ENCLOSURE 2

Calculation CA07718, 2011 Update of ISFSI USAR DSC Leakage Dose Analyses

Calvert Cliffs Nuclear Power Plant, LLC
December 15, 2011

ATTACHMENT 1, CALCULATION COVER SHEET

A. INITIATION Page 1 of 52

Site ☒ CCNPP ☐ NMP ☐ REG

Calculation No.: CA07718 Revision No.: 0000

Vendor Calculation (Check one): ☐ Yes ☒ No

Responsible Group: Nuclear Fuel Services – Nuclear Analysis Unit

Responsible Engineer: John Massari

B. CALCULATION

ENGINEERING DISCIPLINE: ☐ Civil ☐ Instr & Controls ☒ Nuclear

☐ Electrical ☐ Mechanical ☐ Other ____________

Title: 2011 UPDATE OF ISFSI USAR DSC LEAKAGE DOSE ANALYSES

Unit ☐ 1 ☐ 2 ☒ COMMON

Proprietary or Safeguards Calculation ☐ YES ☒ NO

Comments: ECP-09-000128

Vendor Calc No.: N/A REVISION NO.: N/A

Vendor Name: N/A

Safety Class (Check one): ☒ SR ☐ AUGMENTED QUALITY ☐ NSR

There are assumptions that require Verification during walkdown: TRACKING ID: N/A

This calculation **SUPERSEDES**: CA03902

C. REVIEW AND APPROVAL:

Responsible Engineer: John Massari (body) 12/1/2011
Mahmoud Massoud (App A) Mahmoud Massoud
Printed Name and Signature Date

Is Design Verification Required? ☒ Yes ☐ No

If yes, Design Verification Form is ☒ Attached ☐ Filed with:

Independent Reviewer: Gerard Gryczkowski 12/2/2011
Printed Name and Signature Date

Approval: John Massari 12/2/2011
Printed Name and Signature Date

LIST OF EFFECITVE PAGES

Initial Issue; All - Revision 00

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1.0 INTRODUCTION AND OBJECTIVE

The purpose of this analysis is to update previous dose analyses performed to evaluate the off-site dose consequences for leakage of an Independent Spent Fuel Storage Installation (ISFSI) Dry Shielded Canister. This update was required to respond to U.S. Nuclear Regulatory (NRC) Requests for Additional Information (RAIs) for the ISFSI License Renewal Application.

The current licensing basis confinement analysis for the Calvert Cliffs ISFSI is summarized in Calvert Cliffs ISFSI USAR Section 8.2.8 for the NUHOMS-24P canister and Section 12.8.2.8 for the NUHOMS-32P canister, and involves a non-mechanistic instantaneous (puff) release to the environment of the gap inventory of Kr-85 fission gas from all fuel rods contained in a single canister (1.39E3 Ci for the NUHOMS-24P DSC and 8.54E3 Ci for the NUHOMS-32P DSC). The fraction of Kr-85 released from the pellet to the gap is calculated using the American Nuclear Society 5.4-82 method to be 2.1% for the NUHOMS-24P DSC (47 GWd/MTU maximum burnup) and 9.35% for the NUHOMS-32P DSC (52 GWd/MTU maximum burnup). An atmospheric dispersion factor (X/Q) of 3.0E-4 sec/m^3, was used in calculating the maximum potential doses at the 3900 foot (1189 m) distance to the controlled area boundary. The X/Q was calculated using Regulatory Guide 1.145 methodology assuming G stability and 1 m/s wind speed. The resulting calculated doses for the NUHOMS-24P DSC are 0.1 mrem and 17.8 mrem for the maximum off-site total body and skin doses, respectively. The calculated total body and skin doses for the NUHOMS-32P DSC are 0.65 and 109.6 mrem, respectively. Calculations supporting these ISFSI USAR Sections are documented in References 1, 2, and 3.

This calculation will utilize the current NRC guidance for performing confinement analyses, as detailed in References 5 and 6. The calculation will also be expanded to cover normal and off-normal conditions, as well as the accident case evaluated currently.

2.0 CONCLUSIONS

Table 2-1 summarizes the results of the calculations performed in Section 7. The results indicate that all dose limits are met for normal, off-normal, and accident conditions. Note that the normal release assumptions utilized in this calculation are entirely hypothetical. Results of actual air monitoring performed as part of the Radiological Environment Monitoring Program are summarized in the Radiological Environmental Operating Reports issued annually. Review of the past several years reports indicate no airborne releases from the ISFSI have occurred.

Table 2-1. Summary of Normal and Off-Normal Doses (mRem)

Organ	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Normal	1.89E-02	2.77E-03	9.92E-02	9.38E-02	1.14E+00	1.61E-02	4.45E-02	6.66E-02	6.66E-02
Off-Normal	4.40E-03	6.46E-04	2.31E-02	2.18E-02	2.67E-01	3.75E-03	1.04E-02	1.55E-02	1.55E-02
72.104(a) Limit	25	25	25	25	25	75	25	25	25

Table 2-2. Summary of Accident Doses (Rem)

Organ	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Accident	0.557	0.033	3.275	3.014	37.388	0.063	1.408	2.122	0.219
72.106 Limit	50	50	50	50	50	50	50	5	50

3.0 DESIGN INPUTS

The following sections detail the design inputs utilized in preparation of this calculation.

3.1 Source Term

Source terms for a design basis 660 watt assembly were obtained from Calvert Cliffs Calculation CA06721 Section 6.5 (Reference 4), which was approved by the NRC under Calvert Cliffs ISFSI License Amendment 9. Both the gamma and neutron design basis source terms were considered to ensure the calculated dose bounds the range of assemblies licensed for storage in both the NUHOMS-24P and NUHOMS-32P DSCs. The crud Co-60 activity at discharge was based on the 140 μCi/cm^2 recommended for PWRs in Reference 5, Table 5-2. This was then multiplied by a total fuel rod surface area of 2.31E5 cm^2 for a CE 14x14 assembly (176 rods, 147 inches long, 0.44 inch outer diameter), and was decay corrected using a 5.271 year Co-60 half-life to the time indicated for the design basis source in Calvert Cliffs Calculation CA06721 (16y for neutron, 7y for gamma). Both 51 isotope source terms are listed below in Table 3-1. Assignment of isotopes to the various nuclide groups (gasses, volatiles, fines, and crud) is as per NUREG-1567 Table 9.2.

Table 3-1. Confinement Source Term

Isotope	Nuclide Group	Design Basis Neutron (Ci/assembly)	Design Basis Photon (Ci/assembly)
ac227	Fuel Fines	3.65E-06	2.11E-06
am241	Fuel Fines	1.28E+03	6.08E+02
am242	Fuel Fines	3.84E+00	3.43E+00
am242m	Fuel Fines	3.86E+00	3.45E+00
am243	Fuel Fines	2.70E+01	9.40E+00
c14	Gaseous	1.65E+00	9.84E-01
cd113m	Fuel Fines	1.29E+01	1.13E+01
cl36	Gaseous	4.88E-02	2.99E-02
cm242	Fuel Fines	3.18E+00	3.18E+00
cm243	Fuel Fines	1.30E+01	6.32E+00
cm244	Fuel Fines	2.91E+03	8.75E+02
cm245	Fuel Fines	4.57E-01	8.62E-02
cm246	Fuel Fines	2.20E-01	2.08E-02
co60	Crud	3.94E+00	1.29E+01
cs134	Volatile	5.64E+02	7.05E+03
cs135	Volatile	2.35E-01	2.13E-01
cs137	Volatile	4.62E+04	4.43E+04
eu154	Fuel Fines	1.26E+03	1.72E+03
eu155	Fuel Fines	1.91E+02	4.54E+02
h3	Gaseous	1.72E+02	2.25E+02
i129	Gaseous	2.02E-02	1.50E-02
kr81	Gaseous	9.03E-08	3.86E-08
kr85	Gaseous	1.76E+03	2.85E+03
nb94	Fuel Fines	8.56E-02	5.82E-02
np237	Fuel Fines	2.05E-01	1.64E-01
np239	Fuel Fines	2.70E+01	9.40E+00
pa231	Fuel Fines	9.00E-06	1.00E-05

Table 3-1. Confinement Source Term

Isotope	Nuclide Group	Design Basis Neutron (Ci/assembly)	Design Basis Photon (Ci/assembly)
pd107	Fuel Fines	8.73E-02	4.93E-02
pm147	Fuel Fines	1.09E+03	1.29E+04
pu238	Fuel Fines	2.31E+03	1.36E+03
pu239	Fuel Fines	1.37E+02	1.47E+02
pu240	Fuel Fines	2.90E+02	2.22E+02
pu241	Fuel Fines	3.19E+04	4.16E+04
pu242	Fuel Fines	1.84E+00	8.52E-01
ru103	Volatile	0.00E+00	1.73E-14
ru106	Volatile	6.67E+00	2.07E+03
se79	Fuel Fines	4.05E-02	3.25E-02
sm151	Fuel Fines	1.69E+02	1.86E+02
sr89	Volatile	4.84E-30	2.42E-10
sr90	Volatile	2.87E+04	3.25E+04
tc99	Fuel Fines	7.95E+00	6.60E+00
th230	Fuel Fines	6.43E-05	4.89E-05
u232	Fuel Fines	2.08E-02	1.06E-02
u233	Fuel Fines	2.31E-05	1.65E-05
u234	Fuel Fines	4.26E-01	5.69E-01
u235	Fuel Fines	3.24E-03	1.01E-02
u236	Fuel Fines	1.25E-01	1.44E-01
u238	Fuel Fines	1.24E-01	1.25E-01
xe127	Gaseous	0.00E+00	1.99E-23
y90	Fuel Fines	2.87E+04	3.25E+04
zr95	Fuel Fines	2.29E-22	7.16E-07
wt% U-235 Enrichment		3.4%	4.3%
Burnup (GWd/MTU)		52	40
Decay time (years)		16	7

3.2 Dose Conversion Factors

The dose conversion factors (DCFs) were extracted from References 8 and 9. Note that the submersion DCFs provided in Table 3-2 below correspond to the FGR-12 data (Table III.1), while the inhalation DCFs provided in Table 3-3 below correspond to the FGR-11 data (Table 2.1). For the latter, when multiple DCFs were given for an isotope due to differing lung clearance classes based on chemical form, the worst case DCF for each organ was selected, with the exception of uranium isotopes for which the "Year" lung clearance class was used based on the fact that FGR-11, Table 3 indicates this is the appropriate class to use for UO_2.

Table 3-2 – Submersion Dose Conversion Factors (Sv/sec per Bq/m^3)

Isotope	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Ac227	5.78E-18	6.98E-18	5.22E-18	4.59E-18	1.68E-17	5.60E-18	4.92E-18	5.82E-18	1.10E-17
Am241	8.58E-16	1.07E-15	6.74E-16	5.21E-16	2.87E-15	7.83E-16	6.34E-16	8.18E-16	1.28E-15
Am242	6.09E-16	7.30E-16	5.51E-16	4.77E-16	1.88E-15	5.94E-16	5.18E-16	6.15E-16	8.20E-15
Am242m	3.80E-17	6.01E-17	1.72E-17	1.72E-17	7.94E-17	2.95E-17	1.94E-17	3.17E-17	1.36E-16

Table 3-2 – Submersion Dose Conversion Factors (Sv/sec per Bq/m^3)

Isotope	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Am243	2.19E-15	2.61E-15	1.92E-15	1.55E-15	7.47E-15	2.09E-15	1.79E-15	2.18E-15	2.75E-15
C14	2.59E-19	3.52E-19	1.53E-19	1.21E-19	7.06E-19	2.19E-19	1.54E-19	2.24E-19	2.43E-16
Cd113m	7.17E-18	8.76E-18	5.93E-18	5.01E-18	2.10E-17	6.76E-18	5.63E-18	6.94E-18	8.48E-15
Cl36	2.24E-17	2.66E-17	2.02E-17	1.81E-17	5.63E-17	2.19E-17	1.92E-17	2.23E-17	1.47E-14
Cm242	7.83E-18	1.48E-17	1.13E-18	1.89E-18	1.06E-17	4.91E-18	2.27E-18	5.69E-18	4.29E-17
Cm243	5.77E-15	6.68E-15	5.50E-15	5.00E-15	1.50E-14	5.76E-15	5.19E-15	5.88E-15	9.79E-15
Cm244	6.90E-18	1.33E-17	7.08E-19	1.46E-18	8.82E-18	4.19E-18	1.81E-18	4.91E-18	3.91E-17
Cm245	3.88E-15	4.55E-15	3.63E-15	3.17E-15	1.18E-14	3.84E-15	3.40E-15	3.96E-15	5.36E-15
Cm246	6.24E-18	1.20E-17	7.00E-19	1.35E-18	8.17E-18	3.82E-18	1.67E-18	4.46E-18	3.49E-17
Co60	1.23E-13	1.39E-13	1.24E-13	1.23E-13	1.78E-13	1.27E-13	1.20E-13	1.26E-13	1.45E-13
Cs134	7.40E-14	8.43E-14	7.37E-14	7.19E-14	1.20E-13	7.57E-14	7.06E-14	7.57E-14	9.45E-14
Cs135	6.28E-19	8.23E-19	4.19E-19	3.34E-19	1.81E-18	5.50E-19	4.09E-19	5.65E-19	9.06E-16
Cs137*	2.82E-14	3.22E-14	2.80E-14	2.73E-14	4.63E-14	2.88E-14	2.68E-14	2.88E-14	3.73E-14
Eu154	6.00E-14	6.81E-14	5.99E-14	5.87E-14	9.43E-14	6.15E-14	5.75E-14	6.14E-14	8.29E-14
Eu155	2.49E-15	2.95E-15	2.22E-15	1.85E-15	8.09E-15	2.41E-15	2.07E-15	2.49E-15	3.39E-15
H3	0.00E+00	0.00E+00	2.75E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.31E-19	0.00E+00
I129	4.83E-16	6.66E-16	2.14E-16	1.64E-16	1.10E-15	3.86E-16	2.30E-16	3.80E-16	1.10E-15
Kr81	2.62E-16	3.06E-16	2.53E-16	2.39E-16	5.66E-16	2.62E-16	2.41E-16	2.67E-16	4.04E-16
Kr85	1.17E-16	1.34E-16	1.14E-16	1.09E-16	2.20E-16	1.18E-16	1.09E-16	1.19E-16	1.32E-14
Nb94	7.54E-14	8.57E-14	7.51E-14	7.34E-14	1.19E-13	7.72E-14	7.19E-14	7.70E-14	9.52E-14
Np237	1.04E-15	1.26E-15	9.02E-16	7.69E-16	3.20E-15	9.94E-16	8.50E-16	1.03E-15	1.54E-15
Np239	7.53E-15	8.73E-15	7.18E-15	6.50E-15	2.00E-14	7.52E-15	6.76E-15	7.69E-15	1.60E-14
Pa231	1.71E-15	1.99E-15	1.62E-15	1.52E-15	3.64E-15	1.70E-15	1.54E-15	1.72E-15	2.44E-15
Pd107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm147	7.48E-19	9.56E-19	5.45E-19	4.46E-19	2.18E-18	6.75E-19	5.26E-19	6.93E-19	8.11E-16
Pu238	6.56E-18	1.27E-17	1.06E-18	1.68E-18	9.30E-18	4.01E-18	1.99E-18	4.88E-18	4.09E-17
Pu239	4.84E-18	7.55E-18	2.65E-18	2.67E-18	9.47E-18	3.88E-18	2.86E-18	4.24E-18	1.86E-17
Pu240	6.36E-18	1.23E-17	1.09E-18	1.65E-18	9.26E-18	3.92E-18	1.96E-18	4.75E-18	3.92E-17
Pu241	7.19E-20	8.67E-20	6.48E-20	5.63E-20	2.19E-19	6.98E-20	6.09E-20	7.25E-20	1.17E-19
Pu242	5.34E-18	1.03E-17	9.69E-19	1.43E-18	7.90E-18	3.32E-18	1.68E-18	4.01E-18	3.27E-17
Ru103	2.19E-14	2.51E-14	2.18E-14	2.10E-14	3.89E-14	2.24E-14	2.08E-14	2.25E-14	2.77E-14
Ru106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Se79	3.47E-19	4.67E-19	2.11E-19	1.67E-19	9.60E-19	2.96E-19	2.10E-19	3.03E-19	3.71E-16
Sm151	5.20E-20	8.80E-20	7.08E-21	1.13E-20	7.09E-20	3.58E-20	1.49E-20	3.61E-20	1.90E-19
Sr89	7.73E-17	9.08E-17	7.08E-17	6.39E-17	1.94E-16	7.60E-17	6.71E-17	7.73E-17	3.69E-14
Sr90	7.78E-18	9.49E-18	6.44E-18	5.44E-18	2.28E-17	7.33E-18	6.11E-18	7.53E-18	9.20E-15
Tc99	1.74E-18	2.20E-18	1.29E-18	1.05E-18	5.17E-18	1.57E-18	1.24E-18	1.62E-18	2.74E-15
Th230	1.80E-17	2.38E-17	1.43E-17	1.22E-17	5.29E-17	1.63E-17	1.37E-17	1.74E-17	4.51E-17
U232	1.55E-17	2.32E-17	9.84E-18	8.99E-18	3.86E-17	1.29E-17	1.00E-17	1.42E-17	5.92E-17
U233	1.69E-17	2.22E-17	1.35E-17	1.24E-17	4.12E-17	1.55E-17	1.31E-17	1.63E-17	4.57E-17
U234	8.79E-18	1.44E-17	4.38E-18	4.20E-18	1.99E-17	6.69E-18	4.80E-18	7.63E-18	4.25E-17
U235	7.05E-15	8.11E-15	6.75E-15	6.15E-15	1.84E-14	7.05E-15	6.37E-15	7.20E-15	8.64E-15
U236	6.10E-18	1.10E-17	2.18E-18	2.33E-18	1.19E-17	4.19E-18	2.70E-18	5.01E-18	3.57E-17
U238	4.39E-18	8.54E-18	9.96E-19	1.24E-18	7.40E-18	2.72E-18	1.51E-18	3.41E-18	2.91E-17
Xe127	1.23E-14	1.42E-14	1.17E-14	1.08E-14	2.88E-14	1.23E-14	1.11E-14	1.25E-14	1.57E-14
Y90	1.89E-16	2.20E-16	1.77E-16	1.62E-16	4.44E-16	1.87E-16	1.68E-16	1.90E-16	6.24E-14
Zr95	3.53E-14	4.01E-14	3.51E-14	3.43E-14	5.62E-14	3.61E-14	3.36E-14	3.60E-14	4.50E-14

*Values indicated for Cs-137 are conservatively those for Ba-137m which is a short half-life (2.5m) daughter of Cs-137 and the actual source of the 661 keV gamma.

Table 3-3 – Inhalation Dose Conversion Factors (Sv/Bq)

Isotope	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Ac227	3.96E-04	6.66E-08	1.54E-03	2.57E-03	3.21E-02	3.59E-08	1.47E-03	1.81E-03	0.00E+00
Am241	3.25E-05	2.67E-09	1.84E-05	1.74E-04	2.17E-03	1.60E-09	7.82E-05	1.20E-04	0.00E+00
Am242	1.94E-09	2.94E-12	5.20E-08	1.32E-08	1.65E-07	2.52E-12	8.54E-09	1.58E-08	0.00E+00
Am242m	3.21E-05	1.38E-09	4.20E-06	1.69E-04	2.12E-03	5.64E-10	7.48E-05	1.15E-04	0.00E+00
Am243	3.26E-05	1.52E-08	1.78E-05	1.73E-04	2.17E-03	8.29E-09	7.74E-05	1.19E-04	0.00E+00
C14	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	0.00E+00
Cd113m	3.32E-08	3.32E-08	4.09E-07	3.32E-08	3.32E-08	3.32E-08	1.30E-06	4.13E-07	0.00E+00
Cl36	5.04E-10	5.04E-10	4.56E-08	5.04E-10	5.04E-10	5.04E-10	5.36E-10	5.93E-09	0.00E+00
Cm242	5.70E-07	9.44E-10	1.55E-05	3.90E-06	4.87E-05	9.41E-10	2.45E-06	4.67E-06	0.00E+00
Cm243	2.07E-05	6.29E-09	1.94E-05	1.18E-04	1.47E-03	3.83E-09	5.76E-05	8.30E-05	0.00E+00
Cm244	1.59E-05	1.04E-09	1.93E-05	9.38E-05	1.17E-03	1.01E-09	4.78E-05	6.70E-05	0.00E+00
Cm245	3.37E-05	6.69E-09	1.80E-05	1.79E-04	2.24E-03	3.68E-09	7.96E-05	1.23E-04	0.00E+00
Cm246	3.34E-05	4.00E-09	1.82E-05	1.78E-04	2.22E-03	2.26E-09	7.94E-05	1.22E-04	0.00E+00
Co60	4.76E-09	1.84E-08	3.45E-07	1.72E-08	1.35E-08	1.62E-08	3.60E-08	5.91E-08	0.00E+00
Cs134	1.30E-08	1.08E-08	1.18E-08	1.18E-08	1.10E-08	1.11E-08	1.39E-08	1.25E-08	0.00E+00
Cs135	1.20E-09	1.20E-09	1.41E-09	1.20E-09	1.20E-09	1.20E-09	1.20E-09	1.23E-09	0.00E+00
Cs137	8.76E-09	7.84E-09	8.82E-09	8.30E-09	7.94E-09	7.93E-09	9.12E-09	8.63E-09	0.00E+00
Eu154	1.17E-08	1.55E-08	7.92E-08	1.06E-07	5.23E-07	7.14E-09	1.13E-07	7.73E-08	0.00E+00
Eu155	3.56E-10	6.14E-10	1.19E-08	1.43E-08	1.52E-07	2.40E-10	1.11E-08	1.12E-08	0.00E+00
H3	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	1.73E-11	0.00E+00
I129	8.69E-11	2.09E-10	3.14E-10	1.40E-10	1.38E-10	1.56E-06	1.18E-10	4.69E-08	0.00E+00
Kr81	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Kr85	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nb94	4.76E-09	2.24E-08	7.48E-07	2.26E-08	1.97E-08	2.22E-08	4.45E-08	1.12E-07	0.00E+00
Np237	2.96E-05	1.69E-08	1.61E-05	2.62E-04	3.27E-03	1.34E-08	2.34E-05	1.46E-04	0.00E+00
Np239	7.45E-11	1.63E-11	2.36E-09	2.08E-10	2.03E-09	7.62E-12	9.59E-10	6.78E-10	0.00E+00
Pa231	6.90E-09	8.79E-09	7.47E-04	6.97E-04	8.70E-03	7.64E-09	2.87E-07	3.47E-04	0.00E+00
Pd107	9.45E-13	9.45E-13	2.85E-08	5.11E-12	1.36E-11	9.45E-13	2.15E-10	3.45E-09	0.00E+00
Pm147	1.88E-14	3.60E-14	7.74E-08	8.16E-09	1.02E-07	1.98E-14	5.89E-09	1.06E-08	0.00E+00
Pu238	2.80E-05	1.00E-09	3.20E-04	1.52E-04	1.90E-03	9.62E-10	7.02E-05	1.06E-04	0.00E+00
Pu239	3.18E-05	9.22E-10	3.23E-04	1.69E-04	2.11E-03	9.03E-10	7.56E-05	1.16E-04	0.00E+00
Pu240	3.18E-05	9.51E-10	3.23E-04	1.69E-04	2.11E-03	9.05E-10	7.56E-05	1.16E-04	0.00E+00
Pu241	6.82E-07	3.06E-11	3.18E-06	3.36E-06	4.20E-05	1.24E-11	1.31E-06	2.23E-06	0.00E+00
Pu242	3.02E-05	9.45E-10	3.07E-04	1.61E-04	2.01E-03	8.79E-10	7.18E-05	1.11E-04	0.00E+00
Ru103	7.31E-10	6.07E-10	1.56E-08	6.66E-10	6.18E-10	5.97E-10	1.25E-09	2.42E-09	0.00E+00
Ru106	1.38E-08	1.37E-08	1.04E-06	1.37E-08	1.37E-08	1.37E-08	1.69E-08	1.29E-07	0.00E+00
Se79	6.79E-10	6.79E-10	9.81E-09	6.79E-10	6.79E-10	6.79E-10	4.24E-09	2.66E-09	0.00E+00
Sm151	4.03E-14	1.49E-13	3.26E-09	1.10E-08	1.38E-07	1.32E-14	7.51E-09	8.10E-09	0.00E+00
Sr89	4.16E-10	4.16E-10	8.35E-08	5.63E-09	8.37E-09	4.16E-10	3.97E-09	1.12E-08	0.00E+00
Sr90	2.64E-09	2.64E-09	2.86E-06	3.36E-07	7.27E-07	2.64E-09	5.73E-09	3.51E-07	0.00E+00
Tc99	4.52E-11	4.52E-11	1.67E-08	4.52E-11	4.52E-11	1.21E-09	6.26E-10	2.25E-09	0.00E+00
Th230	4.08E-07	4.08E-07	3.00E-04	1.73E-04	2.16E-03	4.08E-07	1.05E-06	8.80E-05	0.00E+00
U232	1.69E-08	2.66E-08	1.48E-03	4.68E-07	7.14E-06	2.43E-08	5.86E-07	1.78E-04	0.00E+00

Table 3-3 – Inhalation Dose Conversion Factors (Sv/Bq)

Isotope	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
U233	2.69E-09	2.73E-09	3.04E-04	7.39E-08	1.16E-06	2.70E-09	1.08E-07	3.66E-05	0.00E+00
U234	2.65E-09	2.68E-09	2.98E-04	7.22E-08	1.13E-06	2.65E-09	1.06E-07	3.58E-05	0.00E+00
U235	2.84E-09	5.37E-09	2.76E-04	7.15E-08	1.05E-06	4.11E-09	1.02E-07	3.32E-05	0.00E+00
U236	2.51E-09	2.54E-09	2.82E-04	6.83E-08	1.07E-06	2.51E-09	1.00E-07	3.39E-05	0.00E+00
U238	2.42E-09	2.91E-09	2.66E-04	6.88E-08	1.01E-06	2.73E-09	9.61E-08	3.20E-05	0.00E+00
Xe127	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y90	9.52E-12	9.52E-12	9.31E-09	2.79E-10	2.79E-10	9.52E-12	3.87E-09	2.28E-09	0.00E+00
Zr95	1.88E-09	1.91E-09	4.07E-08	1.30E-08	1.03E-07	1.44E-09	2.77E-09	6.39E-09	0.00E+00

3.3 Release Fractions

Two types of release fractions are considered for this analysis: fuel-to-DSC release fractions, and DSC-to-Environment release fractions. No credit is taken for retention of material released from the DSC in the Horizontal Storage Module.

Fuel-to-DSC release fractions are the fraction of isotopes in each nuclide group which are released from the interior of the fuel rod to the internal void space of the DSC upon failure of the fuel rod. The fuel-to-DSC release fractions used in this analysis are those specified in NUREG-1567 and NUREG-1536 (References 5 and 6), and are summarized in Table 3-4 below. The basis for these release fractions is cited as being NUREG/CR-6487, which in turn obtained them from SAND90-2406, and they are ultimately based on fuel rod burst tests performed at Oak Ridge National Laboratory and documented in NUREG/CR-0722. Note that the Table 3-4 gaseous release fraction is more conservative than that calculated in Reference 2 for the highest burnup fuel (52 GWd/MTU) that can be stored in the ISFSI using the ANS/ANSI-5.4 method.

Table 3-4 – Fuel-to-DSC Release Fractions by Nuclide Group

Nuclide Group	Normal and Off-Normal	Accident
Gases	0.3	0.3
Volatiles	2.00E-04	2.00E-04
Fines	3.00E-05	3.00E-05
Crud	0.15	1

NUREG-1567 and NUREG-1536 also indicates that other release fractions may be used provided proper justification is given for their usage. For example, the NRC has accepted, with adequate justification, reduction of the mass fraction of fuel fines that can be released from the cask. Information that can be used to form the basis for DSC-to-Environment release fractions can also be found in various NRC and Sandia National Laboratory documents. SAND90-2406 conservatively assumes that only 10% of fuel fines released from fuel rods remains airborne (p. IV-8). This assumption is also based on the fuel rod burst tests documented in NUREG/CR-0722. In those tests, a high burnup fuel rod segment was placed on a quartz holder and inserted into a quartz liner that was prepositioned inside of a quartz furnace tube. The released material that did not deposit on the furnace tube components was carried by a flowing gas mixture of steam-helium or steam argon through a gold foil lined thermal gradient tube where volatile species that are condensable above 150°C were deposited. A filter pack containing HEPA filter papers was located at the end of the 30 cm long tube. These tests found that only 0.8 to 2.9% of the fuel fines ejected from the test specimen were transported more than a few centimeters from the rupture point (NUREG/CR-0722, p. 105) to the filter bank, and this level of transport occurred at flow rates of ~2000 cc/min. Particles which deposited close to the rupture point were typically 150 μm in diameter, and those found on the filter were typically 10 μm in diameter. The smaller particles were estimated to have a fall rate of 3 cm/sec based on the distance traveled and the velocity of the flowing gas.

NUREG/CR-6672 also presents cask-to-environment release fractions calculated using the MELCOR code for a TN-125 cask. Source particles in the cask were assumed to have a size distribution consistent with that released from failed spent fuel rods. The cask was assumed to be pressurized to 5 atm, and cask-to-environment release fractions were calculated as a function of leak area for fines and volatiles. The results, presented in Figure 3-1 below, show that the cask-to-environment release fractions increase as cask leak areas increase. This is to be expected since, after pressurization due to the failure of the fuel rods, cask depressurization times decrease as cask leak areas increase. Thus, a large leak area means a short depressurization time, little time for fission product deposition to cask interior surfaces, and consequently large cask-to-environment release fractions. The CsI and CsOH (volatiles) curves diverge from the $U0_2$ (fuel fines) curve as hole sizes decrease because, when hole sizes are small, and there is significant time for deposition to occur, deposition onto cool interior cask surfaces of the small fraction of volatiles that is initially released as vapors is significantly more efficient than deposition of particulates. It was also noted that the NUREG/CR-6672 cask-to-environment release fractions appear consistent with the fuel fines deposition in the burst tests documented in NUREG/CR-0722. The thermal gradient tube can be considered the "hole" in the larger furnace chamber which contained the fuel rod. While NUREG/CR-0722 doesn't indicate the diameter of the tube, NUREG/CR-4105 indicates that the thermal gradient tube had a diameter of 3.6 mm in a similar apparatus used for follow on experiments. Plotting the 1-3% fraction of particulate that escaped the furnace on Figure 3-1 at the 10 mm^2 leak area (red oval) shows that it is bounded by the MELCOR results.

Finally, it was noted that the NRC staff have previously provided an estimate of particulate release for use in dose analysis of DSC leakage for the Calvert Cliffs ISFSI. In the NRC's March 1991 NRC Environmental Assessment for the Calvert Cliffs ISFSI (see ADAMS Accession Number ML022550053), a fuel-to-environment release fraction of 5E-10 for particulates is used in Tables 6.3 and 6.4 based on SAND80-2124. In addition, the NRC states:

> "particulate releases contribute an insignificant amount to the radiation dose ... accident damage is not expected to provide a pathway with a large cross sectional area from the DSC cavity to the environment; the most likely release pathway would consist of only a small section of a failed DSC. In addition to the small release area, radionuclides can condense, plate out, or be filtered out before escaping the DSC.

Factoring out the 3E-5 fuel-to-DSC release fraction for fines from Table 3-4, suggests that the NRC has previously endorsed use of a DSC-to-environment particulate release fraction of 1.7E-5 for the Calvert Cliffs ISFSI.

Table 3-5 summarizes the DSC-to-environment release fractions used in this calculation based on the above information. The analysis presented in Appendix A demonstrates that normal and off-normal leakage at a rate of 1E-3 atm-cc/sec would require a circular hole no larger than 18 μm in diameter. Since the area of such a hole is much less than 0.1 mm^2, the volatile and fines release fractions from the lower bound of Figure 3-1 are utilized for both normal and off-normal accidents. For the accident case, the volatile and fuel fines release fractions for the 1 mm^2 opening assumed for this accident are utilized. Crud particle size is generally smaller than fuel fines (0.2-20 μm based on SAND88-1358, Figure 5) however, detailed examination of a CASTOR V/21 cask in storage at Idaho National Laboratory found no evidence of crud in the gas samples taken from the cask, and no evidence of major crud spallation from the fuel rod surfaces after 14 years of storage (see EPRI TR-1002882). Based on this crud particulate is taken to have the same DSC-to-environment release fraction as fuel fines. No credit is taken for retention of gasses within the DSC, and thus the DSC-to-environment release fraction is set to 1.

Table 3-5 – DSC-to-Environment Release Fractions by Nuclide Group

Nuclide Group	Normal and Off-Normal	Accident
Gases	1	1
Volatiles	7E-5	8E-4
Fines	0.002	0.02
Crud	0.002	0.02

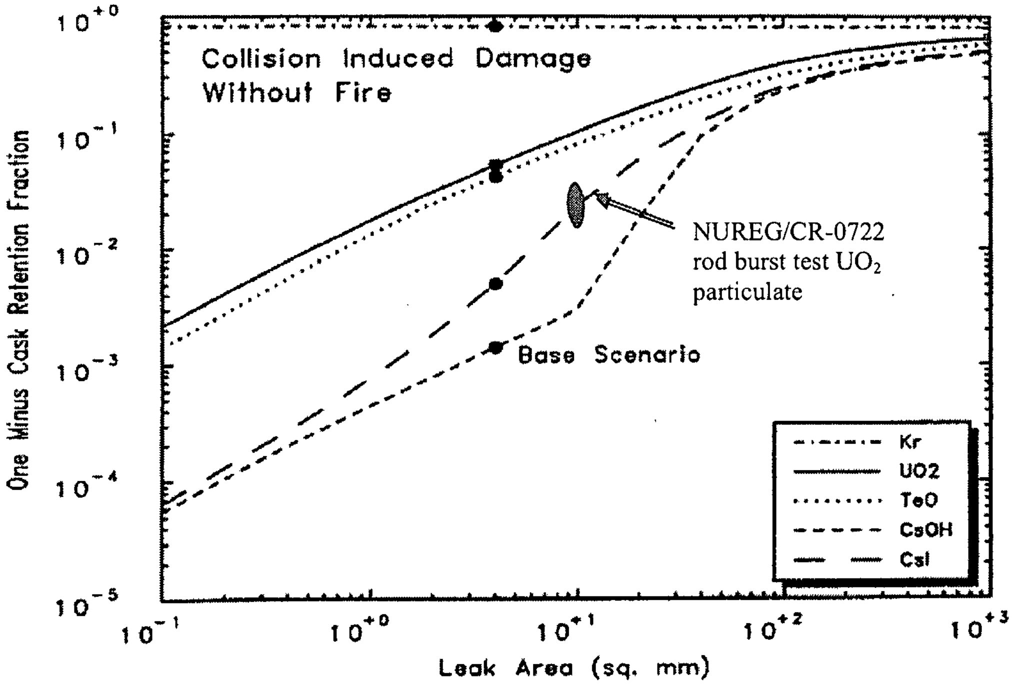

Figure 3-1 – NUREG/CR-6672 Cask to Environment Release Fractions

3.4 Atmospheric Dispersion Coefficients (X/Q)

The 2-hour atmospheric dispersion coefficients at the exclusion area boundary (EAB) were calculated using the same NRC Regulatory Guide 1.145 (Reference 7) methods utilized for the current design basis X/Q in ISFSI USAR Chapter 8.2.8 and 12.8.2.8. The following equations for calculating the X/Q for ground level releases are referenced in NRC Regulatory Guide 1.145:

Equation 1: $X/Q = [\mu\ (\pi\ \sigma_y \sigma_z + A/2]^{-1}$

Equation 2: $X/Q = [\mu\ 3\ \pi\ \sigma_y \sigma_z]^{-1}$

Equation 3: $X/Q = [\mu\ \pi\ \Sigma_y \sigma_z]^{-1}$

where:
μ = average wind speed at the 10m level in meters/second
A = smallest vertical plane cross-sectional area of the HSM in meters
σ_y = the lateral plume spread in meters as function of stability and distance

σ_z = the vertical plume spread in meters as a function of stability and distance
$\Sigma_y = (M-1)\ \sigma_{y800m} + \sigma_y$, where M is obtained from Figure 3 of Regulatory Guide 1.145.

Per NRC Regulatory Guide 1.145 criteria, the results of Equation 1 should be compared to those of Equation 2. The higher of the two should then be compared to those of Equation 3. The lower of the two is the determined X/Q.

While the method of calculating the X/Q remained the same, some inputs were modified to be consistent with current requirements of NUREG-1536 and NUREG-1567. Because any potential release under normal conditions would typically occur over a substantial period of time, References 5 and 6 indicate that the NRC staff accepts an assumption of D-stability diffusion and a wind speed (μ) of 5 m/s. For off-normal conditions, the X/Q is the same as those discussed above for normal conditions. For hypothetical accidents conditions, References 5 and 6 indicate that the NRC staff has accepted calculation of X/Q on the basis of F-stability diffusion, and a wind speed (μ) of 1 m/s. The 1189 meter (3900 feet) distance from the ISFSI to the EAB remains the same as described in the ISFSI USAR and used in the design basis calculation (Reference 3). Similarly, the area (A) of the smallest vertical plane of the HSM remained the same (53 m^2) as that used in the design basis calculation (Reference 3). The values of σ_y and σ_{y800m} were obtained from Figure 1 of Regulatory Guide 1.145. The values of σ_z were obtained from Figure 2 of Regulatory Guide 1.145. Table 3-6 below summarizes the values obtained for all cases, with the current design basis values the same as those currently used in Reference 3. The resulting values of Equations 1, 2, and 3, and the final X/Q for each case are also listed in Table 3-6.

Table 3-6. Atmospheric Dispersion Coefficients

Parameter	**Design Basis**	**Accident**	**Off-Normal & Normal**
Stability	G	F	D
μ (m/s)	1	1	5
A (m^2)	53	53	53
σ_y (m)	27	40.5	80
σ_z (m)	9	15	35
M	6	4	1.2
σ_{y800m} (m)	18	30	60
Σ_y (m)	117	130.5	92
Eq1(sec/m^3)	1.27E-03	5.17E-04	2.27E-05
Eq2(sec/m^3)	4.37E-04	1.75E-04	7.58E-06
Eq3	3.02E-04	1.63E-04	1.98E-05
X/Q (sec/m^3)	**3.02E-04**	**1.63E-04**	**1.98E-05**

3.5 DSC Leakage Rate

A detailed analysis of the characteristics of DSC leakage characteristics for each scenario is provided in Appendix A and summarized in Table 3-7 below. Information on gas temperature, backfill helium moles in the 32P DSC, and moles of fission and fill gas in each fuel rod were taken from CA06300, CA06758, and CA06771. For the normal and off-normal, a 1E-3 atm-cc/sec leak rate was assumed and hole size and fraction released were calculated, while for the accident case, a 1 mm^2 hole was assumed as discussed in Section 4 and leak rate and fraction released were calculated. For the dose calculation, the transfer case from Appendix A was utilized as the off-normal case since it was bounding.

Table 3-7 – Summary of DSC Leak Rate Analysis

Case	DSC Gas Temp (°F)	% Rods Failed	Initial Pressure (atm)	Exposure Duration (hours)	Flow Rate (atm-cc/sec)	Hole Diameter (µm)	Hole Area (mm^2)	% Gas Release During Exposure Duration
Normal	484	1%*	1.72	8760	1E-3*	18.4	2.65E-4	0.42%
Off-Normal	621	10%*	2.35	8760	1E-3*	18.4	2.65E-4	0.59%
Accident	725	100%*	6.68	720	1061.3	1128.4*	1.0*	100%

*Assumed value

3.6 Breathing Rate

For calculations of inhalation dose, an adult breathing rate (BR) of 2.5E-4 m^3/s, as specified in NRC Regulatory Guide 1.109, is utilized.

4.0 ASSUMPTIONS

The following assumptions are made for this work:

1. It is assumed that radionuclides released from fuel rods are uniformly distributed throughout the DSC interior void space, and released in the same proportion as the fuel rod fission and fill and DSC backfill gasses during the exposure duration (settling, plate-out and other removal mechanisms for non-gaseous radionuclides while in the DSC are accounted for via the release fraction discussed in Section 3.3).
2. Per NUREG-1567 (p. 9-11), the following fuel rod breakage fractions were assumed:

   1% for normal conditions

   10% for off-normal conditions

   100% for design basis accident and extreme natural phenomena
3. Per NUREG-1567 (pp. 9-14 to 9-15), the following exposure durations were assumed:

   8760 hours for normal and off-normal conditions

   720 hours for accident conditions
4. Per NUREG-1567 (p. 9-14) for normal conditions, leakage was assumed to occur from all 72 DSCs in the first three phases of the ISFSI. Based on the fact that 48 NUHOMS-24P DSCs and 24 NUHOMS-32P DSCs are stored in the first three phases, this constitutes 1,920 assemblies. Future phases of the ISFSI are not included as those DSCs are assumed to be tested to ANSI-14.5-97 leak tight requirements, and therefore do not require confinement dose analysis per NUREG-1567. Also per NUREG-1567 (p. 9-14) for off-normal and accident conditions, only a single 32P DSC is assumed to be leaking (source term bounds 24P DSCs).
5. For the accident condition a non-mechanistic failure in the form of a 1 mm^2 circular hole is assumed. This size opening is consistent with a pit or crack type penetration which might be associated with the unmitigated effects of aging, and would lead to depressurization of the DSC in approximately 15 hours (from accident pressure to atmospheric). Per NUREG/CR-6672 this size hole was associated with a 60 mph impact of a mechanically sealed rail cask. Thus, this is very conservative for a welded DSC which has been shown to remain unbreached during all credible design basis accidents in the Calvert Cliffs ISFSI USAR Chapters 8 and 12.8.
6. All DSCs are conservatively assumed to be fully loaded with design basis fuel assemblies. This is highly conservative for the normal case as the average time since discharge for all fuel loaded in the first three phases of the ISFSI (69 DSCs as of 11/1/2011) is ~24 years.

5.0 REFERENCES

The following references are used in this work:

1. CCNPP Calculation CA03902, "NUHOMS-24P Fission Gas Release Dose Rates," November 17, 1997.

2. CCNPP Calculation Change Notice CA03902-002, "Extended Burnup NUHOMS-32P Fission Gas Release Dose Rates," June 29, 2007.

3. CCNPP ISFSI Record MS-373, "X/Q Calculation," July 3, 1989.

4. CCNPP Calculation CA06721, "Source Terms for ISFSI 32P Burnup Extension", March 15, 2007

5. NUREG-1536, "Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility," Revision 1, U.S. Nuclear Regulatory Commission, July 2010.

6. NUREG-1567, "Standard Review Plan for Spent Fuel Dry Storage Facilities," U.S. Nuclear Regulatory Commission, February 2000.

7. NRC Regulatory Guide 1.145, "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," Revision 1, February 1983.

8. Federal Guidance Report (FGR) 11, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors," 1989

9. Federal Guidance Report (FGR) 12, "External Exposure to Radionuclides in Air, Water, and Soil," 1993.

10. NUREG/CR-6487, "Containment Analysis for Type B Packages Used to Transport Various Contents," November 1996.

11. SAND90-2406, "A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements," November 1992.

12. CCNPP Calculation CA06751,

13. NUREG/CR-6672, "Reexamination of Spent Fuel Shipment Risk Estimates," March 2000

14. NRC Environmental Assessment for CCNPP ISFSI, March 1991 (ADAMs Accession Number ML022550053)

15. NUREG/CR-0722, "Fission Product Release from Highly Irradiated LWR Fuel," February 1980.

16. NUREG/CR-04105, "An Assessment of Thermal Gradient Tube Results from the HI Series of Fission Product Release Tests," March 1985.

17. SAND88-1358, "Estimate of CRUD Contribution to Shipping Cask Containment Requirements," January 1991.

18. SAND80-2124, "Transportation Accident Scenarios for Commercial Spent Fuel," February 1981

19. EPRI TR-1002882, "Dry Cask Storage Characterization Project," September 2002

20. NRC Regulatory Guide 1.109, Calculation of annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance With 10CFR50 Appendix I," Revision 1, October 1977.

21. CA06300, "NUHOMS-32P Maximum Operating Pressure Storage and Transfer," Revision 1, June 2004

22. CA06758, "Fuel Performance Data for Calvert Cliffs Dry Storage (ISFSI) Analysis for Batches C1N Through C1T and C2M Through C2S," October 2006.

23. CA06771, "Effect of Updated Fuel Performance Data on NUHOMS-32P+ DSC Internal Pressure," September 2008.

6.0 METHOD OF ANALYSIS

An Excel spreadsheet was developed to perform the dose calculation using the inputs discussed in Sections 3 and 4. For each condition (normal, off-normal, and accident) the source released from the DSC(s) for each isotope, Q_i, is determined as follows:

Q_i = (% Failed Fuel per DSC) * (Total Assemblies Involved) * (Ci/assembly for isotope i) * (% Gas Release during Exposure Duration) * (Fuel-to-DSC Release Fraction) * (DSC-to-Environment Release Fraction)

The inhalation component of dose, otherwise known as the Committed Dose Equivalent (CDE) is then determined as follows for each organ (including effective dose and skin dose):

$$\text{CDE} = \Sigma\, [\, Q_i * \text{DCF}_i\,] * X/Q * \text{Breathing Rate} * \text{unit conversion factor}$$

The submersion component of dose, or the Deep Dose Equivalent (DDE) is determined as follows for each organ (including effective dose and skin dose):

$$\text{DDE} = \Sigma\, [\, Q_i * \text{DCF}_i\,] * X/Q * \text{unit conversion factor}$$

For a given organ, the total organ dose equivalent is the sum of the CDE and the DDE. A unit conversion factor of 3.7E12 is utilized in the calculation to convert the DCFs from Sv/Bq to a Rem/Ci basis for the accident case, and a 3.7E15 factor is utilized for normal and off-normal cases to place the final result in terms of mrem. Doses are determined for both the neutron and gamma source terms, and the bounding total organ dose is compared against the limit.

Compliance with the lens dose equivalent (LDE) limit is achieved if the sum of the Total Skin and Effective dose equivalent do not exceed 0.15 Sv (15 rem).

7.0 CALCULATION AND COMPUTATION

7.1 Normal Doses

Table 7-1 provides the calculated release of isotopes to the environment from hypothetical normal leakage of all DSC's in Phases 1 – 3, after consideration of the amount of DSC leakage at the indicated rate in the exposure period as well as all release fractions considered in this analysis. Table 7-2 summarizes the dose calculation based on the inventory released to the environment. Based on CA06751 Table 6-9 the annual direct dose at this location from a fully loaded 120 HSM ISFSI would be less than 4.6E-2 mrem (5.3E-6 mrem/hr x 8760 hours). Thus, the normal annual ISFSI doses from hypothetical releases and direct radiation are a small fraction of the 10 CFR 72.104(a) requirement that the annual dose equivalent to any real individual who is located beyond the controlled area must not exceed 25 mrem to the whole body (effective), 75 mrem to the thyroid and 25 mrem to any other critical organ.

Table 7-1 - Curies Released in 8760 hours from 72 DSCs for Normal Conditions

Isotope	Q neutron (Ci)	Q gamma (Ci)
ac227	1.76E-14	1.02E-14
am241	6.18E-06	2.94E-06
am242	1.86E-08	1.66E-08
am242m	1.86E-08	1.67E-08
am243	1.30E-07	4.54E-08
c14	3.99E-02	2.38E-02
cd113m	6.23E-08	5.46E-08
cl36	1.18E-03	7.22E-04
cm242	1.54E-08	1.54E-08
cm243	6.28E-08	3.05E-08
cm244	1.41E-05	4.23E-06
cm245	2.21E-09	4.16E-10
cm246	1.06E-09	1.00E-10
co60	9.52E-05	3.11E-04
cs134	6.36E-07	7.95E-06
cs135	2.65E-10	2.40E-10
cs137	5.21E-05	4.99E-05
eu154	6.09E-06	8.31E-06
eu155	9.23E-07	2.19E-06
h3	4.15E+00	5.43E+00
i129	4.88E-04	3.62E-04
i137	0.00E+00	0.00E+00
kr81	2.18E-09	9.32E-10
kr85	4.25E+01	6.88E+01
nb94	4.14E-10	2.81E-10
np237	9.90E-10	7.92E-10
np239	1.30E-07	4.54E-08
pa231	4.35E-14	4.83E-14
pd107	4.22E-10	2.38E-10
pm147	5.27E-06	6.23E-05

Isotope	Q neutron (Ci)	Q gamma (Ci)
pu238	1.12E-05	6.57E-06
pu239	6.62E-07	7.10E-07
pu240	1.40E-06	1.07E-06
pu241	1.54E-04	2.01E-04
pu242	8.89E-09	4.12E-09
ru103	0.00E+00	1.95E-23
ru106	7.52E-09	2.33E-06
se79	1.96E-10	1.57E-10
sm151	8.16E-07	8.99E-07
sr89	5.46E-39	2.73E-19
sr90	3.24E-05	3.66E-05
tc99	3.84E-08	3.19E-08
th230	3.11E-13	2.36E-13
u232	1.00E-10	5.12E-11
u233	1.12E-13	7.97E-14
u234	2.06E-09	2.75E-09
u235	1.57E-11	4.88E-11
u236	6.04E-10	6.96E-10
u238	5.99E-10	6.04E-10
xe127	0.00E+00	4.81E-25
xe137	0.00E+00	0.00E+00
y90	1.39E-04	1.57E-04
zr95	1.11E-30	3.46E-15
Total	4.67E+01	7.43E+01

Table 7-2 - Summary of Dose Results for Normal Conditions

Source	Dose Component	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Neutron	DDE (mRem)	3.65E-04	4.18E-04	3.57E-04	3.40E-04	6.87E-04	3.69E-04	3.40E-04	3.72E-04	4.11E-02
	CEDE (mRem)	1.85E-02	1.78E-03	9.88E-02	9.34E-02	1.14E+00	1.57E-02	4.42E-02	6.62E-02	0.00E+00
	Total (mRem)	1.89E-02	2.20E-03	9.92E-02	9.38E-02	1.14E+00	1.61E-02	4.45E-02	6.66E-02	4.11E-02
Gamma	DDE (mRem)	5.93E-04	6.79E-04	5.79E-04	5.53E-04	1.11E-03	5.98E-04	5.53E-04	6.03E-04	6.66E-02
	CEDE (mRem)	1.20E-02	2.09E-03	7.00E-02	5.54E-02	6.66E-01	1.24E-02	2.60E-02	3.96E-02	0.00E+00
	Total (mRem)	1.26E-02	2.77E-03	7.05E-02	5.60E-02	6.67E-01	1.30E-02	2.66E-02	4.02E-02	6.66E-02
Max Total (mRem)		1.89E-02	2.77E-03	9.92E-02	9.38E-02	1.14E+00	1.61E-02	4.45E-02	6.66E-02	6.66E-02
72.104(a) Limit		25	25	25	25	25	75	25	25	25

7.2 Off-Normal Doses

Table 7-3 provides the calculated release of isotopes to the environment from hypothetical off-normal leakage of a single 32P DSC, after consideration of the amount of DSC leakage at the indicated rate in the exposure period as well as all release fractions considered in this analysis. Table 7-4 summarizes the dose calculation based on the inventory released to the environment. Based on CA06751 Table 6-9 the annual direct dose at this location from a fully loaded 120 HSM ISFSI would be less than 4.6E-2 mrem (5.3E-6 mrem/hr x 8760 hrs). Thus, the off-normal annual ISFSI doses from hypothetical releases and direct radiation are a small fraction of the 10 CFR 72.104(a) requirement that the annual dose equivalent to any real individual who is located beyond the controlled area must not exceed 25 mrem to the whole body (effective), 75 mrem to the thyroid and 25 mrem to any other critical organ.

Table 7-3 - Curies Released in 8760 hours from One 32 DSC for Off-Normal Conditions

Isotope	Q neutron (Ci)	Q gamma (Ci)
ac227	4.11E-15	2.37E-15
am241	1.44E-06	6.84E-07
am242	4.32E-09	3.86E-09
am242m	4.34E-09	3.88E-09
am243	3.04E-08	1.06E-08
c14	9.28E-03	5.54E-03
cd113m	1.45E-08	1.27E-08
cl36	2.75E-04	1.68E-04
cm242	3.58E-09	3.58E-09
cm243	1.46E-08	7.11E-09
cm244	3.27E-06	9.85E-07
cm245	5.14E-10	9.70E-11
cm246	2.48E-10	2.34E-11
co60	2.22E-05	7.24E-05
cs134	1.48E-07	1.85E-06
cs135	6.17E-11	5.59E-11
cs137	1.21E-05	1.16E-05
eu154	1.42E-06	1.94E-06
eu155	2.15E-07	5.11E-07
h3	9.68E-01	1.27E+00
i129	1.14E-04	8.44E-05
i137	0.00E+00	0.00E+00
kr81	5.08E-10	2.17E-10
kr85	9.90E+00	1.60E+01
nb94	9.63E-11	6.55E-11
np237	2.31E-10	1.85E-10
np239	3.04E-08	1.06E-08
pa231	1.01E-14	1.13E-14
pd107	9.82E-11	5.55E-11
pm147	1.23E-06	1.45E-05
pu238	2.60E-06	1.53E-06
pu239	1.54E-07	1.65E-07
pu240	3.26E-07	2.50E-07
pu241	3.59E-05	4.68E-05
pu242	2.07E-09	9.59E-10
ru103	0.00E+00	4.54E-24
ru106	1.75E-09	5.44E-07
se79	4.56E-11	3.66E-11
sm151	1.90E-07	2.09E-07
sr89	1.27E-39	6.35E-20
sr90	7.54E-06	8.53E-06
tc99	8.95E-09	7.43E-09
th230	7.24E-14	5.50E-14
u232	2.34E-11	1.19E-11

Isotope	Q neutron (Ci)	Q gamma (Ci)
u233	2.60E-14	1.86E-14
u234	4.79E-10	6.40E-10
u235	3.65E-12	1.14E-11
u236	1.41E-10	1.62E-10
u238	1.40E-10	1.41E-10
xe127	0.00E+00	1.12E-25
xe137	0.00E+00	0.00E+00
y90	3.23E-05	3.66E-05
zr95	2.58E-31	8.06E-16
Total	1.09E+01	1.73E+01

Table 7-4 - Summary of Dose Results for Off-Normal Conditions

Source	Dose Component	GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Neutron	DDE (mRem)	8.51E-05	9.75E-05	8.31E-05	7.93E-05	1.60E-04	8.58E-05	7.93E-05	8.66E-05	9.58E-03
	CEDE (mRem)	4.31E-03	4.16E-04	2.30E-02	2.18E-02	2.66E-01	3.66E-03	1.03E-02	1.54E-02	0.00E+00
	Total (mRem)	4.40E-03	5.13E-04	2.31E-02	2.18E-02	2.67E-01	3.75E-03	1.04E-02	1.55E-02	9.58E-03
Gamma	DDE (mRem)	1.38E-04	1.58E-04	1.35E-04	1.29E-04	2.59E-04	1.39E-04	1.29E-04	1.41E-04	1.55E-02
	CEDE (mRem)	2.79E-03	4.88E-04	1.63E-02	1.29E-02	1.55E-01	2.90E-03	6.06E-03	9.22E-03	0.00E+00
	Total (mRem)	2.93E-03	6.46E-04	1.64E-02	1.30E-02	1.55E-01	3.04E-03	6.19E-03	9.36E-03	1.55E-02
Max Total (mRem)		4.40E-03	6.46E-04	2.31E-02	2.18E-02	2.67E-01	3.75E-03	1.04E-02	1.55E-02	1.55E-02
72.104(a) Limit		25	25	25	25	25	75	25	25	25

7.3 Accident Doses

Table 7-5 provides the calculated release of isotopes to the environment from hypothetical accident leakage of a single 32P DSC, after consideration of the amount of DSC leakage at the indicated rate in the exposure period as well as all release fractions considered in this analysis. Table 7-6 summarizes the dose calculation based on the inventory released to the environment. Based on Calvert Cliffs Calculation CA06751 Table 6-9, the annual direct dose at this location from a fully loaded 120 HSM ISFSI would be less than 3.8E-3 mrem (5.3E-6 mrem/hr x 720 hours). Thus, the 30-day ISFSI accident doses are below the 10 CFR 72.106(b) requirement that any individual located on or beyond the nearest boundary of the controlled area not receive from any design basis accident the more limiting of a total effective dose equivalent of 5 rem, or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 50 rem, 15 rem dose equivalent to the lens of the eye (determined by the sum of the skin and TEDE dose), or 50 rem shallow dose equivalent to the skin or any extremity.

Table 7-5 - Curies Released in 720 hours from One 32P DSC for Accident Conditions

Isotope	Q neutron (Ci)	Q gamma (Ci)
ac227	7.01E-11	4.05E-11
am241	2.46E-02	1.17E-02
am242	7.37E-05	6.59E-05
am242m	7.41E-05	6.62E-05
am243	5.18E-04	1.80E-04
c14	1.58E+01	9.45E+00

Isotope	Q neutron (Ci)	Q gamma (Ci)
cd113m	2.48E-04	2.17E-04
cl36	4.68E-01	2.87E-01
cm242	6.11E-05	6.11E-05
cm243	2.50E-04	1.21E-04
cm244	5.59E-02	1.68E-02
cm245	8.77E-06	1.66E-06
cm246	4.22E-06	3.99E-07
co60	2.52E+00	8.23E+00
cs134	2.89E-03	3.61E-02
cs135	1.20E-06	1.09E-06
cs137	2.37E-01	2.27E-01
eu154	2.42E-02	3.30E-02
eu155	3.67E-03	8.72E-03
h3	1.65E+03	2.16E+03
i129	1.94E-01	1.44E-01
i137	0.00E+00	0.00E+00
kr81	8.67E-07	3.71E-07
kr85	1.69E+04	2.74E+04
nb94	1.64E-06	1.12E-06
np237	3.94E-06	3.15E-06
np239	5.18E-04	1.80E-04
pa231	1.73E-10	1.92E-10
pd107	1.68E-06	9.47E-07
pm147	2.09E-02	2.48E-01
pu238	4.44E-02	2.61E-02
pu239	2.63E-03	2.82E-03
pu240	5.57E-03	4.26E-03
pu241	6.12E-01	7.99E-01
pu242	3.53E-05	1.64E-05
ru103	0.00E+00	8.86E-20
ru106	3.42E-05	1.06E-02
se79	7.78E-07	6.24E-07
sm151	3.24E-03	3.57E-03
sr89	2.48E-35	1.24E-15
sr90	1.47E-01	1.66E-01
tc99	1.53E-04	1.27E-04
th230	1.23E-09	9.39E-10
u232	3.99E-07	2.04E-07
u233	4.44E-10	3.17E-10
u234	8.18E-06	1.09E-05
u235	6.22E-08	1.94E-07
u236	2.40E-06	2.76E-06
u238	2.38E-06	2.40E-06
xe127	0.00E+00	1.91E-22
xe137	0.00E+00	0.00E+00
y90	5.51E-01	6.24E-01
zr95	4.40E-27	1.37E-11
Total	1.86E+04	2.95E+04

Table 7-6 - Summary of Dose Results for Accident Conditions

		GONADS	BREAST	LUNGS	RED MARROW	BONE SURFACE	THYROID	REMAINDER	EFFECTIVE	SKIN
Neutron	DDE (Rem)	0.001	0.002	0.001	0.001	0.003	0.001	0.001	0.001	0.135
	CEDE (Rem)	0.556	0.013	3.273	3.012	37.385	0.058	1.407	2.121	0.000
	Total (Rem)	0.557	0.015	3.275	3.014	37.388	0.059	1.408	2.122	0.135
Gamma	DDE (Rem)	0.003	0.003	0.003	0.002	0.005	0.003	0.002	0.003	0.219
	CEDE (Rem)	0.338	0.030	2.586	1.774	21.739	0.061	0.831	1.289	0.000
	Total (Rem)	0.341	0.033	2.589	1.777	21.743	0.063	0.833	1.291	0.219
Max Total (Rem)		0.557	0.033	3.275	3.014	37.388	0.063	1.408	2.122	0.219
72.106 Limit		50	50	50	50	50	50	50	5	50

8.0 DOCUMENATION OF COMPUTER CODES

Excel and FORTRAN were used as computational support software for performing simple repetitive hand calculations and/or data manipulation and graphing that can be easily checked by hand. No other codes were utilized for performance of this calculation. The FORTRAN source code is included in Appendix A, and Table 8-1 provides the details of other files uploaded to FCMS.

Table 8-1 - List of Native Files to be Loaded to FCMS

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11/20/2011  01:46 PM          2,667,926 CA07718 CONFINEMENT-FINAL.XLSX
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APPENDIX A – DSC LEAKAGE RATE ANALYSIS

A1 PURPOSE & SUMMARY

This appendix is prepared to resolve the RAI's regarding the ISFSI leakage hole size and leakage rate. The purpose of this appendix is twofold:

1. To address the leakage hole diameter as raised in NRC's RAI O-2
2. To use the leakage hole diameter calculated in Part 1 to determine leak rate for three modes of Normal, Off-Normal, and Transport. An additional fourth mode is analyzed referred to as Accident condition. For the fourth mode a hole size of 1 mm^2 is used. For this mode, it is further assumed that 100% of the fuel rods fail, resulting in the release of their fission gas inventory and subsequent pressurization of the DSC.

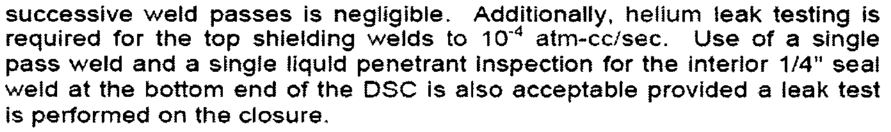
A2 REFERENCES

1. NRC RAI O-2, September 2011.
2. ANSI N14.5-1997, "Leakage Test on Packages for Shipment," Feb. 1998
3. NUREG/CR-6487, "Containment Analysis for Type B Packages Used to Transport Various Contents", November 1996
4. CA06758, "Fuel Performance Data for Calvert Cliffs Dry Storage (ISFSI) Analysis For Batches C1N through C1T and C2M through C2S", October 2006
5. Helge Petersen, RISO Report No. 224, "Properties of Helium, Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressure from 1 to 100 bar and Temperatures to About 1800 K",, September 1970
6. Kestin, J. et al, "Viscosity of the Nobel Gases in the Temperature Range 25-700 C", Journal of Chemical Physics, Volume 56,Number 8, April 1972
7. Massoud, M. "Engineering Thermofluids" Springer 2005
8. CA06300, Rev. 0001, "NUHOMS-32P: MAXIMUM OPERATING PRESSURE, STORAGE AND TRANSFER", May 2004

A3 ADDRESSING LEAKAGE HOLE DIAMETER

This is in response to NRC's staff statement quoted here: "*The licensee should also provide the calculation for the ¡ size penetration¡± (e.g., hole size).* ***Staff calculations show a hole size much larger than 10 µm for leak rates of 1E-4 cc/sec and 1E-3 cc/sec.***"

In order to calculate a hole size, two key input data are required. These are leakage rate and the conditions (DSC pressure and temperature and ambient pressure) at which the leakage rate is specified. To obtain the required information, the Calvert Cliffs ISFSI USAR was reviewed and the following statement regarding leak test was noted:



> successive weld passes is negligible. Additionally, helium leak testing is required for the top shielding welds to 10^{-4} atm-cc/sec. Use of a single pass weld and a single liquid penetrant inspection for the interior 1/4" seal weld at the bottom end of the DSC is also acceptable provided a leak test is performed on the closure.

This statement while specifying helium as Working Fluid (WF), it does not specify the conditions at which such test is performed. Assuming[1] standard upstream pressure of $P_u = 1.5$ atm, upstream temperature of 25 C, and a downstream pressure of 1 atm, leakage hole diameters of about 10.13 and 18.38 micrometer are calculated for "Mass-Like" leakage rates of 1.00E-4 and 1.00E-3 atm-cc/sec, respectively (Table 1). The method of calculation follows the procedure outlined in ANSI N14.5-1997. The formulation, the results, and the corresponding FORTRAN listing (DSC_LEAK.FOR) are presented in this appendix.

Since the calculated hole diameter for 1.0E-4 atm-cc/sec is very close to 10 µm, while the NRC staff statement implies that it should be much larger than 10 µm, additional analyses were performed as described below.

The statement of NRC's staff refers to actual leak rates (in units of cc/sec) as opposed to "mass-like" leak rate (in units of atm-cc/sec). Therefore, two mass-like leakage rates were also used:

A) Mass-like leakage rate of $Q = 1.00\text{E-}4 \times 1.5 = 1.5\text{E-}4$ atm-cc/sec (thus, $L_u = 1.0\text{E-}4$ cc/sec)
B) Mass-like leakage rate of $Q = 1.00\text{E-}3 \times 1.5 = 1.5\text{E-}3$ atm-cc/sec (thus, $L_u = 1.0\text{E-}3$ cc/sec)

Using these augmented leakage rates, we obtain just slightly larger leakage hole diameters of 11.26 µm (for $L_u = 1.0\text{E-}4$ cc/sec) and 20.39 µm (for $L_u = 1.0\text{E-}3$ cc/sec) as summarized in Table 2.

---

[1] Section 5.1.1.3 in the ISFSI USAR contains the following statement, supporting the use of $P_u = 1.5$ atm:

"The maximum leakage rate is 10^{-4} atm-cc/sec. This is the lowest rate measurable for use with portable helium leak detectors. If a pressure of 1.5 atm developed within the DSC cavity for a period of 10 years, a leak rate of 10^{-4} atm-cc/sec would allow 47,300 cm^3 of helium to escape. This would be insignificant compared to the 6.75×10^6 cm^3 of helium in the DSC initially."

To validate the software (DSC_LEAK) from which the above hole diameters were obtained, DSC_LEAK was benchmarked against several worked out examples of ANSI N14.5-1997 with perfect agreement.

It must be noted that the above values are based on a leakage hole length of 1.00 cm. ANSI suggests 0.1, 1.00, and 10.00 cm. The value used in this analysis is reasonable as 0.1 results in excessively small and 10.00 in excessively large diameter. *TransNuclear* in their SAR have used a value of 0.50 cm, which by comparison suggests more conservative value used in our analysis.

Expectedly and due to the capillary nature of the DSC hole, the flow regime for the helium test is *molecular dominant*. However, due to higher pressure and temperature, the flow regime for Normal, Off-Normal, Transport, and Accident conditions is *continuum dominant*.

If flow velocity at exit approaches the speed of sound, flow would become critical. This is the prevailing condition for the case referred to as "Accident" where 100% of all the fuel rods in the DSC are assumed to fail. In contrast, flow in all the three modes of Normal, Off-Normal, and Transfer are subsonic.

A4 CALCULATION OF LEAKGE HOLE DIAMETER

Although DSC_LEAK allows both air or helium to be specified as the working fluid (WF), the leak hole sizes shown in Tables 1 and 2 are calculated based only on helium as the working fluid. The formulation to obtain the leakage hole diameter follows the procedure outlined in the ANSI N14.5-1997. The method to solve the non-linear algebraic equation is based on the Newton-Raphson method as coded in DSC_LEAK. The listing of DSC_LEAK is presented in Section A10.

Q (atm-cm^3/sec):	Mass-Like leakage rate
Pu (atm):	Upstream pressure
P_d (atm):	Downstream pressure
P_a (atm):	Average pressure
T (K):	Upstream Gas Temperature
a (cm):	leakage hole length
μ (cP):	Dynamic viscosity at STP
M (g/gmole):	Molecular weight
$F_c = \frac{2.49\text{E}6D^4}{a\mu}$ (cm^3/atm-sec)	Coefficient of continuum flow conductance
$F_m = \frac{3.81\text{E}3D^3\sqrt{T/M}}{aP_a}$ (cm^3/atm-sec)	Coefficient of free molecular flow conductance
$L_u = (F_c + F_m)(P_u - P_d)(P_a/P_u)$ (cm^3/sec)	Volumetric leak rate based on upstream pressure

Substituting for F_c and F_m in terms of leakage hole diameter into equation for L_u, we obtain:

$$\alpha D^4 + \beta D^3 - \gamma = 0$$

This is a fourth order linear algebraic equation, which is solved by Newton-Raphson using a convergence criterion of 1.00E-6. Coefficients α, β, and γin the above equation are given by such constants as:

$$\alpha = \frac{2.49\text{E}6}{a\mu}$$

$$\beta = \frac{3.81\text{E}3\sqrt{T/M}}{aP_a}$$

$$\gamma = \frac{L_u}{(P_u - P_d)(\frac{P_a}{P_u})}$$

TABLE 1. LEAKAGE HOLE DIAMETER & RELATED INPUT DATA FOR HELIUM LEAKAGE

Q (atm-cc/s)	Pu (atm)	T (C)	T (K)	V (ft^3)	a (cm)	μ (cP)	M (kg/kgmole)	n (gmole)	D (μm)
1E–4	1.5	25	298	171.13	1	0.0198	4	0.2967	10.134
1E–3	1.5	25	298	171.13	1	0.0198	4	0.2967	18.384

Leakage Hole Diameter Corresponding to Q = 1.00E-4 atm-cc/sec of Helium

```
 Determination of Leak Hole Diameter From Leak Rate
 ==================================================
Pressure, Canister      (atm): ..........      1.5000
Pressure, Ambient       (atm): ..........      1.0000
Pressure, Average       (atm): ..........      1.2500
Temperature, Canister   (C): ............     25.0000
Temperature, Canister   (K): ............    298.0000
Canister Free Volume    (ft3): ..........    171.1300
Viscosity, WF           (cP): ...........      0.0198
Molecular Weight, WF    (g/gmole): .......     4.0000
Length, Leakage Hole    (cm): ...........      1.0000
Mass-Like Flow Rate     (atm-cc/sec): ....  0.1000E-03
Leak Rate, Canister     (cc/sec): ........  0.6667E-04
Fc Factor               (cc/atm-sec): ....  0.1326E-03
Fm Factor               (cc/atm-sec): ....  0.2738E-04
Fc/Fm Ratio             (-): ............      4.8441
Number of Iterations    (-): ............           2
Mass of WF              (lbm): ..........      2.6197
Mass of WF              (kg): ...........      1.1867
Moles of WF             (kgmole): ........     0.2967
Diameter, Leakage Hole, (cm): ...........   0.1013E-02
Diameter, Leakage Hole, (micron): ........    10.1338
Working Fluid (WF): .....................   HELIUM
Flow Regime: ...........................    Continuum Dominant
Above data are also saved in:............   HOLE.OUT

 Enter >  1: Calculate Another Hole Diameter
       >  2: Main Menu
       >  3: Exit
```

Leakage Hole Diameter Corresponding to Q = 1.00E-3 atm-cc/sec of Helium

```
 Determination of Leak Hole Diameter From Leak Rate
 ==================================================
Pressure, Canister      (atm): ..........      1.5000
Pressure, Ambient       (atm): ..........      1.0000
Pressure, Average       (atm): ..........      1.2500
Temperature, Canister   (C): ............     25.0000
Temperature, Canister   (K): ............    298.0000
Canister Free Volume    (ft3): ..........    171.1300
Viscosity, WF           (cP): ...........      0.0198
Molecular Weight, WF    (g/gmole): .......     4.0000
Length, Leakage Hole    (cm): ...........      1.0000
Mass-Like Flow Rate     (atm-cc/sec): ....  0.1000E-02
Leak Rate, Canister     (cc/sec): ........  0.6667E-03
Fc Factor               (cc/atm-sec): ....  0.1437E-02
Fm Factor               (cc/atm-sec): ....  0.1635E-03
Fc/Fm Ratio             (-): ............      8.7879
Number of Iterations    (-): ............           7
Mass of WF              (lbm): ..........      2.6197
Mass of WF              (kg): ...........      1.1867
Moles of WF             (kgmole): ........     0.2967
Diameter, Leakage Hole, (cm): ...........   0.1838E-02
Diameter, Leakage Hole, (micron): ........    18.3842
Working Fluid (WF): .....................   HELIUM
Flow Regime: ...........................    Continuum Dominant
Above data are also saved in:............   HOLE.OUT

 Enter >  1: Calculate Another Hole Diameter
       >  2: Main Menu
       >  3: Exit
```

TABLE 2. LEAKAGE HOLE DIAMETER & RELATED INPUT DATA FOR HELIUM LEAKAGE

Q (atm-cc/s)	Pu (atm)	T (C)	T (K)	V (ft^3)	a (cm)	μ (cP)	M (kg/kgmole)	n (gmole)	D (μm)
1.5E–4	1.5	25	298	171.13	1	0.0198	4	0.2967	11.26
1.5E–3	1.5	25	298	171.13	1	0.0198	4	0.2967	20.39

Leakage Hole Diameter Corresponding to Q = 1.50E-4 atm-cc/sec of Helium

```
  Determination of Leak Hole Diameter From Leak Rate
  ==================================================
 Pressure, Canister      (atm): ..........      1.5000
 Pressure, Ambient       (atm): ..........      1.0000
 Pressure, Average       (atm): ..........      1.2500
 Temperature, Canister   (C): ............     25.0000
 Temperature, Canister   (K): ............    298.0000
 Canister Free Volume    (ft3): ..........    171.1300
 Viscosity, WF           (cP): ...........      0.0198
 Molecular Weight, WF    (g/gmole): .......     4.0000
 Length, Leakage Hole    (cm): ...........      1.0000
 Mass-Like Flow Rate     (atm-cc/sec): ....  0.1500E-03
 Leak Rate, Canister     (cc/sec): ........  0.1000E-03
 Fc Factor               (cc/atm-sec): ....  0.2024E-03
 Fm Factor               (cc/atm-sec): ....  0.3759E-04
 Fc/Fm Ratio             (-): ............      5.3841
 Number of Iterations    (-): ............           3
 Mass of WF              (lbm): ..........      2.6197
 Mass of WF              (kg): ...........      1.1867
 Moles of WF             (kgmole): ........     0.2967
 Diameter, Leakage Hole, (cm): ...........  0.1126E-02
 Diameter, Leakage Hole, (micron): ........    11.2635
 Working Fluid (WF): .....................  HELIUM
 Flow Regime: ............................  Continuum Dominant
 Above data are also saved in:............  HOLE.OUT

  Enter >  1: Calculate Another Hole Diameter
        >  2: Main Menu
        >  3: Exit
```

Leakage Hole Diameter Corresponding to Q = 1.50E-3 atm-cc/sec of Helium

```
  Determination of Leak Hole Diameter From Leak Rate
  ==================================================
 Pressure, Canister      (atm): ..........      1.5000
 Pressure, Ambient       (atm): ..........      1.0000
 Pressure, Average       (atm): ..........      1.2500
 Temperature, Canister   (C): ............     25.0000
 Temperature, Canister   (K): ............    298.0000
 Canister Free Volume    (ft3): ..........    171.1300
 Viscosity, WF           (cP): ...........      0.0198
 Molecular Weight, WF    (g/gmole): .......     4.0000
 Length, Leakage Hole    (cm): ...........      1.0000
 Mass-Like Flow Rate     (atm-cc/sec): ....  0.1500E-02
 Leak Rate, Canister     (cc/sec): ........  0.1000E-02
 Fc Factor               (cc/atm-sec): ....  0.2177E-02
 Fm Factor               (cc/atm-sec): ....  0.2233E-03
 Fc/Fm Ratio             (-): ............      9.7501
 Number of Iterations    (-): ............           7
 Mass of WF              (lbm): ..........      2.6197
 Mass of WF              (kg): ...........      1.1867
 Moles of WF             (kgmole): ........     0.2967
 Diameter, Leakage Hole, (cm): ...........  0.2040E-02
 Diameter, Leakage Hole, (micron): ........    20.3971
 Working Fluid (WF): .....................  HELIUM
 Flow Regime: ............................  Continuum Dominant
 Above data are also saved in:............  HOLE.OUT

  Enter >  1: Calculate Another Hole Diameter
        >  2: Main Menu
        >  3: Exit
```

A5 DESCRIPTION OF ANALYZED DSC MODES

Four modes are analyzed in this appendix as shown in Table 3. Three of these modes use the diameter corresponding to Q = 1.E-3 atm-cc/sec (D = 18.38 μm) and the fourth mode uses a diameter corresponding to a flow area of 1 mm^2.

Description of these modes and the key data pertinent to each mode are shown in Table 3. The working fluid for all these four modes is a mixture of helium backfill gas and xenon released due to the assumed failed fuel rods.

TABLE 3. ANALYZED MODES & RELATED INPUT DATA (Q = 1.0E–3 atm-cc/sec)

No.	Mode Description	DSC Temp. (F)*	DSC Temp. (K)	Rods Failed (%)	Hole Diameter (μm)	Hole Area (mm^2)
1	Normal	484	524.27	1	18.38	2.65E-4
2	Off-Normal	509	538.16	10	18.38	2.65E-4
3	Transfer	621	600.38	10	18.38	2.65E-4
4	Accident	725	658.16	100	1128.38	1.000

*: From Reference 8

A6 DETERMINATION OF MOLES OF WORKING FLUID COMPONENTS

DSC pressurization is due to the helium (He) back fill as well as the gases released from the failed fuels as shown in Table 3. The released gases from the failed fuel consist of fission gases and the helium backfill of each rod. Notable fission gases are xenon (Xe), Krypton (Kr), Iodine (I), and Bromide (Br). In the calculation of leak rate, all fission gases are bundled into xenon. Thus the working fluid in the DSC is assumed to be a mixture of helium and xenon.

Formulations for the calculation of the dynamic viscosity of these gases are presented in Section A9. The gram-mole (gmole) of each gas for a given mode is obtained from:

$$n_{Xe} = (N_{Rod/Assy} \times N_{Assy/DSC} \times f_{Failed\ Rod}) \times (f_{Xe} \times n_{ROD})$$
$$n_{He} = (N_{Rod/Assy} \times N_{Assy/DSC} \times f_{Failed\ Rod}) \times (f_{He} \times n_{ROD}) + (DSC_{He} \times 453)$$

where

$N_{Rod/Assy}$ (-): .... Number of assemblies in DSC
$N_{Assy/DSC}$ (-):.. Number of rods per assembly
$f_{Failed\ Rod}$ (%):...................................... Percentage of failed fuel rod (Table 3)
f_{He} (-):... Mole fraction of helium per rod
f_{Xe} (-): .... Mole fraction of xenon per rod
n_{ROD} (gmole):.................................... Total gas gmole per fuel rod
DSC_{He} (lbmole): .... Helium backfill of DSC

Substituting values, the gmole of each working fluid component would be calculated as:

$$n_{Xe} = (176 \times 32 \times \mathrm{Mode}_{\mathrm{Failed\ Rod\%}}) \times (0.525 \times 0.07268)$$
$$n_{He} = (176 \times 32 \times \mathrm{Mode}_{\mathrm{Failed\ Rod\%}}) \times (0.475 \times 0.07268) + (0.419 \times 453)$$

where according to Reference 2, the total gmole gas of a fuel rod at 60 MWd/kgU is $n_{ROD} =$ 0.07268 gmole of which 3.817E-2 (or 52.5%) is fission gas (xenon) and 3.451E-2 gmole (or 47.5%) is helium. The initial DSC helium backfill is 0.419 lbmole (Reference 8).

A7 LEAKAGE RATE FOR VARIOUS MODES

The leakage rate are calculated for various DSC modes as described in Table 2. The method of calculation follows the procedure outlined in ANSI N14.5-1997. The formulation and the results are presented below. The corresponding FORTRAN listing is presented in Section A10.

The leakage rate is obtained, in cm^3/sec, based on the upstream volumetric flow rate:

$$L_u = (F_c + F_m)(P_u - P_d)(P_a / P_u)$$

The downstream pressure is assumed atmospheric ($P_d = 1$ atm). However, upstream pressure is obtained from the summation of the,partial pressure of gases in the DSC, assumed primarily to be xenon (Xe) and Helium (He):

$$P_u = \sum \frac{n_i RT}{V}$$

The molecular weight of the working fluid is obtained from the gmole of the mixture of gases:

$$M_m = \frac{n_{He} \times M_{He} + n_{Xe} \times M_{Xe}}{n_{He} + n_{Xe}}$$

Finally, the dynamic viscosities for helium and xenon at various temperatures are obtained from curve fit to data as shown in Section A9. Similar to the molecular weight, the dynamic viscosity of the mixture is obtained from:

$$\mu_m = \frac{n_{He} \times \mu_{He} + n_{Xe} \times \mu_{Xe}}{n_{He} + n_{Xe}}$$

The above formulations are coded in the FORTRAN program DSC_LEAK, the listing of which is Presented in Section A10.

The results of the DSC_LEAK for the three modes of Normal, Off-Normal, and Transfer are summarized in Table 4.

A8 LEAKAGE RATE FOR CHOKED FLOW

If velocity at exit approaches the speed of sound in the medium the critical flow for the mixture of helium and xenon (assumed as ideal gas) is calculated from (Reference 3 and 7):

$$G_{CR} = \sqrt{\frac{\gamma}{R}(\frac{2}{1+\gamma})^{\frac{\gamma+1}{\gamma-1}}}\frac{P_u}{\sqrt{T_u}}$$

The specific heat ratio, $\gamma$is calculated based on the specific heat ratio of the working fluid constituents and their corresponding mole fractions as follows:

$$\gamma = \frac{n_{He} \times \gamma_{He} + n_{Xe} \times \gamma_{Xe}}{n_{He} + n_{Xe}}$$

The DSC_LEAK program calculates the leakage rate for the Accident model assuming both choked and subsonic. The program then compares the two calculated flow rates to determine whether flow is choked or subsonic.

The leak rate for the choked flow is obtained from calculating the mass flow rate from the above mass flux:

$$\dot{m} = G_{CR}A$$

then dividing by the density of the working fluid:

$$L_u = \frac{\dot{m}}{\rho_m}$$

Where mixture density is obtained from:

$$\rho_m = \frac{P}{\left(\frac{R_u}{M_m}\right)T}\sum_i (n_i)$$

Where R_u is the universal gas constant. It must be emphasized that the values calculated for the accident condition as shown in Table 3 are conservative due to:

- Ignoring the entrance losses to the break
- Ignoring the exit losses from the break
- Ignoring the discharge coefficient at the break

The results of the DSC_LEAK for the Accident mode are summarized in Table 4.

TABLE 4. FLOW RATES & RELATED DATA FOR VARIOUS MODES

Data	Normal	Off-Normal	Transfer	Accident
DSC Volume (ft^3)	171.13	171.13	171.13	171.13
DSC Volume (cc)	4.846E6	4.846E6	4.846E6	4.846E6
Pressure, Canister (psia), P_u	25.295	30.898	34.471	98.122
Pressure, Canister (kPa), P_u	174.40	213.04	237.67	676.52
Pressure, Canister (atm), P_u	1.7208	2.1020	2.3450	6.6750
Pressure, Ambient (atm), P_d	1.0000	1.0000	1.0000	1.0000
Pressure, Average (atm), P_a	1.3604	1.5510	1.6725	3.8375
Temperature, Canister (F)	484.00	509.00	621.00	725.00
Temperature, Canister (R)	955.00	969.00	1081.0	1185.0
Temperature, Canister (C)	251.27	265.16	327.38	385.16
Temperature, Canister (K)	524.27	538.16	600.38	658.16
Viscosity, Mixture (cP)	0.0382	0.0391	0.0428	0.0460
Molecular Weight, Mixture (g/gmole)	5.4108	15.8552	15.8552	49.656
Length, Leakage Hole (cm)	1.0000	1.0000	1.0000	1.0000
Hole Diameter (µm)	18.38	18.38	18.38	1128.4
Hole Diameter (mm)	0.01838	0.01838	0.01838	1.1284
Hole Diameter (cm)	18.38E-4	18.38E-4	18.38E-4	0.1128
Hole Flow Area (mm^2)	2.653E–4	2.653E–4	2.653E–4	1.0000
Fuel Rods Leaking (%)	1.0000	10.000	10.000	100.00
Factor, F_c	0.9622E–3	0.9212E–3	0.8518E–3	0.8771E4*
Factor, F_m	0.1712E–3	0.8886E–4	0.8704E–4	0.5193E1*
Ratio, (F_c/F_m)	5.4108	10.3665	9.7857	1688.904*
Xenon Moles per Fuel Rod (gmole)	0.0382	0.0382	0.0382	0.0382
Xenon Moles in DSC (kgmole)	0.00215	0.0215	0.0215	0.215
Helium Moles in DSC, final (kgmole)	0.1898	0.2093	0.2093	0.3842
Helium Moles in DSC, initial (lbmole)	0.4190	0.4190	0.4190	0.4190
Mixture Density (lbm/ft^3)	0.0058	0.0246	0.0275	0.5070
Mixture Density (kg/m^3)	0.0925	0.3941	0.4397	8.1104
Vapor velocity (ft/sec)	7.9859	10.155	11.1357	597.4
Vapor velocity (m/sec)	2.4341	3.0954	3.3942	182.1
Mass-Like Flow Rate, Q (atm-cc/sec)	1.111E–3	1.7260E–3	2.112E–3	0.1911E6*
Leak Rate, Average, L_a (cc/sec)	0.8169E–3	1.1130E–3	1.263E–3	0.4980E5*
Leak Rate, Upstream, L_u (cc/sec)	0.6458E–3	0.8213E–3	0.901E–3	241
Discharge Duration (hr)	8760	8760	8760	15
Discharge Duration (sec)	31.536E6	31.536E6	31.536E6	5.4E4
Inventory Released (%)	0.4203	0.5345	0.5861	100
Flow Regime	Continuum	Continuum	Continuum	Continuum
Flow Type	Subsonic	Subsonic	Subsonic	Choked

* For information only

The DSC leak rate, inventory, and pressure trend for the Accident mode are shown in Figures A.1 through A.3. The absolute values in these figures have not been updated.

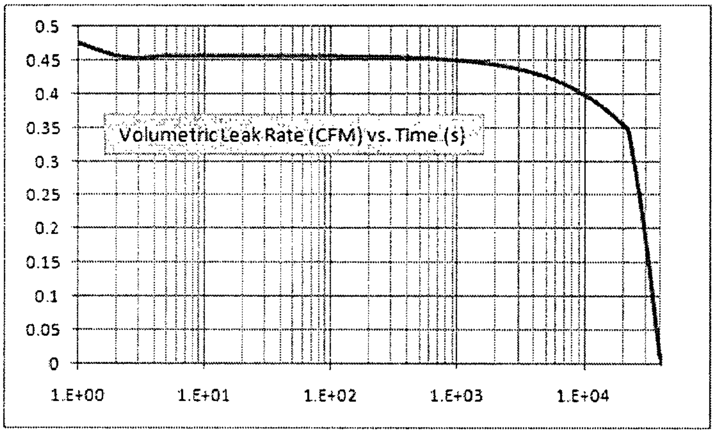


Figure A.1. DSC Leak rate versus time

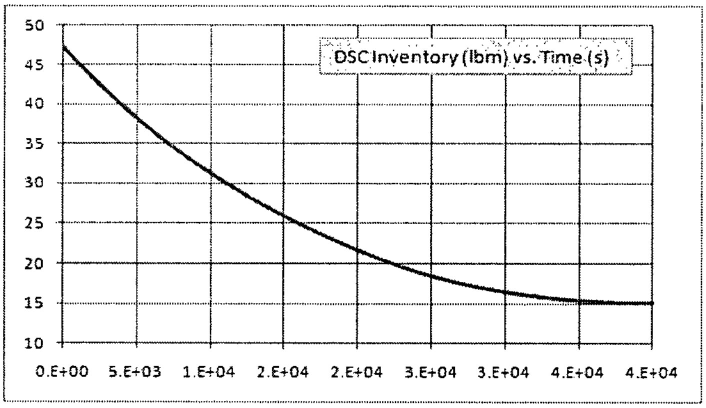


Figure A.2. DSC Inventory versus time following Impact

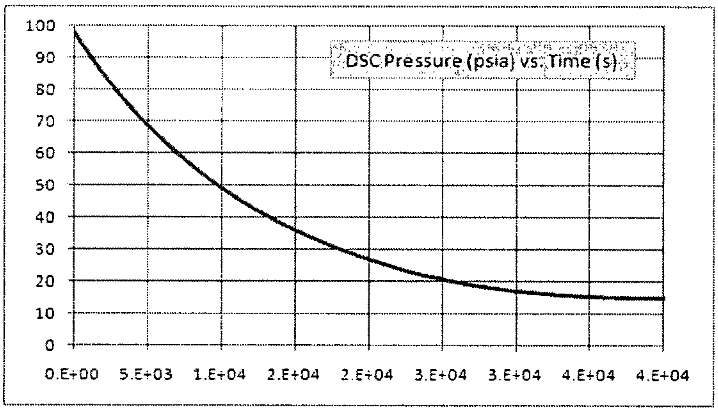


Figure A.3. DSC Pressure versus time

Leakage Flow Rate Corresponding to $D \approx 18\ \mu\text{m}$ for a mixture of Helium & Xenon (NORMAL Conditions with 1% of Rods Failed)

```
Determination of Leakage Rate For Specified Hole Size
=====================================================

Pressure, Canister, Pu   (psia): .........     25.2952
Pressure, Canister, Pu   (kPa): ..........    174.4045
Pressure, Canister, Pu   (atm): ..........      1.7208
Pressure, Ambient,  Pd   (atm): ..........      1.0000
Pressure, Average,  Pa   (atm): ..........      1.3604
Temperature, Canister    (F): ............    484.0000
Temperature, Canister    (K): ............    524.2711
Viscosity, Mixture       (cP): ...........      0.0295
Molecular Weight, Mix.   (g/gmole): ......      5.4108
Length, Leakage Hole     (cm): ...........      1.0000
Rods Leaking             (%): ............      1.0000
Fc/Fm Ratio              (-): ............      5.6212
Fc Factor                (cc/atm-sec): ....  0.9622E-03
Fm Factor                (cc/atm-sec): ....  0.1712E-03
Diameter, Leakage Hole   (cm): ...........  0.1838E-02
Diameter, Leakage Hole   (micron): .......     18.3800
Leakage Area             (cm2): ..........  0.2653E-05
DSC Volume               (ft3): ..........    171.1300
DSC Volume               (m3): ...........      4.8460
Xenon Moles per rod      (gmole): ........      0.0382
Xenon Moles in DSC       (kgmole): .......      0.0021
Helium Moles in DSC      (kgmole): .......      0.1918
Mixture Density          (lbm/ft3): ......      0.0058
Mixture Density          (kg/m3): ........      0.0925
Leakage Velocity         (ft/sec): .......      7.9859
Leakage Velocity         (m/sec): ........      2.4341
Mass-Like Flow Rate, Q   (atm-cc/sec): ....  0.1111E-02
Leak Rate, Average,  L_a (cc/sec): .......  0.8169E-03
Leak Rate, Upstream, L_u (cc/sec): .......  0.6458E-03
Inventory Released       (Volume%) .......  0.4203E+00

Flow Regime: .............................  Continuum Dominant
Above data are also saved in file:........  FLOW.OUT

 Enter >  1: Calculate Another Leak Rate
       >  2: Main Menu
       >  3: Exit
```

Leakage Flow Rate Corresponding to $D \approx 18$ μm for a mixture of Helium & Xenon (OFF-NORMAL Conditions with 10% of Fuel Rods Failed)

```
 Determination of Leakage Rate For Specified Hole Size
 =====================================================

Pressure, Canister, Pu   (psia): .........     30.8986
Pressure, Canister, Pu   (kPa): ..........    213.0385
Pressure, Canister, Pu   (atm): ..........      2.1020
Pressure, Ambient,  Pd   (atm): ..........      1.0000
Pressure, Average,  Pa   (atm): ..........      1.5510
Temperature, Canister    (F): ............    509.0000
Temperature, Canister    (K): ............    538.1600
Viscosity, Mixture       (cP): ...........      0.0308
Molecular Weight, Mix.   (g/gmole): ......     15.8552
Length, Leakage Hole     (cm): ...........      1.0000
Rods Leaking             (%): ............     10.0000
Fc/Fm Ratio              (-): ............     10.3665
Fc Factor                (cc/atm-sec): ....  0.9212E-03
Fm Factor                (cc/atm-sec): ....  0.8886E-04
Diameter, Leakage Hole   (cm): ...........   0.1838E-02
Diameter, Leakage Hole   (micron): .......     18.3800
Leakage Area             (cm2): ..........   0.2653E-05
DSC Volume               (ft3): ..........    171.1300
DSC Volume               (m3): ...........      4.8460
Xenon Moles per rod      (gmole): ........      0.0382
Xenon Moles in DSC       (kgmole): .......      0.0215
Helium Moles in DSC      (kgmole): .......      0.2093
Mixture Density          (lbm/ft3): ......      0.0246
Mixture Density          (kg/m3): ........      0.3941
Leakage Velocity         (ft/sec): .......     10.1554
Leakage Velocity         (m/sec): ........      3.0954
Mass-Like Flow Rate, Q   (atm-cc/sec): ....  0.1726E-02
Leak Rate, Average,  L_a (cc/sec): .......   0.1113E-02
Leak Rate, Upstream, L_u (cc/sec): .......   0.8213E-03
Inventory Released       (Volume%) .......   0.5345E+00

Flow Regime: .............................   Continuum Dominant
Above data are also saved in file:........   FLOW.OUT

 Enter >  1: Calculate Another Leak Rate
       >  2: Main Menu
       >  3: Exit
```

Leakage Flow Rate Corresponding to $D \approx 18$ μm for a mixture of Helium & Xenon (TRANSFER Conditions with 10% of Fuel Rods Failed)

```
 Determination of Leakage Rate For Specified Hole Size
 =====================================================

Pressure, Canister, Pu   (psia): .........     34.4711
Pressure, Canister, Pu   (kPa): ..........    237.6701
Pressure, Canister, Pu   (atm): ..........      2.3450
Pressure, Ambient,  Pd   (atm): ..........      1.0000
Pressure, Average,  Pa   (atm): ..........      1.6725
Temperature, Canister    (F): ............    621.0000
Temperature, Canister    (K): ............    600.3822
Viscosity, Mixture       (cP): ...........      0.0334
Molecular Weight, Mix.   (g/gmole): ......     15.8552
Length, Leakage Hole     (cm): ...........      1.0000
Rods Leaking             (%): ............     10.0000
Fc/Fm Ratio              (-): ............      9.7857
Fc Factor                (cc/atm-sec): ....  0.8518E-03
Fm Factor                (cc/atm-sec): ....  0.8704E-04
Diameter, Leakage Hole   (cm): ...........   0.1838E-02
Diameter, Leakage Hole   (micron): .......     18.3800
Leakage Area             (cm2): ..........   0.2653E-05
DSC Volume               (ft3): ..........    171.1300
DSC Volume               (m3): ...........      4.8460
Xenon Moles per rod      (gmole): ........      0.0382
Xenon Moles in DSC       (kgmole): .......      0.0215
Helium Moles in DSC      (kgmole): .......      0.2093
Mixture Density          (lbm/ft3): ......      0.0275
Mixture Density          (kg/m3): ........      0.4397
Leakage Velocity         (ft/sec): .......     11.1357
Leakage Velocity         (m/sec): ........      3.3942
Mass-Like Flow Rate, Q   (atm-cc/sec): ....  0.2112E-02
Leak Rate, Average,  L_a (cc/sec): .......   0.1263E-02
Leak Rate, Upstream, L_u (cc/sec): .......   0.9006E-03
Inventory Released       (Volume%) .......   0.5861E+00

Flow Regime: ..............................  Continuum Dominant
Above data are also saved in file:.........  FLOW.OUT

 Enter >  1: Calculate Another Leak Rate
       >  2: Main Menu
       >  3: Exit
```

Leakage Flow Rate Corresponding to $A \approx 1$ mm^2 for a mixture of Helium & Xenon (ACCIDENT Conditions with 100% of Fuel Rods Failed)

```
 Determination of Leakage Rate For Specified Hole Size
 =====================================================

Pressure, Canister, Pu   (psia): ..........      98.1215
Pressure, Canister, Pu   (kPa): ...........     676.5245
Pressure, Canister, Pu   (atm): ...........       6.6750
Pressure, Ambient,  Pd   (atm): ...........       1.0000
Pressure, Average,  Pa   (atm): ...........       3.8375
Temperature, Canister    (F): .............     725.0000
Temperature, Canister    (K): .............     658.1600
Viscosity, Mixture       (cP): ............       0.0460
Molecular Weight, Mix.   (g/gmole): .......      49.6565
Length, Leakage Hole     (cm): ............       1.0000
Rods Leaking             (%): .............     100.0000
Fc/Fm Ratio              (-): .............    1688.9035
Fc Factor                (cc/atm-sec): ....   0.8771E+04
Fm Factor                (cc/atm-sec): ....   0.5193E+01
Diameter, Leakage Hole   (cm): ............   0.1128E+00
Diameter, Leakage Hole   (micron): ........    1128.3792
Leakage Area             (cm2): ...........   0.1000E-01
DSC Volume               (ft3): ...........     171.1300
DSC Volume               (m3): ............       4.8460
Xenon Moles per rod      (gmole): .........       0.0382
Xenon Moles in DSC       (kgmole): ........       0.2149
Helium Moles in DSC      (kgmole): ........       0.3842
Mixture Density          (lbm/ft3): .......       0.6363
Mixture Density          (kg/m3): .........      10.1782
Leakage Velocity         (ft/sec): ........   93934.2951
Leakage Velocity         (m/sec): .........   28631.5204
Mass-Like Flow Rate, Q   (atm-cc/sec): ....   0.1911E+06
Leak Rate, Average,  L_a (cc/sec): ........   0.4980E+05
Leak Rate, Upstream, L_u (cc/sec): ........   0.2863E+05
Inventory Released       (Volume%) ........   0.1863E+08

Flow Regime: ..............................   Continuum Dominant

NOTE:  FLOW IS CHOKED.  DISREGARD HIGH LEAK RATE BASED ON BERNOULLI FLOW
       ----------------------------------------------------------------


LEAKAGE RATE BASED ON CRITICAL FLOW AT THE BREAK
================================================

Pressure, Canister, Pu   (psia): ..........      98.1215
Pressure, Canister, Pu   (kPa): ...........     676.5245
Pressure, Canister, Pu   (atm): ...........       6.6750
Temperature, Canister    (F): .............     725.0000
Temperature, Canister    (R): .............    1184.6700
Temperature, Canister    (K): .............     658.1600
Break Area               (mm2): ...........       1.0000
Break Diameter           (micron): ........    1128.3792
Break Diameter           (cm): ............       0.1128
Mixture Density          (lbm/ft3): .......       0.5070
Mixture Density          (kg/m3): .........       8.1104
Mass Flux                (lbm/ft2-sec): ...     302.8684
Mass Flux                (kg/m2-sec): .....    1476.7660
```

```
Break Velocity          (ft/sec): ........    597.3744
Break Velocity          (m/sec): .........    182.0819
Leak Rate, Volumetric   (ft3/sec): .......      0.0064
Leak Rate, Volumetric   (CFM): ...........      0.3858
Leak Rate, Volumetric   (cc/sec): ........  0.1821E+03
Leak Rate, Mass         (lbm/sec): .......  0.3260E-02
Leak Rate, Mass         (kg/sec): ........  0.1477E-02

Above data are also saved in file:.........  FLOW.OUT

 Enter >  1: Calculate Another Leak Rate
       >  2: Main Menu
       >  3: Exit
```

A9 HELIUM AND XENON VISCOSITY

Dynamic viscosity of helium and xenon are obtained from References 5 and 6 as discussed in this section.

HELIUM VISCOSITY

Reference 5 suggests a simple formula for dynamic viscosity of helium in units of kg/m·s as:

$$\mu = 3.674\text{E} - 7T^{0.7}$$

Where in this formula, T is the absolute temperature is in degrees Kelvin. For example, helium viscosity at 600 K is about 0.0323 cP. This relation is used in the FORTRAN program to obtain μ_{He} at various temperatures. Note that the value used in the hand calculation of Section 2 is obtained from another source.

XENON VISCOSITY

Reference 6 provides a table of viscosity versus temperature, as shown in Figure A.1.1. The curve fit to these data is used as a built in formula in the FORTRAN program for calculation of xenon viscosity at various temperatures.

$$\mu = 4\text{E-}14\,T^4 - 1\text{E-}10\,T^3 + 6\text{E-}08\,T^2 + 6\text{E-}05\,T + 0.0019$$

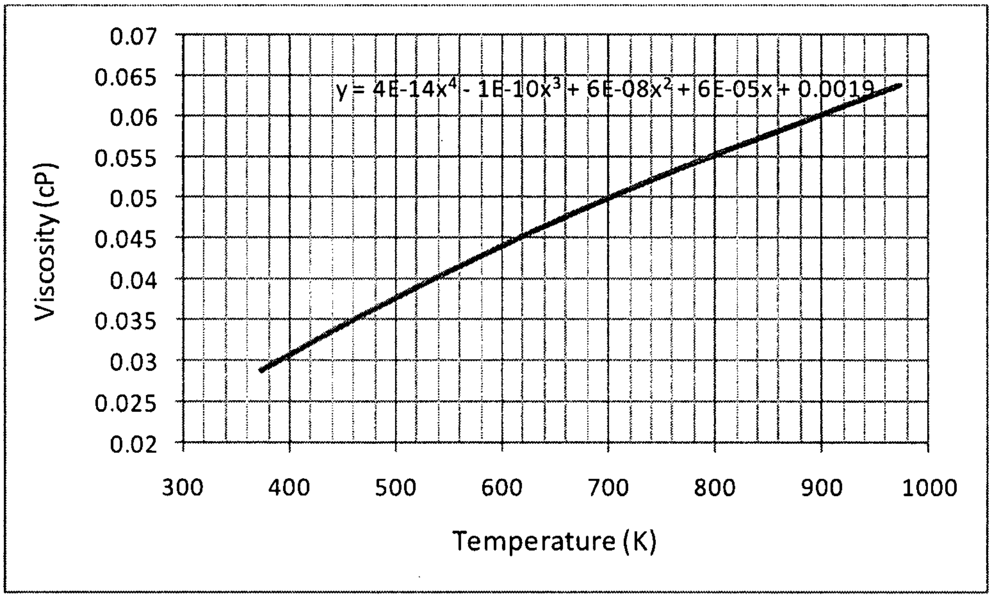


Figure A.1.1. Xenon dynamic viscosity versus temperature

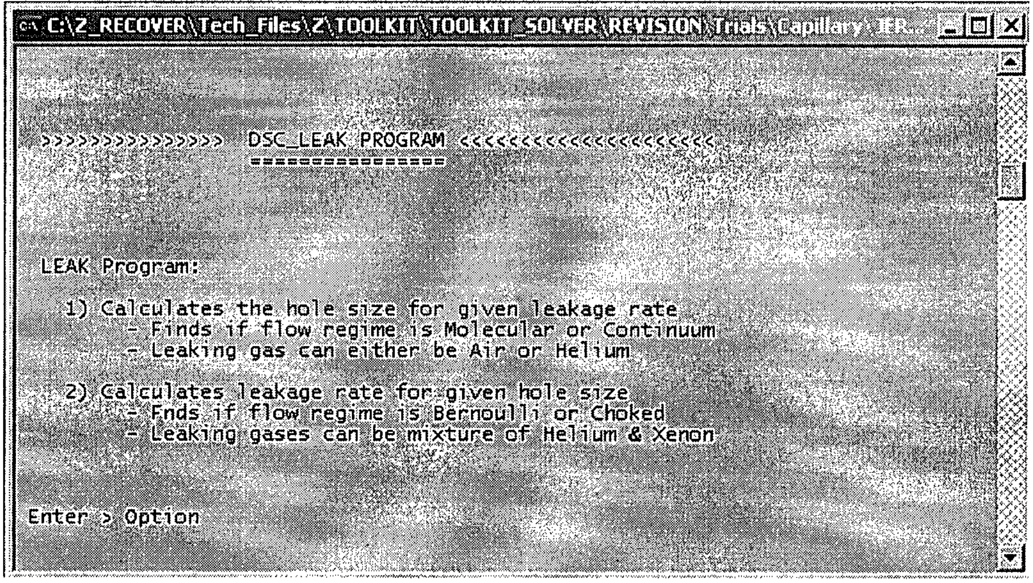
A10 DSC_LEAK PROGRAM

This appendix contains two items:

A) The screen views of DSC_LEAK
B) The listing of the FORTRAN program

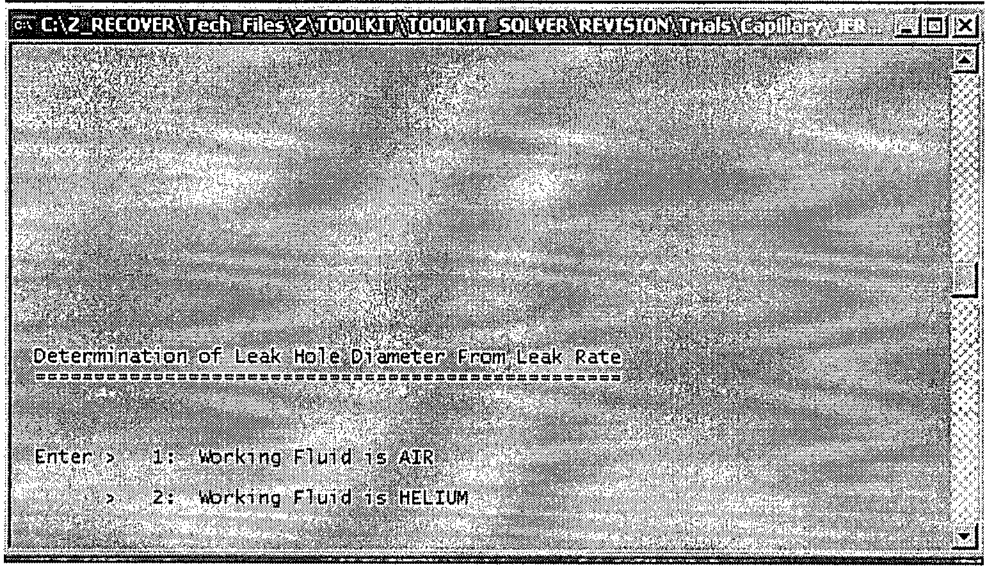
A) SCREEN VIEWS OF DSC_LEAK

The Main Menu of the program is as follows:



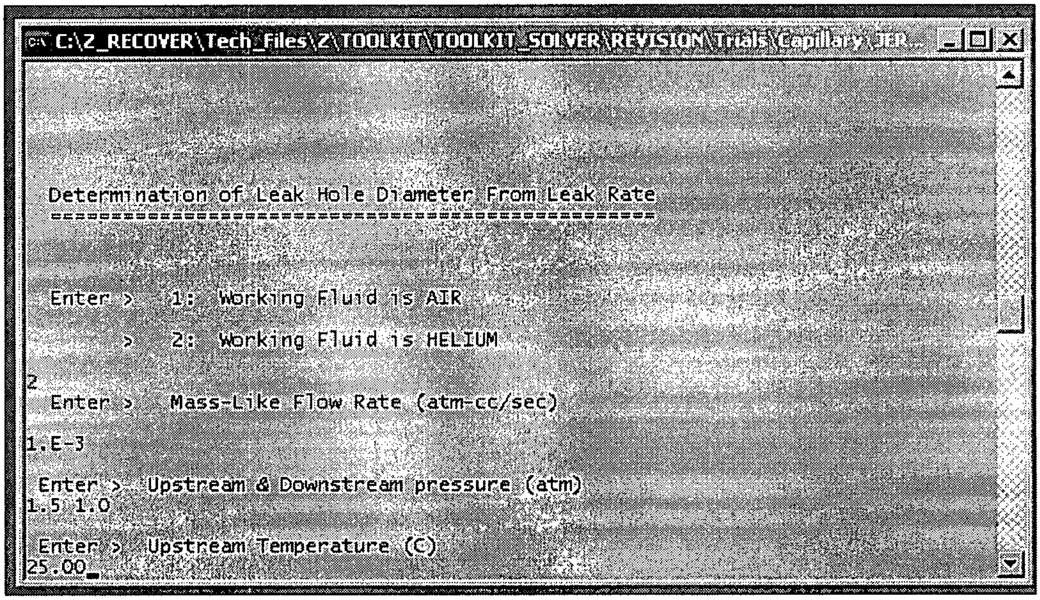
```
>>>>>>>>>>>>>>>  DSC_LEAK PROGRAM <<<<<<<<<<<<<<<<<<<<<
                 ================

LEAK Program:

  1) Calculates the hole size for given leakage rate
      - Finds if flow regime is Molecular or Continuum
      - Leaking gas can either be Air or Helium

  2) Calculates leakage rate for given hole size
      - Fnds if flow regime is Bernoulli or Choked
      - Leaking gases can be mixture of Helium & Xenon


Enter > Option
```

If Option 1 is chosen, the following screen appears:



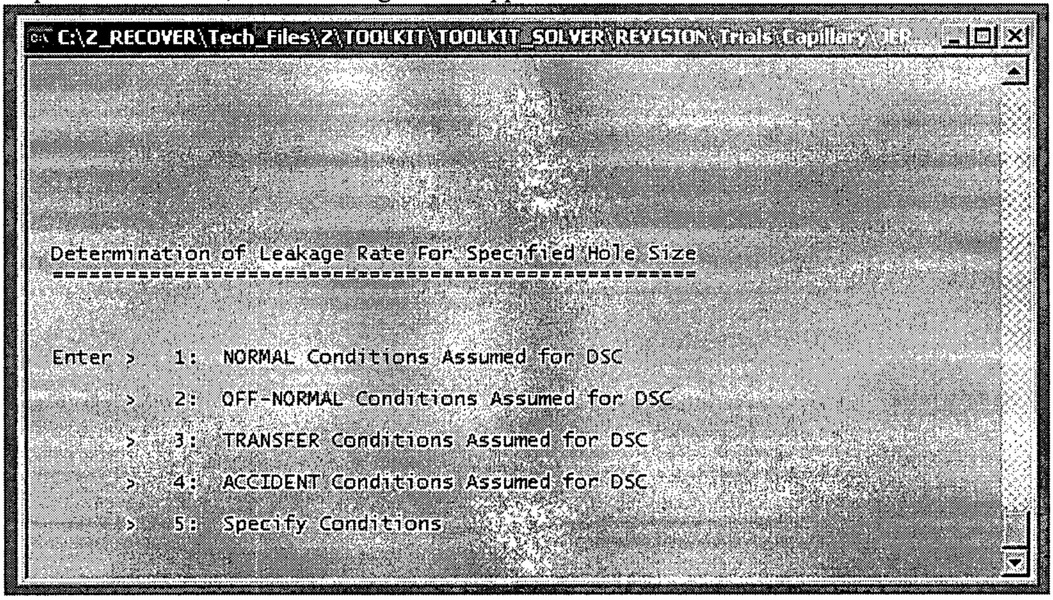
```
Determination of Leak Hole Diameter From Leak Rate
==================================================


Enter >   1:  Working Fluid is AIR

      >   2:  Working Fluid is HELIUM
```

If helium is chosen as the working fluid, the following screen appears:



```
 Determination of Leak Hole Diameter From Leak Rate
 ==================================================


 Enter >   1:  Working Fluid is AIR

       >   2:  Working Fluid is HELIUM

2
 Enter >   Mass-Like Flow Rate (atm-cc/sec)

1.E-3

 Enter >  Upstream & Downstream pressure (atm)
1.5 1.0

 Enter >  Upstream Temperature (C)
25.00_
```

If Option 2 is chosen, the following screen appears:



```
 Determination of Leakage Rate For Specified Hole Size
 =====================================================


 Enter >   1:  NORMAL Conditions Assumed for DSC

       >   2:  OFF-NORMAL Conditions Assumed for DSC

       >   3:  TRANSFER Conditions Assumed for DSC

       >   4:  ACCIDENT Conditions Assumed for DSC

       >   5:  Specify Conditions
```

B) FORTRAN PROGRAMLISTING

The listing of the FORTRAN program to calculate the leakage hole diameter for a specified leakage flow rate or the leakage flow rate for a specified hole diameter is presented below.

```
c
c
c
c
c          The LEAK.FOR program
c             a) Calculates the hole size for given leakage rate
c                  -  Finds if flow regime is Molecular or Continuum
c             b) Calculates leakage rate for given hole size
c                  -  Fnds if flow regime is Subsonic or Choked
c
c
c
100                                                                            continue
write(*,2)
print *,' >>>>>>>>>>>>>>>  DSC_LEAK PROGRAM <<<<<<<<<<<<<<<<<<<<<'
print *,'                  ==============='
print *,' '
print *,' '
print *,' '
print *,' '
print *,' LEAK Program:'
print *,' '
print *,'   1) Calculates the hole size for given leakage rate'
print *,'        - Finds if flow regime is Molecular or Continuum'
print *,'        - Leaking gas can either be Air or Helium'
print *,' '
print *,'   2) Calculates leakage rate for given hole size'
print *,'        - Fnds if flow regime is Bernoulli or Choked'
print *,'        - Leaking gases can be mixture of Helium & Xenon'
print *,' '
print *,' '
print *,' '
print *,'Enter > Option'
print *,' '
read(*,*) i
write(*,2)
if(i.lt.2) call Leak_Hole(i_case)
if(i.lt.2.and.i_case.eq.2) go to 100
if(i.lt.2.and.i_case.gt.2) go to 101
if(i.gt.1) call Leak_Flow(jjj)
if(i.gt.1.and.jjj.eq.2) go to 100
if(i.gt.1.and.jjj.gt.2) go to 101
2                    format(//////////////////////////////////////////////////////////)
101                                                                            continue
stop
end
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc


Subroutine Leak_Flow(i_case)
c
c                           >>>>>>>>    LEAK_FLOW   <<<<<<<<<
c
c     To find the flow rate for a capillary of the DSC
c                                Mass-Like Flow rate (Q) is in units of [atm - cc/sec].
c
c                            REFERENCE:  ANSI N14.5-1997
c
c *** This version considers Accident Condition for which a) 100% rods have failed,
b) T = 725 F, c) Leakge hole size is D = 18.38 micron
```

```
c *** Additionally, for Accident Condition, Choked Flow Analysis is also performed.
Mahmoud Massoud   10/23/2011
c
c
c
implicit real*8(a-h, o-z)
c
data c1, a, P_d             /2.49E6, 1.00, 1.00/
data c2, aM_He, aM_Xe       /3.81E3, 4.00, 131.29/
data D_mic, Vol_ft          /18.38, 171.13/
data T_FN, T_FO, T_FT, T_FA /484.00,509.00,621.00,725.00/
data R_u, He_lbml, Rd_ggml  /8.314, 0.419, 0.07268/
data He_pct, Xe_pct         /0.475,  0.525/
data Ass_n, Rod_a, p_cent   /32.00,176.00,10.00/
data gamma,gc,pai, R_uB     /1.66, 32.20, 3.141592654, 1545.00/
data ttt                    /31.536E6/
c
100   continue
Open (5,file='FLOW.out')
c
print *,' '
Print *,' Determination of Leakage Rate For Specified Hole Size'
print *,' ====================================================='
print *,' '
print *,' '
print *,' '
print *,' Enter >   1:  NORMAL Conditions Assumed for DSC'
print *,' '
print *,'       >   2:  OFF-NORMAL Conditions Assumed for DSC'
print *,' '
print *,'       >   3:  TRANSFER Conditions Assumed for DSC'
print *,'       '
print *,'       >   4:  ACCIDENT Conditions Assumed for DSC'
print *,' '
print *,'       >   5:  Specify Conditions'
print *,' '
read(*,*) i_con
c
if(i_con.lt.5) go to 50
write (*,4)
print *,' '
print *,' '
print *,' '
Print *,'NOTE: Considering Molecular Flow of Helium Only'
print *,'      ======================================='
print *,' '
print *,'Enter >  Hole Diameter (cm)'
read(*,*) D
print *,'Enter >  Upstream and Downstream Pressures (atm)'
read(*,*) P_u, P_d
P_a = 0.5*(P_u + P_d)
print *,'Enter >  Upstream Temperature (C)'
read(*,*) T_C
c
T_K     = T_C + 273.00
aM_He   = 4.00
amu_He  = (3.674E-4)*(T_K**0.7)
a       = 1.00
Fc      = 2.49E6*(D*D*D*D)/(a * amu_He)
Fm      = 3.81E3*(D*D*D)*SQRT(T_K/aM_He)/(a*P_a)
aLu     = (Fc + Fm)*(P_u - P_d)*(P_a/P_u)
c
D_mic   = D * 1.00E4
Q       = aLu * P_u
c
write(*,4)
```

```
print *,' '
Print *,'NOTE: Considering Molecular Flow of Helium Only'
print *,'      ========================================='
write(*,33) a, D, D_mic, P_u, P_d, P_a, T_C, T_K, aM_He, amu_He,
1 Fc, Fm, Q, aLu
go to 107
c
50                                                                            continue
if(i_con.gt.3) go to 1000
print *,' '
print *,' Enter >   Percentage of Fuel Rods Leaking'
print *,' '
read(*,*) P_cent
go to 1001
1000                                                                          continue
P_cent = 100.00
D_mic  =1128.379167
1001  continue
c
D_cm    = D_mic/10000.00
Area_SI = pai*(D_cm*D_cm)/4.00
Vol     = Vol_ft/(3.2808**3)
T_KN    = ((T_FN - 32.00)/1.80) + 273.16
T_KO    = ((T_FO - 32.00)/1.80) + 273.16
T_KT    = ((T_FT - 32.00)/1.80) + 273.16
T_KA    = ((T_FA - 32.00)/1.80) + 273.16
T_RA    = T_FN + 460.00
c
He_kgm1 = (He_lbm1*0.453)
He_kgm2 = (Rd_ggml/1000.00) * He_pct* Ass_n * Rod_a * P_cent/100.00
He_kgml = He_kgm1 + He_kgm2
Xe_ggml = Rd_ggml * Xe_pct
Xe_kgml = (Rd_ggml/1000.00) * Xe_pct* Ass_n * Rod_a * P_cent/100.00
c
if(i_con.gt.1) go to 102
T_K = T_KN
go to 105
102   continue
if(i_con.gt.2) go to 103
T_K = T_KO
go to 105
103   continue
if(i_con.gt.3) go to 104
T_K = T_KT
go to 105
104                                                                           continue
T_K = T_KA
105   continue
amu_He = (3.674E-4)*(T_K**0.7)
amu_Xe = (4.00E-14)*(T_K**4) - (1.00E-10)*(T_K**3) +
1          (6.00E-8)*T_K*T_K +(6.00E-5)*T_K + 0.00190
c
P_u_kPa = (R_u*T_K/Vol) * (He_kgml + Xe_kgml)
P_u_psi = P_u_kPa/6.89476
P_u     = P_u_kPa/101.35209
c
aM  = (He_kgml * aM_He + Xe_kgml * aM_Xe)/(He_kgml + Xe_kgml)
amu = (amu_He * He_kgml + amu_Xe * Xe_kgml)/(He_kgml + Xe_kgml)
c
P_a   = 0.5*(P_u + P_d)
alfa  = c1/(a*amu)
beta  = c2*(Sqrt(T_k/aM))/(a*P_a)
term  = (P_u - P_d)*(P_a/P_u)
c
Fc   = alfa * (D_cm**4)
Fm   = beta * (D_cm**3)
```

```
rat   = Fc/Fm
c
aL_u = (Fc + Fm)*term
aL_a = (Fc + Fm)*(P_u - P_d)
Q    = aL_u * P_u
c
T_FF  = (T_K - 273.16) * 1.80 + 32.00
c
Vdot_tt = aL_u * ttt
Vpcent  = (Vdot_tt/(Vol*1.00E6))*100.00
c
dens    = (144.00*P_u_psi)/((R_uB/aM)*T_RA)
dens    = dens * (He_kgml + Xe_kgml)/0.453
dens_m  = dens*(3.2808**3)*0.453
c
Vel_SI  = aL_u/(Area_SI * 100.00)
Vel_BU  = Vel_SI*3.2808
c
write(*,4)
print *,' '
Print *,' Determination of Leakage Rate For Specified Hole Size'
print *,' ====================================================='
write(5,5)
c
write(*,3) P_u_psi,P_u_kPa,P_u, P_d, P_a, T_FF, T_K, amu, aM, a,
1  P_cent, rat, Fc, Fm, D_cm, D_mic, Area_SI, Vol_ft,Vol,
1  Xe_ggml, Xe_kgml,He_kgml, dens, dens_m, Vel_BU,Vel_SI, Q, aL_a,
1  aL_u,Vpcent
write(5,3) P_u_psi,P_u_kPa,P_u, P_d, P_a, T_FF, T_K, amu, aM, a,
1 P_cent, rat, Fc, Fm, D_cm, D_mic, Area_SI, Vol_ft,Vol,
1  Xe_ggml, Xe_kgml,He_kgml, dens, dens_m, Vel_BU,Vel_SI, Q, aL_a,
1  aL_u,Vpcent
If(rat.gt.1.00) Print *,'Flow Regime: ...........................
1..  Continuum Dominant'
If(rat.lt.1.00) Print *,
1'Flow Regime: ..............................  Molecular Dominant'
c
if(i_con.lt.4) go to 106
T_RA    = T_FA + 459.67
term1   = gamma * gc *aM/R_uB
term2   = (gamma + 1.00)/(gamma - 1.00)
term3   = (2.00/(gamma + 1.00))**term2
term4   = sqrt(term1*term3)
term5   = (144.00*P_u_psi)/Sqrt(T_RA)
G_flx   = term4 * term5
Area_cm2= (pai/4.00)*(D_cm*D_cm)
Area_mm2= Area_cm2*100.00
dens    = (144.00*P_u_psi)/((R_uB/aM)*T_RA)
dens    = dens * (He_kgml + Xe_kgml)/0.453
dens_m  = dens*(3.2808**3)*0.453
Vel_fps = G_flx/dens
Vel_cps = Vel_fps*12.00*2.54
Vel_mps = Vel_fps/3.2808
G_flx_SI= dens_m * Vel_mps
V_Leak_f= Vel_fps*Area_cm2/(2.54*2.54*144.00)
V_Leak_m= V_Leak_f * 60.00
V_Leak  = Vel_cps*Area_cm2
dm_lek  = (G_flx_SI*Area_cm2)/10000.00
dm_BU   = dm_lek/0.453
c
Print *,' '
Print *,'NOTE:  FLOW IS CHOKED.  DISREGARD HIGH LEAK RATE BASED ON
1 BERNOULLI FLOW'
print *,'       ------------------------------------------------
1---------------'
write(5,7)
```

```
c
write(*,6) P_u_psi, P_u_kPa, P_u, T_FA, T_RA, T_KA,
1           Area_mm2, D_mic,D_cm, dens, dens_m, G_flx, G_flx_SI,
1           Vel_fps, Vel_mps, V_Leak_f, V_Leak_m, V_Leak, dm_BU,
1           dm_lek
write(5,6) P_u_psi, P_u_kPa, P_u, T_FA, T_RA, T_KA,
1           Area_mm2, D_mic,D_cm, dens, dens_m, G_flx, G_flx_SI,
1           Vel_fps, Vel_mps, V_Leak_f, V_Leak_m, V_Leak, dm_BU
1           dm_lek
c
106                                                                 continue
c
print *,'Above data are also saved in file:........  FLOW.OUT'
107                                                                 continue
print *,' '
print *,' Enter >  1: Calculate Another Leak Rate'
print *,'       >  2: Main Menu'
print *,'       >  3: Exit'
read(*,*) i_case
if(i_case.gt.1) go to 8
write(*,4)
close(5)
go to 100
3                                                                  Format(/,
1' Pressure, Canister, Pu   (psia): ..........', f12.4,/,
1' Pressure, Canister, Pu   (kPa): ...........', f12.4,/,
1' Pressure, Canister, Pu   (atm): ...........', f12.4,/,
1' Pressure, Ambient,  Pd   (atm): ...........', f12.4,/,
1' Pressure, Average,  Pa   (atm): ...........', f12.4,/,
1' Temperature, Canister    (F): .............', f12.4,/,
1' Temperature, Canister    (K): .............', f12.4,/,
1' Viscosity, Mixture       (cP): ............', f12.4,/,
1' Molecular Weight, Mix.   (g/gmole): .......', f12.4,/,
1' Length, Leakage Hole     (cm): ............', f12.4,/,
1' Rods Leaking             (%): .............', f12.4,/,
1' Fc/Fm Ratio              (-): .............', f12.4,/,
1' Fc Factor                (cc/atm-sec): ....', e12.4,/,
1' Fm Factor                (cc/atm-sec): ....', e12.4,/,
1' Diameter, Leakage Hole   (cm): ............', e12.4,/,
1' Diameter, Leakage Hole   (micron): ........', f12.4,/,
1' Leakage Area             (cm2): ...........', e12.4,/,
1' DSC Volume               (ft3): ...........', f12.4,/,
1' DSC Volume               (m3): ............', f12.4,/,
1' Xenon Moles per rod      (gmole): .........', f12.4,/,
1' Xenon Moles in DSC       (kgmole): ........', f12.4,/,
1' Helium Moles in DSC      (kgmole): ........', f12.4,/,
1' Mixture Density          (lbm/ft3): .......', f12.4,/,
1' Mixture Density          (kg/m3): .........', f12.4,/,
1' Leakage Velocity         (ft/sec): ........', f12.4,/,
1' Leakage Velocity         (m/sec): .........', f12.4,/,
1' Mass-Like Flow Rate, Q   (atm-cc/sec): ....', e12.4,/,
1' Leak Rate, Average,  L_a (cc/sec): ........', e12.4,/,
1' Leak Rate, Upstream, L_u (cc/sec): ........', e12.4,/,
1' Inventory Released       (Volume%) ........', e12.4,/)
4                    format(/////////////////////////////////////////////////////////////)
5                    format(' Determination of Leakage Rate For Specified Hole Size',/,
1' ================================================')
6                                                                format(//,
1' LEAKAGE RATE BASED ON CRITICAL FLOW AT THE BREAK',/,
1' ==============================================',//,
1' Pressure, Canister, Pu   (psia): ..........', f12.4,/,
1' Pressure, Canister, Pu   (kPa): ...........', f12.4,/,
1' Pressure, Canister, Pu   (atm): ...........', f12.4,/,
1' Temperature, Canister    (F): .............', f12.4,/,
1' Temperature, Canister    (R): .............', f12.4,/,
1' Temperature, Canister    (K): .............', f12.4,/,
```

```
1' Break Area               (mm2): ..........', f12.4,/,
1' Break Diameter           (micron): .......', f12.4,/,
1' Break Diameter           (cm): ...........', f12.4,/,
1' Mixture Density          (lbm/ft3): ......', f12.4,/,
1' Mixture Density          (kg/m3): ........', f12.4,/,
1' Mass Flux                (lbm/ft2-sec): ...', f12.4,/,
1' Mass Flux                (kg/m2-sec): .....', f12.4,/,
1' Break Velocity           (ft/sec): .......', f12.4,/,
1' Break Velocity           (m/sec): ........', f12.4,/,
1' Leak Rate, Volumetric    (ft3/sec): ......', f12.4,/,
1' Leak Rate, Volumetric    (CFM): ..........', f12.4,/,
1' Leak Rate, Volumetric    (cc/sec): .......', e12.4,/,
1' Leak Rate, Mass          (lbm/sec): ......', e12.4,/,
1' Leak Rate, Mass          (kg/sec): .......', e12.4,/)
33                                                                    Format(/,
1' Length, Leakage Hole     (cm): ...........', f12.4,/,
1' Diameter, Leakage Hole   (cm): ...........', e12.4,/,
1' Diameter, Leakage Hole   (micron): .......', f12.4,/,
1' Pressure, Canister, Pu   (atm): ..........', f12.4,/,
1' Pressure, Ambient,  Pd   (atm): ..........', f12.4,/,
1' Pressure, Average,  Pa   (atm): ..........', f12.4,/,
1' Temperature, Canister    (C): ............', f12.4,/,
1' Temperature, Canister    (K): ............', f12.4,/,
1' Molecular Weight         (g/gmole): ......', f12.4,/,
1' Viscosity                (cP): ...........', f12.4,/,
1' Fc Factor                (cc/atm-sec): ....', e12.4,/,
1' Fm Factor                (cc/atm-sec): ....', e12.4,/,
1' Mass-Like Flow Rate, Q   (atm-cc/sec): ....', e12.4,/,
1' Leak Rate, Upstream, L_u (cc/sec): .......', e12.4,/)
7                                                                     Format(/,
1'NOTE:  FLOW IS CHOKED.  DISREGARD HIGH LEAK RATE BASED ON
1 BERNOULLI FLOW',/,
1'      -------------------------------------------------
1---------------')
8                                                                      continue
return
end
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
Subroutine Leak_Hole(i_Case)
c
c
c                            >>>>>>>>>>   LEAK HOLE  <<<<<<<<<<
c
c     To find the size of a capillary resulting in a specified leak rate from the
DSC
c       Mass-Like flow rate (Q) is in units of [atm - cc/sec].    M. Massoud 10/20/2011
c
c                             REFERENCE:  ANSI N14.5-1997
c
implicit real*8(a-h, o-z)
c
data P_u, P_d/1.50, 1.00/
data c1, a, amu_A, amu_H/2.49E6, 1.00, 0.0185, 0.0198/
data c2, T, T_C, aM_A, aM_H /3.81E3, 298.00, 25.00, 28.97, 4.00/
data aLu       /3.83E-9/
data Vol_ft3, R_uB /171.13, 1545.00/
c
100   continue
Open (5,file='HOLE.out')
c
print *,' '
Print *,' Determination of Leak Hole Diameter From Leak Rate'
print *,' ==============================================='
print *,' '
print *,' '
print *,' '
```

```
print *,' Enter >   1:  Working Fluid is AIR'
print *,' '
print *,'       >   2:  Working Fluid is HELIUM'
print *,' '
read(*,*) i_WF
print *,' Enter >   Mass-Like Flow Rate (atm-cc/sec)'
print *,' '
read(*,*) Q
print *,' '
print *,'Enter >  Upstream & Downstream pressure (atm)'
read(*,*) P_u, P_d
print *,' '
print *,'Enter >  Upstream Temperature (C)'
read(*,*) T_C
T_K = T_C + 273.00
aLu = Q/P_u
if(i_WF.gt.1) go to 102
amu = amu_A
aM  = aM_A
go to 103
102   continue
amu = amu_H
aM  = aM_H
103   continue
P_a   = 0.5*(P_u + P_d)
alfa  = c1/(a*amu)
beta  = c2*Sqrt(T_K/aM)/(a*P_a)
term  = (P_u - P_d)*(P_a/P_u)
gamma = aLu/term
D     = 1.00E-3
n     = 0
1                                                                   continue
FOFD  = alfa*(D**4) + beta*(D**3) - gamma
FPOD  = 4.00*alfa*(D**3) + 3.00*beta*(D**2)
D_new = D - (FOFD/FPOD)
eps   = Abs((D_new - D)/D)
if(eps.le.1.00E-6) go to 2
D = D_new
n = n + 1
if(n.ge.50) go to 2
go to 1
2                                                                   continue
Dm    = D*1.00E4
c
Fc    = alfa * (D**4)
Fm    = beta * (D**3)
rat   = Fc/Fm
c
P_u_psi = P_u*14.70
T_F     = (T - 273.00)*1.80 + 32.00
T_R     = T_F + 460.00
am_WF   = P_u_psi*144.00*Vol_ft3/((R_uB/aM)*T_R)
am_WF_SI= am_WF*0.453
an_WF   = am_WF / aM
an_WF_SI= am_WF_SI/aM
c
write(*,4)
print *,' '
Print *,' Determination of Leak Hole Diameter From Leak Rate'
print *,' =================================================='
c
write(*,3) P_u, P_d, P_a, T_C, T, Vol_ft3, amu, aM, a, Q, aLu,
1           Fc, Fm, rat, n, am_WF, am_WF_SI, an_WF_SI, D, Dm
write(5,3) P_u, P_d, P_a, T_C, T, Vol_ft3, amu, aM, a, Q, aLu,
1           Fc, Fm, rat, n, am_WF, am_WF_SI, an_WF_SI, D, Dm
if(i_WF.lt.2) print *,'Working Fluid (WF):.......................
```

```
1  AIR'
if(i_WF.gt.1) print *,'Working Fluid (WF): ......................
1 HELIUM'
If(rat.gt.1.00) Print *,'Flow Regime: ...........................
1   Continuum Dominant'
If(rat.lt.1.00) Print *,
1'Flow Regime: ............................  Molecular Dominant'
print *,'Above data are also saved in:............  HOLE.OUT'
print *,' '
print *,' '
print *,' Enter >  1: Calculate Another Hole Diameter'
print *,'       >  2: Main Menu'
print *,'       >  3: Exit'
read(*,*) i_case
if(i_case.gt.1) go to 5
write(*,4)
close(5)
go to 100
3                                                                    Format(/,
1' Pressure, Canister      (atm): ...........', f12.4,/,
1' Pressure, Ambient       (atm): ...........', f12.4,/,
1' Pressure, Average       (atm): ...........', f12.4,/,
1' Temperature, Canister   (C): .............', f12.4,/,
1' Temperature, Canister   (K): .............', f12.4,/,
1' Canister Free Volume    (ft3): ...........', f12.4,/,
1' Viscosity, WF           (cP): ............', f12.4,/,
1' Molecular Weight, WF    (g/gmole): .......', f12.4,/,
1' Length, Leakage Hole    (cm): ............', f12.4,/,
1' Mass-Like Flow Rate     (atm-cc/sec): ....', e12.4,/,
1' Leak Rate, Canister     (cc/sec): ........', e12.4,/,
1' Fc Factor               (cc/atm-sec): ....', e12.4,/,
1' Fm Factor               (cc/atm-sec): ....', e12.4,/,
1' Fc/Fm Ratio             (-): .............', f12.4,/,
1' Number of Iterations    (-): .............', i12,/,
1' Mass of WF              (lbm): ...........', f12.4,/,
1' Mass of WF              (kg): ............', f12.4,/,
1' Moles of WF             (kgmole): ........', f12.4,/,
1' Diameter, Leakage Hole, (cm): ............', e12.4,/,
1' Diameter, Leakage Hole, (micron): ........', f12.4)
4                   format(//////////////////////////////////////////////////////////////)
5                                                                     continue
return
end
```