (no pits) | 86.0 (no pits) | .... |

* Based on *Progress Report* 6 to Chemical Foundation, Corrosion Committee of Massachusetts Institute of Technology, 1938, and also unpublished data of the author.

† Using "Drop Tester," H. A. Smith, *Progress Report* 2 to Chemical Foundation, Corrosion Committee of Massachusetts Institute of Technology, 1936.

TABLE 3. ANALYSES OF STAINLESS STEELS IN TABLE 2

| Stainless Steel | Cr | Ni | C | Mn | Si | S | P | |
|---|---|---|---|---|---|---|---|---|
| 18-8, 3% Mo | 20.92 | 9.75 | 0.06 | 0.40 | 0.36 | 0.02 | 0.014 | 2.90% Mo |
| 18-8 | | | | | | | | |
| A | 18.75 | 10.55 | 0.06 | 0.41 | 0.41 | 0.01 | 0.009 | |
| B | 18.00 | 9.66 | 0.07 | 0.38 | 0.25 | 0.01 | 0.008 | |
| C | 18.18 | 8.20 | 0.095 | 0.45 | 0.40 | 0.02 | 0.018 | |
| (Steckel Mill) | | | | | | | | |
| 18% Cr | 17.90 | .... | 0.095 | 0.45 | 0.40 | 0.02 | 0.018 | |
| 18-8, 0.2% Ti | 17.92 | 8.97 | 0.09 | 0.48 | 0.45 | 0.01 | 0.016 | 0.2% Ti |
| 18-8, 0.4% Ti | 18.6 | 8.8 | 0.05 | 0.36 | 0.41 | 0.002 | 0.02 | 0.36% Ti |
| 18-8, 0.9% Cb | 7.98 | 9.4 | 0.07 | 0.60 | 0.65 | 0.006 | 0.02 | 0.86% Cb |

## CONTACT CORROSION

This is corrosion produced at the region of contact of usually non-metallic materials with passive metals. It is also called crevice corrosion.[10] It may occur at washers, under barnacles, sand grains or applied protective films, and at pockets formed by threaded joints. Whether or not stainless steels are free of pit nuclei, they are always susceptible to this kind of corrosion, because a nucleus is not necessary.

Contact corrosion may begin through action of an oxygen concentration cell. The accumulation of passivity-destroying corrosion products at stagnant areas soon convert the cell to a more rapidly acting passive-active cell. Corrosion then proceeds by a mechanism identical to that described above for pit growth. Contact corrosion of stainless steels is discussed further, beginning p. 155.

[10] E. H. Wyche, L. R. Voigt, and F. L. LaQue, *Trans. Electrochem. Soc.*, **89**, 149 (1946).



METHODS TO

According to theory anc
expedients are recommend
environment or the metal.

*Environment*

1. Avoid concentration o
2. Insure uniform oxyge
of stagnant liquid.
3. Either increase oxyg
capacity of the solutic
$H_2SO_4$, through whicl
of 400 mdd, but at
passive).[11] On the otl
for example in salt so
4. Increase $pH$. Apprec
compared with neutra
5. Operate at lowest te
6. Add passivators to
chromate is effectiv
examples of passiva
halogen ions should
7. Apply cathodic pro
cathodically by galv
water. (See *Behavior*

*The Alloy*

1. Homogenize. Rapidl
2. Treat final article in
for 15 to 30 min. Th
A more active pickl
It consists of 10 vol
150° F). The latter
Ventilation is impe
3. Cleanse and burnish
Alkaline cleaners a
4. Use alloy containi
added to nickel-sta
chloride solutions
eventually may oc
also appreciably m
contact or crevice

* In a study of crevice cor
cases out of 200 (48%), wher
only 11 cases out of 48 (23%
York, N. Y.)

[11] R. McKay and R. Wort
Corp., New York, 1936.
[12] F. L. LaQue, (Discussio

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TABLE 19. CONVERSION FACTORS FOR CORROSION UNITS

(Prepared by the Editor)

| *Multiply* | *by* | *to Obtain* |
|---|---|---|
| in. penetration per yr (ipy) | 696 × density | mg per sq dm per day (mdd) |
| cm penetration per yr (cmpy) | 274 × density | " |
| oz per sq ft per day | 3050 | " |
| grams per sq meter per yr | 0.0274 | " |
| grams per sq meter per day | 10 | " |
| grams per sq meter per hour | 240 | " |
| mg per sq dm per day (mdd) | 0.00144/density | in. penetration per yr (ipy) |
| cm penetration per yr (cmpy) | 0.394 | " |
| oz per sq ft per day | 4.39/density | " |
| grams per sq meter per yr | 0.0000394/density | " |
| grams per sq meter per day | 0.0144/density | " |
| grams per sq meter per hour | 0.346/density | " |

| Metal | Density (grams per cc) | $\frac{0.00144}{\text{Density}}$ | 696 × Density |
|---|---|---|---|
| Aluminum | 2.72 | 0.000529 | 1890 |
| Aluminum-magnesium-silicon (98, 0.5, 1.0) | 2.69 | 0.000535 | 1870 |
| Aluminum-manganese (99, 1) | 2.73 | 0.000528 | ·1901 |
| Aluminum-copper (duralumin) (Cu 4, Mn 0.5, Mg 0.5, Al remainder) | 2.79 | 0.000516 | 1940 |
| Brass (Admiralty) | 8.54 | 0.000168 | 5950 |
| Brass (rod) | 8.75 | 0.000164 | 6100 |
| Brass (yellow) | 8.47 | 0.000170 | 5880 |
| Bronze (10 % tin) | 8.77 | 0.000164 | 6100 |
| Bronze (18 % tin) | 8.80 | 0.000163 | 6135 |
| Bronze (phosphorus, 5% tin) | 8.86 | 0.000162 | 6170 |
| Bronze (silicon) | 8.54 | 0.000168 | 5950 |
| Bronze (manganese) (Cu 66.5, Zn 19, Al 6, Fe 4.5, Mn 4) | 7.89 | 0.000182 | 5500 |
| Cadmium | 8.65 | 0.000167 | 6020 |
| Columbium | 8.4 | 0.000171 | 5850 |
| Copper | 8.92 | 0.000161 | 6210 |
| Copper-nickel (70, 30) | 8.95 | 0.000161 | 6210 |
| Copper-nickel-zinc (75, 20, 5) | 8.86 | 0.000162 | 6170 |
| Copper-nickel-zinc (65, 18, 17) | 8.75 | 0.000164 | 6100 |
| Copper-silicon-manganese (96, 3, 1) | 8.53 | 0.000168 | 5950 |
| Copper-nickel-tin (70, 29, 1) | 8.87 | 0.000162 | 6170 |
| Iron | 7.87 | 0.000183 | 5480 |
| Iron-chromium (86–88, 12–14, 0.3 C) | 7.7 | 0.000187 | 5360 |
| Iron-chromium (82–84, 16–18, .12 C) | 7.7 | 0.000187 | 5360 |
| Iron-chromium (73–77, 23–27, .35 C) | 7.6 | 0.000189 | 5290 |
| Iron-chromium-nickel [18–8] (75–79, 17–19, 8–10, .1 C) | 7.9 | 0.000182 | 5500 |
| Iron-silicon (Duriron) (84, 14.5, 0.9 C, 0.4 Mn) | 7.0 | 0.000205 | 4870 |

CON

| Metal |
|---|
| Lead (chemical) |
| Lead (antimony) (99, 1) |
| Magnesium |
| Nickel |
| Nickel-copper (Monel) (70, 3 |
| Nickel-chromium-iron (Incoı |
| Nickel-molybdenum-iron (H: 20) |
| Silver |
| Tantalum |
| Tin |
| Zinc |