Preliminary Report:

Bases for Containment Analysis for Transportation of Aluminum-Based Spent Nuclear Fuel

Savannah River Technology Center Strategic Materials Technology Department Materials Technology Section

Publication Date: October 1998

UNCLASSIFIED DOES NOT CONTAIN UNCLASSIFIED CONTROLLED NUCLEAR INFORMATION

ADC & Reviewing Til.Comber Official: 10/2/198

Date:

Westinghouse Savannah River Company Savannah River Site **Aiken, SC 29808**

This document was prepared in connection with work done under Contract No. DE-AC09-96SR18500 with the U.S. Department of Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DOCUMENT: WSRC-TR-98-00317

 TITLE:
 PRELIMINARY REPORT: BASES FOR CONTAINMENT ANALYSIS

 OF TRANSPORTATION OF ALUMINUM-BASED SPENT NUCLEAR
 FUEL

APPROVALS

D. W. Vinson, Author

SRTC-MATERIALS TECHNOLOGY SECTION

Blanton

P. S. Blanton, Author SRTC-ENGINEERING DEVELOPMENT SECTION

ZAidela

R.L. Sindelar, Author SRTC-MATERIALS TECHNOLOGY SECTION

N.C. Iyer, Author U SRTC-MATERIALS TECHNOLOGY SECTION

. Vlacock X

H. B. Peacock, Jr., Technical Review SRTC-MATERIALS TECHNOLOGY SECTION

I ch Conolita

T. L. Capeletti, Manager SRTC-MATERIALS TECHNOLOGY SECTION

Ray Stwank

R. J. Skwarek, Manager Engineering Department SPENT FUEL STORAGE DIVISION

Date: 10/16/98

Date: 10/16/98

Date: 10/16/98

Date: 10/16/98

Date: 10/21/98

Date: 10/21/98

Date: 10/21/98

Table of Contents

| 1.0 | 0 | SUMMARY | 1 |
|-----|------------------------|--|-----------|
| 2.0 | 0 | INTRODUCTION AND BACKGROUND | 3 |
| 3.0 | 0 | METALLURGY OF ALUMINUM-BASED SPENT NUCLEAR FUEL | 4 |
| 4.(| 0 | OVERVIEW OF CONTAINMENT ANALYSIS OF SHIPPING CASK | 7 |
| | 4.1 | Approach | 7 |
| | 4.2 | RADIONUCLIDE INVENTORY | 7 |
| | 4.3 | EXAMPLE CONTAINMENT ANALYSIS | 7 |
| | 4. | 3.1 Calculation of Permissible Leakage Rates | 7 |
| | 4. | 3.2 Activity Density Determination | 9 |
| | 4. | 3.3 Activity Values for Radionuclides | 11 |
| | 4. | 3.4 Determination of the Maximum Permissible Leakage Rate | 11 |
| | 4. | 3.5 Maximum Permissible Leakage Rate at Standard Conditions | 12 |
| 5.(| 0 | BASES FOR INPUT/ASSUMPTIONS FOR AL-SNF | 14 |
| | 5.1 | BASIS FOR DAMAGED FUEL FRACTION AND EXPOSED SURFACE AREA | 14 |
| | 5. | 1.1 Pitting and General Corrosion of Al-SNF in Basin Storage | 14 |
| | 5. | 1.2 Basis for Through-clad Pitting Criteria for Corrosion Nodules | 17 |
| | 5. | 1.3 Bases for the Damaged Fuel Fraction and Exposed Surface Area | 17 |
| | 5.2 | BASIS FOR RELEASE OF FINES FROM EXPOSED FUEL MEAT | 18 |
| | 5.3 | GASEOUS AND VOLATILE SPECIE RELEASE CHARACTERISTICS OF OXIDES ON AL-SINF – BASIS | 20 |
| | 5 | 3.1 Cas Palaasa | 20 |
| | 5 | 3.2 Volatile Release | 20 |
| | 5.4 | BASIS FOR CRUD SOURCE TERM | 22 |
| | . | | |
| 6.0 | J | SENSITIVITY OF VOLUMETRIC LEAKAGE RATE AT STANDARD CONDITIONS TO ASSUMED FUEL CONDITION | 24 |
| | | | |
| | 6.1 | DEPENDENCE ON FUEL BURNUP | 24 |
| | 6.2 | DEPENDENCE ON THE NUMBER OF ASSEMBLIES | 24 |
| | 6.3 | DEPENDENCE ON DECAY TIME | 25 |
| | 0. 4 6 5 | DEPENDENCE ON BREACHED FUEL FRACTION | 20 |
| | 6.5 | 5.1 Dependence on Penetration Depth | 27 |
| | 6. | 5.2 Dependence on Fraction of Surface Area with Through-Clad Penetration | 28 |
| | 6.6 | DEPENDENCE ON CRUD | 29 |
| | 6.7 | DEPENDENCE ON VOLATILE SPECIE | 29 |
| | 6.8 | DEPENDENCE ON GAS | 30 |
| 7.0 | D | LIST OF SYMBOLS | 31 |
| 8.0 | 0 | REFERENCES | 33 |
| | Δ | EVANDLE CALCULATION #1 | |
| A. | U A 1 | EXAMPLE CALCULATION #1 | AI |
| | A.I | GAS CALCULATIONS. | Al |
| | A | 1.1 ACUVILY VALUES FOR GASES | AI |
| | | VOI ATH E CALCHI ATIONS | ۸1. ۸2 |
| | п.2 А | 2.1 Activity Values for Volatiles. | |
| | A | .2.2 Activity Density of Volatiles | A3 |

| A.3 Fini | ES CALCULATIONS | A3 |
|----------|---|-----|
| A.3.1 | Activity Values for Fines | A3 |
| A.3.2 | Activity Density of Fines | A5 |
| A.4 Cru | JD CALCULATIONS | A5 |
| A.5 COM | ABINING THE SOURCES OF RADIOACTIVE MATERIAL IN THE CASK FREE VOLUME | A6 |
| A.6 MA | XIMUM PERMISSIBLE RELEASE RATE AND MAXIMUM PERMISSIBLE LEAKAGE RATE | A7 |
| A.7 Per | MISSIBLE LEAK RATE AT STANDARD CONDITIONS | A8 |
| A.7.1 | Normal Conditions of Transport | A8 |
| A.7.2 | Accident Conditions of Transport | A10 |
| RA FY | ΑΜΡΙ Ε CALCULATION #2 | ۸12 |
| D.U LA | AMI LE CALCULATION #2 | A12 |
| B.1 GAS | CALCULATIONS | A12 |
| B.1.1 | Activity Values for Gases | A12 |
| B.1.2 | Activity Density of Gases | A12 |
| B.2 VOI | ATILE CALCULATIONS | A13 |
| B.2.1 | Activity Values for Volatiles | A13 |
| B.2.2 | Activity Density of Volatiles | A14 |
| B.3 Fini | ES CALCULATIONS | A14 |
| B.3.1 | Activity Values for Fines | A14 |
| B.3.2 | Activity Density of Fines | A16 |
| B.4 Cru | ID CALCULATIONS | A16 |
| B.5 COM | IBINING THE SOURCES OF RADIOACTIVE MATERIAL IN THE CASK FREE VOLUME | A17 |
| B.6 MA | XIMUM PERMISSIBLE RELEASE RATE AND MAXIMUM PERMISSIBLE LEAKAGE RATE | A18 |
| B.7 Per | MISSIBLE LEAK RATE AT STANDARD CONDITIONS | A19 |
| B.7.1 | Normal Conditions of Transport | |
| B.7.2 | Accident Conditions of Transport | A21 |

1.0 SUMMARY

Aluminum-based spent nuclear fuel (Al-SNF) from foreign and domestic research reactors (FRR/DRR) is being shipped to SRS under the site FRR/DRR Receipts Program. Shipment of the FRR/DRR assemblies requires that the cask with loaded fuel be certified by the U. S. Nuclear Regulatory Commission (for U. S.-owned casks) or the U. S. Department of Transportation (for foreign-owned casks) to comply with the requirements in 10CFR71 [1].

A typical containment analysis has been prepared to support the transportation of aluminumbased spent nuclear fuel (Al-SNF) from research reactor sites to the Savannah River Site in standard fuel shipping casks. Calculations for the analysis were performed in accordance with the methodology provided in ANSI N14.5 [2] and adopted by the U. S. Nuclear Regulatory Commission in NUREG/CR-6487 [3] to meet the requirements of 10CFR71 [1]. The technical bases for the inputs and assumptions were developed by evaluating the characteristics of Al-SNF received from basin and dry storage systems and its subsequent performance under normal and postulated accident shipping conditions.

The results of the calculations, including those with representative inputs and assumptions, show that Al-SNF with minor cladding breaches can be transported in standard shipping casks and maintained within the allowable release rates under normal and accident conditions. The limiting standard leakage rate, L_R , i.e. the limiting allowable leak rate at standard conditions, is 8.99×10^{-5} std•cm³/sec for Example Cask #1. The cask is assumed to be fully loaded with a total of 42 fuel assemblies (Example Fuel #1), a small fraction of which have minor cladding breaches. The assumed test leakage rate of 1.0×10^{-6} atm•cm³/sec for this cask [4] is within L_R . The limiting standard leakage rate for Example Cask #2, fully-loaded with a total of 33 fuel assemblies (Example Fuel #2), of which a small fraction have minor cladding breaches, show that the limiting reference leakage rate is 1.09×10^{-4} std•cm³/sec. The assumed test leakage rate of 1.0×10^{-4} atm•cm³/sec for this cask [5] is within L_R . Thus, the containment requirements of 10 CFR71 would be met for both example casks. Details of the example calculations inputs assumptions along with the results are presented in this report.

A sensitivity analysis has been conducted to evaluate the effects of modifying assumptions and to assess options for fuel at conditions that are not bounded by the present analysis. These options would include one or more of the following: reduce the fuel loading; increase fuel cool time; reduce the degree of conservatism in the bounding assumptions; or measure the actual leak rate of the cask and seal system. That is, containment analysis for alternative inputs at fuel-specific conditions and at cask-loading-specific conditions could be performed to demonstrate that release is within the allowable leak rates.

As part of the sensitivity analysis, the limit for total exposed fuel surface area in Example Cask #1 has also been determined. The limit is given for the conditions of cask free volume with Example Fuel #1 fully loaded (i.e., 42 assemblies) in the cask. The figure below shows the results for the total exposed fuel surface area as a function of the leakage rate of the cask. For example, if the leak rate of the cask is 1×10^{-5} std cm³/s or less, the cask can be fully loaded with breached fuel and that the total exposed surface area can be at least 250 cm².



Figure 1 Exposed Surface Area Limit per Cask as a Function of Cask Leakage Rate and Number of Breached Assemblies.

The conservative assumptions and analysis presented in this report are intended to serve as examples and will be refined as additional SNF characterization data is developed. Further, the analysis presented herein only serve as an example to define the baseline fuel characteristics that may be used for containment analysis. It is anticipated that the cask vendors will use fuel-specific conditions in cases where the fuel is not bounded by the above assumptions.

2.0 INTRODUCTION AND BACKGROUND

Foreign and domestic research reactor spent nuclear fuel is being shipped to SRS under the site FRR/DRR Receipts Program. The cladding of a small percentage of this fuel has been breached due to corrosion or mechanical damage [6]. Recommended criteria for acceptance of aluminum-based spent nuclear fuel (Al-SNF) for direct storage in the SRS basins, is provided in Reference 7. Fuel with minor breaches can be directly stored in the SRS basins because of the expected low release levels of radioactivity from the fuel [8].

The broad-based criteria for acceptance of the fuel [7] includes that transportation of the fuel must comply with all Certificate of Compliance (COC) conditions for the U. S. shipping casks and Certificate of Competent Authority (CoCA) for the foreign casks. Specifically, to enter the United States, the cask needs to comply with the U. S. Code of Federal Regulations (CFRs). The requirements for transportation, contained in 10CFR71 [1], include demonstration of containment under normal and accident conditions. The NRC recognizes ANSI N14.5 [2] as an approved methodology to perform the analyses for containment. Sample calculations of containment analyses for transportation are given in NUREG/CR-6487 [3], which used ANSI N14.5 methodology.

The inputs and assumptions for commercial spent nuclear fuel are not, in general, applicable to research reactor fuel. This present document develops the bases for the assumptions and inputs that are applicable to containment analysis for shipping Al-SNF. Example calculations using the methodology of NUREG/CR-6487 is provided in this report for two fully-loaded reference casks. A key element of the containment analysis, namely the calculation of the source term for the fuel, is also presented in this report.

The following source terms for containment analyses of Al-SNF during shipping are evaluated in this report:

- Fuel Fines;
- Gaseous Fission Product Species;
- Volatile Fission Product Species; and
- Fuel Assembly Crud (activity associated with the oxide layer of the cladding material).

Information from cask Safety Analysis Reports (SARs) and other technical information from the literature and SRS testing and analysis results are applied to develop the bases for the assumptions and inputs.

3.0 METALLURGY OF ALUMINUM-BASED SPENT NUCLEAR FUEL

A majority of the aluminum-based spent nuclear fuel (Al-SNF) contains highly enriched uranium (HEU) with up to 93% enrichment. The Materials Test Reactor (MTR) design assembly, which is comprised of fuel elements or plates of aluminum-clad, aluminum-based fuel, is the dominant design (approximately 80% of total) for research reactors. The MTR type of fuel design is used in the majority of research reactors. The range of thermal powers of these reactors is from 1 MW to 50 MW. Figure 2 and Figure 3 show typical fuel elements with the MTR design. The number of fuel plates in an element varies between 6 and 23, and the initial ²³⁵U content varies between 37 g and 420 g per element. Similarly, the average burnup of a discharged spent nuclear fuel is between 15 and 76 percent. The initial uranium enrichment used for this type of fuel varies from just below 20 percent to 95 percent. The cooling times in a basin also vary from 1+ years to >20 years.

The aluminum-based fuel material is characterized as a dispersion of uranium compounds in an aluminum matrix. The dominant aluminum-based fuel material is uranium-aluminum alloy, U-Al alloy, or aluminum-uranium aluminide material (UAl_x-Al), both of which contain particles of UAl_x as dispersoids in the aluminum matrix. In addition, some reactor fuel assemblies were fabricated from aluminum-uranium silicide material (U_3Si_2 -Al) or aluminum-uranium oxide material (U_3O_8 -Al), which contain particles of U_3Si_2 and U_3O_8 , respectively as dispersoids in the aluminum matrix. The fuel elements are clad with one of the aluminum alloys 1100, 5052, or 6061 or their foreign equivalents. Metallurgical bonding between the clad and the fuel meat is achieved through high temperature rolling or extrusion. The initial structure of the U-Al alloy fuel is shown in Figure 4. The fuel meat consists of a dispersion of UAl_x particles in a matrix of aluminum alloy. The dispersoids are irregular or faceted and are typically oriented in the extrusion or rolling direction.

A photomicrograph of the irradiated UAl_x -Al fuel at high burnup is shown in Figure 5. During irradiation, centerline temperatures of up to ~200°C can occur which enhances diffusion of uranium and aluminum in the fuel meat. For these fuels, limited reaction occurs at the particle-matrix boundary because of the thermodynamic stability of the aluminide phase present in the fuel as shown in Figure 5. A full metallurgical bond is retained at the clad/fuel meat interface throughout the irradiation exposure. In comparison to commercial fuel, the irradiated fuel microstructure is typically devoid of cracks and fissures and the fuel retains significant ductility.

Spent nuclear fuel from commercial reactors is characterized as pellets of UO_2 with an annular gap between the fuel pellets and the zircaloy cladding. Upon irradiation, the UO_2 pellets swell resulting in cracks and fissures of the pellet. Further, the annual gap between the pellet and the cladding is reduced and/or constricted due to pellet swelling.

The significant differences in the characteristics of Al-SNF and commercial fuel including the fuel materials, microstructure, mechanical properties, fabrication techniques and irradiation performance make it obvious that the assumptions for containment analysis for commercial fuel are in general not directly applicable to the Al-SNF.



Figure 2 Typical (Boxed-Type/Flat-Plate) Aluminum-Based Fuel Element Schematic



Figure 3 Typical (Boxed-Type/Curved-Plate) Aluminum-Based Fuel Element Schematic



Figure 4(a) Aluminum-18 wt% Uranium Alloy in Longitudinal Direction (500X)(b) Aluminum-18 wt% Uranium Alloy in Transverse Direction (500X)



Figure 5 High Burnup UAl_x-Al Fuel Irradiated in Research and Test Reactors (100X)

4.0 OVERVIEW OF CONTAINMENT ANALYSIS OF SHIPPING CASK

An overview of the analysis method for containment of Al-SNF in shipping casks is provided in this section. Appendix A to this report is the spreadsheet calculation set of the two cases, Example Fuel #1 in Example Cask #1 and Example Fuel #2 in Example Cask #2. The analysis is performed as described below.

4.1 Approach

The calculations follow NUREG/CR-6487 [3], which adopts ANSI N14.5 [2] as a methodology for containment analysis. An overview of the calculations to determine the radionuclide inventory of Example Fuel #1 at 1-year cooling and Example Fuel #2 at 2-years cooling is given in Section 4.2. An overview of the calculations for the containment analysis is given in Section 4.3. Appendices A & B contain the full set of sample calculations and results of the analyses.

4.2 Radionuclide Inventory

A radionuclide production/depletion analysis was performed to estimate the fuel-specific activity. The following sections summarize the assumptions and input to the analysis.

Determination of the isotopic content of the spent fuel is made through use of the SAS2h module of SCALE4.3. SAS2h is a coupled one-dimensional depletion and shielding analysis module. This module generates tables containing the concentrations of the individual isotopes produced by the exposure received in reactor service and by the radioactive decay. The table of curie concentrations is used in the containment analysis as described later. Execution of the SAS2h module requires only basic data. These data include:

- the specific power, exposure time and shutdown time of the fuel assembly in each appropriate cycle of the reactor history;
- the material densities of the fresh-fuel assembly;
- the material temperatures; and
- the material zone dimensions, including active fuel width, thickness, and length, pitch, clad thickness, total fuel volume, and number of plates per assembly.

The assumptions used for SAS2h input are provided on a per assembly basis in Table 1.

4.3 Example Containment Analysis

The following describes the containment analysis. The complete set of results is provided in the appendices to this report. Input for the analysis was provided in the respective SARs for the casks and from technically-based assumptions developed in Section 5.

4.3.1 Calculation of Permissible Leakage Rates

The containment criterion for Type B packages requires that a package have a radioactive release rate less than A_2x10^{-6} in one hour and A_2 per week under normal conditions of transport and for accident conditions, respectively. The parameter A_2 has units of curies (Ci) and is isotope dependent. A_2 is calculated from the isotopic curie concentration in the fuel as determined through use of the SAS2h module of SCALE4.3 (see Section 4.2). The assumed release fractions for the various radionuclides transported in a Type B package is summarized in Table 2.

| Parameter | Example Fuel #1 | Example Fuel #2 |
|----------------------------|--------------------|--------------------|
| Specific Power [MW] | 1.07 | 1.472 |
| Burn Time [days] | 197 | 125 |
| Cool Time [days] | 365.25 | 730.5 |
| Moderator | D ₂ O | D_2O |
| Moderator Temperature [K] | 325 | 325 |
| Clad Temperature [K] | 446 | 446 |
| Fuel Temperature [K] | 447 | 447 |
| Active Meat Thickness [cm] | 0.058 | 0.051 |
| Active Meat Width [cm] | 5.715 | 6.71 |
| Active Meat Length [cm] | 57.79 | 60 |
| Number of Plates | 18 | 23 |
| Clad Thickness [cm] | 0.035 | 0.038 |
| Pitch [cm] | 0.381 | 0.345 |
| Fuel Material Masses [g] | | |
| U-235 | 351.00 | 450.00 |
| U-238 | 26.42 | 33.87 |
| 0 | 68.46 | 87.77 |
| Al | 668.82 | 857.47 |

Table 1Input Assumptions for SAS2h

 Table 2
 Data Summary of Inputs to Example Release Calculations

| Parameter | Normal Conditions of Transport | Hypothetical Accident Conditions |
|---|-----------------------------------|---|
| Fraction of Breached Fuel in a Cask, f _b | 0.10 | 1.00 |
| This is the fraction of assemblies in a cask that | | |
| fuel surface area exposure. | | |
| Fission Gas Release Fraction, f _G | 0.30 | 1.00 |
| Volatile Release Fraction, f _V | 1E-06 | 1E-06 |
| Amount of Meat Surface Area Exposed, ESA. | 1% of outside plates | 1% of outside plates |
| This can be applied on a per assembly or a per | (e.g., 27.8 cm^2 for | $(e.g., 27.8 \text{ cm}^2 \text{ for})$ |
| cask basis. | Example Cask #1) | Example Cask #1) |
| Fraction of Fuel Meat Corrosion Product Layer | 0.15 | 1.00 |
| Released due to Spallation, T _F | | |
| Crud Spallation Fraction, f _C | 0.15 | 1.00 |

Assuming that the release rate is independent of time, the maximum permissible release rates for normal (R_N) and accident (R_A) conditions of transport, respectively, can be expressed as follows:

$$\begin{aligned} R_{\rm N} &= L_{\rm N} C_{\rm N} \leq A_{2,{\rm N}} \ge 2.78 \pm 10^{-10} \text{/second,} \\ R_{\rm A} &= L_{\rm A} C_{\rm A} \leq A_{2,{\rm A}} \ge 1.65 \pm 10^{-6} \text{/second,} \end{aligned} \tag{Eq. 1} \end{aligned}$$

where:

- R_i is the release rate for normal (R_N) and accident (R_A) conditions of transport [Ci/s],
- L_i is the volumetric gas leakage rate [cm³/s] under normal (L_N) and accident (L_A) conditions of transport,
- C_i is the curies per unit volume of the radioactive material, "activity density", that passes through the leak path for normal (C_N) and accident (C_A) conditions of transport [Ci/cm³], and
- $A_{2,i}$ is the mixture A_2 of the radionuclides available for release under normal $A_{2,N}$ and $A_{2,A}$ accident conditions of transport [Ci].

Additionally, for accident conditions, an effective A_2 value equal to $10 \cdot A_2$ may be used for krypton-85.

4.3.2 Activity Density Determination

There are four sources of radioactive material that may become airborne during transportation. These sources are gases, volatiles, fines, and crud. The contributions to the total activity density in the shipping cask free volume from the four sources are treated separately as follows.

$$C_{\text{total}} = C_{\text{gas}} + C_{\text{vol}} + C_{\text{fines}} + C_{\text{crud}}, \tag{Eq. 3}$$

where:

- C_{total} is the total releasable activity density inside the containment vessel [Ci/cm³],
- C_{gas} is the releasable activity density inside the containment vessel due to the release of gas [Ci/cm³],
- C_{vol} is the releasable activity density inside the containment vessel due to the release of volatiles [Ci/cm³],
- C_{fines} is the releasable activity density inside the containment vessel due to the release of fines [Ci/cm³], and
- C_{crud} is the releasable activity density inside the containment vessel as a result of crud spallation [Ci/cm³].

The releasable activity density $[Ci/cm^3]$ inside the containment vessel due to the release of gas may be described by either Eq. 4or Eq. 5.

$$C_{gas} = (A_G \bullet f_b \bullet f_G) / V_C, \qquad (Eq. 4)$$

$$C_{gas} = (A_{gb} \bullet N_b \bullet f_G) / V_C, \qquad (Eq. 5)$$

where:

- A_G is the total number of curies of all gaseous radionuclides in all assemblies in the cask. It is the product of the number of assemblies and the number of curies of all gaseous isotopes per assembly (i.e., as output by ORIGEN-S) [Ci],
- f_b is the fraction of fuel assemblies that are breached in a cask [$f_{b,N}=0.1$, $f_{b,A}=1.0$],
- f_G is the fraction of gas that escapes the breached fuel assembly [$f_{G,N}=0.3, f_{G,A}=1.0$],
- V_C is the free volume of the cask [cm³],
- A_{gb} is the number of curies of all gaseous radionuclides in a single breached assembly (i.e., as output by ORIGEN-S) [Ci], and
- N_b is the number of breached fuel assemblies in cask.

The releasable activity density [Ci/cm³] inside the containment vessel due to the release of volatiles may be described by either Eq. 6 or Eq. 7.

$$C_{vol} = (A_V \bullet f_b \bullet f_V) / V_C, \qquad (Eq. 6)$$

$$C_{vol} = (A_{vb} \bullet N_b \bullet f_V) / V_C, \qquad (Eq. 7)$$

where:

- A_V is the total number of curies of all volatile radionuclides in all assemblies in the cask.
 It is the product of the number of assemblies and the number of curies of all volatile isotopes per assembly (i.e., as output by ORIGEN-S) [Ci],
- f_b is the fraction of fuel assemblies that are breached in a cask $[f_{b,N}=0.1, f_{b,A}=1.0],$
- f_V is the fraction of gas that escapes the breached fuel assembly [$f_{V,N}=f_{V,A}=1E-6$],
- $V_{\rm C}$ is the free volume of the cask [cm³],
- A_{vb} is the number of curies of all volatile radionuclides in a single breached assembly (i.e., as output by ORIGEN-S) [Ci], and
- N_b is the number of breached fuel assemblies in cask.

The releasable activity density [Ci/cm³] inside the containment vessel due to the release of fines is described by Eq. 8.

$$C_{\text{fines}} = (A_F \bullet ESA \bullet P \bullet T_F / V_M) \bullet (1/V_C), \qquad (Eq. 8)$$

where:

- A_F is the total number of curies of all radionuclides in all assemblies in the cask (excluding gases). It is the product of the number of assemblies and the number of curies of the all isotopes (excluding gases) per assembly (i.e., as output by ORIGEN-S) [Ci],
- ESA is the amount of exposed meat surface area per cask [cm²/cask],
- P is the depth of corrosion attack [5.E-04-cm],
- T_F is the oxide spallation fraction [$T_{F,N}$ =0.15, $T_{F,A}$ =1.0],
- V_M is the volume of the meat region of the fuel per cask [cm³/cask], and
- V_C is the free volume of the cask [cm³].

The releasable activity density [Ci/cm³] inside the containment vessel as a result of crud spallation is described by Eq. 9.

$$C_{\text{crud}} = (f_{\text{C}} \bullet S_{\text{C}} \bullet S_{\text{A}}) / V_{\text{C}}, \tag{Eq. 9}$$

where:

- f_C is the crud spallation fraction [$f_{C,N}$ =0.15, $f_{C,A}$ =1.0],
- S_C is the crud surface activity [1.39E-7 Ci/cm²],
- S_A is the sum of the surface areas of all assemblies [cm²], and
- V_C is the free volume of the cask [cm³].

The free volumes inside the containment vessel for Example Cask #1 and Example Cask #2 are assumed equal to 2.239×10^5 cm³ and 2.27×10^5 cm³, respectively. A total of 42 and 33 assemblies are assumed to be loaded in Example Cask #1 and Example Cask #2, respectively.

4.3.3 Activity Values for Radionuclides

 A_2 values for the fuel gases, volatiles, fines, and crud are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

$$A_2 = (\sum (R_i / A_{2i}))^{-1},$$
 (Eq. 10)

where:

R_i is the fraction activity of nuclide *i* in the mixture and

 A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by Eq. 10 for gases, volatiles, fines, and crud. These mixture A_2 values are then combined using Eq. 11 to obtain a total cask mixture A_2 .

$$A_2 = (\sum (F_i / A_{2i}))^{-1},$$
 (Eq. 11)

where:

- F_i is the fraction activity density of contributor *i* (i.e., gas, volatiles, fines, or crud) in the mixture and
- A_{2i} is the appropriate A_2 value for mixture *i* [Ci].

4.3.4 Determination of the Maximum Permissible Leakage Rate

The maximum permissible leak rate is calculated by using the solutions to Eq. 11 and Eq. 3 and solving for L_i in Eq. 1 and Eq. 2 at normal conditions of transport and accident conditions of transport, respectively. The values of these parameters are provided in the Tables 6 and 7 for normal conditions of transport and accident conditions, respectively.

 Table 3
 Maximum Permissible Leakage Rates for Normal Conditions of Transport

| Cask | C _{gas} [Ci/cm ³] | C _{vol} [Ci/cm ³] | C _{fines} [Ci/cm ³] | C _{crud} [Ci/cm ³] | C _{total} [Ci/cm ³] | A ₂ [Ci] | L _N [cm ³ /s] |
|-------|---|---|---|--|---|------------------------|--|
| Ex #1 | 3.69E-4 | 5.80E-8 | 5.96E-7 | 8.21E-8 | 3.70E-4 | 1.33E+2 | 9.97E-5 |
| Ex #2 | 2.34E-4 | 2.36E-8 | 1.65E-7 | 9.45E-8 | 2.34E-4 | 1.58E+2 | 1.87E-4 |

| Table 4 | Maximum Permissible Leakage Rates for Hypothetical Accident Co | nditions |
|---------|--|----------|
| | 8 1 | |

| Cask | C _{gas} [Ci/cm ³] | C _{vol} [Ci/cm ³] | C _{fines} [Ci/cm ³] | C _{crud} [Ci/cm ³] | C _{total} [Ci/cm ³] | A ₂ [Ci] | L _A [cm ³ /s] |
|-------|---|---|---|--|---|------------------------|--|
| Ex #1 | 1.23E-2 | 5.80E-7 | 3.97E-5 | 5.47E-7 | 1.23E-2 | 1.00E+2 | 1.34E-2 |
| Ex #2 | 7.79E-3 | 2.36E-7 | 1.10E-5 | 6.30E-7 | 7.80E-3 | 1.57E+2 | 3.32E-2 |

4.3.5 Maximum Permissible Leakage Rate at Standard Conditions

The volumetric gas leak rate is modeled as a combination of continuum and molecular flow through a single leak path. The leak path is modeled as a smooth, right-circular cylinder with sharp edges. Based on these assumptions, the equation for gas leaking from the cask takes the following form.

$$\mathbf{L} = \mathbf{L}_{\mathrm{c}} + \mathbf{L}_{\mathrm{m}},\tag{Eq. 12}$$

where:

- L is the volumetric gas flow rate at P_u [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec], and
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].

The volumetric flow rate, L_c, for continuum flow is given by

$$L_{c} = \left[(2.49 \times 10^{6} \text{ D}^{4}) / a \mu \right] \bullet \left(P_{u} - P_{d} \right) \left(P_{a} / P_{u} \right) = F_{c} (P_{u} - P_{d}) \left(P_{a} / P_{u} \right),$$
(Eq. 13)

where:

- F_c is the continuum flow coefficient [cm³/s],
- D is the capillary diameter [cm],
- a is the capillary length [cm] (typically found in the SAR of a given cask),
- μ is the fluid viscosity [cP] (typically found in CRC Handbook),
- P_u is the upstream pressure [atm] (typically found in the SAR of a given cask),
- P_d is the downstream pressure [atm], and
- P_a is the average pressure, $(P_u P_d)/2$ [atm].

The volumetric flow rate, L_m, for molecular flow is given by

$$L_{m} = \left[(3.81 \times 10^{3} D^{3} (T/M)^{0.5}) / a P_{a} \right] \bullet (P_{u} - P_{d}) (P_{a}/P_{u}) = F_{m} (P_{u} - P_{d}) (P_{a}/P_{u}), \quad (Eq. 14)$$

where:

- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- F_m is the molecular flow coefficient [cm³/atm•s],
- D is the capillary diameter [cm],
- T is the gas temperature [K] (typically found in the SAR of a given cask),
- M is the gas molecular weight [g/mole] (typically found in CRC Handbook),
- a is the capillary length [cm] (typically found in the SAR of a given cask),
- P_a is the average pressure, $(P_u P_d)/2$ [atm],
- P_u is the upstream pressure [atm], and
- P_d is the downstream pressure [atm].

The volumetric flow rates described above are flow rates at the upstream pressure.

To correlate the maximum permissible leak rates as summarized in Table 3 and Table 4 to the leak rate at standard temperature and pressure, Eq. 12 is solved for the capillary diameter (see Eq. 13 and Eq. 14) at the expected environmental conditions. The resulting diameter is then used in Eq. 12 with the temperature equal to 298-K, the upstream and downstream pressures equal to 1.0

atm and 0.01 atm, respectively, and the gas molecular weight and viscosity equal to that of dry air at standard temperature and pressure. The assumptions used in this conversion and the resulting standard leak rates are provided in the following table.

| | Normal C | onditions | Accident Conditions | |
|---|--------------------|--------------------|----------------------------|--------------------|
| Parameter | Example Cask #1 | Example Cask #2 | Example Cask #1 | Example Cask #2 |
| Backfill Gas | He | He | He | He |
| Capillary Length [cm] | 1.0 | 0.6 | 1.0 | 0.6 |
| Gas Temperature [K] | 474 | 438 | 574 | 459 |
| Upstream Pressure [atm] | 1.99 | 2.694 | 11.4 | 5.803 |
| Downstream Pressure [atm] | 1.00 | 1.00 | 1.00 | 1.00 |
| L _R [std cm ³ /sec] | 8.99E-5 | 1.09E-4 | 2.08E-3 | 8.66E-3 |

 Table 5
 Correlation of Maximum Permissible Leakage Rates to Standard Leakage Rates

5.0 BASES FOR INPUT/ASSUMPTIONS FOR AL-SNF

The condition of the Al-SNF in basin or dry storage prior to shipment is presented in Section 5.1. This as-received condition has been used as the baseline or initial condition for the performance of the fuel during transportation. The initial condition, plus the change in fuel condition postulated during extreme conditions during transportation, forms the basis for the contributions of fines, gases, volatiles, and crud as discussed in Sections 5.2, 5.3, and 5.4. The conditions represented in this report bound the majority of the fuels. For fuel that is not bounded by the assumptions, it is anticipated that the cask vendors will use the fuel-specific conditions for their analysis.

5.1 Basis for Damaged Fuel Fraction and Exposed Surface Area

Most of the SNF assemblies from research reactors are being stored in water-filled basins in the U.S. and around the world. Some of this fuel has been in water storage for longer than 35 years and the water quality, in several cases, has been aggressive to cause corrosion during some portion of this storage time. This has resulted in pitting corrosion of some of the fuel assemblies. The corrosion process results in nodular white corrosion products on the cladding surfaces of the fuel elements of the assemblies. This product can be readily observed by visual inspection of the fuel while still in the basins. Storage of fuel in a dry condition can not cause further damage unless water enters the dry storage system.

5.1.1 Pitting and General Corrosion of Al-SNF in Basin Storage

During reactor operation, the aluminum cladding on aluminum-based fuel develops an aluminum oxide coating, ranging from a few angstroms to several tens of μ m in thickness, depending on the conditions of irradiation. The aluminum-clad fuel plates may appear grayish or off-white in color, which is due to the presence of oxide film that is protective against corrosion [9]. The aluminum oxide films are very tenacious and resistant to spallation. However, fuel handling can cause scratches in the coating, resulting in breach of the oxide and provide sites susceptible to initiation of pitting corrosion [9]. If the water chemistry is aggressive, pitting can occur. Laboratory corrosion testing has established the role of water chemistry and conductivity on pitting initiation of aluminum alloys [10].

The external surfaces of the rectangular shaped MTR fuel assembly is readily visible for inspection as the assembly is brought to within a few feet of the water surface. The two external fuel plates are the most visible and important surface areas of the visual inspection (see Figure 2 and Figure 6). The top edges of the internal fuel plates are visible from above the surface of the water. The two external surfaces are considered to be a conservative representation of the condition of the non-visible surfaces of the fuel assembly because:

- a) Pitting corrosion is initiated when the oxide surface is breached [9]. The external plates, which surround the interior fuel plates, are most susceptible to scratches in the protective oxide coating formed during irradiation of the fuel element, resulting in a higher probably of pitting corrosion than on the interior fuel plates,
- b) Impurities in the water can plate out or deposit on the aluminum to form localized anodic/cathodic sites have direct access to the external plates, whereas flow to the interior plates is lower and somewhat restricted by the geometry.
- c) The external plates are the contact points for a galvanic couple between stainless steel or other dissimilar-metal storage racks and aluminum with corrosion currents highest at these

contact locations. Corrosion currents are lower on the interior plates, not only because they are further away from the contact points, but also because the current does not readily flow around a corner [11].



Figure 6 MTR Assembly Free of Corrosion Damage

Numerous field assessments confirm the above hypothesis. A non-irradiated MTR type fuel stored in stainless steel storage racks at the IPEN IEA-R1 Research Reactor in Brazil has shown pitting corrosion only on external fuel plates. The staff at the IPEN IEA-R1 stated that this assembly was disassembled and reassembled showed no nodular pitting on the internal plate surfaces. This has been documented in an internal IPEN report [12]. Additionally, the results of an analysis of the release of radioactivity from the IEA-R1 assemblies directly correlated to the exposed fuel meat area on the external plate surface [8]. Further SRS plant experience with production Al-U fuel and Al clad depleted U core targets also confirm that the inner fuel or target element is corrosion free even under the extreme conditions where the outer fuel or target may have had significant corrosion. Figure 7 shows an extremely corroded Al clad depleted U core outer target in comparison to corrosion free inner target. It should be noted that the extreme corrosion on the outer clad target is due to the corrosion characteristics of depleted uranium and is being presented here only to graphically show the difference in corrosion characteristics where, in the worst case, is shown in Figure 8.

Corrosion products located outside the fuel meat region of the assembly (side plates, end fittings and extremities of the fuel plates) have no potential for the release of fission products, because these locations contain no active fuel meat.



Figure 7 Mk-31 Outer and Inner Target Tubes. The tubes are aluminumclad uranium metal. (from J. Howell Data)

The corrosion potential and corrosion rate of fuel meat material is similar to that of aluminum cladding in both basin-quality water chemistry [10] and aggressive water chemistry [13]. If conditions to aggressive corrosion of the fuel meat material are present, the fuel meat will dissolve and no passivating film (oxide film) will form (e.g. J-13 water chemistry) [13]. If conditions conducive to aggressive corrosion (e.g. pitting) are not present, both exposed aluminum and uranium-aluminum alloy fuel meat will form stable, passive films in waters with pH levels from approximately 4 to 10, up to moderate temperatures $(100+^{\circ}C)$. These films provide a high resistance to continued corrosion. The film thickness, f, under these conditions can be expressed as logarithmic function:

$$FilmThickness = a + b\ln(time)$$
(Eq. 15)

Where the coefficients *a* and *b* are dependent on the temperature and water flow rate. Using distilled, deionized water with a conductivity of $0.71 \,\mu\text{S}$ /cm and low flow conditions, Draley [14] measured the weight gains and weight losses of aluminum 1100, a cladding alloy, in both low oxygen (helium-saturated water) and oxygen saturated water conditions at 50, 70, and 95°C. Basins are open to air and are oxygen-saturated. Using the data in Reference 14, approximately 1 to 2 μ m of aluminum would corrode and be retained in an oxide film layer of approximately 2 to 4 μ m.

Presently, the water qualities in foreign basin storage are good [6]. For this reason, exposed fuel meat should be passivated with a hydrated oxide film. An initial fuel meat thickness of 1 μ m incorporated in the hydrated oxide film is applied as an initial condition for potential fines from breached fuel.





Figure 8 Nodular Pitting Corrosion on Fuel Plate of MTR Assembly Before and After Nodules Removed (Assembly IEA-53)

5.1.2 Basis for Through-clad Pitting Criteria for Corrosion Nodules

Corrosion nodules, if sufficiently large, are indicative of a cladding penetration on the Al-SNF assemblies. The size of a corrosion nodule at which cladding penetration has likely occurred is based on several years of corrosion surveillance testing of aluminum alloys in SRS basins and on the analysis of the underwater video of the MTR type aluminum-clad spent fuel at the IPEN-IEA-R1 Research Reactor [15]. Using underwater photography, corrosion nodules of a diameter of about 1/8 inch, or greater, are associated with a pit through the 15-mil (0.015 in) clad as judged from comparisons of drilled holes of a known diameter on the edges of the side plates. Nodules of less than 1/8 inch in diameter did not appear to have underlying pits penetrating the cladding.

5.1.3 Bases for the Damaged Fuel Fraction and Exposed Surface Area

Recent visual examination of over 1700 aluminum-clad, aluminum-based spent fuel (Al-SNF) assemblies in storage at foreign and domestic research reactor locations has shown a total of approximately 7% of the SNF assemblies to contain through-clad penetrations [6]. The majority of the breached fuels are primarily located at three storage sites, Australia, Brazil, and Thailand. The failed fuels at these sites have been considered for the purposes of this report. Excluding these sites, approximately 2% of the fuels have cladding breaches based on the examination criteria.

Assembly IEA-53 from the IEA-R1 reactor in Brazil contains the greatest level of exposed fuel meat observed in the world-wide examinations. This fuel has been characterized as having approximately 10 pits of approximately ¹/₄ -inch diameter or a total of 0.5 square inches (3.2 cm²) of exposed fuel meat (see Figure 9). This corresponds to an area fraction of 1% for the one side of the fuel plate. As discussed above, the outer fuel plates are typically the only ones that should

exhibit corrosion damage. Therefore in the example calculations, the assumption is made to use 1% as the exposed area of each side of each external fuel plate per assembly.



Figure 9 Weight Gain Relationship for Oxidation of 30% UAl₄-Al in the Range 400 to 600°C (reproduced from Reference 16)

5.2 Basis for Release of Fines from Exposed Fuel Meat

If a pit has penetrated the cladding in basin storage, the fuel meat would begin to corrode while in basin storage. As stated above, the corrosion of uranium-aluminum alloy materials in water is similar to aluminum metal corrosion and an initial hydrated oxide film of 2 to 4 μ m incorporating a layer of 1 to 2 μ m of fuel meat would be formed in high quality waters after several years storage.

The initial oxide film on the exposed fuel in dry shipping casks is subject to growth under time/temperature conditions. The resulting film is taken to be a simple summation of the passive film thickness in water storage plus the change in thickness at the environmental conditions (after a passive film has formed at those conditions).

The kinetics of oxidation of the intermetallic compounds UAl_2 , UAl_3 , and UAl_4 in aluminum in dry air in the temperature range of 250 to 600°C have been studied [16]. The results from the 30% UAl_4 -Al alloy are reproduced in Figure 9. An estimate of the rate of weight gain at temperatures up to 400°C for linear extrapolation is 10 µg/dm²/hour. Assuming the oxide to be predominantly Al_2O_3 , a maximum thickness of 3.7 µm of fuel meat would be corroded and retained in the oxide for a one-year exposure. For the SAR condition of <200°C (normal operation), the oxide film thickness will be <3.7 µm.

Corrosion of aluminum and uranium-aluminum alloys has been studied under wet air conditions [17]. The results show a strong dependency on relative humidity and a strong temperature dependency to alloys with an initial 600 grit finish. Subsequent exposure to a wet or dry air condition, however, results in a parabolic trend of oxide film formation. That is, the continued growth rate of a film slows as the film thickness increases.

Shipping casks are drained and shipped dry. The maximum humidity expected in the casks should be << 50% at 200°C [18]. The rate of 15 µgm/dm²/hour is the approximate rate of weight gain on aluminum alloy materials in at 50% relative humidity vapor (RH) at 150°C at the end of several months exposure [17]. Linear extrapolation with this rate is used to estimate the weight gain after exposure for one year. Using the following correlation [17],

Metal Loss (mils) = $1.193 \times 10^{-6} x$ Wt. Gain (μ g/dm²) Oxide Film Thickness (Boehmite film in nm) = 0.0533319 x Wt. Gain (μ g/dm²),

the thickness of fuel meat within the formed hydrated oxide is $4\mu m$ after exposure for one year. It must be noted that the formation of the oxide is time-dependent. That is, if the exposed fuel is exposed to the environmental condition 50% RH at 150°C, 4 μm of corroded fuel meat are not immediately available for release.

Exposure of U-Al alloy at saturated water vapor (100% RH) at 200°C results in a slightly greater rate of oxide film growth. Figure 10 shows that, using linear extrapolation, a rate 20 to 22 μ g/dm²/hr is observed for extruded U-Al. At 22 μ g/dm²/hr for a one-year exposure, 5.8 μ m of fuel meat would be expected in the oxide film. It should be recognized however that a condition of 200°C, 100% RH is not reasonable.

A total of 5 μ m of fuel meat is assumed for both normal and accident transport conditions. The fuel meat will be incorporated into the oxide layer. These assumptions are used to determine the amount of radioisotopes that are available for release as fines in the bounding case analysis of the oxide film on exposed fuel meat of aluminum-based fuel.

In reality, the oxide films formed on aluminum and uranium-aluminum are tenacious and not readily removed. Figure 11 shows a ring specimen of exposed 18U-Al before and after exposure to saturated vapor at 150° C for one year. Although it appeared blackish, Boehmite, Al₂O₃•H₂O, was the predominant oxide determined by x-ray diffraction analysis. It was extremely difficult to remove (scrape) the oxide for XRD analysis. Thus, the oxide film that forms on uranium-aluminum alloys exposed to dry and wet air environments is highly adherent and not expected to dislodge unless deliberately scraped. A value of 0.15, consistent with the fraction of crud assumed to dislodge in commercial fuel, is used as the fraction of the oxide film that is removed during transport under normal conditions. A value of 1, or all of the oxide film, is assumed to dislodge during transport under accident conditions.



Figure 10 Weight Gain of U-Al Alloy at 200°C in Saturated Water Vapor

5.3 Gaseous and Volatile Specie Release Characteristics of Oxides on Al-SNF – Basis for Gas and Volatile Species Source Term

5.3.1 Gas Release

Release of gaseous species namely Kr, H₃, Xe, and I from Al-SNF are diffusion-limited (timetemperature dependent), in contrast to a direct release mechanism for commercial SNF. The gases in the aluminum SNF reside in trap sites at the defects produced during irradiation in the fuel microstructure. Transport of these gases to the exposed fuel surface involves a series of detrap/trap interactions of the solute with traps (microstructural features) in the fuel in combination with diffusion. The release of gases is therefore a function of the energy required to detrap the gases and migrate to the surface of the fuel. The energy required to detrap the gases can be calculated through complex models while the diffusion of gases in a trap-free microstructure can be readily estimated.



Figure 11 (a) As Received Fuel Tube showing Capsule Aluminum 8001 Cladding and Aluminum 18 wt% Uranium Core (b) Corroded Specimen in a Initial 100% R. H. Water Vapor and Nitric Acid at 150°C for 12-Month Exposure

For each of the aforementioned gases, the diffusion coefficient of the species has been measured or estimated. However the trapping/detrapping energies were not easily calculable in the near term. Hence until definitive models are developed and calculations made, the release fraction of gases were assumed to be 30%, which is consistent with that used for commercial SNF.

A simple diffusion model may be applied to conservatively estimate the release of gas from Al-SNF. The model for diffusion out of a slab [19] is adopted as a preliminary model for the release of gaseous and volatile species from a fully-exposed fuel plate. The fraction of gas remaining in a slab is given as:

$$\frac{C(t)}{C_{\circ}} = \frac{8}{\pi^2} \sum_{j=0}^{\infty} \frac{1}{(2j+1)^2} \exp(-\left[\frac{(2j+1)\pi}{h}\right]^2 Dt)$$

where C(t) is the average concentration at time t remaining in a slab of material of thickness h that had an initial gas concentration of C_0 . D is the diffusion coefficient. Trapping of the gas species is typically considered through a reduction in the diffusion coefficient.

Assuming no trapping of gas, an evaluation is made for Xe release using this model. The diffusivity of Xe in aluminum at 200°C is 2.8E-13 cm²/sec [20]. Using the fuel meat thickness of 0.05 cm, approximately 85% of the species would be retained in a de-clad fuel material. A similar calculation for tritium using a value of 10^{-6} cm²/sec for tritium diffusivity at 200°C reveals that essentially all of the tritium may be released. This however is contrary to SRS experience (wherein tritium is not released until >400°C) and is consistent with the assumed gaseous release of tritium from commercial SNF wherein a value of 30% is assumed.

The fractional release of iodine has been experimentally shown to be $<10^{-6}$ at temperatures $<550^{\circ}$ C [21]. Also, literature shows that there is no measurable release of Krypton from Al-U

alloys at <600°C [22]. These results are consistent with the understanding that species are not released until the solid reaches a temperature of the species boiling point [23].

Therefore, taking the gas release fraction for breached fuel to be 0.3 for normal conditions of transport and 1.0 for accident conditions of transport is very conservative.

5.3.2 Volatile Release

The volatile release considered in this analysis includes Cs, Sr, and Rb. The melting point of Cs is 28°C and the vapor pressure is 6E-1 atm at 600°C. Both strontium and rubidium have a higher melting point and a higher vapor pressure than cesium. Hence, cesium is expected to dominate the release of volatiles. The fractional release of volatiles is estimated at <1E-6 based on experimental data on the release of fission products during fuel melting experiments. Those volatiles that occupy the volume fraction of fuel meat that is release as fines is also included in the fines calculation.

The release of fission product gases and volatiles at high temperatures (> 300° C), including fuel melt down, from clad uranium-aluminum fuel plates was studied experimentally [21]. The fuel consisted of uranium enriched to 40% and irradiated in the Oak Ridge Reactor to 60% burnup. The equipment was designed to trap and measure very small traces of Xe and I and Cs. The experiment showed that fission product gases and volatiles are released in three stages as the temperature is elevated. The release of fission products at temperatures below 550°C was observed to be negligible (< 10^{-6} of the fission product inventory of each specie) [21].

Two heating tests on segments of irradiated aluminum-based fuel that has been de-clad have been recently completed for SRS at ANL [22]. No radionuclide release was detected from segments of either U_3Si_2 -Al or UAl_x-Al during furnace tests at 275°C for times up to four months. In the first test, a segment of fuel element irradiated in the Oak Ridge reactor was heated at 275°C for 30 days. The fuel was a dispersion of U_3Si_2 (19.8% enriched) particles in an aluminum matrix clad with 6061-T6 aluminum. Average burnup was 51.4%. The area of fuel exposed to air in the test chamber was 0.6 cm². In the second test, the fuel element segment was a dispersion of UAl_x particles (19.8% enriched) in aluminum clad with 6061-T6 aluminum. The fuel element had been irradiated in the Oak Ridge reactor to an average burnup of 66.5%. The area of fuel exposed to air in the test chamber was 0.5 cm². The release of gases and volatile fission products were analyzed through both mass spectrometer and analysis of collector plates. There was no release of gas or volatile fission products in either test nor were there any significant changes in fuel microstructure, core-clad interface, or surface oxide thickness detectable by optical microscopy (see Figure 12).

5.4 Basis for Crud Source Term

Aluminum spent fuel do not acquire crud in the same manner as commercial SNF. The surface activity of Al-SNF is primarily a result of storage in radioactively contaminated water. The surface activity is estimated from "sip" data. Radioactivity releases from fuel or from contaminated surfaces into water can be measured directly by performing a "sip" test. The test is performed by measuring the activity concentration in a specified volume of water before and after the material "rests" in the water for a specified period.

Sip data taken from onsite fuel shipments was used to develop the basis of the crud source term and its A_2 value for U-Al alloy fuel. Onsite fuel shipments are made in water-filled fuel casks. Sip data taken from onsite shipments was compared to sip data taken from offsite shipments (dry casks) received at SRS Receiving Basin for Off-site Fuels over the last 2 years. Data for fuel shipments in wet environments resulted in sip values 2 to 3 orders of magnitude greater than for dry shipments. For conservatism wet shipment sip data is used to develop the basis for releasable source term associated with U-Al alloy fuel crud.



Figure 12 Microstructure of UAl_x-Al Fuel Core at Cladding Interface following 66.5% Burn-up plus 4 Months at 275°C. (Optical micrograph courtesy of A. B. Cohen, Argonne National Laboratory)

Worst case sip results associated with onsite data for MURR fuel were averaged. The source term value represented in dpm/ml, was converted to Ci/cm² for a single Al-U SNF assembly and compared to the NRC LWR crud source. LWR crud source term is provided in ANSI N14.5. Converting the source term value of dpm/ml to Ci/ml and multiplying the resultant dose per volume by the cask volume and dividing by assembly surface area results in the desired dose per area (Ci/cm²). The calculated value of 1.39E-7 Ci/cm² is used in the containment analysis.

The A_2 value used by the NRC for LWR fuel is based on Cobalt and an A_2 value of 10.8 Ci. Gamma spectrography taken on sip samples from SRS basin water was used to develop an effective A_2 value for the crud. The calculated A_2 value is 0.270 Ci. The major contributor to the A_2 quantity is Cs-137. It is assumed that the basin level isotope activities are proportional to cask activity levels.

Calculation of source term in the described manner includes several levels of conservatism. The surface area used was 25% of the actual surface area of a single assembly. The total curie content in the cask resulted from 12 fuel assemblies but only one is used for calculation of surface area contamination. Further conservatism is introduced in the use of wet shipment data for dry shipment calculation.

6.0 SENSITIVITY OF VOLUMETRIC LEAKAGE RATE AT STANDARD CONDITIONS TO ASSUMED FUEL CONDITION

The Volumetric Leakage Rate at Standard Conditions for a given cask/fuel combination is dependent on several parameters. The calculated Volumetric Leakage Rate at Standard Conditions is significant in that a cask must be demonstrated to maintain a leak rate lower than the Volumetric Leakage Rate at Standard Conditions during transport. This section addresses the relative sensitivity of the calculated Volumetric Leakage Rate at Standard Conditions to changes in various fuel dependent parameters. For fuel that is not bounded by the assumptions in this report, the sensitivity analyses can be used to assess alternative fuel conditions.

Example Cask #1 with Example Fuel #1 at the conditions given in Section 4 is used as the initial cask/fuel condition in the sensitivity analysis. However, the intent of this analysis is only to evaluate relative effects of fuel condition and should not be taken to represent any particular fuel/cask combination. The parameters are addressed with respect to the Volumetric Leakage Rate at Standard Conditions under normal conditions of transport. The normal conditions of transport will generally bound the accident conditions of transport. Following is a summary of the impact of several key inputs to the containment analysis.

6.1 Dependence on Fuel Burnup

The Volumetric Leakage Rate at Standard Conditions of a cask/fuel combination is dependent on the radionuclide inventory of the fuel being transported. The radionuclide inventory of the fuel is likewise dependent on the fuel burnup. Spent Nuclear Fuels (SNF) with higher burnup contain higher concentrations of the radioactive products of the fission reaction. Assuming all other parameters are constant, increasing the burnup of a given fuel will result in a higher activity density (the number of curies of individual radionuclides per cubic centimeter of fuel material) in the fuel and consequently higher levels of activity released to the cask cavity. The result is a lower allowable release rate and a lower Volumetric Leakage Rate at Standard Conditions.

6.2 Dependence on the Number of Assemblies

The calculated Volumetric Leakage Rate at Standard Conditions is strongly dependent on the number of assemblies with exposed fuel meat loaded in a cask. The number of assemblies effects the Volumetric Leakage Rate at Standard Conditions in a manner similar to the effect of burnup (Figure 13). Decreasing the number of assemblies will decrease the amount of activity available for release to the cask cavity, all else being equal. The reduced activity of the gas in the cask cavity results in an increase in the Volumetric Leakage Rate at Standard Conditions. An order of magnitude decrease in the number of assemblies (i.e., number of breached assemblies) being transported results in an approximate order of magnitude increase in the calculated Volumetric Leakage Rate at Standard Conditions.

The data point in Figure 13, denoted with a circle, represents the case of a cask containing 42 assemblies that exhibits 7 cm² of exposed fuel meat per breached assembly. This corresponds to 30 cm^2 of exposed fuel meat per cask by:

$$ESA_{c} = ESA_{b} * N_{A} * f_{b} = 7 * 42 * 0.1 = 30 \text{ cm}^{2}$$
,

where:

| ESA _c | is the total exposed surface area per cask [30 cm ²], |
|------------------|---|
| ESA _b | is the exposed surface area per breached assembly [7 cm ²], |

 N_A is the total number of assemblies in cask [42], and

 f_b is the fraction of breached assemblies (i.e., with through clad pits) [0.1].

The calculated volumetric leakage rate at standard conditions of transport for this case is shown in the figure as $8.70E-5 \text{ cm}^3/\text{s}$.





6.3 Dependence on Decay Time

As fuel elements are stored after discharge and prior to shipment, the activity of the fission products present in the elements decrease due to radioactive decay. Radioactive decay of SNF results in a decrease in the activity density of the fuel, and thus a decrease in the activity released to the cavity volume (all else being equal). However, the effect that decay time has on the calculated Volumetric Leakage Rate at Standard Conditions is suppressed by the nature of the radioisotopes. Many of the short-lived radioisotopes decay by emitting electrons or photons, while many of the long lived radioisotopes generally decay by alpha-decay. Due to the dependence of the maximum allowable release rate (MARR) on the A₂ value of the mixture of radioisotopes, increased cooling times result in a decrease in the MARR. The net result is a significant, but not overwhelming, increase in the Volumetric Leakage Rate at Standard Conditions due to increasing the decay time from 1 year to 30 years).

The data point in Figure 14, denoted with a circle, represents the case of a cask with fuel that has cooled for one year that exhibits 7 cm² of exposed fuel meat per breached assembly. This corresponds to 30 cm² of exposed fuel meat per cask by:

$$ESA_{c} = ESA_{b} * N_{A} * f_{b} = 7 * 42 * 0.1 = 30 \text{ cm}^{2}$$
,

where:

| ESA _c | is the total exposed surface area per cask $[30 \text{ cm}^2]$, |
|------------------|--|
| ESA _b | is the exposed surface area per breached assembly [7 cm ²], |
| N _A | is the total number of assemblies in cask [42], and |
| f _b | is the fraction of breached assemblies (i.e., with through clad pits) [0.1]. |

The calculated volumetric leakage rate at standard conditions of transport for this case is shown in the figure as $8.70E-5 \text{ cm}^3/\text{s}$.





6.4 Dependence on Breached Fuel Fraction

The Volumetric Leakage Rate at Standard Conditions decreases with an increase in the fraction of breached fuel loaded in a cask. This effect is equivalent to that of increasing the number of assemblies loaded in the cask while maintaining a constant fraction of breached fuel. Doubling the fraction of breached fuel loaded in a cask will result in approximately a fifty-percent reduction in the Volumetric Leakage Rate at Standard Conditions (Figure 15).

The data point in Figure 15, denoted with a circle, represents the case of a cask that has 42 assemblies. Of the 42 assemblies loaded, 10% of the assemblies exhibit through clad pits (i.e., are breached). The breached fuel assemblies exhibit 7 cm² of exposed fuel meat each. This corresponds to 30 cm² of exposed fuel meat per cask by:

$$ESA_{c} = ESA_{b} * N_{A} * f_{b} = 7 * 42 * 0.1 = 30 \text{ cm}^{2},$$

where:

| ESA _c | is the total exposed surface area per cask $[30 \text{ cm}^2]$, |
|------------------|--|
| ESA _b | is the exposed surface area per breached assembly [7 cm ²], |
| N _A | is the total number of assemblies in cask [42], and |
| f _b | is the fraction of breached assemblies (i.e., with through clad pits) [0.1]. |

The calculated volumetric leakage rate at standard conditions of transport for this case is shown in the figure as $8.70E-5 \text{ cm}^3/\text{s}$.





6.5 Dependence on Fines

Fines are a significant contributor to the calculated Volumetric Leakage Rate at Standard Conditions. The removal of the contribution due to the release of fines from the containment analysis results in an increase of approximately 70% in the calculated Volumetric Leakage Rate at Standard Conditions.

6.5.1 Dependence on Penetration Depth

The depth of attack associated with the degradation of the meat material within DOE SNF provides only a slight impact on the calculated value of the Volumetric Leakage Rate at Standard Conditions, relative to the impact provided by increased fraction of meat surface area with through clad penetration. Increasing the depth of attack on the meat material by a factor of two $(5\mu m \rightarrow 10\mu m)$ yields only an approximate 30-percent decrease in the calculated Volumetric Leakage Rate at Standard Conditions as seen in Figure 16.

The data point in Figure 16, denoted with a circle, represents the case of a cask with fuel that has been penetrated by pitting to a depth of 5 μ m of meat and that exhibits 7 cm² of exposed fuel meat per breached assembly. This corresponds to 30 cm² of exposed fuel meat per cask by:

$$ESA_{c} = ESA_{b} * N_{A} * f_{b} = 7 * 42 * 0.1 = 30 \text{ cm}^{2}$$
,

where:

| ESA _c | is the total exposed surface area per cask [30 cm ²], |
|------------------|--|
| ESA _b | is the exposed surface area per breached assembly [7 cm ²], |
| N _A | is the total number of assemblies in cask [42], and |
| f _b | is the fraction of breached assemblies (i.e., with through clad pits) [0.1]. |

The calculated volumetric leakage rate at standard conditions of transport for this case is shown in the figure as $8.70E-5 \text{ cm}^3/\text{s}$.





6.5.2 Dependence on Fraction of Surface Area with Through-Clad Penetration

Increasing the fraction of meat surface area exposed in the SNF, being transported in a cask, results in a significant decrease in the Volumetric Leakage Rate at Standard Conditions (Figure 17). This parameter represents the single most significant input to the containment analysis. An increase in the fraction of surface are exhibiting through clad penetration from the value of \sim 0.000556 to a value of 0.05 results in a significant decrease in the calculated Volumetric Leakage Rate at Standard Conditions.

The data point in Figure 17, denoted with a circle, represents the case of a cask with fuel that exhibits 30 cm^2 of exposed fuel meat per cask. This corresponds to 7 cm^2 of exposed fuel meat per breached assembly by:

$$ESA_b = ESA_c / (N_A * f_b) = 30 / (42 * 0.1) = 7 \text{ cm}^2$$
,

where:

| ESA _b | is the exposed surface area per breached assembly $[7 \text{ cm}^2]$, |
|------------------|--|
| ESA _c | is the total exposed surface area per cask [30 cm ²], |
| N _A | is the total number of assemblies in cask [42], and |
| f _b | is the fraction of assemblies with through clad pits [0.1]. |

The calculated volumetric leakage rate at standard conditions of transport for this case is shown in the figure as $8.70E-5 \text{ cm}^3/\text{s}$.



Figure 17

6.6 Dependence on Crud

The presence of crud in the containment analysis for DOE Al-SNF has a very slight effect on the calculated Volumetric Leakage Rate at Standard Conditions. The removal of the contribution due to crud from the containment analysis results in less than 1-percent increase in the calculated Volumetric Leakage Rate at Standard Conditions.

6.7 Dependence on Volatile Specie

The presence of volatiles in the containment analysis for DOE Al-SNF has a very slight effect on the calculated Volumetric Leakage Rate at Standard Conditions. The removal of the contribution due to volatiles from the containment analysis results in less than 1-percent increase in the calculated Volumetric Leakage Rate at Standard Conditions.

6.8 Dependence on Gas

The contribution of the gaseous radioisotopes to the calculated Volumetric Leakage Rate at Standard Conditions is significantly higher than the contributions from volatiles and crud. The removal of the contribution due to the release gaseous radioisotopes from the containment analysis results in an approximate 95-percent increase in the calculated Volumetric Leakage Rate at Standard Conditions.

7.0 LIST OF SYMBOLS

- μ is the fluid viscosity [cP] (typically found in CRC Handbook).
- a is the capillary length [cm] (typically found in the SAR of a given cask).
- $A_{2,A}$ is the mixture A_2 of the radionuclides available for release under accident conditions of transport [Ci].
- $A_{2,N}$ is the mixture A_2 of the radionuclides available for release under normal conditions of transport [Ci].
- A_{2i} is the appropriate A_2 value for mixture *i* [Ci].
- A_{2_i} is the appropriate A_2 value for nuclide *i* [Ci].
- A_F is the total number of curies of all radionuclides in all assemblies in the cask (excluding gases). It is the product of the number of assemblies and the number of curies of the all isotopes (excluding gases) per assembly (i.e., as output by ORIGEN-S) [Ci].
- A_G is the total number of curies of all gaseous radionuclides in all assemblies in the cask. It is the product of the number of assemblies and the number of curies of all gaseous isotopes per assembly (i.e., as output by ORIGEN-S) [Ci].
- A_{gb} is the number of curies of all gaseous radionuclides in a single breached assembly (i.e., as output by ORIGEN-S) [Ci].
- A_i is the activity of nuclide *i* in the mixture.
- A_v is the total number of curies of all volatile radionuclides in all assemblies in the cask. It is the product of the number of assemblies and the number of curies of all volatile isotopes per assembly (i.e., as output by ORIGEN-S) [Ci].
- A_{vb} is the number of curies of all volatile radionuclides in a single breached assembly (i.e., as output by ORIGEN-S) [Ci]
- C_A is the curies per unit volume of the radioactive material, "activity density", that passes through the leak path for accident (C_A) conditions of transport [Ci/cm³].
- C_{crud} is the releasable activity density inside the containment vessel as a result of crud spallation [Ci/cm³].
- C_{fines} is the releasable activity density inside the containment vessel due to the release of fines [Ci/cm³].
- C_{gas} is the releasable activity density inside the containment vessel due to the release of gas [Ci/cm³].
- C_i is the activity density of contributor *i* (i.e., gas, volatiles, fines, or crud).
- C_N is the curies per unit volume of the radioactive material, "activity density", that passes through the leak path for normal conditions of transport [Ci/cm³].
- C_{total} is the total releasable activity density inside the containment vessel [Ci/cm³].
- C_{vol} is the releasable activity density inside the containment vessel due to the release of volatiles [Ci/cm³].
- D is the capillary diameter [cm].
- ESA is the amount of exposed meat surface area per cask $[cm^2/cask]$.
- ESA_b is the amount of exposed meat surface area per breached assembly [cm²/assembly].
- ESA_c is the amount of exposed meat surface area per cask [cm²/cask].
- f_b is the fraction of fuel assemblies that are breached in a cask [$f_{b,N}=0.1$, $f_{b,A}=1.0$].
- F_c is the continuum flow coefficient [cm³/s].
- f_C is the crud spallation fraction [$f_{C,N}$ =0.15, $f_{C,A}$ =1.0].
- f_G is the fraction of gas that escapes the breached fuel assembly [$f_{G,N}=0.3, f_{G,A}=1.0$].
- F_i is the fraction activity density of contributor *i* (i.e., gas, volatiles, fines, or crud) in the mixture.
- F_m is the molecular flow coefficient [cm³/atm•s].
- f_V is the fraction of gas that escapes the breached fuel assembly $[f_{V,N}=f_{V,A}=1E-6]$

- L is the volumetric gas flow rate at P_u [cm³/sec].
- L_A is the volumetric gas leakage rate [cm³/s] under accident conditions of transport.
- L_c is the volumetric flow rate due to continuum flow [cm³/sec].
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].
- L_N is the volumetric gas leakage rate [cm³/s] under normal conditions of transport.
- L_R is the volumetric leakage rate at standard conditions correlating to the most limiting conditions of transport [std cm³/sec].
- $L_{R,A}$ is the volumetric leakage rate at standard conditions correlating to accident conditions of transport [cm³/sec].
- $L_{R,N}$ is the volumetric leakage rate at standard conditions correlating to normal conditions of transport [cm³/sec].
- M is the gas molecular weight [g/mole] (typically found in CRC Handbook).
- N_A is the total number of assemblies in cask [42].
- N_b is the number of breached fuel assemblies in cask.
- P is the depth of corrosion attack [5.E-04-cm].
- P_a is the average pressure, $(P_u P_d)/2$ [atm].
- P_d is the downstream pressure [atm].
- P_u is the upstream pressure [atm] (typically found in the SAR of a given cask).
- R_A is the release rate for accident conditions of transport [Ci/s].
- R_i is the fraction activity of nuclide *i* in the mixture.
- $R_{\rm N}$ is the release rate for normal conditions of transport [Ci/s].
- S_A is the sum of the surface areas of all assemblies [cm²]
- S_C is the crud surface activity [1.39E-7 Ci/cm²].
- T is the gas temperature [K] (typically found in the SAR of a given cask).
- T_F is the oxide spallation fraction [$T_{F,N}=0.15$, $T_{F,A}=1.0$].
- V_C is the free volume of the cask [cm³].
- V_M is the volume of the meat region of the fuel per cask [cm³/cask].

8.0 **REFERENCES**

- 1. "Packaging and Transportation of Radioactive Material," **10CFR71**.
- 2. "American national Standard for Radioactive materials Leakage Tests on Packages for Shipment," **ANSI N14.5-1987**.
- "Containment Analysis for Type B Packages Used to Transport Various Contents," NUREG/CR-6487.
- 4. "Safety Analysis Document" for Example Cask #1.
- 5. "Safety Analysis Document" for Example Cask #2.
- 6. "Characterization of FRR SNF in Basin and Dry Storage Systems," Peggy Brooks and Robert L. Sindelar, presented at the Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management and published in the proceedings, American Nuclear Society, Charleston, SC, September 1998.
- 7. **SFS-RSE-970167**, "Proposed New Criteria for Acceptance of Al-SNF for SRS Basin Storage (U)," February 11, 1998.
- "Radioactivity Release from Aluminum-Based Spent Nuclear Fuel in Basin Storage," R. L. Sindelar, S. D. Burk, and J. P. Howell, presented at the Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management and published in the proceedings, American Nuclear Society, Charleston, SC, September 1998.
- 9. M. R. Louthan, Jr., et al, "Corrosion of Aluminum-Clad Fuel and Target Elements: the Importance of Oxide Films and Irradiation History," in the Proceedings of the Embedded Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management, American Nuclear Society: La Grange Park, Illinois, 1996, pp. 57-61.
- G. T. Chandler, R. L. Sindelar, and P. S. Lam, "Evaluation of Water Chemistry on the Pitting Susceptibility of Aluminum," CORROSION/97, Paper No. 104, National Association of Corrosion Engineers, International, Houston, TX, 1997.
- 11. ASM Handbook, Volume 13 Corrosion.
- 12. Verbal Communication Dr. Jose Perrotta, IPEN, Brazil to SRTC, September 1998.
- "Evaluation of Test Methodologies for Dissolution and Corrosion of Al-SNF," B. J. Wiersma, J. I. Mickalonis, and M. R. Louthan, Jr., presented at the Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management and published in the proceedings, American Nuclear Society, Charleston, SC, September 1998.
- 14. J. E. Draley, S. Mori, and R. E. Loess, J. Electrochemical Soc. 114 (1967) p. 353.
- 15. **SRT-MTS-96-2041**, "TRIP REPORT: Characterization of IEA-R1 Spent Nuclear Fuels at the IPEN, Sao Paulo, Brazil, July 22 July 31, 1996 (U), R. L. Sindelar, H. B. Peacock, Jr., J. P. Howell, S. D. Burke, and A. S. Busby, Westinghouse Savannah River Co., Savannah River Technology Center.
- 16. P. R. Openshaw and L. L. Shreir, "Oxidation of Uranium-Aluminum Intermetallic Compounds," Corrosion Science, 1963, Vol. 3 pp. 217 to 237.
- 17. "Vapor Corrosion of Aluminum Cladding Alloy," P. S. Lam, R. L. Sindelar, and H. B. Peacock, Jr., presented at the Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management and published in the proceedings, American Nuclear Society, Charleston, SC, September 1998.
- 18. Steam Tables.
- 19. P. Shewmon, <u>Diffusion in Solids</u>, The Minerals, Metals, & Materials Society, 1989.
- 20. F.H. Mohlbier, ed. John Askill, <u>Tracer Diffusion Data for Metals and Alloys</u>.
- T. Shibata, T. Tamai, M. Hayashi, J. C. Posey, and J. L. Snelgrove, "Release of Fission Products from Irradiated Aluminide Fuel at High Temperatures," Nuclear Science and Engineering, 87 (1984) pp. 405-417.

- 22. M. B. Reynolds, "Fission Gas Behavior in the Uranium-Aluminum System," Nuclear Science and Engineering, 3 (1958) pp. 428-434.
- 23. "Fission Product Release from Spent Nuclear Fuel During Melting," J. P. Howell and J. F. Zino, presented at the Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Material Management and published in the proceedings, American Nuclear Society, Charleston, SC, September 1998.
- 24. Interlaboratory Memo from Argonne National Laboratory to SRTC, SRTC Fission Product Collection Test 96-2, August 20, 1997.

A.0 EXAMPLE CALCULATION #1

There are four sources of radioactive material that may become airborne during transportation. These sources are gases, volatiles, fines, and crud. The contributions to the total activity density in the shipping cask free volume from the four sources are treated separately. Therefore, the A_2 values of the four sources are determined separately. Following is an example calculation for Example Cask #1 fully loaded with Example Fuel #1. Because the total quantity of krypton-85 in the cask is less than 10•A₂, the special requirement pertaining to krypton-85 release does not impact this analysis. Although the regulation allows us to use $10•A_2$, we are using the A_2 value.

A.1 Gas Calculations

A.1.1 Activity Values for Gases

 A_2 values for the fuel gases are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

 $A_2 = (\sum (R_i / A_{2i}))^{-1},$

where:

 R_i is the fraction activity of nuclide i in the mixture and

 A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for gases. The mixture A_2 value for gases is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] $R_i=A_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|-------------|--|------------------------------------|--|--|
| h3 | 1.0800E+03 | 1.7300E-02 | 2.6397E-04 | 2.4442E-07 |
| h3 | 1.0800E+03 | 2.3200E+00 | 3.5400E-02 | 3.2777E-05 |
| kr85 | 2.7000E+02 | 6.3200E+01 | 9.6434E-01 | 3.5716E-03 |
| Sum Totals: | ΣΑ, | = 6.5537E+01 | $\Sigma R_i/I$ | A _{2i} = 3.6046E-03 |
| | | | A ₂ | gas= 2.7742E+02 Ci |

 Table A.1 Mixture A2 Determination for Gases (per assembly)

A.1.2 Activity Density of Gases

The releasable activity density inside the containment vessel due to the release of gas is described by:

 $C_{gas} = (A_G \bullet f_b \bullet f_G) / V_{C,}$

where:

- A_G is the total number of curies of all gaseous radionuclides in all assemblies (42) in the cask. It is the product of the number of assemblies and the number of curies of all gaseous isotopes per assembly (i.e., as output by ORIGEN-S) [2.75E+3-Ci],
- f_b is the fraction of fuel assemblies in a cask that are breached [$f_{b,N}$ =0.1, $f_{b,A}$ =1.0],
- f_G is the fraction of gas that escapes the breached fuel assembly [$f_{G,N}$ =0.3, $f_{G,A}$ =1.0],
- $V_{\rm C}$ is the free volume of the cask [2.239E+5-cm³],

The releasable activity density inside the containment vessel due to the release of gas is thus:

 $C_{gas,N} = (2.75E+3\cdot0.1\cdot0.3)/2.239E+5 = 3.69E-4 \text{ Ci/cm}^3$ $C_{gas,A} = (2.75E+3\cdot1.0\cdot1.0)/2.239E+5 = 1.23E-2 \text{ Ci/cm}^3$

A.2 Volatile Calculations

A.2.1 Activity Values for Volatiles

 A_2 values for the fuel volatiles are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

$$A_2 = (\sum (R_i / A_{2i}))^{-1},$$

where:

- R_i is the fraction activity of nuclide *i* in the mixture and
- A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for volatiles. The mixture A_2 value for volatiles is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] $R_i=A_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|-------------|--|------------------------------------|--|--|
| sr89 | 1.3500E+01 | 2.0400E+02 | 6.5977E-02 | 4.8872E-03 |
| sr90 | 2.7000E+00 | 5.5500E+02 | 1.7950E-01 | 6.6480E-02 |
| cs134 | 1.3500E+01 | 1.7600E+03 | 5.6921E-01 | 4.2164E-02 |
| cs135 | 2.4300E+01 | 2.4700E-03 | 7.9884E-07 | 3.2874E-08 |
| cs137 | 1.3500E+01 | 5.7300E+02 | 1.8532E-01 | 1.3727E-02 |
| Sum Totals: | ΣΑι | = 3.0920E+03 | $\Sigma R_i/I$ | A _{2i} = 1.2726E-01 |
| | | | A ₂ | _{vol} = 7.8581E+00 Ci |

 Table A.2 Mixture A2 Determination for Volatiles (per assembly)

A.2.2 Activity Density of Volatiles

The releasable activity density inside the containment vessel due to the release of volatiles is described by:

 $C_{vol} = (A_V \bullet f_b \bullet f_V) / V_C,$

where:

- A_V is the total number of curies of all volatile radionuclides in an assembly. It is the product of the number of assemblies and the number of curies of all volatile isotopes per assembly (i.e., as output by ORIGEN-S) [1.30E+5-Ci],
- f_b is the fraction of fuel assemblies that are breached in a cask [$f_{b,N}$ =0.1, $f_{b,A}$ =1.0],
- f_V is the fraction of gas that escapes the breached fuel assembly [$f_{V,N}=f_{V,A}=1E-6$],
- V_C is the free volume of the cask [2.239E+5-cm³],

The releasable activity density inside the containment vessel due to the release of volatiles is thus:

$$C_{vol,N} = (1.30E+5 \cdot 0.1 \cdot 1E \cdot 6)/2.239E+5 = 5.80E \cdot 8 \text{ Ci/cm}^3$$

 $C_{vol,A} = (1.30E+5 \cdot 1.0 \cdot 1E \cdot 6)/2.239E+5 = 5.80E \cdot 7 \text{ Ci/cm}^3$

A.3 Fines Calculations

A.3.1 Activity Values for Fines

 A_2 values for the fuel fines are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

$$A_2 = (\sum (R_i / A_{2i}))^{-1},$$

where:

- R_i is the fraction activity of nuclide *i* in the mixture and
- A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for fines. The mixture A_2 value for fines is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] R _i =A _i /ΣA _i | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|---------|--|------------------------------------|---|--|
| mn54 | 2.7000E+01 | 1.3800E-01 | 6.2490E-06 | 2.3144E-07 |
| pa233 | 2.4300E+01 | 1.0400E-02 | 4.7094E-07 | 1.9380E-08 |
| u236 | 2.7000E-02 | 3.2600E-03 | 1.4762E-07 | 5.4674E-06 |
| u237 | 5.0000E-01 | 3.2700E-03 | 1.4807E-07 | 2.9615E-07 |
| np237 | 5.4100E-03 | 1.0400E-02 | 4.7094E-07 | 8.7049E-05 |
| np239 | 1.3500E+01 | 2.9200E-02 | 1.3222E-06 | 9.7944E-08 |

 Table A.3 Mixture A2 Determination for Fines (per assembly)

| | AValue | Activity | Fraction | Er/A. |
|------------------|------------|------------|--|--------------------------|
| Taotope | | [Ci] | [Fr] | [1/Ci] |
| Isocope | [C1] A. | Δ. | $D = \lambda / \Sigma \lambda$ | |
| | 1 00000 00 | 4 07000 00 | $\frac{\mathbf{R}_{i} - \mathbf{A}_{i}}{1 0.22 (\Pi 0.7)}$ | 1 00200 05 |
| pu236 | 1.8900E-02 | 4.2/00E-03 | 1.9336E-07 | 1.0230E-05 |
| pu237 | 5.41008+02 | 1.0300E-03 | 4.6641E-08 | 8.6212E-11 |
| pu238 | 5.4100E-03 | 1.3000E+02 | 5.8867E-03 | 1.0881E+00 |
| pu239 | 5.4100E-03 | 2.2100E-01 | 1.0007E-05 | 1.8498E-03 |
| pu240 | 5.4100E-03 | 9.2900E-02 | 4.2067E-06 | 7.7758E-04 |
| pu241 | 2.7000E-01 | 1.3700E+02 | 6.2037E-03 | 2.2977E-02 |
| pu242 | 5.4100E-03 | 1.3000E-03 | 5.8867E-08 | 1.0881E-05 |
| am241 | 5.4100E-03 | 2.4600E-01 | 1.1139E-05 | 2.0590E-03 |
| am242m | 5.4100E-03 | 3.4400E-03 | 1.5577E-07 | 2.8793E-05 |
| am242 | 5.0000E-01 | 3.4200E-03 | 1.5487E-07 | 3.0973E-07 |
| am243 | 5.4100E-03 | 2.9200E-02 | 1.3222E-06 | 2.4441E-04 |
| cm242 | 2.7000E-01 | 3.5400E+00 | 1.6030E-04 | 5.9370E-04 |
| cm243 | 8.1100E-03 | 1.4200E-02 | 6.4301E-07 | 7.9286E-05 |
| cm244 | 1.0800E-02 | 7.9100E+00 | 3.5818E-04 | 3.3165E-02 |
| cm245 | 5.4100E-03 | 2.7700E-03 | 1.2543E-07 | 2.3185E-05 |
| se79 | 5.4100E+01 | 3.7600E-03 | 1.7026E-07 | 3.1472E-09 |
| y89m | 5.4100E+01 | 1.9000E-02 | 8.6036E-07 | 1.5903E-08 |
| y90 | 5.4100E+00 | 5.5500E+02 | 2.5132E-02 | 4.6454E-03 |
| y91 | 8.1100E+00 | 4.8400E+02 | 2.1917E-02 | 2.7024E-03 |
| zr93 | 5.4100E+00 | 7.2500E-03 | 3.2830E-07 | 6.0683E-08 |
| zr95 | 2.4300E+01 | 7.6200E+02 | 3.4505E-02 | 1.4200E-03 |
| nb95 | 2.7000E+01 | 1.6900E+03 | 7.6527E-02 | 2.8343E-03 |
| nb95m | 2.4300E+01 | 8 9700E+00 | 4 0618E-04 | 1.6715E-05 |
| ± c 9 9 | 2 4300E+01 | 5 8200E-02 | 2.6354E-06 | 1.0845E-07 |
| ru103 | 2.1300E+01 | 3 3300E+01 | 1 5079E-03 | 6 2054E-05 |
| rh103m | 1 0800E+03 | 3.3200E+01 | 1 5034F-03 | 1 3920F-06 |
| ru106 | 5 4100E+00 | 6 7500E+02 | 3 0566E-02 | 5 6498E-03 |
| rh106 | 5.0000F-01 | 6 7500E+02 | 3.0566F-02 | 6 1131F-02 |
| ag110 | 2 4400F+01 | 5 5500E-02 | 2 5132F-06 | 1 0300F-07 |
| ag110 | 1 0800E+01 | 1 0800E+00 | 1 8475E_04 | 1.0300E 07 1.7107E-05 |
| agii0m adii2m | 2 4200E+01 | 9 3600E+00 | 2 7856F-06 | 1.7107E-05 |
| cdl15m | 2.4300E+00 | 8.3000E-02 | 5.7850E-00 | 1.5579E-00 |
| | 0.1100E+00 | 1.3900E-02 | 0.2942E-07 | 7.7011E-08 |
| SHIIYM milli | 1.0800E+03 | 1.9600E-01 | 8.8/53E-00 | 8.21/9E-09 |
| SIII 21 | 1.3500E+01 | 3.9400E-03 | 1.7841E-07 | 1.3216E-08 |
| SNIZIM | 2.4300E+01 | 5.0800E-03 | 2.3003E-07 | 9.4664E-09 |
| SN123 | 1.3500E+01 | 1.1900E+00 | 5.3886E-05 | 3.9916E-06 |
| tel23m | 1.8900E+02 | 4.2000E-02 | 1.90198-06 | 1.0063E-08 |
| sb124 | 1.3500E+01 | 3.0900E-01 | 1.3992E-05 | 1.0365E-06 |
| sb125 | 2.4300E+01 | 2.3500E+01 | 1.0641E-03 | 4.3792E-05 |
| tel25m | 2.4300E+02 | 5.7000E+00 | 2.5811E-04 | 1.0622E-06 |
| sn126 | 8.1100E+00 | 1.4000E-03 | 6.3395E-08 | 7.8169E-09 |
| sb126m | 5.0000E-01 | 1.4000E-03 | 6.3395E-08 | 1.2679E-07 |
| te127 | 1.3500E+01 | 1.1900E+01 | 5.3886E-04 | 3.9916E-05 |
| tel27m | 1.3500E+01 | 1.2100E+01 | 5.4792E-04 | 4.0586E-05 |
| te129 | 1.3500E+01 | 3.3100E-01 | 1.4988E-05 | 1.1103E-06 |
| tel29m | 1.3500E+01 | 5.1700E-01 | 2.3411E-05 | 1.7341E-06 |
| bal37m | 5.0000E-01 | 5.4100E+02 | 2.4498E-02 | 4.8995E-02 |
| ce141 | 1.3500E+01 | 1.5700E+01 | 7.1093E-04 | 5.2662E-05 |
| ce144 | 5.4100E+00 | 6.2600E+03 | 2.8347E-01 | 5.2397E-02 |
| pr144 | 5.0000E-01 | 6.2600E+03 | 2.8347E-01 | 5.6693E-01 |
| pr144m | 5.0000E-01 | 8.7700E+01 | 3.9713E-03 | 7.9425E-03 |

| | A ₂ -Value | Activity | Fraction | Fr/A_2 |
|-------------|-----------------------|--------------|--------------------------|--------------------------------|
| Isotope | [Ci] | [Ci] | [Fr] | [1/Ci] |
| | A _{2i} | Ai | $R_i = A_i / \Sigma A_i$ | R_i/A_{2i} |
| pm146 | 1.3500E+01 | 4.0400E-03 | 1.8294E-07 | 1.3551E-08 |
| pm147 | 2.4300E+01 | 4.2300E+02 | 1.9154E-02 | 7.8825E-04 |
| pm148 | 1.3500E+01 | 1.5100E-02 | 6.8376E-07 | 5.0649E-08 |
| pm148m | 1.3500E+01 | 2.8500E-01 | 1.2905E-05 | 9.5596E-07 |
| sm151 | 1.0800E+02 | 4.5000E+00 | 2.0377E-04 | 1.8868E-06 |
| eu152 | 2.4300E+01 | 7.0700E-03 | 3.2015E-07 | 1.3175E-08 |
| gd153 | 1.3500E+02 | 3.9300E-03 | 1.7796E-07 | 1.3182E-09 |
| eu154 | 1.3500E+01 | 6.1600E+01 | 2.7894E-03 | 2.0662E-04 |
| eu155 | 5.4100E+01 | 8.1700E+01 | 3.6996E-03 | 6.8384E-05 |
| tb160 | 1.3500E+01 | 3.0400E-01 | 1.3766E-05 | 1.0197E-06 |
| sr89 | 1.3500E+01 | 2.0400E+02 | 9.2376E-03 | 6.8427E-04 |
| sr90 | 2.7000E+00 | 5.5500E+02 | 2.5132E-02 | 9.3080E-03 |
| cs134 | 1.3500E+01 | 1.7600E+03 | 7.9697E-02 | 5.9035E-03 |
| cs135 | 2.4300E+01 | 2.4700E-03 | 1.1185E-07 | 4.6028E-09 |
| cs137 | 1.3500E+01 | 5.7300E+02 | 2.5947E-02 | 1.9220E-03 |
| Sum Totals: | ΣΑι | = 2.2084E+04 | $\Sigma R_{i}/2$ | A _{2i} = 1.9238E+00 |
| | | | A _{2fi} | _{nes} = 5.1979E-01 Ci |

A.3.2 Activity Density of Fines

The releasable activity density inside the containment vessel due to the release of fines is described by:

$$C_{\text{fines}} = (A_F \bullet ESA \bullet P \bullet T_F / V_M) \bullet (1/V_C),$$

where:

 A_F is the total number of curies of all radionuclides in an assembly (excluding gases). It is the product of the number of assemblies and the number of curies of the all isotopes (excluding gases) per assembly (i.e., as output by ORIGEN-S) [9.28E+5-Ci],

ESA is the amount of exposed meat surface area per cask [ESA_N= $2.78E+1-cm^2/cask$, ESA_A= $2.78E+2-cm^2/cask$],

- P is the depth of corrosion attack [5.E-04-cm],
- T_F is the oxide spallation fraction [$T_{F,N}$ =0.15, $T_{F,A}$ =1.0]
- V_M is the volume of the meat region of the fuel per cask [1.45E+4-cm³/cask], and
- $V_{\rm C}$ is the free volume of the cask [2.239E+5-cm³].

The releasable activity density inside the containment vessel due to the release of fines is thus:

$$C_{\text{fines},N} = (9.28\text{E}+5\bullet2.78\text{E}+1\bullet5\text{E}-4\bullet0.15/1.45\text{E}+4)\bullet(1/2.239\text{E}+5) = 5.96\text{E}-7 \text{ Ci/cm}^{3}$$

$$C_{\text{fines},A} = (9.28\text{E}+5\bullet2.78\text{E}+2\bullet5\text{E}-4\bullet1.0/1.45\text{E}+4)\bullet(1/2.239\text{E}+5) = 3.97\text{E}-5 \text{ Ci/cm}^{3}$$

A.4 Crud Calculations

The A_2 value for the crud associated with this fuel is provided by Section 5.4 of this report as 0.270 curies. The releasable activity density inside the containment vessel due to the release of fines is described by:

 $C_{crud} = (f_C \bullet S_C \bullet S_A) / V_C,$

where:

- f_C is the crud spallation fraction [f_{C,N}=0.15, f_{C,A}=1.0],
- S_C is the crud surface activity [1.39E-7 Ci/cm²],
- S_A is the sum of the surface areas of all assemblies [8.81E+5-cm²], and
- V_C is the free volume of the cask [2.239E+5-cm³].

The releasable activity density inside the containment vessel due to the release of fines is thus:

$$C_{crud,N} = (0.15 \cdot 1.39E \cdot 7 \cdot 8.81E + 5)/2.239E + 5 = 8.21E \cdot 8$$

 $C_{crud,A} = (1.0 \cdot 1.39E \cdot 7 \cdot 8.81E + 5)/2.239E + 5 = 5.47E \cdot 7$

A.5 Combining the Sources of Radioactive Material in the Cask Free Volume

The contributions to the total activity density in the shipping cask free volume from the four sources are combined by:

$$C_{\text{total}} = C_{\text{gas}} + C_{\text{vol}} + C_{\text{fines}} + C_{\text{crud}},$$

 C_{total} is the total releasable activity density inside the containment vessel [Ci/cm³],

- C_{gas} is the releasable activity density inside the containment vessel due to the release of gas [$C_{gas,N}$ = 3.69E-4 Ci/cm³, $C_{gas,A}$ = 1.23E-2 Ci/cm³],
- C_{vol} is the releasable activity density inside the containment vessel due to the release of volatiles [$C_{vol,N}$ = 5.80E-8 Ci/cm³, $C_{vol,A}$ = 5.80E-7 Ci/cm³],
- C_{fines} is the releasable activity density inside the containment vessel due to the release of fines [$C_{\text{fines},N}$ = 5.96E-7 Ci/cm³, $C_{\text{fines},A}$ = 3.97E-5 Ci/cm³], and
- C_{crud} is the releasable activity density inside the containment vessel as a result of crud spallation [$C_{crud,N}$ = 8.21E-8 Ci/cm³, $C_{crud,A}$ = 5.47E-7 Ci/cm³].

The total releasable activity density inside the containment vessel due to the release of gases, volatiles, fines, and crud is thus:

$$C_{total,N} = C_N = 3.69E-4 + 5.80E-8 + 5.96E-7 + 8.21E-8 = 3.70E-4 \text{ Ci/cm}^3$$

 $C_{total,A} = C_A = 1.23E-2 + 5.80E-7 + 3.97E-5 + 5.47E-7 = 1.23E-2 \text{ Ci/cm}^3$

The mixture A_2 values derived previously are combined to determine a group A_2 for normal and accident conditions of transport, respectively, using the following equation.

$$A_2 = (\sum (F_i / A_{2i}))^{-1},$$

where:

- F_i is the fraction activity density of contributor *i* (i.e., gas, volatiles, fines, or crud) in the mixture and
- A_{2i} is the appropriate A_2 value for mixture *i*.

The mixture A₂ value for gases is calculated in the following table.

| Source | A ₂ -Value [Ci] A _{2i} | Concentration [Ci/cm ³] C _i | Fraction [Fr] $F_i=F_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] F _i /A _{2i} |
|-------------|--|--|--|--|
| Gas | 2.7742E+02 | 3.6881E-04 | 9.9801E-01 | 3.5975E-03 |
| Volatiles | 7.8581E+00 | 5.8001E-08 | 1.5695E-04 | 1.9973E-05 |
| Fines | 5.1979E-01 | 5.9567E-07 | 1.6119E-03 | 3.1010E-03 |
| Crud | 2.6990E-01 | 8.2071E-08 | 2.2208E-04 | 8.2284E-04 |
| Sum Totals: | ΣC | i= 3.6955E-04 | $\Sigma F_{i}/2$ | A _{2i} = 7.5413E-03 |
| | | | Group A | _{2,N} = 1.3260E+02 Ci |

 Table A.4
 Normal Conditions of Transport

| Source | A ₂ -Value [Ci] A _{2i} | Concentration [Ci/cm ³] C _i | Fraction [Fr] $F_i=F_i/\Sigma A_i$ | Fr/A_2 [1/Ci] F_i/A_{2i} |
|-------------|--|--|--|------------------------------|
| Gas | 2.7742E+02 | 1.2294E-02 | 9.9669E-01 | 3.5927E-03 |
| Volatiles | 7.8581E+00 | 5.8001E-07 | 4.7023E-05 | 5.9841E-06 |
| Fines | 5.1979E-01 | 3.9711E-05 | 3.2195E-03 | 6.1938E-03 |
| Crud | 2.6990E-01 | 5.4714E-07 | 4.4358E-05 | 1.6435E-04 |
| Sum Totals: | ΣC_{i} | = 1.2335E-02 | $\Sigma F_{i}/2$ | A _{2i} = 9.9569E-03 |
| | | | Group A | • →= 1.0043E+02 Ci |

 Table A.5
 Accident Conditions of Transport

A.6 Maximum Permissible Release Rate and Maximum Permissible Leakage Rate

Assuming that the release rate is independent of time, the maximum permissible release rates for normal and accident conditions of transport, respectively, can be expressed as follows:

$$\begin{split} R_{N} &= A_{2,N} \; x \; 2.78 x 10^{^{-10}} \, / \text{second}, \\ R_{A} &= A_{2,A} \; x \; 1.65 x 10^{^{-6}} \, / \text{second}, \end{split}$$

where:

- R_i is the release rate for normal (R_N) and accident (R_A) conditions of transport [Ci/s] and
- $A_{2,i}$ is the mixture A_2 of the radionuclides available for release under normal $A_{2,N}$ and $A_{2,A}$ accident conditions of transport [$A_{2,N}$ = 132.6 Ci, $A_{2,A}$ = 100.4 Ci].

The maximum permissible release rate for normal and accident conditions of transport are thus:

 $\begin{array}{ll} R_{N} = 132.6 \; x \; 2.78 x 10^{-10} & = 3.69 E{\text -}8 \; Ci/s \\ R_{A} = 100.4 \; x \; 1.65 x 10^{-6} & = 1.66 E{\text -}4 \; Ci/s \end{array}$

The maximum permissible leakage rate is given by:

 $L_{\rm N} = R_{\rm N}/C_{\rm N},$ $L_{\rm A} = R_{\rm A}/C_{\rm A},$

where:

- L_i is the volumetric gas leakage rate or maximum permissible leakage rate [cm³/s] under normal (L_N) and accident (L_A) conditions of transport,
- R_i is the release rate for normal (R_N) and accident (R_A) conditions of transport calculated above [R_N = 3.69E-8 Ci/s, R_A = 1.66E-4 Ci/s], and
- C_i is the curies per unit volume of the radioactive material, "activity density", that passes through the leak path for normal (C_N) and accident (C_A) conditions of transport [C_N = 3.70E-4 Ci/cm³, C_A = 1.23E-2 Ci/cm³].

Substitution of the appropriate values into the previous equation gives:

 $L_N = 3.69E-8/3.70E-4 = 9.97E-5 \text{ cm}^3/\text{s}$ $L_A = 1.66E-4/1.23E-2 = 1.34E-2 \text{ cm}^3/\text{s}$

A.7 Permissible Leak Rate at Standard Conditions

A.7.1 Normal Conditions of Transport

The volumetric gas leak rate is modeled as a combination of continuum and molecular flow through a single leak path. The leak path is modeled as a smooth, right-circular cylinder with sharp edges. Based on these assumptions, the equation for gas leaking from the cask takes the following form.

 $\mathbf{L} = \mathbf{L}_{\mathrm{c}} + \mathbf{L}_{\mathrm{m}},$

where:

- L is the volumetric gas flow rate at P_u [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec], and
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].

The volumetric flow rate, L_c, for continuum flow is given by

$$L_c = (2.49 \times 10^6 \text{ D}^4)/a\mu \cdot (P_u - P_d)(P_a/P_u),$$

where:

- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- D is the capillary diameter [cm],
- a is the capillary length [1-cm] (typically found in the SAR of a given cask),
- μ is the fluid viscosity [0.02736-cP] (typically found in CRC Handbook),
- P_u is the upstream pressure [1.99-atm] (typically found in the SAR of a given cask),
- P_d is the downstream pressure [1-atm], and
- P_a is the average pressure, $(P_u P_d)/2$ [1.495-atm].

The volumetric flow rate, L_m, for molecular flow is given by

$$L_{\rm m} = (3.81 \times 10^3 {\rm D}^3 {\rm (T/M)^{0.5}}) / a {\rm P}_{\rm a} \bullet ({\rm P}_{\rm u} - {\rm P}_{\rm d}) ({\rm P}_{\rm a} / {\rm P}_{\rm u}),$$

where:

- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [1-cm],
- T is the gas temperature [474-K] (typically found in the SAR of a given cask),
- M is the gas molecular weight [4-g/mole] (typically found in CRC Handbook),
- a is the capillary length [1-cm] (typically found in SAR for given cask),
- P_a is the average pressure, $(P_u P_d)/2$ [1.495-atm],
- P_u is the upstream pressure [1.99-atm] (typically found in the SAR of a given cask), and
- P_d is the downstream pressure [1-atm].

The volumetric gas flow rate at the upstream pressure is therefore given by:

$$\begin{split} L_{N} &= \left\{ (2.49 \times 10^{6} \cdot D^{4}) / (1 \cdot 0.02736) + (3.81 \times 10^{3} \cdot D^{3} (474/4)^{0.5}) / (1 \cdot 1.495) \right\} \bullet \\ &\qquad (1.99 - 1) (1.495 / 1.99) \\ L_{N} &= \left\{ 9.10 E + 7 \cdot D^{4} + 2.77 E + 4 \cdot D^{3} \right\} (0.74) \\ L_{N} &= 6.73 E + 7 \cdot D^{4} + 2.05 E + 4 \cdot D^{3} \end{split}$$

Substituting $L_N = 9.97E-5-cm^3/s$ and solving for D yields a capillary diameter of 1.033E-3-cm.

To correlate the maximum permissible leak rate above to the leak rate at standard temperature and pressure, the following calculation is made.

$$L_{R,N} = L_c + L_m = \left\{ (2.49 \times 10^6 \text{ D}^4)/a\mu + (3.81 \times 10^3 \text{D}^3 (\text{T/M})^{0.5})/aP_a \right\} \bullet (P_u - P_d)(P_a/P_u),$$

where:

- $L_{R,N}$ is the volumetric leakage rate at standard conditions correlating to normal conditions of transport [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [1.033E-3 cm],
- a is the capillary length [1-cm] (typically found in the SAR of a given cask),
- μ is the fluid viscosity [0.018494-cP] (typically found in CRC Handbook),
- P_u is the upstream pressure [1-atm],
- P_d is the downstream pressure [0.01-atm],
- P_a is the average pressure, $(P_u P_d)/2$ [0.505-atm],
- T is the gas temperature [298-K], and
- M is the gas molecular weight [29-g/mole] (typically found in CRC Handbook).

The volumetric leakage rate at the standard conditions is therefore given by:

$$L_{R,N} = \{(2.49 \times 10^{6} \cdot (1.033 \text{E} \cdot 3)^{4})/(1 \cdot 0.018494) + (3.81 \times 10^{3} \cdot (1.033 \text{E} \cdot 3)^{3} \cdot (298/29)^{0.5})/(1 \cdot 0.505)\} \cdot (1 - 0.01)(0.505/1)$$

$$L_{R,N} = \{1.53 \text{E} \cdot 4 + 2.66 \text{E} \cdot 5\}(0.50)$$

$$L_{R,N} = 8.99 \text{E} \cdot 5 \text{ cm}^{3}/\text{s}$$

A.7.2 Accident Conditions of Transport

The volumetric gas leak rate is modeled as a combination of continuum and molecular flow through a single leak path. The leak path is modeled as a smooth, right-circular cylinder with sharp edges. Based on these assumptions, the equation for gas leaking from the cask takes the following form.

 $\mathbf{L} = \mathbf{L}_{\mathrm{c}} + \mathbf{L}_{\mathrm{m}},$

where:

- L is the volumetric gas flow rate at P_u [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec], and
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].

The volumetric flow rate, L_c, for continuum flow is given by

$$L_{c} = [(2.49 \times 10^{6} \text{ D}^{4})/a\mu] \bullet (P_{u} - P_{d})(P_{a}/P_{u}),$$

where:

- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- D is the capillary diameter [cm],
- a is the capillary length [1-cm] (typically found in the SAR of a given cask),
- μ is the fluid viscosity [0.03129-cP] (typically found in CRC Handbook),
- P_u is the upstream pressure [11.4-atm] (typically found in the SAR of a given cask),
- P_d is the downstream pressure [1-atm], and
- P_a is the average pressure, $(P_u P_d)/2$ [6.2-atm].

The volumetric flow rate, L_m, for molecular flow is given by

$$L_{\rm m} = \left[(3.81 \times 10^3 {\rm D}^3 {\rm (T/M)^{0.5}}) / {\rm aP_a} \right] \bullet ({\rm P_u} - {\rm P_d}) ({\rm P_a} / {\rm P_u}),$$

where:

- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [cm],
- T is the gas temperature [574-K] (typically found in the SAR of a given cask),
- M is the gas molecular weight [4-g/mole] (typically found in CRC Handbook),
- a is the capillary length [1-cm] (typically found in the SAR of a given cask),
- P_a is the average pressure, $(P_u P_d)/2$ [6.2-atm],
- P_u is the upstream pressure [11.4-atm] (typically found in the SAR of a given cask), and

P_d is the downstream pressure [1-atm].

The volumetric gas flow rate at the upstream pressure is therefore given by:

$$L_{A} = \{(2.49 \times 10^{6} \cdot D^{4})/(1 \cdot 0.03129) + (3.81 \times 10^{3} \cdot D^{3}(574/4)^{0.5})/(1 \cdot 6.2)\} \cdot (11.4 - 1)(6.2/11.4)$$

$$L_{A} = \{7.96 E + 7 \cdot D^{4} + 7.36 E + 3 \cdot D^{3}\}(5.66)$$

$$L_{A} = 4.50 E + 8 \cdot D^{4} + 4.16 E + 4 \cdot D^{3}$$

Substituting $L_A = 1.34E-2$ -cm³/s and solving for D yields a capillary diameter of 2.315E-3-cm.

To correlate the maximum permissible leak rate above to the leak rate at standard temperature and pressure, the following calculation is made.

$$L_{R,A} = L_c + L_m = \left\{ (2.49 \times 10^6 \text{ D}^4)/a\mu + (3.81 \times 10^3 \text{D}^3(\text{T/M})^{0.5})/aP_a \right\} \bullet (P_u - P_d)(P_a/P_u),$$

where:

- $L_{R,A}$ is the volumetric leakage rate at standard conditions correlating to accident conditions of transport [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [2.315E-3 cm],
- a is the capillary length [1-cm] (typically found in the SAR of a given cask),
- μ is the fluid viscosity [0.018494-cP] (typically found in CRC Handbook),
- P_u is the upstream pressure [1-atm],
- P_d is the downstream pressure [0.01-atm],
- P_a is the average pressure, $(P_u P_d)/2$ [0.505-atm],
- T is the gas temperature [298-K], and
- M is the gas molecular weight [29-g/mole] (typically found in CRC Handbook).

The volumetric leakage rate at the standard conditions is therefore given by:

$$\begin{split} L_{R,A} &= \Big\{ (2.49 \times 10^{6} \cdot (2.315 \text{E} \cdot 3)^{4}) / (1 \cdot 0.018494) + \\ &\quad (3.81 \times 10^{3} \cdot (2.315 \text{E} \cdot 3)^{3} \cdot (298/29)^{0.5}) / (1 \cdot 0.505) \Big\} \cdot \\ &\quad (1 - 0.01) (0.505/1) \\ L_{R,A} &= \Big\{ 3.86 \text{E} \cdot 3 + 3.00 \text{E} \cdot 4 \Big\} (0.50) \\ L_{R,A} &= 2.08 \text{E} \cdot 3 \text{ cm}^{3} / \text{s} \end{split}$$

B.0 EXAMPLE CALCULATION #2

There are four sources of radioactive material that may become airborne during transportation. These sources are gases, volatiles, fines, and crud. The contributions to the total activity density in the shipping cask free volume from the four sources are treated separately. Therefore, the A_2 values of the four sources are determined separately. Following is an example calculation for Example Cask #2 fully loaded with Example Fuel #2. Because the total quantity of krypton-85 in the cask is less than 10•A₂, the special requirement pertaining to krypton-85 release does not impact this analysis. Although the regulation allows us to use 10 A_2 , we are using A_2 in this calculation.

B.1 Gas Calculations

B.1.1 Activity Values for Gases

 A_2 values for the fuel gases are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendices. The A_2 value for mixtures of isotopes is calculated from:

$$A_2 = (\sum (R_i/A_{2i}))^{-1},$$

where:

- R_i is the fraction activity of nuclide *i* in the mixture and
- A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for gases. The mixture A_2 value for gases is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] $R_i=A_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|-------------|--|------------------------------------|--|--|
| h3 | 1.0800E+03 | 1.1100E-02 | 2.0709E-04 | 1.9175E-07 |
| h3 | 1.0800E+03 | 1.8900E+00 | 3.5260E-02 | 3.2649E-05 |
| kr85 | 2.7000E+02 | 5.1700E+01 | 9.6453E-01 | 3.5723E-03 |
| Sum Totals: | ΣΑ, | = 5.3601E+01 | $\Sigma R_{i}/2$ | A _{2i} = 3.6052E-03 |
| | | | A ₂ | _{gas} = 2.7738E+02 Ci |

 Table B.1 Mixture A2 Determination for Gases (per assembly)

B.1.2 Activity Density of Gases

The releasable activity density inside the containment vessel due to the release of gas is described by:

$$C_{gas} = (A_G \bullet f_b \bullet f_G) / V_C,$$

where:

- A_G A_G is the total number of curies of all gaseous radionuclides in all assemblies in the cask. It is the product of the number of assemblies and the number of curies of all gaseous isotopes per assembly (i.e., as output by ORIGEN-S) (i.e., as output by ORIGEN-S) [1.77E+3-Ci],
- f_b is the fraction of fuel assemblies that are breached in a cask [$f_{b,N}$ =0.1, $f_{b,A}$ =1.0],
- f_G is the fraction of gas that escapes the breached fuel assembly [$f_{G,N}$ =0.3, $f_{G,A}$ =1.0],
- V_C is the free volume of the cask [2.27E+5-cm³],

The releasable activity density inside the containment vessel due to the release of gas is thus:

 $C_{gas,N} = (1.77E+3 \cdot 0.1 \cdot 0.3)/2.27E+5 = 2.34E-4 \text{ Ci/cm}^3$ $C_{gas,A} = (1.77E+3 \cdot 1.0 \cdot 1.0)/2.27E+5 = 7.79E-3 \text{ Ci/cm}^3$

B.2 Volatile Calculations

B.2.1 Activity Values for Volatiles

 A_2 values for the fuel volatiles are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

$$A_2 = (\sum (R_i/A_{2i}))^{-1},$$

where:

R_i is the fraction activity of nuclide *i* in the mixture and

 A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for volatiles. The mixture A_2 value for volatiles is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] $R_i=A_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|-------------|--|------------------------------------|--|--|
| sr89 | 1.3500E+01 | 1.7400E+00 | 1.0723E-03 | 7.9427E-05 |
| sr90 | 2.7000E+00 | 4.7300E+02 | 2.9148E-01 | 1.0796E-01 |
| cs134 | 1.3500E+01 | 6.6500E+02 | 4.0980E-01 | 3.0356E-02 |
| cs135 | 2.4300E+01 | 2.2100E-03 | 1.3619E-06 | 5.6045E-08 |
| cs137 | 1.3500E+01 | 4.8300E+02 | 2.9764E-01 | 2.2048E-02 |
| Sum Totals: | ΣA_j | = 1.6227E+03 | $\Sigma R_i/I$ | A _{2i} = 1.6044E-01 |
| | | | A2 | _{vol} = 6.2329E+00 Ci |

 Table B.2 Mixture A₂ Determination for Volatiles (per assembly)

B.2.2 Activity Density of Volatiles

The releasable activity density inside the containment vessel due to the release of volatiles is described by:

$$C_{\rm vol} = (A_{\rm V} \bullet f_{\rm b} \bullet f_{\rm V}) / V_{\rm C},$$

where:

- A_V is the total number of curies of all volatile radionuclides in all assemblies in the cask. It is the product of the number of assemblies and the number of curies of all volatile isotopes per assembly (i.e., as output by ORIGEN-S) [5.35E+4-Ci],
- f_b is the fraction of fuel assemblies that are breached in a cask $[f_{b,N}=0.1, f_{b,A}=1.0],$
- f_V is the fraction of volatiles that escapes the breached fuel assembly [$f_{V,N}=f_{V,A}=1E-6$],
- $V_{\rm C}$ is the free volume of the cask [2.27E+5-cm³],

The releasable activity density inside the containment vessel due to the release of volatiles is thus:

$$C_{vol,N} = (5.35E+4.0.1.1E-6)/2.27E+5 = 2.36E-8 \text{ Ci/cm}^3$$

 $C_{vol,A} = (5.35E+4.1.0.1E-6)/2.27E+5 = 2.36E-7 \text{ Ci/cm}^3$

B.3 Fines Calculations

B.3.1 Activity Values for Fines

 A_2 values for the fuel fines are derived from the values provided in Appendix A, Table A-1 of 10CFR71. The A_2 values for those isotopes for which no specific A_2 value is specified are determined using the guidance provided in the appendix. The A_2 value for mixtures of isotopes is calculated from:

 $A_2 = (\sum (R_i / A_{2_i}))^{-1},$

where:

- R_i is the fraction activity of nuclide *i* in the mixture and
- A_{2i} is the appropriate A_2 value for nuclide *i*.

A mixture A_2 is determined by the previous equation for fines. The mixture A_2 value for fines is calculated in the following table.

| Isotope | A ₂ -Value [Ci] A _{2i} | Activity [Ci] A _i | Fraction [Fr] R _i =A _i /ΣA _i | Fr/A ₂ [1/Ci] R _i /A _{2i} |
|---------|--|------------------------------------|---|--|
| mn54 | 2.7000E+01 | 3.5300E-02 | 3.9783E-06 | 1.4734E-07 |
| pa233 | 2.4300E+01 | 6.8100E-03 | 7.6748E-07 | 3.1584E-08 |
| u236 | 2.7000E-02 | 3.4700E-03 | 3.9107E-07 | 1.4484E-05 |
| u237 | 5.0000E-01 | 2.4800E-03 | 2.7950E-07 | 5.5899E-07 |
| np237 | 5.4100E-03 | 6.8100E-03 | 7.6748E-07 | 1.4186E-04 |

Table B.3Mixture A2 Determination for Fines (per assembly)

| | AValue | Activity | Fraction | Fr / A |
|------------|--------------------------|--------------------------|--|------------------------------------|
| Tsotope | | [Ci] | [Fr] | [1/Ci] |
| тросоре | | A, | $\mathbf{R} = \mathbf{A} \cdot / \mathbf{\Sigma} \mathbf{A} \cdot$ | $\mathbf{R}_{i} / \mathbf{A}_{2i}$ |
| nn239 | 1 3500E+01 | 7 3000E-03 | 8 2271E-07 | 6 0941E-08 |
| np235 | 1 8900E-02 | 7.9000E-04 | 8 9033E-08 | 4 7107E-06 |
| pu238 | 5 4100E-03 | 4 1300E+01 | 4 6545E-03 | 8 6035E-01 |
| pu230 | 5.4100E-03 | 2 7300E-01 | 3.0767E-05 | 5 6871E-03 |
| pu239 | 5.4100E-03 | 1 0800E-01 | 1 2172E = 05 | 2 2498E-03 |
| 241 | 2 7000E-01 | 1.0000E+02 | 1.1721E-02 | 4 3410E-02 |
| am241 | 5 4100E-03 | 3 6200E-01 | 4 0797E - 05 | 7 5411E-03 |
| am242m | 5 4100E-03 | 1 7300E-03 | 1.0797E - 07 | 3 6039E-05 |
| am242 | 5.0000E-01 | 1.7200E-03 | 1.9384E-07 | 3.8769E-07 |
| am243 | 5.4100E-03 | 7.3000E-03 | 8.2271E-07 | 1.5207E-04 |
| cm242 | 2.7000E-01 | 2.1500E-01 | 2.4230E-05 | 8.9742E-05 |
| cm243 | 8.1100E-03 | 2.4100E-03 | 2.7161E-07 | 3.3490E-05 |
| cm244 | 1.0800E-02 | 9.3800E-01 | 1.0571E-04 | 9.7882E-03 |
| se79 | 5.4100E+01 | 3.2500E-03 | 3.6627E-07 | 6.7703E-09 |
| v89m | 5.4100E+01 | 1.6200E-04 | 1.8257E-08 | 3.3747E-10 |
| v90 | 5.4100E+00 | 4.7300E+02 | 5.3307E-02 | 9.8534E-03 |
| v91 | 8.1100E+00 | 7.8500E+00 | 8.8469E-04 | 1.0909E-04 |
| zr93 | 5.4100E+00 | 6.4500E-03 | 7.2691E-07 | 1.3436E-07 |
| zr95 | 2.4300E+01 | 1.7500E+01 | 1.9722E-03 | 8.1162E-05 |
| nb95 | 2.7000E+01 | 3.9700E+01 | 4.4742E-03 | 1.6571E-04 |
| nb95m | 2.4300E+01 | 2.0500E-01 | 2.3103E-05 | 9.5076E-07 |
| tc99 | 2.4300E+01 | 5.8800E-02 | 6.6267E-06 | 2.7271E-07 |
| ru103 | 2.4300E+01 | 6.7500E-02 | 7.6072E-06 | 3.1305E-07 |
| rh103m | 1.0800E+03 | 6.7400E-02 | 7.5960E-06 | 7.0333E-09 |
| ru106 | 5.4100E+00 | 2.7200E+02 | 3.0654E-02 | 5.6662E-03 |
| rh106 | 5.0000E-01 | 2.7200E+02 | 3.0654E-02 | 6.1309E-02 |
| ag110 | 2.4400E+01 | 8.2200E-03 | 9.2639E-07 | 3.7967E-08 |
| ag110m | 1.0800E+01 | 6.0500E-01 | 6.8183E-05 | 6.3133E-06 |
| cd113m | 2.4300E+00 | 5.4400E-02 | 6.1309E-06 | 2.5230E-06 |
| cd115m | 8.1100E+00 | 5.0900E-05 | 5.7364E-09 | 7.0733E-10 |
| sn119m | 1.0800E+03 | 4.7700E-02 | 5.3758E-06 | 4.9776E-09 |
| sn121 | 1.3500E+01 | 3.1600E-03 | 3.5613E-07 | 2.6380E-08 |
| sn121m | 2.4300E+01 | 4.0800E-03 | 4.5981E-07 | 1.8922E-08 |
| sn123 | 1.3500E+01 | 1.7300E-01 | 1.9497E-05 | 1.4442E-06 |
| tel23m | 1.8900E+02 | 1.3300E-03 | 1.4989E-07 | 7.9307E-10 |
| sb124 | 1.3500E+01 | 2.4700E-03 | 2.7837E-07 | 2.0620E-08 |
| sb125 | 2.4300E+01 | 1.5800E+01 | 1.7807E-03 | 7.3278E-05 |
| tel25m | 2.4300E+02 | 3.8500E+00 | 4.3389E-04 | 1./856E-06 |
| sn126 | 8.1100E+00 E 0000E 01 | 1.1500E-03 | 1.2960E-07 | 1.5981E-08 |
| SD12000 | 5.0000E-01 | 1.1500E-03 | 1.2960E-07 | 2.592IE-07 |
| te127 | 1.3500E+01 | 1.2200E+00 | 1.3749E-04 1 4087E-04 | 1.0105E-05 |
| to129 | 1 3500E+01 | 2.3500E+00 | 2.6484E-08 | 1 96195-00 |
| te129m | 1 3500E+01 | 2.5500E 04 3 6600F-04 | 2.0404E 00 4 1248F-08 | 3 0554F-09 |
| ba137m | 5 0000E-01 | 4 5600E+02 | 5 1391E-02 | 1.0278E-01 |
| ce141 | 1 3500E+01 | 8 9600E-03 | 1 0098E-06 | 7 4799E-08 |
| ce144 | 5.4100E+00 | 2.4500E+03 | 2.7611E-01 | 5.1038E-02 |
| pr144 | 5.0000E-01 | 2.4500E+03 | 2.7611E-01 | 5.5223E-01 |
| pr144m | 5.0000E-01 | 3.4200E+01 | 3.8543E-03 | 7.7087E-03 |
| pm146 | 1.3500E+01 | 2.0000E-03 | 2.2540E-07 | 1.6696E-08 |
| pm147 | 2.4300E+01 | 5.3200E+02 | 5.9956E-02 | 2.4673E-03 |

| | A_2 -Value | Activity | Fraction | Fr/A_2 |
|-------------|--------------|--------------|--------------------------|--------------------------------|
| Isotope | [Ci] | [Ci] | [Fr] | [1/Ci] |
| | A_{2i} | A_i | $R_i = A_i / \Sigma A_i$ | R_i/A_{2i} |
| pm148 | 1.3500E+01 | 5.5200E-05 | 6.2210E-09 | 4.6082E-10 |
| pm148m | 1.3500E+01 | 1.0400E-03 | 1.1721E-07 | 8.6821E-09 |
| sm151 | 1.0800E+02 | 4.7200E+00 | 5.3194E-04 | 4.9254E-06 |
| eu152 | 2.4300E+01 | 7.9200E-03 | 8.9258E-07 | 3.6732E-08 |
| gd153 | 1.3500E+02 | 3.7200E-04 | 4.1924E-08 | 3.1055E-10 |
| eu154 | 1.3500E+01 | 3.5300E+01 | 3.9783E-03 | 2.9469E-04 |
| eu155 | 5.4100E+01 | 3.5400E+01 | 3.9896E-03 | 7.3744E-05 |
| tb160 | 1.3500E+01 | 2.7400E-03 | 3.0880E-07 | 2.2874E-08 |
| sr89 | 1.3500E+01 | 1.7400E+00 | 1.9610E-04 | 1.4526E-05 |
| sr90 | 2.7000E+00 | 4.7300E+02 | 5.3307E-02 | 1.9743E-02 |
| cs134 | 1.3500E+01 | 6.6500E+02 | 7.4945E-02 | 5.5515E-03 |
| cs135 | 2.4300E+01 | 2.2100E-03 | 2.4907E-07 | 1.0250E-08 |
| cs137 | 1.3500E+01 | 4.8300E+02 | 5.4434E-02 | 4.0321E-03 |
| Sum Totals: | ΣΑι | = 8.8731E+03 | $\Sigma R_{i}/2$ | A _{2i} = 1.7527E+00 |
| | | | A _{2fi} | _{nes} = 5.7054E-01 Ci |

B.3.2 Activity Density of Fines

The releasable activity density inside the containment vessel due to the release of fines is described by:

$$C_{\text{fines}} = (A_F \bullet ESA \bullet P \bullet T_F / V_M) \bullet (1 / V_C),$$

where:

- A_F is the total number of curies of all radionuclides in all assemblies in the cask (excluding gases). It is the product of the number of assemblies and the number of curies of the all isotopes (excluding gases) per assembly (i.e., as output by ORIGEN-S) [2.93E+5-Ci],
- ESA is the amount of exposed meat surface area per cask [ESA_N= $2.66E+1-cm^2/cask$, ESA_A= $2.66E+2-cm^2/cask$],
- P is the depth of corrosion attack [5.E-04-cm],
- T_F is the oxide spallation fraction [$T_{F,N}=0.15$, $T_{F,A}=1.0$]
- V_M is the volume of the meat region of the fuel per cask [1.56E+4-cm³/cask], and
- $V_{\rm C}$ is the free volume of the cask [2.27E+5-cm³].

The releasable activity density inside the containment vessel due to the release of fines is thus:

$$\begin{split} C_{\text{fines},\text{N}} &= (2.93\text{E}+5\bullet2.66\text{E}+1\bullet5\text{E}-4\bullet0.15/1.56\text{E}+4)\bullet(1/2.27\text{E}+5) &= 1.65\text{E}-7 \text{ Ci/cm}^3\\ C_{\text{fines},\text{A}} &= (2.93\text{E}+5\bullet2.66\text{E}+2\bullet5\text{E}-4\bullet1.0/1.56\text{E}+4)\bullet(1/2.27\text{E}+5) &= 1.10\text{E}-5 \text{ Ci/cm}^3 \end{split}$$

B.4 Crud Calculations

The A_2 value for the crud associated with this fuel is provided by Section 5.4 of this report as 0.270 curies. The releasable activity density inside the containment vessel due to the release of fines is described by:

 $C_{crud} = (f_C \bullet S_C \bullet S_A) / V_C,$

where:

- f_C is the crud spallation fraction [$f_{C,N}=0.15$, $f_{C,A}=1.0$],
- S_C is the crud surface activity [1.39E-7 Ci/cm²],
- S_A is the sum of the surface areas of all assemblies [1.03E+6-cm²], and
- V_C is the free volume of the cask [2.27E+5-cm³].

The releasable activity density inside the containment vessel due to the release of fines is thus:

$$C_{crud,N} = (0.15 \cdot 1.39E \cdot 7 \cdot 1.03E + 6)/2.27E + 5 = 9.45E \cdot 8$$

$$C_{crud,A} = (1.0 \cdot 1.39E \cdot 7 \cdot 1.03E + 6)/2.27E + 5 = 6.30E \cdot 7$$

B.5 Combining the Sources of Radioactive Material in the Cask Free Volume

The contributions to the total activity density in the shipping cask free volume from the four sources are combined by:

$$C_{total} = C_{gas} + C_{vol} + C_{fines} + C_{crud},$$

- C_{total} is the total releasable activity density inside the containment vessel [Ci/cm³],
- C_{gas} is the releasable activity density inside the containment vessel due to the release of gas [$C_{gas,N}$ = 2.34E-4 Ci/cm³, $C_{gas,A}$ = 7.79E-3 Ci/cm³],
- C_{vol} is the releasable activity density inside the containment vessel due to the release of volatiles [$C_{vol,N}$ = 2.36E-8 Ci/cm³, $C_{vol,A}$ = 2.36E-7 Ci/cm³],
- C_{fines} is the releasable activity density inside the containment vessel due to the release of fines [$C_{\text{fines},N}$ = 1.65E-7 Ci/cm³, $C_{\text{fines},A}$ = 1.10E-5 Ci/cm³], and
- C_{crud} is the releasable activity density inside the containment vessel as a result of crud spallation [$C_{crud,N}$ = 9.45E-8 Ci/cm³, $C_{crud,A}$ = 6.30E-7 Ci/cm³].

The total releasable activity density inside the containment vessel due to the release of gases, volatiles, fines, and crud is thus:

$$\begin{split} C_{total,N} &= C_N = 2.34\text{E-}4 + 2.36\text{E-}8 + 1.65\text{E-}7 + 9.45\text{E-}8 = 2.34\text{E-}4 \text{ Ci/cm}^3 \\ C_{total,A} &= C_A = 7.79\text{E-}3 + 2.36\text{E-}7 + 1.10\text{E-}5 + 6.30\text{E-}7 = 7.80\text{E-}3 \text{ Ci/cm}^3 \end{split}$$

The mixture A_2 values derived previously are combined to determine a group A_2 for normal and accident conditions of transport, respectively, using the following equation.

$$A_2 = (\sum (F_i / A_{2i}))^{-1},$$

where:

- F_i is the fraction activity density of contributor *i* (i.e., gas, volatiles, fines, or crud) in the mixture and
- A_{2i} is the appropriate A_2 value for mixture *i*.

The mixture A₂ value for gases is calculated in the following table.

| Source | A ₂ -Value [Ci] A _{2i} | Concentration [Ci/cm ³] C _i | Fraction [Fr] $F_i=F_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] F _i /A _{2i} |
|-------------|--|--|--|--|
| Gas | 2.7738E+02 | 2.3377E-04 | 9.9879E-01 | 3.6008E-03 |
| Volatiles | 6.2329E+00 | 2.3591E-08 | 1.0079E-04 | 1.6171E-05 |
| Fines | 5.7054E-01 | 1.6503E-07 | 7.0513E-04 | 1.2359E-03 |
| Crud | 2.6990E-01 | 9.4507E-08 | 4.0379E-04 | 1.4961E-03 |
| Sum Totals: | $\Sigma C_i = 2.3405E-04$ $\Sigma F_i / A_{2i} = 6.3490E-03$ | | | |
| | | | Group A | _{2,N} = 1.5751E+02 Ci |

 Table B.4
 Normal Conditions of Transport

 Table B.5
 Accident Conditions of Transport

| Source | A ₂ -Value [Ci] A _{2i} | Concentration [Ci/cm ³] C _i | Fraction [Fr] $F_i=F_i/\Sigma A_i$ | Fr/A ₂ [1/Ci] F _i /A _{2i} |
|-------------|--|--|--|--|
| Gas | 2.7738E+02 | 7.7922E-03 | 9.9848E-01 | 3.5997E-03 |
| Volatiles | 6.2329E+00 | 2.3591E-07 | 3.0228E-05 | 4.8498E-06 |
| Fines | 5.7054E-01 | 1.1002E-05 | 1.4098E-03 | 2.4710E-03 |
| Crud | 2.6990E-01 | 6.3004E-07 | 8.0732E-05 | 2.9912E-04 |
| Sum Totals: | $\Sigma C_{i} = 7.8041E - 03$ | | $\Sigma F_{i}/A_{2i} = 6.3747E-03$ | |
| | | | Group A | _{2,A} = 1.5687E+02 Ci |

B.6 Maximum Permissible Release Rate and Maximum Permissible Leakage Rate

Assuming that the release rate is independent of time, the maximum permissible release rates for normal and accident conditions of transport, respectively, can be expressed as follows:

 $R_{N} = A_{2,N} \ge 2.78 \times 10^{-10}$ /second, $R_{A} = A_{2,A} \ge 1.65 \times 10^{-6}$ /second,

where:

- R_i is the release rate for normal (R_N) and accident (R_A) conditions of transport [Ci/s] and
- $A_{2,i}$ is the mixture A_2 of the radionuclides available for release under normal $A_{2,N}$ and $A_{2,A}$ accident conditions of transport [$A_{2,N}$ = 157.5 Ci, $A_{2,A}$ = 156.9 Ci].

The maximum permissible release rate for normal and accident conditions of transport are thus:

 $\begin{array}{ll} R_{N} = 157.5 \ x \ 2.78 x 10^{-10} & = 4.38 E\text{--}8 \ Ci/s \\ R_{A} = 156.9 \ x \ 1.65 x 10^{-6} & = 2.59 E\text{--}4 \ Ci/s \end{array}$

The maximum permissible leakage rate is given by:

 $L_{\rm N} = R_{\rm N}/C_{\rm N} ,$ $L_{\rm A} = R_{\rm A}/C_{\rm A} ,$

where:

- L_i is the volumetric gas leakage rate or maximum permissible leakage rate [cm³/s] under normal (L_N) and accident (L_A) conditions of transport,
- R_i is the release rate for normal (R_N) and accident (R_A) conditions of transport calculated above [R_N = 4.38E-8 Ci/s, R_A = 2.59E-4 Ci/s], and
- C_i is the curies per unit volume of the radioactive material, "activity density", that passes through the leak path for normal (C_N) and accident (C_A) conditions of transport [C_N = 2.34E-4 Ci/cm³, C_A = 7.80E-3 Ci/cm³].

Substitution of the appropriate values into the previous equation gives:

 $L_N = 4.38E-8/2.34E-4 = 1.87E-4 \text{ cm}^3/\text{s}$ $L_A = 2.59E-4/7.80E-3 = 3.32E-2 \text{ cm}^3/\text{s}$

B.7 Permissible Leak Rate at Standard Conditions

B.7.1 Normal Conditions of Transport

The volumetric gas leak rate is modeled as a combination of continuum and molecular flow through a single leak path. The leak path is modeled as a smooth, right-circular cylinder with sharp edges. Based on these assumptions, the equation for gas leaking from the cask takes the following form.

 $\mathbf{L} = \mathbf{L}_{\mathrm{c}} + \mathbf{L}_{\mathrm{m}},$

where:

- L is the volumetric gas flow rate at P_u [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec], and
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].

The volumetric flow rate, L_c, for continuum flow is given by

$$L_{c} = [(2.49 \times 10^{6} \text{ D}^{4})/a\mu] \cdot (P_{u} - P_{d})(P_{a}/P_{u}),$$

where:

- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- D is the capillary diameter [cm],
- a is the capillary length [0.6-cm],
- μ is the fluid viscosity [0.02592-cP],
- P_u is the upstream pressure [2.694-atm],
- P_d is the downstream pressure [1-atm], and
- P_a is the average pressure, $(P_u P_d)/2$ [1.847-atm].

The volumetric flow rate, L_m, for molecular flow is given by

$$L_{\rm m} = \left[(3.81 \times 10^3 {\rm D}^3 {\rm (T/M)^{0.5}}) / {\rm aP_a} \right] \bullet ({\rm P_u} - {\rm P_d}) ({\rm P_a} / {\rm P_u}),$$

where:

- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [1-cm],
- T is the gas temperature [438-K],
- M is the gas molecular weight [4-g/mole],
- a is the capillary length [0.6-cm],
- P_a is the average pressure, $(P_u P_d)/2$ [1.847-atm],
- P_u is the upstream pressure [2.694-atm], and
- P_d is the downstream pressure [1-atm].

The volumetric gas flow rate at the upstream pressure is therefore given by:

$$\begin{split} L_{N} &= \left\{ (2.49 \times 10^{6} \cdot D^{4}) / (1 \cdot 0.02592) + (3.81 \times 10^{3} \cdot D^{3} (438/4)^{0.5}) / (1 \cdot 1.847) \right\} \cdot \\ &\qquad (2.694 - 1) (1.847/2.694) \\ L_{N} &= \left\{ 1.60 E + 8 \cdot D^{4} + 3.60 E + 4 \cdot D^{3} \right\} (1.16) \\ L_{N} &= 1.86 E + 8 \cdot D^{4} + 4.18 E + 4 \cdot D^{3} \end{split}$$

Substituting $L_N = 1.87E-4$ -cm³/s and solving for D yields a capillary diameter of 9.497E-4-cm.

To correlate the maximum permissible leak rate above to the leak rate at standard temperature and pressure, the following calculation is made.

$$L_{R,N} = L_c + L_m = \left\{ (2.49 \times 10^6 \text{ D}^4)/a\mu + (3.81 \times 10^3 \text{D}^3(\text{T/M})^{0.5})/aP_a \right\} \bullet (P_u - P_d)(P_a/P_u),$$

where:

- $L_{R,N}$ is the volumetric leakage rate at standard conditions correlating to normal conditions of transport [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [9.497E-4 cm],
- a is the capillary length [0.6-cm],
- μ is the fluid viscosity [0.018494-cP],
- P_u is the upstream pressure [1-atm],
- P_d is the downstream pressure [0.01-atm],
- P_a is the average pressure, $(P_u P_d)/2$ [0.505-atm],
- T is the gas temperature [298-K], and
- M is the gas molecular weight [29-g/mole].

The volumetric leakage rate at the standard conditions is therefore given by:

$$\begin{split} L_{R,N} &= \left\{ (2.49 \times 10^{6} \cdot (9.497 \text{E-4})^{4}) / (0.6 \cdot 0.018494) + \\ &\quad (3.81 \times 10^{3} \cdot (9.497 \text{E-4})^{3} \cdot (298/29)^{0.5}) / (0.6 \cdot 0.505) \right\} \cdot \\ &\quad (1 - 0.01) (0.505/1) \\ L_{R,N} &= \left\{ 1.83 \text{E-4} + 3.49 \text{E-5} \right\} (0.50) \\ L_{R,N} &= 1.09 \text{E-4 cm}^{3} / \text{s} \end{split}$$

B.7.2 Accident Conditions of Transport

The volumetric gas leak rate is modeled as a combination of continuum and molecular flow through a single leak path. The leak path is modeled as a smooth, right-circular cylinder with sharp edges. Based on these assumptions, the equation for gas leaking from the cask takes the following form.

 $\mathbf{L} = \mathbf{L}_{\mathrm{c}} + \mathbf{L}_{\mathrm{m}},$

where:

- L is the volumetric gas flow rate at P_u [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec], and
- L_m is the volumetric flow rate due to molecular flow [cm³/sec].

The volumetric flow rate, L_c, for continuum flow is given by

$$L_{c} = (2.49 \times 10^{6} \text{ D}^{4})/a\mu \bullet (P_{u} - P_{d})(P_{a}/P_{u}),$$

where:

- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- D is the capillary diameter [cm],
- a is the capillary length [0.6-cm],
- μ is the fluid viscosity [0.02676-cP],
- P_u is the upstream pressure [5.8-atm],
- P_d is the downstream pressure [1-atm], and
- P_a is the average pressure, $(P_u P_d)/2$ [3.4-atm].

The volumetric flow rate, L_m, for molecular flow is given by

$$L_{\rm m} = (3.81 \times 10^3 {\rm D}^3 {\rm (T/M)}^{0.5}) / a P_{\rm a} \bullet (P_{\rm u} - P_{\rm d}) (P_{\rm a}/P_{\rm u}),$$

where:

- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [cm],
- T is the gas temperature [459-K],
- M is the gas molecular weight [4-g/mole],
- a is the capillary length [0.6-cm],
- P_a is the average pressure, $(P_u P_d)/2$ [3.4-atm],
- P_u is the upstream pressure [5.8-atm], and

P_d is the downstream pressure [1-atm].

The volumetric gas flow rate at the upstream pressure is therefore given by:

$$\begin{split} L_A &= \left\{ (2.49 \times 10^6 \cdot D^4) / (1 \cdot 0.02676) + (3.81 \times 10^3 \cdot D^3 (459/4)^{0.5}) / (1 \cdot 3.4) \right\} \cdot \\ &\quad (5.8 - 1) (3.8/5.8) \\ L_A &= \left\{ 1.55 E + 8 \cdot D^4 + 2.00 E + 4 \cdot D^3 \right\} (2.82) \\ L_A &= 4.37 E + 8 \cdot D^4 + 5.63 E + 4 \cdot D^3 \end{split}$$

Substituting $L_A = 3.32E-2$ -cm³/s and solving for D yields a capillary diameter of 2.921E-3-cm.

To correlate the maximum permissible leak rate above to the leak rate at standard temperature and pressure, the following calculation is made.

$$L_{R,A} = L_c + L_m = \left\{ (2.49 x 10^6 \text{ D}^4)/a \mu + (3.81 x 10^3 \text{D}^3 (\text{T/M})^{0.5})/a P_a \right\} \bullet (P_u - P_d) (P_a/P_u),$$

where:

- $L_{R,A}$ is the volumetric leakage rate at standard conditions correlating to accident conditions of transport [cm³/sec],
- L_c is the volumetric flow rate due to continuum flow [cm³/sec],
- L_m is the volumetric flow rate due to molecular flow [cm³/sec],
- D is the capillary diameter [2.921E-3 cm],
- a is the capillary length [0.6-cm],
- μ is the fluid viscosity [0.018494-cP],
- P_u is the upstream pressure [1-atm],
- P_d is the downstream pressure [0.01-atm],
- P_a is the average pressure, $(P_u P_d)/2$ [0.505-atm],
- T is the gas temperature [298-K], and
- M is the gas molecular weight [29-g/mole].

The volumetric leakage rate at the standard conditions is therefore given by:

$$\begin{split} \mathbf{L}_{\text{R,A}} &= \left\{ (2.49 \text{x} 10^{6} \text{\cdot} (2.921 \text{E-3})^{4}) / (0.6 \text{\cdot} 0.018494) + \\ &\quad (3.81 \text{x} 10^{3} \text{\cdot} (2.921 \text{E-3})^{3} \text{\cdot} (298/29)^{0.5}) / (0.6 \text{\cdot} 0.505) \right\} \text{\cdot} \\ &\quad (1 - 0.01) (0.505/1) \\ \mathbf{L}_{\text{R,A}} &= \left\{ 1.63 \text{E-2} + 1.01 \text{E-3} \right\} (0.50) \\ \mathbf{L}_{\text{R,A}} &= \mathbf{8.66 \text{E-3 cm}^{3}/\text{s}} \end{split}$$