ENGINEERING CHANGE NOTICE

Page 1 of 21. ECN **658200**Proj.
ECN

2. ECN Category (mark one) Supplemental ☐ Direct Revision ☒ Change ECN ☐ Temporary ☐ Standby ☐ Supersedure ☐ Cancel/Void ☐	3. Originator's Name, Organization, MSIN, and Telephone No. D.L. Sherrell, R3-86, 376-0937		4. USQ Required? See block 15 ☒ Yes ☐ No	5. Date 10/02/00
	6. Project Title/No./Work Order No. SNF Project		7. Bldg./Sys./Fac. N/A	8. Approval Designator E. S^M, S^{FP}, Q
	9. Document Numbers Changed by this ECN (includes sheet no. and rev.) HNF-2155 Rev 1, All Sheets		10. Related ECN No(s) N/A	11. Related PO No. N/A
12a. Modification Work ☐ Yes (fill out Blk 12b) ☒ No (NA Blks. 12b, 12c, 12d)	12b. Work Package No. N/A	12c. Modification Work Complete N/A _____ Design Authority/Cog. Engineer Signature & Date	12d. Restored to Original Condition (Temp. or Standby ECN only) N/A _____ Design Authority/Cog. Engineer Signature & Date	

13a. Description of Change

13b. Design Baseline Document? ☐ Yes ☒ No

This ECN replaces all pages of HNF-2155 Rev 1 (*Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria*) with Rev 2 of that document. Revision 2: 1) replaces the reference (in sec 4.4) to a steady state analysis from the SARP with a non-steady state cooldown analysis (Apndx F); 2) replaces the 42C max fill temperature (from the SARP) with a 50C non-steady state value (this does not invalidate the SARP's 42C steady state value); 3) establishes a 5 hr minimum cooling time, a 15 gpm minimum cooling water flow rate, and a 15C max cooling water skid discharge temperature for the CVDF's MCO cooldown operation based on the new analysis; 4) replaces the CSB storage tube volume calculation in section 4.7 with a reference to the volume calculation in SNF-3328 (CSB design Basis Accident Analysis) while retaining the more conservative values used in Rev 1 of this document; 5) revises the minimum required staging time for Case 1 in section 5.1.1.1 from 2 yrs to 4 yrs (note that 4 yrs is the requirement, not the result, which is 40 yrs); 6) based on the higher (50C) fill temp and a 1/2 vol% helium impurity allowance, revises the minimum He backfill inventory result in sec 7.1.2.1.1 from 31.9 mol to 31.0 mol; 7) adds a new calculation in section 7.1.2.1.2 to account for the void space under the weld cap; 8) revises the allowable helium loss criteria in sections 7.1.2.1.3/4 to reflect the revised initial He inventory; 9) revises the helium loss calculations in section 7.2.1.5.1 to reflect the revised initial He inventory; 10) adds a new calculation (Apndx G) to show that a process hold is not needed to ensure that backfill gas has reached the acceptable backfill temperature range; 11) addresses Paragraph 3-4 of NFPA 69 (Instrumentation); 12) adds sec 6.1.2.1 to compare ANSI N14.5-1997 Draft J and ANSI N14.5-1997; 13) reorganizes sec 5.1.1 to clarify the backfill press/temp bases; 14) adds new sub-secs to secs 7.1.2 and 7.1.3, and adds a new spread sheet listing to address helium loss for the worst oxygen case MCO; 15) adds sections 4.3.1.1/.2/.3, 4.3.2, and 4.3.2.1 (including two additional spread sheet listings) to reconcile differences between this document and HNF-SD-SNF-TI-040 Rev 3B regarding hydrogen inventories and MCO pressures; and 16) revises all supporting and/or affected text to reflect the above changes.

14a. Justification See block 14b

Criteria Change ☒ Design Improvement ☐ Environmental ☐ Facility Deactivation ☐As-Found ☐ Facilitate Const ☐ Const. Error/Omission ☐ Design Error/Omission ☐

14b. Justification Details

Items 1, 2 and 3 ensure that the calculated initial backfill quantity is conservative; Item 4 is consistent with references in other SNF documentation; Item 5 accommodates current CSB operations planing; Items 6, 8, 9 and 11 implement items 1, 2, and 3; Item 7 refines the acceptable helium loss value for interim storage; Item 10 confirms that the MCO pressure can be recorded immediately after the MCO's helium backfill is topped off; Item 11 corrects an error of omission in Rev 1; Item 12 confirms that leakage calcs from Rev 0 and Rev 1 remain valid, even though they were based on a draft of the current ANSI std.; Item 13 clarifies the fill press/temp bases; Item 14 supports the oxygen concentration calculations in TI-040; and Item 15 addresses revised MCO hydrogen inventory estimates and MCO pressure estimates that were recently provided by Rev 3B of TI-040.

15. Distribution (include name, MSIN, and no. of copies) See distribution sheet.

USQ Tracking Numbers: (K-Basins K-00-0099) CVDF-00-1881; CSB-00-1074

NOTE: The SNF Project currently intends to reduce the maximum allowed MCO backfill pressure to 11.5 psig (from 12.5 psig). Because no change is contemplated to the minimum backfill pressure (9.5 psig), the only impact of that change would be to add conservatism to the hydrogen release rate results of this document (HNF-2155, Rev 2), i.e., the worst case hydrogen release rate would be less than the rate calculated by this document if the maximum helium backfill pressure were to be reduced.

A-7900-013-2 (05/96) GEF095

ENGINEERING CHANGE NOTICE				Page 2 of 2		1. ECN (use # from pg. 1) 658200	
16. Design		17. Cost Impact				18. Schedule Impact (days)	
Verification Required [] Yes [x] No		ENGINEERING		CONSTRUCTION		Improvement [N/A] Delay [N/A]	
		Additional [N/A] \$	Savings [N/A] \$	Additional [N/A] \$	Savings [N/A] \$		
19. Change Impact Review: Indicate the related documents (other than the engineering documents identified on Side 1) that will be affected by the change described in Block 13. Enter the affected document number in Block 20.							
SDB/DD	[N/A]	Seismic/Stress Analysis	[N/A]	Tank Calibration Manual	[N/A]		
Functional Design Criteria	[N/A]	Stress/Design Report	[N/A]	Health Physics Procedure	[N/A]		
Operating Specification	[N/A]	Interface Control Drawing	[N/A]	Spares Multiple Unit Listing	[N/A]		
Criticality Specification	[N/A]	Calibration Procedure	[N/A]	Test Procedures/Specification	[N/A]		
Conceptual Design Report	[N/A]	Installation Procedure	[N/A]	Component Index	[N/A]		
Equipment Spec.	[N/A]	Maintenance Procedure	[N/A]	ASME Coded Item	[N/A]		
Const. Spec.	[N/A]	Engineering Procedure	[N/A]	Human Factor Consideration	[N/A]		
Procurement Spec.	[N/A]	Operating Instruction	[N/A]	Computer Software	[N/A]		
Vendor Information	[N/A]	Operating Procedure	[X]	Electric Circuit Schedule	[N/A]		
OH Manual	[N/A]	Operational Safety Requirement	[N/A]	ICRS Procedure	[N/A]		
FSAR/SAR	[N/A]	IEFD Drawing	[N/A]	Process Control Manual/Plan	[N/A]		
Safety Equipment List	[N/A]	Cell Arrangement Drawing	[N/A]	Process Flow Chart	[N/A]		
Radiation Work Permit	[N/A]	Essential Material Specification	[N/A]	Purchase Requisition	[N/A]		
Environmental Impact Statement	[N/A]	Fac. Proc. Samp. Schedule	[N/A]	Tickler File	[N/A]		
Environmental Report	[N/A]	Inspection Plan	[N/A]		[]		
Environmental Permits	[N/A]	Inventory Adjustment Request	[N/A]		[]		
20. Other Affected Documents: (NOTE: Documents listed below will not be revised by this ECN.) Signatures below indicate that the signing organization has been notified of other affected documents listed below.							
Document Number/Revision		Document Number/Revision		Document Number/Revision			
		HNF-SD-SNF- OCD-001 (Product Spec)					
21. Approvals		Signature			Signature		
Design Authority	L. H. Goldmann	<i>L. H. Goldmann</i> 10/4/2000			Design Agent		
					PE		
					QA		
					Safety		
Cog. Mgr.	J.R. Frederickson	<i>J.R. Frederickson</i> 10/3/2000					
QA	D.W. Smith	<i>D.W. Smith</i> 10/5/00			Independent Review	MJ Packer	<i>MJ Packer</i> 10/5/00
Environmental	J.E. Turnbaugh	<i>J.E. Turnbaugh</i> 10/4/00			CVD Design Authority	JJ Irwin	<i>JJ Irwin</i> 10/4/2000
Nuclear Safety	C.T. Miller	<i>C.T. Miller</i> 10/5/00			CSB Design Authority	SA Krieg	<i>SA Krieg</i> 10/4/00
Fire Protection	D.W. Mertz	<i>D.W. Mertz</i> 10/5/00			Fac. Operations	OM Serrano	<i>DLS</i> 10/4/00
Independent Review	Y. Justin Liu	<i>Y. Justin Liu</i> 10/5/00			Fac. Operations	JR Gregory	<i>JR Gregory</i> OCT 4 2000

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution	Process Engineering	Date 10/6/00
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Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria (OCRWM) -- HNF-2155, Rev 2		ECN No. 658200

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Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria (OCRWM)

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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P.O. Box 1000
Richland, Washington

Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria (OCRWM)

Division: SNF
D. L. Sherrell
Fluor Hanford

Date Published
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Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

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RECORD OF REVISION		(1) Document Number HNF-2155	Page 1
(2) Title Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria			
CHANGE CONTROL RECORD			
(3) Revision	(4) Description of Change - Replace, Add, and Delete Pages	Authorized for Release	
		(5) Cog. Engr.	(6) Cog. Mgr. Date
0	(7) Initial Release EDT# 623984 (2/11/98)	DL Sherrell 2/20/98	JR Frederickson 2/20/98
1	Released via ECN# 652276 (2/11/99). Completely replaces all pages of HNF-2155 with Rev 1 of that document. Revision 1: 1) eliminates calculations for shipping casks, which are now covered by the SARP; 2) updates all calculations and supporting bases, assumptions, etc., to reflect the new, reduced pressure now listed by the project databook for a safety basis MCO; 3) eliminates calculations for nominal pressure MCOs, which are no longer necessary; 4) revises the minimum helium fill pressure and maximum helium fill MCO temperature to ensure that all MCOs will retain at least 30.3 gmoI of helium after 40 years of storage (to support the oxygen gettering results of HNF-SNF-TI-40, and to provide maximum flexibility for the CVDF helium back-fill operation); 5) takes advantage of the reduced hydrogen leak rates associated with the new safety basis pressure to allow for staging two mechanically sealed MCOs within one tube; 6) based on the new, reduced leakage rates, provides formal calculations to show that vented CSB tubes will never reach 1 vol% hydrogen (even for two worst case leakage MCOs); and 7) revises all text and hand calculations, as necessary, to reflect all of the above changes.	DL Sherrell 2/17/99	JR Frederickson 2/17/99

CHANGE CONTROL RECORD			
(3) Revision	(4) Description of Change - Replace, Add, and Delete Pages	Authorized for Release	
		(5) Cog. Engr.	(6) Cog. Mgr. Date
RS 2	Released via ECN# 658200 (10/02/00). Completely replaces all pages of HNF-2155 Rev 1 with Rev 2 of that document. Revision 2: 1) replaces the reference (in sec 4.4) to a steady state analysis from the SARP with a non-steady state cooldown analysis (Apndx F); 2) replaces the 42C max fill temperature with a 50C non-steady state value; 3) establishes a 5 hr minimum cooling time, a 15 gpm minimum cooling water flow rate, and a 15C max cooling water skid discharge temperature for the CVDF's MCO cooldown operation based on the new analysis; 4) replaces the CSB storage tube volume calculation in section 4.7 with a reference to the volume calculation in SNF-3328 while retaining the more conservative values used in Rev 1 of this document; 5) revises the minimum required staging time for Case 1 in section 5.1.1.1.1 from 2 yrs to 4 yrs; 6) based on the higher fill temp and a 1/2 vol% helium impurity allowance, revises the minimum He backfill inventory result in sec 7.1.2.1.1 from 31.9 mol to 31.0 mol; 7) adds a new calculation in section 7.1.2.1.2 to account for the void space under the weld cap; 8) revises the allowable helium loss criteria in sections 7.1.2.1.3/.4 to reflect the revised initial He inventory; 9) revises the helium loss calculations in section 7.2.1.5.1 to reflect the revised initial He inventory; 10) adds a new calculation (Apndx G) to show that a process hold is not needed to ensure that backfill gas has reached the acceptable backfill temperature range; 11) addresses Paragraph 3-4 of NFPA 69; 12) adds sec 6.1.2.1 to compare ANSI N14.5-1997 Draft J and ANSI N14.5-1997; 13) reorganizes sec 5.1.1 to clarify the backfill press/temp bases; 14) adds new sub-secs to secs 7.1.2 and 7.1.3, and adds a new spread sheet listing to address helium loss for the worst oxygen case MCO; 15) adds sections 4.3.1.1/.2/.3, 4.3.2, and 4.3.2.1 (including two additional spread sheet listings) to reconcile differences between this document and HNF-SD-SNF-TI-040 Rev 3B regarding hydrogen inventories and MCO pressures; and 16) revises all supporting and/or affected text to reflect the above changes.	DL Sherrell <i>DL Sherrell</i> 10/3/00	JR Frederickson <i>J. R. Frederickson</i> 10/3/00

HNF-2155, REV. 2

MULTI-CANISTER OVERPACK
COMBUSTIBLE GAS MANAGEMENT
LEAK TEST ACCEPTANCE CRITERIA
(OCRWM)

TASK ORDER: CACN 105355 / BOA BA40

SUB-PROJECT: MCO, CVD, CSB

PREPARED BY:

10/02/00
D. L. Sherrell Date

TECHNICAL CHECKER:

10/2/00
Y. Justin Liu Date

TECHNICAL CHECKER:

10/3/00
M. J. Packer Date

**MULTI-CANISTER OVERPACK COMBUSTIBLE GAS MANAGEMENT
LEAK TEST ACCEPTANCE CRITERIA (OCRWM)
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ACRONYMS/ABBREVIATIONS

atm	absolute pressure in atmospheres (1 atm = 101 kPa)
CSB	Canister Storage Building
CVDF	Cold Vacuum Drying Facility
DOE	U.S. Department of Energy
LOC	Limiting Oxidant Concentration
LFL	Lower Flammable Limit
MCO	multi-canister overpack
MHM	MCO Handling Machine
mol	gram mole
NFPA	National Fire Protection Association
psia	absolute pressure, pounds per square inch
psig	gage pressure, pounds per square inch
SNF	Spent Nuclear Fuel

EXECUTIVE SUMMARY

Leak test acceptance criteria for mechanically sealed and weld sealed multi-canister overpacks (MCO) were evaluated to ensure that, in the unlikely event the leak test results for an MCO were to approach either of those criteria, it could still be handled and stored in stagnant air without compromising the Spent Nuclear Fuel Project's overall strategy to prevent accumulation of combustible gas mixtures within MCOs or within their surroundings. Note: with the exception of the mechanical seal's leak test acceptance criterion itself (which is evaluated by this document), this document does not apply to MCOs until they have been completely processed and acceptance tested at the Cold Vacuum Drying Facility (CVDF). Also note that this document does not address release of radiological contamination.

Results for Mechanically Sealed MCOs

The recommended 1×10^{-5} std cc/sec integrated leak test acceptance criterion for mechanically sealed MCOs will ensure:

- 1) that a positive helium gage pressure will remain below the mechanical seal of any MCO (at temperatures down to -31°C) for well over 40 years without replenishment;
- 2) that it would take over 3 years for the hydrogen concentration to reach 1 vol% within a sealed (no allowance for loss via the tube's vent port) singly occupied storage tube containing a safety basis pressure MCO with mechanical seals (note that the gas inventory required to produce the pressure used for this leakage calculation is not expected within any MCO during the first years of storage, nor within the majority of MCOs during up to 40 years of storage);
- 3) that it would take over ten months for the hydrogen concentration to reach 1 vol% within a sealed storage tube containing two safety basis pressure MCOs with mechanical seals;
- 4) that, based on barometrically induced air exchange alone (i.e., no credit is taken for volume expansion from thermal cycling or for diffusion), a vented CSB tube containing the worst case MCO payload for hydrogen leakage (2 each, mechanically sealed, safety basis pressure MCOs) will never exceed 1 vol% hydrogen (see section 7.3); and
- 5) that, based on diffusion alone (i.e., no credit is taken for barometrically induced air exchange or thermal cycling), a vented CSB tube containing the worst case MCO payload for hydrogen leakage (2 each, mechanically sealed, safety basis pressure MCOs) will never exceed 1 vol% hydrogen (see Appendix C).

Results for Weld Sealed MCOs

The recommended 1×10^{-7} std cc/sec leak test acceptance criterion for MCO welds was determined to be adequate to meet all current and foreseeable needs of the project for storage of spent N-Reactor fuel. Note that this leak test acceptance criterion has not yet been evaluated for storage of Single Pass Reactor (SPR) fuel, however there is no reason to expect that it will not be adequate for that function.

1.0 PURPOSE

The purpose of this document is to support the Spent Nuclear Fuel Project's combustible gas management strategy while avoiding the need to impose any requirements for oxygen free atmospheres within storage tubes that contain multi-canister overpacks (MCO). In order to avoid inerting requirements it is necessary to establish and confirm leak test acceptance criteria for mechanically sealed and weld sealed MCOs that are adequate to ensure that, in the unlikely event the leak test results for any MCO were to approach either of those criteria, it could still be handled and stored in stagnant air without compromising the SNF Project's overall strategy to prevent accumulation of combustible gas mixtures within MCOs or within their surroundings. To support that strategy, this document: 1) establishes combustible gas management functions and minimum functional requirements for the MCO's mechanical seals and closure weld(s); 2) establishes a maximum practical value for the minimum required initial MCO inert backfill gas pressure; and 3) based on items 1 and 2, establishes and confirms leak test acceptance criteria for the MCO's mechanical seal and final closure weld(s).

1.1 SCOPE

The overall scope of this document is limited to consideration of leak testing criteria that pertain directly to the above stated purpose(s). This document does not address release of radiological contamination from MCOs (i.e., it does not address the implications of a given leak test acceptance criterion with respect to the MCO's radiological confinement function).

The scope is further limited to evaluation of gas leakage: 1) from mechanically sealed, pressurized MCOs that have successfully undergone leak testing at the Cold Vacuum Drying Facility (CVDF) following completion of the CVDF process; and 2) from pressurized MCOs that have successfully undergone leak testing following completion of their final closure weld(s) at the Canister Storage Building (CSB). Any evaluation of MCO gas leakage prior to completion of the CVDF process is beyond the scope of this document.

1.1.1 Loss of Hydrogen From CSB Tubes via Tube Vents

Whereas Revision 0 of this document did not quantitatively address (nor take credit for) loss of hydrogen from tubes via the stagnant tube vents, section 7.3 of Revision 1 provided calculations to confirm that no vented CSB tube, regardless of its payload configuration, will ever exceed 1 vol% hydrogen. An alternate calculation was also added by Revision 1 (see Appendix C) to further substantiate the conclusions of section 7.3.

1.1.2 Replacement of Backfill Gas At CSB

This document does not address replacement of backfill gas for MCOs that are sampled at the CSB.

1.1.3 Hydrogen Release to MCO/Cask Assembly During Transport Operations

As of Revision 1, this document no longer addresses hydrogen release from MCOs into the MCO transportation cask. Those calculations are now provided by the *Safety Analysis Report for Packaging (Onsite) Multi-canister Overpack* (HNF-SD-TP-SARP-017).

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

2.1 RECOMMENDATIONS

The following recommendations are based on functions and requirements developed in section 5.0.

2.1.1 Recommendations For MCOs With Mechanical Seals

The integrated leak test acceptance criterion for mechanically sealed MCOs should continue to be specified as 1×10^{-5} std cc/sec. The above leak test acceptance criterion should not be difficult to meet in light of the *Test Report For Multiple Canister Overpack Mechanical Closure Prototype Testing* (WHC-SD-SNF-TRP-018). The last paragraph of section 3.2 in that report states that the prototype mechanical seal "...had a leak rate of 1.4×10^{-7} std-cc/s..." at the MCO's 132°C maximum design temperature for CSB storage operations.

2.1.2 Recommendations For MCOs With Welded End Closures

The current integrated leak test acceptance criterion for MCOs with welded end closures (1×10^{-7} std cc/sec) should be retained. This criterion is reasonable for a welded closure and is more than adequate to meet all of the functional requirements that are imposed in section 5.0. It is also adequate to accommodate any foreseeable changes to the functional requirements that might be expected to occur as the project evolves.

2.2 RESULTS AND CONCLUSIONS FOR MECHANICALLY SEALED MCOs

2.2.1 Helium Retention

The recommended leak test acceptance criterion for the MCO's mechanically sealed end closure (1×10^{-5} std cc/sec) will ensure a positive helium gage pressure (requires 25.2 mol of helium per 500 L of void) within MCOs for well over 40 years without the need to replenish their helium backfill gas, and without the need to install their weld sealed end closures. It will further ensure retention of sufficient helium to support all the conclusions of the oxygen gettering analysis for over 40 years, without the need to replenish an MCO's helium backfill gas unless it has been purposely removed by a sampling operation. With respect to supporting the conclusions of the oxygen gettering analysis, no credit is taken, nor can be taken, for the weld sealed end closure (see section 5.1.1.1.4, below).

| 2.2.2 Hydrogen Within CSB Tubes

Hydrogen Within Singly Occupied, Un-Vented CSB Tubes

- | The recommended leak test acceptance criterion for the MCO's mechanically sealed end closure (1×10^{-5} std cc/sec) will ensure that it would take over 3 years for the hydrogen concentration to reach 1 vol% (25% of its Lower Flammable Limit -- LFL) within an un-vented, singly occupied storage tube containing a safety basis pressure case MCO with mechanical seals. Note that the gas inventory required to produce the pressure used for this leakage calculation is not expected within any MCO during the first years of storage, nor within the majority of MCOs during up to 40 years of storage.

Hydrogen Within Doubly Occupied, Un-vented CSB Tubes

- | The recommended leak test acceptance criterion for the MCO's mechanically sealed end closure (1×10^{-5} std cc/sec) will ensure that it would take over ten months for the hydrogen concentration to reach 1 vol% within an un-vented storage tube containing two safety basis pressure MCOs with mechanical seals.

Hydrogen Within Vented CSB Tubes

- | Based on dilution of hydrogen via the air exchange that accrues from barometric pressure variations alone (i.e., with no additional allowance for gas transport due to thermal cycling or diffusion), the recommended leak test acceptance criterion for the MCO's mechanically sealed end closure (1×10^{-5} std cc/sec) will ensure that no vented CSB tube will ever exceed 1 vol% hydrogen, even if it contains two safety basis pressure MCOs with mechanical seals (see section 7.3). Appendix C provides an alternate calculation that reaches the same conclusion, based on static diffusion alone, with no allowance for air exchange from barometric or thermal cycling. In view of the fact that both mechanisms (mass flow and static diffusion) will actually be active at the same time, the overall conclusion is that no vented CSB tube will ever reach 1 vol% hydrogen unless it contains an MCO with a defective seal or breached wall, etc..

2.3 RESULTS AND CONCLUSIONS FOR WELD SEALED MCOs

2.3.1 Helium Retention

- | The current leak test acceptance criterion for the welded MCO closure (1×10^{-7} std cc/sec) is more than adequate to retain a positive helium gage pressure within safety basis pressure case MCOs for hundreds of years beyond the 40 year project life.

| 2.3.2 Hydrogen Within CSB Tubes

| Hydrogen Within Un-Vented CSB Tubes

| The recommended 1×10^{-7} std cc/sec leak test acceptance criterion for MCO welds is adequate to maintain the hydrogen concentration below 1 vol% for over 100 years within a completely sealed storage tube containing two safety basis pressure MCOs, each of which almost failed the leak test.

| Hydrogen Within Vented Storage Tubes

| Based on dilution of hydrogen within vented CSB tubes by air exchange that accrues from barometric pressure variations alone (i.e., with no additional allowance for thermal cycling or diffusion), the recommended leak test acceptance criterion for MCO welds (1×10^{-7} std cc/sec) will ensure that no vented CSB tube will ever reach 1 vol% hydrogen (see section 7.3).

2.4 NATIONAL FIRE PROTECTION ASSOCIATION COMPLIANCE

| Appendix B provides a summary of the National Fire Protection Association (NFPA) *Standard on Explosion Prevention Systems* (NFPA 69), along with a general discussion of its application to the MCO. Section 5.2.2 of this document describes the project's status with respect to Chapter 3 (Combustible Concentration Reduction) of NFPA 69 and concludes, based on the hydrogen leakage calculation results of section 7.2 (summarized on the last sheet of Appendix A) and the subsequent atmospheric air exchange calculations of section 7.3 (and Appendix C), that all MCO handling, staging, and storage operations currently envisioned for the CSB can be performed in compliance with the requirements of NFPA 69 Paragraph 3-3. See section 5.2.2 for discussion of the project's status with respect to NFPA 69 Paragraph 3-4 (Instrumentation). Finally, see section 5.2.1 for a description of the project's status with respect to NFPA 69 Chapter 2 (Oxidant Concentration Reduction), which applies to conditions within MCOs.

3.0 ASSUMPTIONS

All assumptions are identified and justified as they are applied.

4.0 SOURCES

4.1 COMBUSTIBLE GAS MANAGEMENT DEFINITIONS AND REQUIREMENTS

| Section 12.2 (Fire Protection, Fire Protection Program) of the SNF Project's
| *Standards/Requirements Identification Document* (HNF-SD-SNF-RD-001) invokes all
| applicable NFPA codes and standards, listing the requirement source as
| Section 5 of DOE 5480.7A (Fire Protection). Because MCOs are expected to
contain hydrogen gas, the overall process design (including, but not limited
to, the design of the MCO itself) is required to comply with all applicable
sections of NFPA 69 (*Standard on Explosion Prevention Systems*). See Appendix
B of this document for a summary description of NFPA 69, along with a general
discussion of its application to the MCO.

Additional requirements for evaluation of bounding case MCOs are taken from
NRC Regulatory Guide 1.7 (*Control of Combustible Gas Concentrations in
Containment Following a Loss-of-Coolant Accident*).

4.2 LEAK RATE DEFINITIONS AND LEAK RATE CORRELATION EQUATIONS

Section 4.13 of the current MCO performance specification (HNF-S-0426)
requires all MCO seals to be "...leakage rate testable in accordance with ANSI
N14.5...." Therefore all leak rate definitions and leak rate correlation
equations used in this document are taken from the *American National Standard
For Radioactive Materials -- leakage tests on packages for shipment* (ANSI
N14.5). See section 6.1, below, for additional detail.

4.3 MCO GAS INVENTORIES

4.3.1 Backfill Gas

| 4.3.1.1 **Minimum Backfill Gas Inventory for Minimum Void MCO.** The minimum
| backfill gas inventory (31.0 mol) to be used for backfill gas loss
| calculations is developed in section 7.1.2.1.1, based on a 500 L minimum void
| volume MCO (see Table 4.2.2-1 of HNF-2169), on the 9.5 psig minimum backfill
| pressure established in section 5.1.1.1.3, and on the 50°C maximum MCO
| temperature established in section 5.1.1.1.4. See sections 5.1.1.1.3 and
| 5.1.1.1.4, respectively, for a more detailed explanation of the maximum
| backfill pressure and minimum backfill temperature bases.

4.3.1.2 Maximum Backfill Gas Inventory for Minimum Void MCO. The maximum backfill gas inventory (41.3 mol) to be used for hydrogen release calculations is developed in section 7.1.2.3.1, based on a 500 L minimum MCO void volume that has been backfilled to a maximum pressure of 12.5 psig (27.2 psia -- 1.85 atm) at a minimum MCO/Cask assembly temperature of 0°C. Note that this corresponds to a 0°C internal gas temperature because a zero power MCO is conservative for calculation of the maximum backfill gas inventory. See sections 5.1.1.1.3 and 5.1.1.1.4, respectively, for a more detailed explanation of the maximum backfill pressure and minimum backfill temperature bases.

4.3.1.3 Minimum Backfill Gas Inventory for 530 L Void MCO. The minimum backfill gas inventory to be used with a 530 L void volume MCO for comparison of helium loss rates (see section 4.3.2.1, below) is 32.9 mol, based on the same minimum backfill conditions that resulted in the 31.0 mol helium inventory listed for a 500 L void volume MCO in section 4.3.1.1, above:

$$(31.0 \text{ mol}) (530 \text{ L}/500 \text{ L}) = 32.9 \text{ mol}$$

4.3.2 Maximum Hydrogen Inventory at 40 Years

The hydrogen inventory used for all hydrogen release calculations, and for the maximum helium loss calculation, is based on a total gas inventory that corresponds to the maximum pressure reached in the plot on page K-17 of HNF-SD-TI-40, Rev. 3 (*MCO Internal Gas Composition and Pressure During Interim Storage*), given the 30.3 mol backfill gas inventory and the other conditions and/or assumptions upon which that plot is based. Sections 7.1.2.1 and 7.1.2.3, below, develop total gas inventories, based on combination of the resulting hydrogen inventory with helium inventories and helium impurity inventories that are appropriate to the needs of each calculation. Note that this approach conservatively takes all other gases (oxygen, fission gas, or any other gas that may be included in the 95.8 mol total) as hydrogen.

The hydrogen inventory used to calculate helium losses from worst oxygen case MCOs is based on a total gas inventory (40.2 mol) that corresponds to the 2.0 atm (absolute) maximum pressure reached in the plot on page I-13 of HNF-SD-TI-40, Rev. 3, given the 30.3 mol backfill gas inventory and the other conditions and/or assumptions upon which that plot is based. Section 7.1.2.2, below, develops the total gas inventory for this calculation, based on combination of the resulting 9.9 mol hydrogen inventory with the minimum backfill gas inventory from section 7.1.2.1.1. This approach conservatively takes all other gases (oxygen, fission gas, backfill gas impurities, etc.) as hydrogen.

4.3.2.1 Reconciliation of Hydrogen Inventory Bases. Because the leakage calculations in this document continue to be based on the simplifying assumption that the worst case hydrogen inventory for any MCO (regardless of its void space) could occur within a minimum void space MCO (500 L), despite the fact that it is not possible for a minimum void space MCO to generate that much hydrogen, the worst case high pressure (5.9 atm) that is used for some calculations in this document exceeds the 5.7 atm maximum safety basis MCO pressure calculated by HNF-SD-TI-040, *MCO Internal Gas Composition and Pressure During Interim Storage (OCRWM)*. Revision 3B of that document adds Appendix N ("Interim Storage Maximum MCO Pressure With Variable He Backfill") in order to: 1) address increased backfill gas inventories that resulted when Revision 1 of this document (HNF-2155) revised the backfill pressure conditions; and 2) provide a more detailed basis for bounding pressure MCOs. The last paragraph in the summary (Section 2.0) of HNF-SD-TI-040, Rev 3B, now reads, in part:

A bounding MCO pressure at 40 years is found in the maximum decay heat and surface area case (two scrap baskets, 653 W, 11.4 m² reactive area on a per basket basis, zero Al(OH)₃ assemblies, bounding canister and adhering particulate). The pressure is 5.7 atm (rounded for convenience from a calculated 5.65 atm). The helium backfill gas assumed for the maximum pressure case was 43.4 moles..."

Page N-2 of HNF-SD-TI-040 Appendix N states that the MCO void volume used for the above case was 530 L, and that "... the final hydrogen inventory was 67.57 gram moles and is [sic] independent of backfill conditions." However, a final hydrogen inventory anywhere near 67.6 mol would be impossible in a 500 L void volume MCO because any MCO containing one or more scrap baskets, which are the main source of hydrogen, would have a void volume above 500 L.

Revision 2 of this document (HNF-2155) provides two additional spread sheet calculations in order to confirm that all of the calculations retained from Revision 1 remain conservative and, therefore, do not need to be revised to reflect HNF-SD-TI-040, Rev 3B. The first of these, which addresses hydrogen release rates, is the most straightforward because it can be based on the exact set of conditions used by HNF-SD-TI-040 to obtain the 5.7 atm worst case high pressure.

Comparison of Predicted Hydrogen Release Rates

The sixth sheet of Appendix A, below, is based on the following set of conditions taken directly from Appendix N of HNF-SD-TI-040:

MCO void -- 530 L

MCO Gas Inventory at 40 yrs -- $67.6 \text{ mol H}_2 + 43.4 \text{ mol He} = 111.0 \text{ mol}$

MCO Gas Temperature at 40 yrs -- 56.3°C (from page N-62 of HNF-SD-TI-040)

Maximum MCO Gas Pressure -- 5.66 atm (Occurs at 40 Years).

The " $6.801\text{E-}04$ " mol/day per MCO hydrogen leakage rate predicted for a mechanically sealed MCO under the above conditions (see the sixth sheet of Appendix A, below) is less than the " $7.348\text{E-}04$ " value that is shown on the fifth sheet of Appendix A. Therefore, all of the atmospheric breathing calculations in section 7.3 ("Maximum Steady State Hydrogen Concentration in CSB Tubes") are based on a conservative hydrogen release rate and do not need to be revised to reflect Revision 3B of HNF-SD-TI-040. This is also the case for the alternate [diffusion based] calculations in Appendix C.

Comparison of Predicted Helium Loss Rates

Comparison of predicted helium loss rates is complicated by the fact that the existing calculations are based on the minimum possible helium inventory whereas the 5.7 atm worst case pressure calculated by HNF-SD-TI-040 is based on a maximum helium inventory. Therefore, the seventh sheet of Appendix A, below, is based on the following conditions which are, with the exception of the helium inventory and resulting pressure, taken from Appendix N of HNF-SD-TI-040. The 32.9 mol [initial] helium inventory is developed in section 4.3.1.3, above:

MCO void -- 530 L

MCO Gas Inventory at 40 yrs -- $67.6 \text{ mol H}_2 + 32.9 \text{ mol He} = 100.5 \text{ mol}$

MCO Gas Temperature at 40 yrs -- 56.3°C (from page N-62 of HNF-SD-TI-040)

Maximum MCO Gas Pressure -- 5.12 atm (Occurs at 40 years)

The " 0.1153 " mol/year helium leakage rate predicted for a mechanically sealed MCO under the above conditions (see the seventh sheet of Appendix A) is less than the " 0.1209 " value shown on the second sheet of Appendix A. The existing helium loss rate calculations are therefore based on conservative conditions and do not require revision to reflect Rev 3B of HNF-SD-TI-040.

4.4 MCO BACKFILL TEMPERATURE AND MCO/CSB TUBE OPERATING TEMPERATURES

The MCO gas temperature range (0°C minimum to 50°C maximum) used for calculation of backfill gas quantities is based on: 1) the minimum MCO Transport Cask temperature (0°C) assumed for performance of the final MCO back-fill operation at the CVDF and the assumption that there will be no temperature differential between the MCO interior and the MCO Transport Cask for a zero power MCO (which is conservative for the maximum backfill inventory calculation); and 2) the maximum average gas temperature (50°C) calculated for a worst case high heat MCO following post CVD circulation of cooling water through the MCO/Cask annulus (see section 5.1.1.1.4 and Appendix F). Appendix G calculates the maximum time required for freshly introduced backfill gas to reach the allowable MCO backfill temperature range. Finally, the maximum average gas temperature (51°C) used in section 7.2.1.1 to calculate the initial helium inventory of the cover cap void space is based on the 51°C maximum upper wall temperature listed in section 5.11.4 of HNF-2256 (*Simulation of Normal and Off-Normal Multi-Canister Overpack Behavior*) for an MCO after eight hours at the CSB's weld station.

The MCO gas temperature used for hydrogen release and worst case helium loss calculations is taken as the average fuel temperature (64°C) that corresponds to the same point in time (40 years out) that the maximum pressure is reached in the plot on page K-17 of HNF-SD-TI-040, Rev. 3 (*MCO Internal Gas Composition and Pressure During Interim Storage*). The corresponding CSB storage tube gas temperature (64°C) was conservatively assumed to be equal to the MCO gas temperature. That assumption is conservative because it results in a shorter time for the tube to reach 1 vol% hydrogen than would be the case if the calculation were based on the actual storage tube gas temperature (something less than the MCO gas temperature).

The 31°C MCO gas temperature used for helium loss calculations to support the oxygen gettering analysis is taken as the average fuel temperature that corresponds to the same point in time (40 years out) that the maximum oxygen concentration is reached in the plot on page I-13 of HNF-SD-TI-040 (*MCO Internal Gas Composition and Pressure During Interim Storage*). That plot depicts conditions within a "zero scrap, bounding water, low area, worst power [for oxygen]" MCO, as described by section 4.2 in Appendix I of HNF-SD-TI-040. That document evaluates a number of other cases that result in higher oxygen concentrations (~4 vol%, as compared to 1.8 vol% for this case), however is the 1.8 vol% plot used in this evaluation depicts the worst case evaluated for any non-zero fuel area or non-zero helium over-pressure MCO and, as such, it represents the maximum realistic worst case for evaluation by this document. Consequently, for the purposes of the helium leakage criteria developed and evaluated by this document, the MCO described by section 4.2 in Appendix I of HNF-SD-TI-040 will be regarded as, and sometimes referred to as, the "worst oxygen case MCO."

The minimum MCO operating temperature used for the calculation to confirm that the MCO's internal pressure never goes negative was conservatively taken as the lowest temperature on record (-23°F -- -31°C), in Table 3.9 of the *Hanford Site Climatological Data Summary 1996 With Historical Data* (PNNL-11471).

4.5 GAS PROPERTY DATA

Gas property data were obtained from: ANSI N-14.5 1997, Table B.1; from *Fundamentals of Momentum, Heat and Mass Transfer*, Appendix I (Welty 1969); from the *Handbook of Chemistry and Physics* (49th Edition), and from page 208 of the Scott Specialty Gases catalog (Scott Environmental Technology Inc.).

4.6 BAROMETRIC DATA

Local barometric effects (used for calculations in section 7.3.1) have most recently been documented in *Barometric Pressure Variations* (WHC-EP-0651). Table 6 of that report provides minimum, average, and maximum integrated short-term data for periods from one hour to one year.

4.7 CSB STORAGE TUBE VOID VOLUMES

Table 5-1 of SNF-3328, Rev. 1 (*Canister Storage Building Design Basis Accident Analysis Documentation*) lists the free volume of a storage tube containing one MCO as 2,890 L. The same table lists the free volume of a storage tube containing two MCOs as 1,530 L. To allow for any future refinements to the calculations that support those values, and to avoid the need to revise existing hydrogen concentration calculations in this document (i.e., the calculations in HNF-2155, Rev. 1), the more conservative values (i.e., 2500 L and 1200 L, respectively) are retained in this revision (Rev. 2).

Finally, based on dimensions from Sheet 2 of H-2-120918, Draft Rev 0, the hold-up volume for each of the storage tube shield plug's two identical vent ports can be estimated as:

Length -- 30 cm (~11") + 100% allowance for nipple, etc. = 60 cm

Diameter -- 1.9 cm (0.75 inch)

Volume = $\pi(1.9/2 \text{ cm})^2 \times 60 \text{ cm} = 170 \text{ cm}^3$; For two ports USE 0.40 L

5.0 COMBUSTIBLE GAS MANAGEMENT FUNCTIONS AND REQUIREMENTS

Significant quantities of hydrogen can be generated within MCOs during the first few years of storage as a result of chemical reactions between exposed uranium metal and any moisture that is retained by fuel particulate. Depending on the amount of sludge and retained moisture within a given MCO (and a number of other factors) both hydrogen and oxygen may continue to be generated by radiolysis within MCOs throughout the 40 year CSB operating life.

The SNF Project addresses the potential for combustion of the hydrogen with an overall strategy that, depending on the process step, employs one of two general approaches recommended by NFPA 69 to avoid accumulation of a combustible gas mixture. The functions and requirements that implement the project's overall combustible gas management strategy are listed below.

5.1 FUNCTION: PRECLUDE COMBUSTIBLE MIXTURES INSIDE MCOs

Because significant quantities of hydrogen are anticipated within MCOs, it will be necessary to provide this function by limiting the concentration of oxygen within MCOs. Reduction of oxygen concentrations within MCOs has been addressed by a number of different, but related, studies, analyses, and reports as the process design has evolved, culminating in Revision 3B of HNF-SD-SNF-TI-040 (*MCO Internal Gas Composition and Pressure During Interim Storage*). Revision 0 of that document initially evaluated the ability of exposed uranium metal surfaces within the MCO to remove any oxygen that is generated by radiolysis of water, established 4 vol% as the Limiting Oxidant Concentration (LOC) for the worst case gas mixture within an MCO, and then used 4 vol% as the maximum allowable oxygen concentration. This allowable is lower (4% vs 5%) than that permitted by the applicable NRC regulatory guide (*Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident*, NRC Regulatory Guide 1.7) because the LOC itself is lower for the MCO's worst case conditions. Consequently, Table 4-1 of the *Spent Nuclear Fuel Project Product Specification* (HNF-SD-SNF-OCD-001) specifies a 4 vol% maximum oxygen concentration instead of the 5 vol% NRC limit.

5.1.1 Functional Requirement: Preclude Air Ingress to MCOs

Although, the analyses in HNF-SD-SNF-TI-040 do not specifically address accumulation of oxygen within MCOs due to air ingress, the results indicate that there is little or no excess gettering capacity to accommodate ingress of oxygen into the MCO. Consequently, one functional requirement of the MCO handling and storage system (including, but not limited to the MCO vessel and its seals) is to essentially preclude (as opposed to limit) air ingress to an MCO (unless MCOs are periodically purged and backfilled).

5.1.1.1 Implementation Criteria. If air ingress to MCOs is to essentially be precluded it will either be necessary to maintain an air free (i.e., oxygen free) atmosphere around MCOs at all times (which will not be practical, or even possible) or to maintain MCOs at positive gage pressures at all times.

While it is possible to design and fabricate seals that are capable of precluding any measurable air ingress, this requirement can be more easily satisfied by simply maintaining the MCO at a positive gage pressure. This approach has the added advantage that it will automatically gain additional time for a leaking seal because the positive gage pressure must first be lost before any significant amount of air can even begin to enter the vessel.

The following criteria must be satisfied in order to maintain the MCO at a positive gage pressure, and thereby preclude air ingress, under all operating conditions.

5.1.1.1.1 Minimum Time To Maintain Positive Pressure. There are two cases that must be considered in order to establish the minimum time during which MCO seals must retain sufficient backfill gas to maintain positive gage pressure under all operating temperature conditions.

Case 1 -- Transport to the CSB and Initial Staging

- Minimum Requirement -- 4 years
- Design Goal -- 40 years

The MCOs will employ mechanical seals during transport to the CSB. While most of the MCOs will be provided with welded end closures a short time after they are received at the CSB, a limited number of MCOs will undergo periodic inspection and gas sampling prior to installation of their welded caps. It may prove necessary to maintain these mechanically sealed MCOs within the CSB for several years.

In addition to the mechanically sealed MCOs discussed above, it may be necessary to provide a weld station queue area (i.e., designated storage tubes) capable of staging mechanically sealed MCOs while they await installation of their welded closures. Because the turnaround time in an active process queue should be on the order of days or weeks, and because the MCOs within the queue should be easy to keep track of during process delays a two year minimum backfill retention time should be adequate for these in-process MCOs.

Based on the above considerations, and allowing for a 100% contingency, the minimum time for a mechanically sealed MCO to maintain positive backfill pressure is four years. While, four years is the minimum retention period, CSB operations would be simplified if there were no limit (beyond the CSB's current 40 year design life) to the time that mechanically sealed MCOs can retain positive backfill pressure. Consequently, it is a highly desirable (although not absolutely necessary) goal to confirm that a mechanically sealed MCO will maintain a positive backfill pressure for at least 40 years.

Note that MCO temperatures will vary as a result of decay heat variations among the MCOs, and as a result of seasonal variations in the CSB's cooling air inlet temperature. While the minimum molar quantity of backfill gas must be calculated at the minimum anticipated MCO gas temperature, the backfill gas leakage rate must be calculated at the gas temperature that corresponds to the maximum anticipated gas pressure). Also note that, even though the backfill gas leakage calculation must include the maximum possible generated gas inventory, no allowance can be included for any of the generated gas when establishing the minimum end-point pressure because all, or most, of it could be gettered by uranium at any time during the project life.

Case 2 -- Long Term ("Interim") Storage

- Minimum Requirement -- 40 years

For the purposes of this document, long term storage (i.e., "Interim Storage") will not begin for any given MCO until its weld closure has been installed. Following weld closure installation, MCOs must retain an adequate quantity of backfill gas to maintain a positive gage pressure for 40 years.

Design Goal for Retention of Additional Backfill Gas

Considerable time and expense that would otherwise be required to perform additional computer analyses will be avoided if it can also be demonstrated that the main void space (i.e., that under the shield plug) of a worst oxygen case MCO will never contain less than 95% of the 30.3 mol nominal helium inventory that was assumed by the oxygen gettering analysis (HNF-SD-SNF-TI-040, Rev 3) for calculation of oxygen concentrations within MCOs. The 95% criterion limits the impact on the maximum oxygen concentration calculated for a "...zero scrap, bounding water, low area, worst power [for oxygen]..." MCO to 0.1 vol% (i.e., oxygen levels would increase from 1.8 vol% to 1.9 vol%). That document (HNF-SD-SNF-TI-040) evaluates a number of cases that result in higher oxygen concentrations. However, for the purposes of the helium leakage criteria developed and evaluated by this document (HNF-2155), the MCO described by section 4.2 in Appendix I of HNF-SD-TI-040 will be regarded as (and sometimes referred to as) the "worst oxygen case MCO" because that is the worst case evaluated for any non-zero fuel area, non-zero helium over-pressure

| MCO and, as such, it represents the maximum realistic worst case for oxygen
| concentrations within MCOs.

5.1.1.1.2 Type of Backfill Gas. The backfill gas must be inert. Gasses that might be consumed by reacting or otherwise interacting with uranium metal (e.g., hydrogen or nitrogen) are unacceptable because there is no way to be certain that they will be replaced by generation of additional hydrogen, or that any additional hydrogen that is generated will not be gettered by the uranium. At this point in the project, helium has been selected as the backfill gas. Consequently, the leakage calculations that support this document are based on a helium backfill.

| **5.1.1.1.3 Backfill Pressure.** The backfill pressure requirement is that the
| actual backfill pressure (not the gage reading) can be proven to have been
| somewhere between 9.5 psig and 12.5 psig when the backfill pressure was
| measured (after all corrections for calibration errors that may be discovered
| after the fact, etc.). The CVDF operations manual (SNF-2356) ensures that the
| above requirement will be met by specifying an 11 psig pressure and a ± 0.5
| psi tolerance band. Despite the fact that the helium loss calculations in
| this document are based on a minimum molar inventory within a minimum void
| space MCO (500 L), the backfill pressure is controlled, as opposed to the
| molar inventory (see section 5.1.1.1.4 for MCO temperature requirements). For
| those MCOs (i.e., most of them) that exceed the minimum void volume, the
| actual backfill gas quantity will increase proportionally with the increase in
| void volume, which means that an initial backfill pressure that is adequate
| for a minimum void volume MCO will also be adequate for a maximum void MCO.
| This automatic compensation effect also applies to the maximum acceptable
| backfill pressure. While the actual quantity will vary upwards from the value
| calculated for a minimum void MCO at the maximum fill pressure, the larger
| backfill quantity will not result in over pressurization because the backfill
| gas quantity represents less than half of the worst case gas allocation used
| to calculate the maximum pressure. In other words, for a given backfill
| pressure and temperature, larger MCO volumes will result in lower worst case
| pressures. Backfill pressure and temperature were therefore specified instead
| of moles in order to take advantage of this automatic compensation effect.

| Basis for Maximum Acceptable Backfill Pressure

| The 12.5 psig maximum backfill pressure limits the total gas inventory of a
| 500 L MCO to less than 107 mol after up to 40 years of interim storage (see
| section 7.1.2.3), which limits the maximum MCO pressure calculated by this
| document to 5.9 atm at 40 years (see section 7.1.3.3). The maximum pressure
| is limited to 5.9 atm in order to avoid exceeding the 6.0 atm initial blowdown
| pressure used in the CSB's Hazard and Accident Analyses (see section A3.4.1.2
| of the *Spent Nuclear Fuel Project Final Safety Analysis Report*, HNF-3553).

Note that the 12.5 psig maximum backfill pressure criterion is slightly more conservative than the calculated 5.9 atm maximum pressure would indicate, based on a recent revision (Rev 3B) of HNF-SD-TI-040 (*MCO Internal Gas Composition and Pressure During Interim Storage*), which has shown that the maximum pressure of any MCO will not exceed 5.7 atm at 40 years. See section 4.3.2.1 of this document (HNF-2155) for additional details.

Basis for Minimum Acceptable Backfill Pressure

This document has established the minimum acceptable backfill pressure criterion as 9.5 psig, based on: 1) allowing a 3 psi margin below the 12.5 psig maximum backfill pressure; 2) using the resulting 9.5 psig value to calculate the minimum backfill gas inventory in section 7.1.2.1; 3) plugging the resulting minimum initial helium inventory (31.0 mol) into the helium loss calculations of section 7.2.1.5.1 and Appendix A; and 4) comparing the resulting values for the final helium inventory at 40 years to the minimum requirement of section 7.1.2.1.3 and the minimum design goal of section 7.1.2.2.1. Note that the 3 psi acceptable backfill pressure range is not intended to provide a 3 psi range in the acceptable backfill pressure gage reading or set point -- see the first sentence of this section (5.1.1.1.3).

5.1.1.1.4 Backfill Temperature. The backfill temperature requirement is that the average gas temperature within the MCO can be proven to have been somewhere between 0°C and 50°C at the time the backfill pressure was measured. The CVDF is not required to measure Cask or MCO temperatures during the Cask/MCO cooldown step that precedes the MCO backfill operation.

Basis for Maximum Backfill Temperature

The worst case high backfill temperature was determined analytically (see Appendix F), based on completion of the cooldown procedure specified in the operations manual (SNF-2356). The cooldown analysis predicts a 48°C average gas temperature, which has been conservatively rounded up to 50°C. The room temperature is taken as the highest temperature (114°F) listed for the Hanford site (PNNL-11471). The following process conditions must be met to support the cooldown analysis:

- 1) The MCO must be refilled with helium (following the final pressure rise test) and maintained at a positive gage pressure (14.7 psia or higher);
- 2) Cooling water (i.e., tempered water) must be circulated at ≥ 15 gpm;
- 3) The tempered water skid's discharge temperature must be maintained at or below 15 °C [the analysis conservatively assumes a 17°C maximum Cask/MCO annulus inlet temperature]; and

- 4) The above conditions must be maintained for at least five hours (not required to be contiguous) of the six hour period that the operations manual allocates to cooldown.

Basis for Minimum Backfill Temperature

The worst case low end of the allowable backfill temperature range is based on a 0°C minimum Cask/MCO assembly temperature, which corresponds to a 0°C internal gas temperature because a zero power MCO is conservative for calculation of the maximum backfill gas inventory. The assumption of a 0°C worst case low temperature eliminates the need to impose a process control limit on the minimum discharge temperature of the demineralized water circulation system (i.e., the tempered water system) that is used to cool the Cask/MCO assembly because it would be impossible to circulate demineralized cooling water at temperatures below freezing.

5.1.2 NFPA 69 Chapter 2 Compliance Status

Chapter 2 of NFPA 69 covers application of that standard's oxidant reduction technique. Paragraph 2-7.2 provides the operating limits and instrumentation requirements for systems that will be operated below the Limiting Oxidant Concentration (LOC). Paragraph 2-7.2.2 requires that the LOC for a given system be based on the worst credible case gas mixture yielding the smallest LOC. Paragraph 2-7.2.3 requires that a safety margin be maintained between the LOC and normal working concentration in the system. See Appendix B of this document for an overall summary description of NFPA 69.

5.1.2.1 Non-Compliance with Specific Requirements. Paragraph 2-7.2.5 of NFPA 69 states: "Where the oxidant concentration is continually monitored, a safety margin of at least 2 volume percent below the measured worst credible case LOC shall be maintained unless the LOC is less than 5 percent, in which case the equipment shall be operated at no more than 60 percent of the LOC." Paragraph 2-7.2.5 can not be applied to an MCO after it leaves the CVDF because it will have no provision for continuous monitoring.

Paragraph 2-7.2.6 states, in part: "Where the oxygen concentration is not continuously monitored, the oxygen concentration shall be designed to operate at no more than 60 percent of the LOC, or 40 percent of the LOC if the LOC is below 5 percent." Based on the 4 vol% LOC discussed in section 2.1 above, compliance with the letter of the above statement would require that the overall SNF Project fuel removal and storage process (e.g., the fuel cleaning process, maximum MCO fuel and/or scrap inventory, fuel drying process, MCO backfill gas type and/or quantity, etc.) be designed to ensure that the oxygen concentration within MCOs will not exceed 1.6 vol% at any time during their service life. In view of the fact that the current oxygen gettering goal is

to maintain the oxygen concentration within all MCOs at or below the LOC (as opposed to 40% of the LOC), the SNF Project does not appear to comply with the above NFPA 69 requirement. With respect to this apparent non-compliance, it is important to recognize that NRC Regulatory Guide 1.7 is also apparently out of compliance. Given a 5 vol% LOC, the NRC guide's maximum allowable would have to be specified as 60% of the 5 vol% LOC, or 3 vol%, versus 5 vol%.

Paragraph 2-7.2.6 further states: "If the oxygen concentration is not continuously monitored, the oxygen concentration shall be checked on a regularly scheduled basis." The SNF Project will be unable to comply with this requirement once a given MCO's weld closure has been installed.

5.1.2.2 NFPA 69 Paragraph 2-7.2 Equivalency. Although it is impossible to claim strict compliance with NFPA 69 Paragraph 2-7.2 in light of the situation described in section 5.1.2.1 above, it should be possible to demonstrate that both the SNF Project and the NRC Regulatory Guide 1.7 do provide an equivalent level of protection. Paragraph 1-1.3 of NFPA 69 provides for demonstration of equivalency (see Appendix B of this document).

In order to demonstrate equivalency to the oxygen concentration limits and monitoring requirements invoked by Paragraph 2-7.2, despite the project's inability to strictly comply with those limits and requirements, it is necessary to compare the operational bases that drove the NFPA 69 requirements to those that drove the MCO's 4 vol% oxygen limit and the similar 5 vol% limit established by the NRC Regulatory Guide.

In the instance of the 5 vol% oxygen limit invoked by NRC Regulatory Guide 1.7 (*Control of Combustible Gas Concentrations in Containment Following a Loss-of-Coolant Accident*), the difference is apparent from the phrase "loss of coolant accident" in the guide's title. Whereas the concentration limits and monitoring requirements of NFPA 69 are based on normal operation at concentration levels that approach the specified maximum (3 vol% oxygen for the NRC's 5 vol% oxygen LOC), the NRC's 5 vol% limit has nothing to do with normal operation but is, instead, directed toward a design basis accident.

The MCO's situation is similar, but not identical, to that addressed by the NRC. There is no basis for a "normal operating limit" for oxygen within a reactor containment because there is normally no hydrogen to react with that oxygen, which is why the scope of NRC Regulatory Guide 1.7 is limited to the loss of coolant accident. While it may be necessary to inert the containment building during normal operation in order to ensure that oxygen levels can not exceed 5 vol% during or after a postulated accident, the inerting requirement is directed purely at the accident condition, as opposed to normal operation.

The MCO, on the other hand, must be assumed to contain significant quantities of hydrogen during normal operation, therefore any limitation on the oxygen

concentration must, by definition, be directed at normal operation. Whereas the difference between the NRC basis and the NFPA 69 basis is that of an accident condition versus a normal operating condition, the difference between the MCO's basis and NFPA 69's basis concerns the methodology that is used to preclude combustion.

For most applications governed by NFPA 69, it is simply a matter of maintaining a purge gas blanket and/or flow that normally will not exceed the particular limit imposed. The logic is that, in the event that something goes wrong with the purge gas system (e.g., a leaking flange on the intake side of an "inert gas" compressor's first stage, etc.), the additional margin afforded by NFPA 69's requirements will generally be sufficient to prevent the LOC from being greatly exceeded for any significant period of time. No one has to demonstrate by a rigorous analytical model that it will not be reached.

In view of the above, it may be possible to provide documentation that satisfies NFPA 69, Paragraph 1-1.3, which addresses situations where it is either impossible or inappropriate to meet any or all of the detailed requirements that it invokes. That paragraph states: "Nothing in this standard shall be intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, fire resistance, effectiveness, durability, and safety over those prescribed by this standard, provided technical documentation is made available to the authority having jurisdiction to demonstrate equivalency and the system, method, or device is approved for the intended purpose."

| **5.1.2.2.1 Strategy To Demonstrate Equivalency.** Formal recommendation of the SNF Project strategy to document and obtain official recognition of NFPA 69 Paragraph 2-7.2 equivalency is beyond the scope of this document. However, based on the conclusions of the oxygen gettering analysis (HNF-SD-TI-040), it should be possible to document equivalency by demonstrating that the vast majority of MCOs will not contain oxygen at concentrations that even approach the 1.6 vol% normal operating limit, and that the 4 vol% LOC would only be approached by a bounding case MCO. Failing that, it may be possible to demonstrate that an MCO can safely contain a deflagration (as opposed to a detonation) for a worst case set of conditions in accordance with Chapter 5 of NFPA 69. Because, Paragraph 1-1.2 of NFPA 69 excludes detonations from its scope, evaluation of the corresponding detonation would then be performed to DOE and NRC requirements.

5.2 FUNCTION: PRECLUDE COMBUSTIBLE MIXTURES OUTSIDE MCOs

In order to permit MCOs to be handled and stored within air filled shipping casks and storage tubes, it will be necessary to provide this function by limiting the concentration of hydrogen within the casks and tubes.

5.2.1 Functional Requirement: Limit H₂ Release From MCOs

In order to limit the concentration of hydrogen within the air filled casks and tubes that handle and store MCOs, it will either be necessary to continuously or periodically exchange the cask or tube air, or it will be necessary to limit the release of hydrogen from MCOs. Because it would be very difficult to ensure absolutely reliable active (e.g., exhaust fans, etc.) air exchange through the casks and CSB tubes, the project will provide that function by limiting the release of hydrogen from MCOs.

5.2.1.1 Implementation Criteria.

5.2.1.1.1 Acceptable H₂ Concentration. ≤ 1.0 vol% H₂

5.2.1.1.2 Minimum Time To Maintain Acceptable H₂ Concentration.

Case 1 -- Mechanically Sealed MCOs (Singly Occupied CSB Tube): 1 year

This would require that a given tube containing a mechanically sealed MCO be sampled and ventilated every 8 months or so. Note that, while one year is the minimum criterion for a singly occupied tube containing a mechanically sealed MCO, it is recognized that maximum operating flexibility and minimum cost would be realized if the mechanical seals (in conjunction with dilution via the storage tube vent ports) can be shown to limit steady state hydrogen concentrations to 1 vol% or less within un-sealed tubes containing two mechanically sealed MCOs.

Case 2 -- Welded MCOs (Doubly Occupied CSB Tube): 40 years

5.2.2 NFPA 69 Chapter 3 Compliance Status

Chapter 3 of NFPA 69 covers application of the combustible reduction technique. Paragraph 3-3 provides design and operating requirements for systems that will be operated below the Lower Flammable Limit (LFL). Paragraph 3-4 provides instrumentation requirements. See Appendix B of this document for an overall summary description of NFPA 69.

Paragraph 3-3.1 of NFPA 69 requires that the combustible concentration be maintained at or below 25% of the LFL (i.e., 25% of 4 vol% for hydrogen in air is 1 vol%). An exception is provided to allow combustible concentrations up to 60% of the LFL for systems that have the capability to automatically shut off the source of combustible material or otherwise prevent a combustion event (automatic activation of quenching systems, etc.) by means of instrumentation with safety interlocks.

In view of the current hydrogen management goal to maintain the hydrogen concentration within any CSB storage tube (including those that contain safety basis pressure MCOs) at or below 25% of the LFL (i.e., at or below 1 vol%), and in view of the results in this document, which confirm the ability of MCO seals to meet the 1 vol% maximum concentration goal, it should be possible to demonstrate that the SNF Project provides an equivalent level of protection, provided that all the necessary documents are in place (e.g., gas inventory calculations, hydrogen leak rate and build-in calculations [provided by this document], leak test reports, etc.), and provided that the hydrogen leakage and build-in calculations are considered an acceptable replacement for the instrumentation requirements.

6.0 PREDICTION OF OPERATIONAL LEAKAGE FROM LEAK TEST RESULTS

The current *Performance Specification for the Spent Nuclear Fuel Multi-Canister Overpack* (HNF-S-0426) specifies the following leak test acceptance criteria for the MCO:

- 1×10^{-5} scc/sec maximum integrated leak rate prior to installation of final closure weld.
- 1×10^{-7} scc/sec maximum integrated leak rate following installation of final closure weld.

In order to either confirm that the above leak test acceptance criteria are adequate or establish revised criteria, the calculations must: 1) assume that some of the MCOs will include leak paths that would produce testing results corresponding to those criteria (i.e., that some MCOs almost fail the leak test -- considered unlikely); 2) predict leakage rates that would result from those leak paths under the actual operating conditions, e.g., gas composition, pressure, temperature, etc.; and 3) evaluate the predicted leakage rates against the MCO's gas management functions and requirements.

6.1 LEAKAGE CORRELATION DEFINITIONS AND METHODOLOGY

Section 3 (*Definitions*) of the *American National Standard For Radioactive Materials -- leakage tests on packages for shipment* (ANSI N14.5-1987) defines the term "std cm³/s" as a leakage rate "referring to the standard conditions for dry air at 1 atmosphere (atm) absolute pressure (101 kPa) and 298 K (25°C)." That section also defines "leaktight" as "a leakage rate less than or equal to 1×10^{-7} std cm³/s, at an upstream pressure of 1 atm abs and a downstream pressure of 0.01 atm abs or less, irrespective of the radioactive contents."

Section 4.13 of the current MCO performance specification (HNF-S-0426) requires all MCO seals to be "...leakage rate testable in accordance with ANSI N14.5." Therefore it follows from the above definitions that the MCO's specified 1×10^{-5} scc/sec and 1×10^{-7} scc/sec leakage acceptance criteria refer to the volume of dry air (as opposed to helium or hydrogen), corrected to an absolute pressure of one atmosphere and 25°C, that will flow through a leak path from an upstream cavity with an absolute pressure of one atmosphere into a downstream cavity that has been evacuated to 0.01 atm abs, or less.

While the ANSI standard provides a wide range of options with respect to basic testing methods (pressure decay, gas detection, etc.), physical testing arrangements (inward flow, outward flow, etc.), and test conditions (test

medium, temperature, pressure, etc.), the test results are always reported as an air leakage rate that would have occurred at the exact combination of upstream pressure, downstream pressure, and temperature that is spelled out in the above paragraph.

6.1.1 Shortcomings Of The ANSI N14.5-1987 Approach

All of the calculations in this document that predict operational leakage (i.e., leakage "at pressure") from standard leak test acceptance criteria are based on the flow correlation equations that are provided by Appendix B of ANSI N14.5-1997, Draft J, as opposed to the equations and guidance provided by the released version (ANSI N14.5-1987). Justification for using the current draft version instead of the 1987 version is provided below (also see section 6.1.2.1 for a comparison of the Draft J to the released 1997 version). ANSI N14.5 provides guidance for correlation of leakage under test conditions to leakage under actual operating conditions. To accomplish this, it provides a set of equations to establish the diameter of a fictitious single "hole" that would result in the observed test flow rate. The fictitious hole is assigned an arbitrary length, typically 1 cm (preliminary calculations for this document used values from 1 cm down to 0.025 cm). The standard then predicts the flow rate at the operating conditions by applying the calculated hole diameter and assumed length to the same equations (or others, depending on the flow regime) after adjusting various parameters (temperature, pressure, gas composition, etc.) to represent the actual operating conditions.

Specifically, Appendix B of the 1987 release provides *Eq B2*, total flow; *Eq B3*, continuum flow, and *Eq B4*, molecular flow, all of which are limited to calculation of unchoked flow. It provides *Eq B7* for choked flow. Finally, it provides *Eq B5* to determine whether or not choked flow is possible, based on the ratio of continuum flow to molecular flow (the critical pressure ratio must also be satisfied). Because most leak testing is performed under conditions that favor molecular flow, the apparent hole diameter is typically calculated via *Eqs B2* through *B3*. The 1987 version of the standard then uses an orifice type equation (*Eq B7*) to predict the flow rate under high pressure plant conditions at which the flow is mostly continuum and therefore choked (per *Eq B5* -- the critical pressure ratio is satisfied in both cases).

The shortcomings of the above approach are inherent (although not immediately apparent) in *Table B2 (Air Leakage for Various Hole Diameters)* of the 1987 release, which provides calculated flow rates based on the equations and guidelines provided by the standard. The calculated values in the first column of the table indicate a discontinuity in the flow region between 10^{-3} std cc/sec and 10^{-6} std cc/sec. This would imply a "transitional" flow regime spanning many decades. That table has been completely revised in the 1997 draft of the standard.

Problems were first encountered during the initial attempt to determine whether the standard leak conditions would result in choked flow or unchoked flow at the mechanical seal's [then] specified 1×10^{-4} scc/s leak rate. When the equations for unchoked flow were used, Eq B5 determined that the flow was choked, whereas that same equation determined the flow to be unchoked when applied to results from the choked flow equation. This condition is typically referred to as "transitional flow," although in many cases it is really an artifact of the predictive methodology and has nothing to do with actual flow.

While the above "transitional flow" problems were not encountered with initial calculations for the 1×10^{-7} scc/sec leak test acceptance criterion, the underlying problems in the overall approach eventually became apparent. The flow regime was plainly unchoked at the test conditions and plainly choked at the operating conditions, which was encouraging. However, the subsequent calculation predicted that a pipe weld would exhibit gross leakage at the operating conditions, despite the fact that the weld had satisfied a 1×10^{-7} scc/sec leak test acceptance criterion, which is defined as "leak tight" by the ANSI standard (see section 6.1 above). The reason for this situation is that the choked flow equation (Eq B7) does not consider the hole's length at all, whereas the hole's diameter was obtained using equations (Eq B2, et. al.) wherein the calculated flow rate for a given hole diameter is an inverse linear function of the hole's length.

6.1.2 The Revised Approach In ANSI N14.5-1997 Draft J

In order to eliminate the problems inherent in the 1987 release, Section B4 (*Correlation Between Gas Leakage Rates at Different Conditions*) of ANSI N14.5-1997 J eliminates all guidance for correlation of molecular flow conditions to choked flow conditions and eliminates the choked flow equation (Eq B7). Section B3 (*Gas Leakage*) provides a new flow equation (B-5), however this equation is not a replacement for Eq B7 and has nothing to do with choked flow, nor with the original Eq B5 (see section 6.1.1 above), which has also been eliminated. The new equation B-5 is just an extension of the original Eq B2, which (now labeled B-2) remains the basic flow equation. Equation B-5 was introduced in order to formalize the pressure basis relationships among the various volumetric flow rates that can be calculated for the same molar flow rate, depending on whether the flow rate is calculated at the upstream pressure, the downstream pressure, or the average pressure.

The net result of these changes is that the first column of the revised Table B2 (now labeled Table B.2) provides five different calculated leakage rates between 1.2×10^{-3} scc/sec and 2×10^{-8} scc/sec whereas the old (released) version provided none in that range. And, whereas the old version listed a calculated leakage rate of 1.4×10^{-3} scc/sec for a 3×10^{-4} cm hole diameter, the

new version lists a calculated leakage rate below 10^{-6} scc/sec for the same hole (note that the hole's length is listed as 1 cm in both cases). Again, the reason for the gross discrepancy (over three orders of magnitude) between the released version of the table and the new draft version is that the released version calculated these leakage rates (i.e., those listed in the first column) by using *Eq B2* for some holes, and *Eq B7* (which disregards the hole's length) for others, whereas the draft revision calculates all leakage rates using equation *B-5* (equivalent to *Eq B2*).

6.1.2.1 Comparison of Draft J to Released 1997 Version. The draft version of ANSI N-14.5 1997 (*American National Standard For Radioactive Materials -- Leakage tests on packages for shipment*) was approved at about the same time this leak test acceptance criteria document (HNF-2155) was released, however there is no intention to revise or eliminate the above discussions regarding the problems that were inherent in the previous (1987) release of the ANSI standard because those discussions provide useful insights into the problems associated with prediction of operational leakage rates based on leak test results. None the less, it is necessary to compare draft revision 1997 J to the released version of ANSI N-14.5 1997 in order to ensure that all of the equations taken from draft revision 1997 J remain valid. Based on this comparison it is concluded that there were no changes between Draft J and the released version that would have any impacts on the calculations/results of this document (HNF-2155). As a case in point, the symbol L_R is defined as

L_R = reference air leakage rate at *standard* conditions of 25°C and 1 atm
abs, *std.cm³/s*

in section **B2.** of the draft version, whereas it is defined as

L_R = reference air leakage rate at *reference* conditions of 25°C and 1 atm
abs, *ref.cm³/s*

in section **B.2** of the released version (**bold type** highlights differences).

It can be seen from this example that the only differences involve: 1) the heading format, i.e., "B2." versus "B.2"; and 2) the use of the word "reference" instead of "standard" to describe the same set of conditions, probably to avoid conflict with the more common definition of standard conditions as 0°C and 1 atm. With respect to the equations used in this document, the difference is limited to the heading format.

7.0 CALCULATIONS

7.1 MCO OPERATING CONDITIONS

7.1.1 MCO Gas Temperatures

The maximum and minimum operating MCO gas temperatures to be used for calculation of MCO gas pressures or gas leakage rates within the CSB have been established as 64°C and -31°C respectively. See section 4.4.

7.1.2 MCO Gas Inventories

See section 4.3 for references and additional discussions that justify use of the following gas inventories for MCO leakage calculations.

7.1.2.1 Worst Case Gas Inventory For Calculating Maximum Helium Loss. The following gas inventory assignments are appropriate for evaluation of the MCO's leak test acceptance criteria against its backfill gas (He) retention requirements (see section 7.1.2.1.1, below, for the calculation that develops the minimum initial helium backfill inventory).

• Hydrogen (safety basis inventory + 0.2 mol)	----- 65.7 mol
• Helium (minimum fill quantity)	----- 31.0 mol
• Backfill Gas Impurities (0.2 mol taken as H ₂)	----- 0 mol
• Alpha decay helium (taken as hydrogen)	----- 0 mol
• Noble gasses (Kr, Xe -- taken as hydrogen)	----- 0 mol
• Oxygen (taken as hydrogen)	----- 0 mol
• TOTAL	----- 96.7 mol

7.1.2.1.1 Minimum Initial Backfill Gas Quantity. The minimum initial backfill quantity is calculated below. This minimum quantity is based on a minimum backfill pressure at a maximum (worst case) calculated gas temperature within the MCO. Although the calculated minimum molar quantity [for a 500 L minimum void space MCO] will not appear as an operations requirement, it will probably have the same administrative force because the minimum fill pressure and prerequisite cooldown operation are expected to become operations requirements. See sections 5.1.1.1.3 and 5.1.1.1.4 for the minimum pressure and maximum temperature bases. Note that there is no need to impose a process hold to allow time for freshly introduced backfill gas to reach MCO

| temperatures prior to taking the final backfill pressure measurement. This
 | conclusion is based on backfill gas temperature equilibration criteria,
 | calculations, and results provided in Appendix G.

| Maximum MCO gas temperature during backfill -- $T = 323 \text{ K (50}^\circ\text{C)}$

Minimum MCO void volume -- $V = 500 \text{ L}$

Minimum backfill pressure -- $P = (24.2 \text{ psia}) / (14.7 \text{ psia/atm}) = 1.65 \text{ atm}$

| $R = 0.08206 \text{ L atm/mol K}$

$PV = nRT$; $n_{\text{initial}} = PV/RT = \text{minimum initial backfill gas inventory, mol}$;

| $n_{\text{initial}} = (1.65 \text{ atm})(500 \text{ L}) / [(0.08206 \text{ L atm/mol K})(323 \text{ K})] = 31.13 \text{ mol}$

| Correction for Helium Impurities

| The *Cold Vacuum Drying Facility Design Requirements* document (HNF-SD-SNF-DRD-
 | 002) allows up to 0.5 vol% total impurities within the helium that is used to
 | backfill MCOs. Therefore a 0.995 correction factor must be applied to the
 | initial backfill gas inventory (n_{initial}) to obtain the worst case (low) initial
 | helium backfill inventory ($n_{\text{He_initial}}$):

| $n_{\text{He_initial}} = 0.995 \times n_{\text{initial}} = 0.995 \times 31.13 \text{ mol} = 31.0 \text{ mol}$

| Initial Helium Inventory Within Cover Cap Void Space

| In order to prevent excessive conservatism in the calculation that determines
 | the maximum acceptable helium loss from an MCO following installation of its
 | welded cover cap (see section 7.1.2.1.3), it is desirable to add the helium
 | inventory that is initially within the void space to that which remains within
 | the MCO proper when it is welded.

| Section 7.1.2.1.2 includes a calculation that establishes the cover cap void
 | volume as 28.4 L. Following completion of the welding and helium leak testing
 | operations on the main circumferential weld, a mechanically sealed plug will be
 | installed into the weld cap's threaded purge gas/inspection port, after which
 | a small plate will be seal welded into place above the purge/inspection port
 | plug. Upon installation of the port plug, the cover cap void space will
 | contain essentially pure helium at one atmosphere and 51°C (see section 4.4
 | for basis):

Cover cap void space gas temperature when sealed -- $T = 324 \text{ K } (51^{\circ}\text{C})$

Cover cap void space volume -- $V = 28.4 \text{ L}$

Cover cap void space pressure -- $P = 1.0 \text{ atm absolute}$

$R = 0.8206 \text{ L atm/mol K}$

Helium Purity Correction Factor = 0.995 (from above)

$PV = nRT$; $n_{\text{initial}} = PV/RT = \text{initial cover cap gas inventory, mol};$

$n_{\text{initial}} = (1.0 \text{ atm})(28.4 \text{ L})(0.995) / [(0.8206 \text{ L atm/mol K})(324 \text{ K})] = \underline{1.06 \text{ mol}}$

USE -- 1.0 mol -- This provides a 6% allowance for barometric pressure variations, etc.

7.1.2.1.2 Minimum Required MCO Helium Inventory. Section 5.1.1.1 requires that the MCO be maintained at a positive gage pressure at all times, and section 5.1.1.1.2 stipulates that the positive gage pressure be based solely on an inert backfill gas because the hydrogen could be gettered by uranium metal. Therefore, the leak test acceptance criteria must be evaluated to ensure that the minimum backfill case MCO (31.0 mol of He) will still retain a sufficient amount of helium to maintain a positive gage pressure at the worst case minimum operating temperature after the specified storage time(s) at the highest anticipated pressure(s).

Minimum Helium Inventory Required for a Mechanically Sealed MCO

The minimum inventory required for a mechanically sealed MCO (i.e., the minimum inventory that must be retained in order to ensure that the MCO will always be at a positive gage pressure) can be calculated directly from the worst case minimum MCO operating temperature and the mechanically sealed MCO's minimum void volume. Note that the minimum void volume can be used here (despite the fact that the maximum void volume would normally control) because the minimum initial backfill quantity is itself based on a minimum fill pressure within a minimum void volume MCO. Where the actual void volume exceeds the 500 L minimum void volume (which will almost always be the case), the initial backfill quantity will also exceed the minimum initial backfill quantity by a proportional amount. Of course, the minimum required helium inventory will also be higher for that MCO, but so will the amount of expendable helium. The minimum required helium inventory for a mechanically sealed MCO is based on the following (See section 4.0 for bases):

Minimum MCO temperature during CSB storage -- $T = 242 \text{ K}$ (-31°C)

MCO void volume (see above discussion) -- $V = 500 \text{ L}$

Minimum Acceptable Helium Pressure -- $P = 1.0 \text{ atm}$

| $R = 0.08206 \text{ L atm/mol K}$

| $PV = nRT$; $n_{\text{He}_{\text{final}}} = PV/RT = \text{minimum required helium inventory, mol};$

| $n_{\text{He}_{\text{final}}} = (1.0 \text{ atm})(500 \text{ L})/[(0.08206 \text{ L atm/mol K})(242 \text{ K})] = 25.2 \text{ mol}.$

| Minimum Helium Inventory Required for an MCO with Welded Cover Cap

| The minimum helium inventory required for an MCO after installation of its
 | welded cover cap is slightly larger than that required for a mechanically
 | sealed MCO because of the additional void space under the weld cap. Where-as
 | any additional void space within the mechanically sealed portion of an MCO
 | automatically results in a proportionate increase in the initial helium
 | inventory, the additional void space gained by installation of the weld cap
 | will not provide a proportionate increase because that space will not be
 | pressurized above one atmosphere. To address this issue, the following:
 | 1) calculates the cover cap void space; 2) adds the cover cap void space to
 | the mechanically sealed MCO's 500 L minimum; and 3) calculates the minimum
 | helium inventory requirement for the welded configuration using the same
 | equations that are used for the mechanically sealed configuration. Note that
 | subsequent calculations (in section 7.1.2.1.3) to determine the maximum
 | acceptable helium loss include an estimate of the cover cap's initial helium
 | inventory at one atmosphere.

Figure 7-1: Sectional View of Weld Cap Void Space

Figure 7-1 provides a section view of the shield plug and weld cap, with dimensions that are either taken directly from sheets 1 & 3 of H-2-828042 ("MCO Mechanical Closure") and sheet 1 of H-2-828045 ("MCO Mechanical Closure Shield Plug") or obtained by difference, as shown below.

The clear height above the top surface (2.875") is obtained by subtracting the distance (2.455") that the shield plug extends above the weld seam from the inside height (5.330") of the weld cap. The inside height of the weld cap is shown on sheet 3 of H-2-828042, along with its 24.25" I.D., whereas the 2.455" value must, itself, be obtained by difference. To obtain the 2.455" plug extension distance, the depth (6.105") of the MCO's mechanical seal interface land (i.e., the shield plug stop) must be subtracted from the length (8.56") of the shield plug. The length of the shield plug is shown on sheet 1 of H-2-828045, while the 6.105" depth is shown on sheet 1 of H-2-828042. The void space above the top surface of the shield plug is then:

$$2.875 \times (24.25/2)^2 \times 3.142 = 1328 \text{ in}^3 = 21.8 \text{ L}$$

Sheet 2 of H-2-828042 provides the height of the annular space (2.46"), along with the major (20.38") and minor (18.75") outside diameters of the grapple interface feature of the locking & lifting ring. The annular void space between the average O.D. of the ring and I.D. of the weld cap is then:

$$3.142 \times 2.46 \times [(24.25/2)^2 - [(18.75 + 20.38)/2]^2] = 396.7 \text{ in}^3 = 6.5 \text{ L}$$

The total void space under the weld cap is then $21.8 \text{ L} + 6.5 \text{ L} = 28.3 \text{ L}$.

The 28.3 L estimate is considered reasonable, even though it doesn't address a number of small "nooks and crannies," because it also ignores the sweep radius on the underside of the weld cap.

The minimum total void space of an MCO after the welded end closure has been installed is then: $500 \text{ L} + 28.3 \text{ L} = 528.3 \text{ L}$.

The minimum acceptable helium inventory after welding can then be calculated as follows:

Minimum MCO temperature during CSB storage -- $T = 242 \text{ K} \text{ } (-31^\circ\text{C})$

Minimum void volume of MCO (w weld cap) -- $V = 528.3 \text{ L}$

Minimum Acceptable Helium Pressure -- $P = 1.0 \text{ atm}$

$R = 0.08206 \text{ L atm/mol K}$

$PV = nRT$; $n_{\text{He}_{\text{final}}} = PV/RT = \text{minimum required helium inventory, mol}$;

$n_{\text{He}_{\text{final}}} = (1.0 \text{ atm})(528.3 \text{ L}) / [(0.08206 \text{ L atm/mol K})(242 \text{ K})] = 26.6 \text{ mol}$.

7.1.2.1.3 Maximum Acceptable Helium Loss. Either of the two following calculations for maximum acceptable helium loss may apply to a given MCO, depending on whether or not it's welded cover cap has been installed.

Maximum Acceptable Helium Loss for Mechanically Sealed MCO

Given an MCO with a 500 L minimum void volume (see section 4.3), and given the minimum initial helium backfill inventory and minimum required helium inventory developed in sections 7.1.2.1.1 and 7.1.2.1.2, the maximum acceptable helium loss (to meet this functional requirement) is:

$$n_{\text{loss}} = n_{\text{initial}} - n_{\text{final}} = 31.0 \text{ mol} - 25.2 \text{ gmol} = 5.8 \text{ mol}, \text{ where:}$$

n_{loss} = maximum acceptable total helium leakage over time;

n_{initial} = minimum initial helium quantity (per sec 7.1.2.1.1); and

n_{final} = minimum required helium inventory (per sec 7.1.2.1.2).

Maximum Acceptable Helium Loss for MCO with Welded Cover Cap

Per the second calculation in section 7.1.2.1.2, installation of the welded cover cap will increase the minimum effective void volume of the MCO from 500 L to 528.4 L, requiring that the MCO retain at least 26.6 moles of helium (including the helium inventory of the cover cap void) in order to maintain a positive pressure at worst case (i.e., cold) storage conditions. And, per the last calculation in section 7.1.2.1.1, the cover cap void will contain at least 1.0 moles of helium after installation. For a worst case low initial helium inventory after welding, installation of the cover cap may be assumed to occur at any time during the 40 year interim storage period (i.e., after up to 40 years of mechanically sealed storage). Therefore the maximum initial helium inventory applicable to helium loss calculations for welded MCOs will be 1.0 mole plus the worst case minimum calculated for a mechanically sealed MCO after 40 years of storage. The second spread sheet listing in Appendix A predicts a 26.1 mole minimum helium inventory for a maximum hydrogen inventory MCO after 40 years of mechanically sealed storage. The worst case low initial helium inventory of a welded MCO then becomes 1.0 mol + 26.1 mol = 27.1 mol. Note that this minimum inventory does not apply to a worst oxygen case MCO because that is not a maximum hydrogen inventory MCO.

$$n_{\text{loss}} = n_{\text{initial}} - n_{\text{final}} = 27.1 \text{ mol} - 26.6 \text{ gmol} = 0.5 \text{ mol}, \text{ where:}$$

n_{loss} = maximum acceptable total helium leakage over time;

n_{initial} = minimum initial helium quantity; and

n_{final} = minimum required helium inventory (per sec 7.1.2.1.2).

7.1.2.2 Gas Inventory For Calculating Helium Loss From Worst O₂ Case MCOs.

The following gas inventory assignments are appropriate for evaluation of the MCO's leak test acceptance criteria against its helium retention goal for worst oxygen case MCOs.

- Hydrogen (see last paragraph of section 4.3) ----- 10.1 mol
- Helium (minimum fill quantity) ----- 31.0 mol
- Backfill Gas Impurities (0.2 mol taken as H₂) ----- 0 mol
- Alpha decay helium (taken as hydrogen) ----- 0 mol
- Noble gasses (Kr, Xe -- taken as hydrogen) ----- 0 mol
- Oxygen (taken as hydrogen) ----- 0 mol
- TOTAL ----- 41.1 mol

7.1.2.2.1 Design Goal for Maximum Helium Loss from Worst O₂ Case MCO. The MCO's seals will also be evaluated against the helium retention design goal discussed in the last paragraph of section 5.1.1.1.1. That goal is to ensure that the main void space (i.e., that under the shield plug) of a worst oxygen case MCO will never contain less than 95% of the 30.3 mol nominal helium inventory that was assumed by HNF-SD-TI-040 for calculation of oxygen concentrations within MCOs. The 95% criterion limits the impact on the maximum oxygen concentration calculated for a "...zero scrap, bounding water, low area, worst power..." MCO to 0.1 vol% (i.e., it would increase from 1.8 vol% to 1.9 vol%). See pages I-12 and I-13 of HNF-SD-SNF-TI-040, Rev 3.

Per the same approach used in section 7.1.2.1.3, above, the maximum helium loss goal is:

$$n_{\text{loss}} = n_{\text{initial}} - n_{\text{final}} = 31.0 \text{ mol} - 28.8 \text{ mol} = 2.2 \text{ mol}, \text{ where:}$$

n_{loss} = design goal for maximum total helium leakage over time;

n_{initial} = minimum initial backfill quantity (per sec 7.1.2.1.1); and

n_{final} = minimum helium inventory goal (0.95 X 30.3 = 28.8 mol).

7.1.2.3 Worst Case Gas Inventory For Calculating Hydrogen Release. The following gas inventory assignments represent a worst case condition for evaluation of the MCO's leak test acceptance criteria against the project's functional requirements to limit the hydrogen concentration to 1 vol% within

the space that surrounds a bounding pressure case MCO. Application of this inventory to mechanically sealed MCOs during the first two or three years of their operation is very conservative because the inventory represents all of the hydrogen that could possibly be generated within the MCO during 40 years, whereas only about one tenth of that inventory is expected to be generated during the first several years of service.

- Hydrogen ----- 65.7 mol
- Helium (maximum fill quantity) ----- 41.1 mol
- Backfill gas impurities (0.2 mol taken as H₂) ----- 0 mol
- Alpha decay helium -- (taken as hydrogen) ----- 0 mol
- Noble gasses (Kr, Xe) -- (taken as hydrogen)----- 0 mol
- Oxygen -- (taken as hydrogen) ----- 0 mol
- TOTAL ----- 106.8 mol

7.1.2.3.1 Maximum Initial Backfill Gas Quantity. The maximum initial backfill quantity is calculated below. This maximum quantity is based on a maximum specified backfill pressure (see section 5.1.1.1.3) at a minimum (worst case) gas temperature (see section 5.1.1.1.4) within the MCO. Although the calculated maximum molar quantity [for a 500 L minimum void space MCO] will not appear as an operations requirement, it will probably have the same administrative force because the maximum fill pressure is expected to become an operations requirement. Note that there is no need to impose a process hold to allow time for freshly introduced backfill gas to reach MCO temperatures prior to taking the final backfill pressure measurement (see Appendix G).

Minimum MCO gas temperature during backfill -- $T = 273 \text{ K } (0^{\circ}\text{C})$

MCO void volume -- $V = 500 \text{ L}$

Maximum backfill pressure -- $P = (27.2 \text{ psia}) / (14.7 \text{ psia/atm}) = 1.85 \text{ atm}$

$R = 0.08206 \text{ L atm/mol K}$

$PV = nRT$; $n_{\text{initial}} = PV/RT = \text{maximum backfill gas inventory, mol [per 500 L]}$;

$n_{\text{initial}} = (1.85 \text{ atm})(500 \text{ L}) / [(0.08206 \text{ L atm/mol K})(273 \text{ K})] = 41.3 \text{ mol}$

Correction for Helium Impurities

The *Cold Vacuum Drying Facility Design Requirements* document (HNF-SD-SNF-DRD-002) allows up to 0.5 vol% total impurities within the helium that is used to backfill MCOs. Therefore 99.5% of the backfill gas is taken as helium and the potential impurities (i.e., 0.5% of the gas) are all taken as hydrogen, which is worst case for these leakage calculations:

$$n_{\text{He_initial}} = 0.995 \times n_{\text{initial}} = 0.995 \times 41.3 \text{ mol} = 41.1 \text{ mol}$$

$$n_{\text{H}_2\text{_initial}} = 0.005 \times n_{\text{initial}} = 0.005 \times 41.3 \text{ mol} = 0.2 \text{ mol}$$

7.1.3 MCO Operating Pressures

7.1.3.1 Maximum Pressure For Helium Loss Calculations. Based on a 96.7 mol total gas inventory (see section 7.1.2.1), on a 64°C (337 K) operating temperature (see section 4.4), and on a 500 L internal void volume (see section 4.3), the maximum operating pressure (P_{upstream}) required for helium loss calculations is:

$$P_{\text{upstream}} = nRT/V = (96.7 \text{ mol})(0.08206 \text{ L atm/mol.K})(337 \text{ K})/500 \text{ L} = 5.35 \text{ atm}$$

7.1.3.2 Maximum Pressure For Worst O₂ Case Helium Loss Calculations. Based on a 41.1 mol total gas inventory (see section 7.1.2.2), on a 31°C (304 K) operating temperature (see section 4.4), and on a 500 L internal void volume (see section 4.3), the maximum operating pressure (P_{upstream}) required for helium loss calculations is:

$$P_{\text{upstream}} = nRT/V = (41.1 \text{ mol})(0.08206 \text{ L atm/mol.K})(304 \text{ K})/500 \text{ L} = 2.05 \text{ atm}$$

7.1.3.3 Maximum Pressure For Hydrogen Release Calculations. Based on a 106.8 mol total gas inventory (see section 7.1.2.3), on a 64°C (337 K) maximum MCO temperature, and on a 500 L minimum MCO void volume, the worst case operating pressure (P_{upstream}) required for hydrogen release calculations is:

$$P_{\text{upstream}} = nRT/V = (106.8 \text{ mol})(0.08206 \text{ L atm/mol.K})(337 \text{ K})/500 \text{ L} = 5.91 \text{ atm}$$

7.2 DOCUMENTATION AND VALIDATION OF FLOW CORRELATION CALCULATIONS

Appendix A provides spread sheet listings of the calculations that were performed to predict actual in-service leak rates from leak rate acceptance criteria. The symbol definitions, equations, and hand calculations provided in the following sections demonstrate, document, and validate the equations that were input to the Excel® program to produce the spread sheet listings.

7.2.1 ANSI N-14.5 Draft 1997 J Equations and Guidelines

The equations recommended by Appendix B of ANSI N-14.5 Draft 1997 J are listed in section 7.2.1.1 below, along with definitions for their parameters and references to the particular sections of ANSI N-14.5 Appendix B that govern their application.

7.2.1.1 Definition Of Symbols. The following symbols and their definitions are taken from section B2 of ANSI N-14.5 Draft 1997 J:

a = leakage hole length, cm

D = leakage hole diameter, cm

F_c = coefficient of continuum flow conductance per unit pressure, $\text{cm}^3/\text{atm}\cdot\text{s}$

F_m = coefficient of free molecular flow conductance per unit pressure, $\text{cm}^3/\text{atm}\cdot\text{s}$

k = ratio of specific heat at constant pressure to specific heat at constant volume

L = volumetric leakage rate, cm^3/s

L_d = downstream volumetric leakage rate, cm^3/s

L_m = measured leakage rate, cm^3/s

L_R = reference air leakage rate at standard conditions of 25°C and 1 atm abs, std cm^3/s

L_u = upstream volumetric leakage rate, cm^3/s

M = molecular weight, g/mol

P = fluid pressure, atm abs

P_a = average stream pressure = $1/2(P_u + P_d)$, atm abs

P_d = fluid downstream pressure, atm abs

P_i = partial pressure of one component of a gas mixture, atm abs

P_m = total pressure of a gas mixture, atm abs

P_u = fluid upstream pressure, atm abs

Q = mass-like leakage rate, $\text{atm}\cdot\text{cm}^3/\text{sec}$

R_0 = universal gas constant, $8.31 \times 10^7 \text{ erg/mol}\cdot\text{K}$

T = fluid absolute temperature, K

T_s = standard temperature, 298 K

μ = fluid viscosity, cP (centipoise)

r_f = ratio of F_c to F_m , dimensionless (no longer used in the 1997 standard)

ρ_g = gas density, g/cm^3

7.2.1.2 Basic Flow Equations. Section B3 (*Gas Leakage*) of ANSI N-14.5 1997-J, Appendix B, lists the following equations and describes their application.

(B-1) $Q = L \cdot P \text{ atm.cm}^3/\text{s}$ -- A mass-like flow rate.

(B-2) $L_a = (F_c + F_m)(P_u - P_d) \text{ cm}^3/\text{s}$ -- Used to estimate volume leakage rate at the average pressure.

where (B-3) $F_c = [2.49 \times 10^6 \cdot D^4] / (a\mu) \text{ cm}^3/\text{atm.s}$

and where (B-4) $F_m = [3.81 \times 10^3 \cdot D^3 \cdot (T/M)^{0.5}] / (aP_a) \text{ cm}^3/\text{atm.sec}$.

(B-5) $L_u = (F_c + F_m)(P_u - P_d)(P_a/P_u) \text{ cm}^3/\text{s}$ OR $L_d = (F_c + F_m)(P_u - P_d)(P_a/P_d) \text{ cm}^3/\text{s}$

-- used to express leakage rates in terms of upstream or downstream pressure conditions, as opposed to the average stream pressure basis used by equation (B-2).

(B-6) $P_m = \sum_{i=1}^n P_i$; (B-7) $M_m = \sum_{i=1}^n P_i M_i / P_m$; and (B-8) $\mu_m = \sum_{i=1}^n P_i \mu_i / P_m$

-- used to calculate equivalent pressure, molecular weight, and viscosity for ideal gasses in terms of component properties of an n-component mixture weighted by the ratio of partial to total pressure.

7.2.1.3 Hand Calculation At Reference Conditions. The left hand column of Table B.2 (*Upstream Air Leakage for Various Hole Diameters*) of ANSI N-14.5 Draft 1997 J includes a calculated air leakage rate of $7.94 \times 10^{-5} \text{ std cm}^3/\text{s}$. The flow conditions and the leak reporting basis specified for the leak rates listed on the left side of the table were selected to match the standard's definition for the "reference air leakage rate" (L_r) that is the basis for all leak test acceptance criteria under ANSI N-14.5.

The following hand calculation is provided to demonstrate the basic flow equations used to obtain the $7.94 \times 10^{-5} \text{ std cm}^3/\text{s}$ flow rate and to validate their implementation in the spread sheet program. The spread sheet listing for this calculation is provided on the first sheet of Appendix A in this document. All of the following equation numbers, table numbers, etc., refer to Appendix B of ANSI B-14.5 Draft 1997 J, unless stated otherwise.

Equation B-3

$$F_c = [2.49 \times 10^6 \times D^4] / (a\mu) \text{ cm}^3/\text{atm.s} \quad \text{-- where:}$$

a = hole length = 1 cm (from Table B.2)
D = hole diameter = 1×10^{-3} cm (from Table B.2)
 μ = viscosity of air at 298 K (25°C) = 0.0185 cP (from Table B.1)

$$F_c = [2.49 \times 10^6 \times (1 \times 10^{-3} \text{ cm})^4] / (1 \text{ cm})(0.0185 \text{ cP}) = \underline{1.346 \times 10^{-4} \text{ cm}^3/\text{atm.s}}$$

Note that the 2.49×10^6 multiplier includes the conversion factor to get from centipoise (10^{-2} dyne.sec/cm²) to atm.sec. Other than to make that observation, this document will not break the conversion factor out of the overall multiplier, nor will it attempt to carry the units. This also applies to similar situations with other parameters that occur in subsequent equations. The justification for this approach is that the purpose of this section is to demonstrate that the spread sheet calculations correctly implement the ANSI standard's equations, as opposed to validating the equations themselves.

Equation B-4

$$F_m = [3.81 \times 10^3 \times D^3 (T/M)^{0.5}] / (aP_a) \text{ cm}^3/\text{atm.sec.} \quad \text{-- where:}$$

T = 298 K (from Table B.2)
M = 29.0 g/mol (From Table B.1)
 P_a = average stream pressure = $1/2(P_u + P_d)$ atm abs (from Section B2)
 P_u = upstream pressure = 1 atm abs (from Table B.2)
 P_d = downstream pressure = 0.01 atm abs (from Table B.2)

$$F_m = [3.81 \times 10^3 \times (1 \times 10^{-3} \text{ cm})^3 (298 \text{ K} / 29.0 \text{ g/mol})^{0.5}] / [(1 \text{ cm} \times 1/2(P_u + P_d))] =$$

$$[3.81 \times 10^{-6} \times (10.276)^{0.5}] / [1/2(0.01 + 1.00)] = [3.81 \times 10^{-6} \times 3.206] / [0.505] =$$

$$\underline{2.42 \times 10^{-5} \text{ cm}^3/\text{atm.sec}}$$

Equation B-5

$$L_u = (F_c + F_m)(P_u - P_d)(P_a/P_u) \text{ cm}^3/\text{s} \quad \text{-- all parameters are listed above.}$$

$$L_u = (1.346 \times 10^{-4} + 2.42 \times 10^{-5})(1.00 - 0.01)(0.505/1.00) = 7.94 \times 10^{-5} \text{ cm}^3/\text{s}$$

This result exactly matches the leak rate listed in Table B.2, as does the value for L_u in the left hand "Air - Std" column of the spread sheet listing on the first sheet of Appendix A (in this document). In order to verify correct implementation of equations B-3, B-4, and B-5 in the calculations for welded MCO's (on the right hand side of each spread sheet listing), a 2×10^{-4} cm hole diameter was input to the spread sheet program. Again, the resulting flow rate for upstream pressure conditions ($2.04 \times 10^{-7} \text{ cm}^3/\text{s}$) exactly matched that listed by Table B.2 for that hole diameter.

7.2.1.4 Hand Calculation At Test Conditions. This section provides a hand calculation to demonstrate the general approach used to correlate leakage rates between different conditions. The hole diameters that are used for the MCO leak calculations (5.81×10^{-4} and 1.63×10^{-4} cm, respectively) were obtained by iterating trial diameters until the values representing the leak test criteria (1×10^{-5} and 1×10^{-7} scc/s, respectively) appeared at the top of the "Air (Lr)" columns of the second spread sheet in Appendix A. Once those were obtained, the spread sheet calculation used these hole diameters to obtain the values at the top of the "He - Test" columns, which predict the helium leak rates that would be observed at the anticipated leak testing conditions that correspond to the reference criteria. In this case, the only difference in conditions is the use of helium instead of air.

Section B4 (*Correlation Between Gas Leakage Rates at Different Conditions*) of ANSI B-14.5 Draft 1997 J states (in sub-section B4.1): "Using Equation B-2 or Equation B-5, the leakage hole diameter is found for the known conditions. Leakage is found at other conditions using the calculated diameter, Equation B-2 or Equation B-5, and the specified conditions." Consequently, the correlation between the reference leak (L_R) and the measured helium leak test flow is performed by simply substituting helium parameters for those of air in the previous calculations (see section 7.2.1.3).

Equation B-3

$$F_c = [2.49 \times 10^6 \times D^4] / (a\mu) \text{ cm}^3/\text{atm.s} \quad \text{-- where:}$$

a = hole length = 1 cm (from Table B.2)
 D = hole diameter = 5.81×10^{-4} cm (see above)
 μ = viscosity of helium at 298 K (25°C) = 0.0198 cP (from Table B.1)

$$F_c = [2.49 \times 10^6 \times (5.81 \times 10^{-4} \text{ cm})^4] / (1 \text{ cm})(0.0198 \text{ cP}) = \underline{1.43 \times 10^{-5} \text{ cm}^3/\text{atm.s}}$$

Equation B-4

$$F_m = [3.81 \times 10^3 \times D^3 (T/M)^{0.5}] / (aP_a) \text{ cm}^3/\text{atm.sec.} \quad \text{-- where:}$$

T = 298 K (from Table B.2)
 M = 4.0 g/mol (From Table B.1)
 P_a = average stream pressure = $1/2(P_u + P_d)$ atm abs (from Section B2)
 P_u = upstream pressure = 1 atm abs (from Table B.2)
 P_d = downstream pressure = 0.01 atm abs (from Table B.2)

$$F_m = [3.81 \times 10^3 \times (5.81 \times 10^{-4} \text{ cm})^3 (298 \text{ K} / 4.0 \text{ g/mol})^{0.5}] / [(1 \text{ cm} \times 1/2(P_u + P_d))] =$$

$$[3.81 \times 10^3 \times 1.96 \times 10^{-10} \times (74.5)^{0.5}] / [1/2(0.01 + 1.00)] =$$

$$[7.5 \times 10^{-7} \times 8.63] / [0.505] = \underline{1.28 \times 10^{-5} \text{ cm}^3/\text{atm.sec}}$$

Equation B-5

$$L_u = (F_c + F_m)(P_u - P_d)(P_a/P_u) \text{ cm}^3/\text{s} \text{ -- all parameters are listed above.}$$

$$L_u = (1.43 \times 10^{-5} + 1.28 \times 10^{-5})(1.00 - 0.01)(0.505/1.00) = \underline{1.36 \times 10^{-5} \text{ cm}^3/\text{s}}$$

This result matches the value for L_u in the "He-Test" column on the left side of the second spread sheet in Appendix A of this document. The hand calculation for the helium rate at the maximum acceptance criterion for a welded seal (1×10^{-7} scc/s) would be identical, other than for the smaller hole size.

Notice that the increase in calculated flow rate upon substitution of helium for air is only about one third of the generally accepted rule of thumb, which holds that the helium flow rate will be about twice that of the air flow rate. That discrepancy does not, however, mean that the above calculations are in error. For conditions that lead to calculated air flows above 10^{-7} cm^3/s , the validity of the rule decreases as the air flow increases. Consequently, there is very little difference between the calculated flow rates for air and helium in the 10^{-5} std cm^3/s range. The reason for this is that continuum flow dominates in that region ($F_c/F_m = 3.2$ for air, and 1.1 for helium), whereas the rule of thumb applies to flow on the order of 10^{-7} cm^3/s or less, where free molecular flow begins to dominate. This trend is apparent on consideration of the flow rates calculated for air (1.0×10^{-7} cm^3/s) and helium (1.86×10^{-7} cm^3/s) that appear on the right side of the spread sheet listing, where the helium flow rate is about 1.9 times the air flow rate. At these conditions the helium flow is plainly in the free molecular regime ($F_c/F_m=0.32$) and air flow is split about evenly between them ($F_c/F_m= 0.91$).

7.2.1.5 Hand Calculation At Operating Conditions. The calculations required to predict leak rates for mixtures of gases at anticipated worst case operating conditions are more complex than those demonstrated in sections 7.2.1.3 and 7.2.1.4, which involved single component gases at essentially ambient conditions. None the less, the basic approach is unchanged from that outlined by section B4.1 of ANSI B-14.5 Draft 1997 J (see section 7.2.1.4). The primary difference is that it is necessary to calculate composite gas properties for the mixture using equation B-6. The second spread sheet in Appendix A of this document was used [by iterating hole diameters against resulting values for L_u] to establish the equivalent single-hole diameter (5.81×10^{-4} cm) that would result in the specified maximum standard leak test result (1×10^{-5} scc/s). The spread sheet listings then go on to duplicate and summarize the hand calculations of sections 7.2.1.5.1 and 7.2.1.5.2 below.

7.2.1.5.1 Helium Loss Calculations.

Helium Inventory From Section 7.1.2.1

- Hydrogen (safety basis inventory + 0.2 mol) ----- 65.7 mol
- Helium (minimum fill quantity) - ----- 31.0 mol
- Backfill Gas Impurities (0.2 gmol taken as H₂) ----- 0 mol
- Alpha decay helium (taken as hydrogen) ----- 0 mol
- Noble gasses (Kr, Xe -- taken as hydrogen) ----- 0 mol
- Oxygen (taken as hydrogen) ----- 0 mol
- TOTAL ----- 96.7 mol

Calculation of Effective Molecular Weight for Gas Mixture

$$(B-6) P_m = \sum_{i=1}^n P_i; \text{ but } (P_i/P_m) = (\text{mol component}_i / \text{mol mixture}_m) = \text{mol-fraction}_i$$

$$(B-7) M_m = \sum_{i=1}^n P_i M_i / P_m; \text{ from equation B-6, } M_m = \sum_{i=1}^n \text{mol-fraction}_i M_i$$

$$\text{Mol-fraction H}_2 = 65.7 \text{ mol} / 96.7 \text{ mol} = 0.6794; \text{ and } M_{\text{hydrogen}} = 2 \text{ g/mol}$$

$$\text{Mol-fraction H}_e = 31.0 \text{ mol} / 96.7 \text{ mol} = 0.3206; \text{ and } M_{\text{helium}} = 4 \text{ g/mol}$$

$$M_m = 0.6794 \times 2 \text{ g/mol} + 0.3206 \times 4 \text{ g/mol} = 1.359 \text{ g/mol} + 1.282 \text{ g/mol} \\ = \underline{2.64 \text{ g/mol}}$$

Calculation of Effective Viscosity for Gas Mixture

$$(B-8) \mu_m = \sum_{i=1}^n P_i \mu_i / P_m; \text{ from equation B-6, } \mu_m = \sum_{i=1}^n \text{mol-fraction}_i \mu_i$$

$$\text{Mol-fraction H}_2 = 0.6794; \text{ and } \mu_{\text{hydrogen}} @ 337 \text{ K} = 0.0096 \text{ cP}$$

$$\text{Mol-fraction H}_e = 0.3206; \text{ and } \mu_{\text{helium}} @ 337 \text{ K} = 0.0212 \text{ cP}$$

$$\mu_m = 0.6794 \times 0.0096 \text{ cP} + 0.3206 \times 0.0212 \text{ cP} = \\ 0.00652 + 0.00680 = \underline{0.01332 \text{ cP}}$$

Calculation of Leak Rate for Gas Mixture

$$(B-3) F_c = [2.49 \times 10^6 \times D^4] / (a\mu) \text{ cm}^3/\text{atm.s} \quad \text{-- where:}$$

$$a = \text{hole length} = 1 \text{ cm (from Table B.2)}$$

$$D = \text{hole diameter} = 5.81 \times 10^{-4} \text{ cm}$$

Note -- The hole diameter (D) is obtained by iterating the hole size against the upstream flow rate (L_u) in the first column of the second spread sheet in Appendix A of this document. The final value used for "D" corresponds to the diameter that results in the specified leak test criterion (1×10^{-5} scc/s in this case).

$$\mu_m = \text{viscosity of gas mixture at 337 K} = 0.01332 \text{ cP}$$

$$F_c = [2.49 \times 10^6 \times (5.81 \times 10^{-4} \text{ cm})^4] / (1 \text{ cm})(0.01332 \text{ cP}) = \\ [2.49 \times 10^6 \times (1.14 \times 10^{-13})] / 0.01332 = 2.837 \times 10^{-7} / 0.01332 = \\ \underline{2.130 \times 10^{-5} \text{ cm}^3/\text{atm.s}}$$

$$(B-4) F_m = [3.81 \times 10^3 \times D^3 (T/M)^{0.5}] / (a P_a) \text{ cm}^3/\text{atm.sec.} \text{ -- where:}$$

$$T = 337 \text{ K (from section 4.4)}$$

$$M_m = 2.64 \text{ g/mol}$$

$$P_u = 5.35 \text{ atm abs (from section 7.1.3.1)}$$

$$P_d = 1 \text{ atm abs (MCO leaks are to ambient or near-ambient pressure)}$$

$$P_a = 1/2(P_u + P_d) \text{ atm abs} = 1/2(5.35 + 1) \text{ atm abs} = 3.17 \text{ atm abs}$$

$$F_m = [3.81 \times 10^3 \times (5.81 \times 10^{-4} \text{ cm})^3 (337 \text{ K} / 2.64 \text{ g/mol})^{0.5}] / [(1 \text{ cm} \times 3.17 \text{ atm}) = \\ [(3.81 \times 10^3)(1.961 \times 10^{-10})(127.7)^{0.5}] / 3.17 = (7.47 \times 10^{-7})(11.30) / 3.17 \\ = \underline{2.66 \times 10^{-6} \text{ cm}^3/\text{atm.sec}}$$

$$(B-5) L_{u(\text{mix})} = (F_c + F_m)(P_u - P_d)(P_a / P_u) \text{ cm}^3/\text{s} \text{ -- all parameters are listed above.}$$

$$L_{u(\text{mix})} = (2.130 \times 10^{-5} + 2.64 \times 10^{-6})(5.35 - 1.0)(3.17 / 5.35) = \\ (2.39 \times 10^{-5} \text{ cm}^3/\text{atm.sec})(4.35)(0.593) = \underline{6.17 \times 10^{-5} \text{ cm}^3/\text{s}}$$

Calculation of Leak Rate for the Helium Component of Gas Mixture

From the above calculation: $F_c = 2.12 \times 10^{-5} \text{ cm}^3/\text{atm.s}$, and $F_m = 2.63 \times 10^{-6} \text{ cm}^3/\text{atm.sec}$ ($.263 \times 10^{-5} \text{ cm}^3/\text{atm.s}$), such that $F_c/F_m = 8.1$, which is to say that continuum flow dominates. This, in turn, means that the mole fraction of helium on the downstream side of the leak will be essentially identical to its mole fraction on the upstream side. To put it another way, the helium will simply be swept out of the MCO by the leaking gas mixture:

$$L_{u(\text{helium})} = L_{u(\text{mix})} \times \text{mole-fraction}_{\text{He}} = 6.17 \times 10^{-5} \text{ cm}^3/\text{s} \times 0.3206 = \underline{1.98 \times 10^{-5} \text{ cm}^3/\text{s}}$$

For helium, the issue is time to minimum acceptable inventory, consequently the result is expressed as mol of helium lost per unit of time via $PV = nRT$, or $n = PV/RT$:

$$\begin{aligned} P_u &= 5.35 \text{ atm abs} \\ T_u &= 337 \text{ K} \\ R &= 0.08206 \text{ L.atm/mol.K} \end{aligned}$$

$$\begin{aligned} L_{\text{He(molar)}} &= (L_{\text{He(volumetric)}})(5.35 \text{ atm}) / [(0.08206 \text{ L.atm/mol.K})(337 \text{ K})] = \\ &= (1.98 \times 10^{-5} \text{ cm}^3/\text{s})(0.001 \text{ L/cm}^3)(5.35 \text{ atm}) / [27.65 \text{ L.atm/mol}] = \\ &= 3.83 \times 10^{-9} \text{ mol/sec} = 3.33 \times 10^{-4} \text{ mol/day} = \underline{0.121 \text{ mol/year}} \end{aligned}$$

The above result exactly matches that listed under the "He - CSB" column on the second sheet of Appendix A, which confirms the spread sheet calculations for helium loss rates.

7.2.1.5.2 Hydrogen Release Calculations.

Worst Case Gas Inventory For Hydrogen Release From Section 7.1.2.3

• Hydrogen -----	65.7 mol
• Helium (maximum fill quantity) -----	41.1 mol
• Backfill gas impurities (0.2 mol taken as H ₂) -----	0 mol
• Alpha decay helium -- (taken as hydrogen) -----	0 mol
• Noble gasses (Kr, Xe) -- (taken as hydrogen)-----	0 mol
• Oxygen -- (taken as hydrogen) -----	0 mol
• TOTAL -----	106.8 mol

Calculation of Effective Molecular Weight for Gas Mixture

$$(B-6) P_m = \sum_{i=1}^n P_i; \text{ where } (P_i/P_m) = \text{mol-frac}_i$$

$$(B-7) M_m = \sum_{i=1}^n P_i M_i / P_m; \text{ from equation B-6, } M_m = \sum_{i=1}^n \text{mol-frac}_i M_i$$

$$\text{Mol-frac H}_2 = 65.7 \text{ mol}/106.8 \text{ mol} = 0.6152; \text{ and } M_{\text{hydrogen}} \approx 2 \text{ g/mol}$$

$$\text{Mol-frac He} = 41.1 \text{ mol}/106.8 \text{ mol} = 0.3848; \text{ and } M_{\text{helium}} \approx 4 \text{ g/mol}$$

$$M_m = 0.6152 \times 2 \text{ g/mol} + 0.3848 \times 4 \text{ g/mol} =$$

$$1.230 \text{ g/mol} + 1.539 \text{ g/mol} = \underline{2.77 \text{ g/mol}}$$

Calculation of Effective Viscosity for Gas Mixture

$$(B-8) \mu_m = \sum_{i=1}^n P_i \mu_i / P_m; \text{ from equation B-6, } \mu_m = \sum_{i=1}^n \text{mol-frac}_i \mu_i$$

| Mol-frac H_2 = 0.6152; and μ_{hydrogen} @ 337 K = 0.0096 cP

| Mol-frac H_e = 0.3848; and μ_{helium} @ 337 K = 0.0212 cP

| $\mu_m = 0.6152 \times 0.0096 \text{ cP} + 0.3848 \times 0.0212 \text{ cP} =$

| $0.00591 + 0.00816 = \underline{0.01407 \text{ cP}}$

Calculation of Leak Rate for Gas Mixture

$$(B-3) F_c = [2.49 \times 10^6 \times D^4] / (a\mu) \text{ cm}^3/\text{atm.s} \quad \text{-- where:}$$

a = hole length = 1 cm (from Table B.2)

D = hole diameter = $5.81 \times 10^{-4} \text{ cm}$

| Note -- The hole diameter (D) is obtained by iterating the hole size against
| the upstream flow rate (L_u) in the first column of the second spread sheet in
| Appendix A of this document. The final value used for "D" corresponds to the
| diameter that results in the specified leak test criterion ($1 \times 10^{-5} \text{ scc/s}$ in
| this case).

| μ_m = viscosity of gas mixture at 337 K = 0.01407 cP

| $F_c = [2.49 \times 10^6 \times (5.81 \times 10^{-4} \text{ cm})^4] / (1 \text{ cm})(0.01407 \text{ cP}) =$
| $\underline{2.017 \times 10^{-5} \text{ cm}^3/\text{atm.s}}$

$$(B-4) F_m = [3.81 \times 10^3 \times D^3 (T/M)^{0.5}] / (aP_a) \text{ cm}^3/\text{atm.sec.} \quad \text{-- where:}$$

T = 337 K (from section 4.4)

$M_m = 2.77 \text{ g/mol}$

| $P_u = 5.91 \text{ atm abs}$ (from section 7.1.3.3)

$P_d = 1 \text{ atm abs}$ (MCO leaks are to ambient or near-ambient pressure)

| $P_a = 1/2(P_u + P_d) \text{ atm abs} = 1/2(5.91 + 1) \text{ atm abs} = 3.45 \text{ atm abs}$

| $F_m = [3.81 \times 10^3 \times (5.81 \times 10^{-4} \text{ cm})^3 (337 \text{ K} / 2.77 \text{ g/mol})^{0.5}] / [(1 \text{ cm} \times 3.45 \text{ atm})] =$
| $[7.47 \times 10^{-7} \times (121.7)^{0.5}] / 3.45 = [7.47 \times 10^{-7} \times 11.03] / 3.45 =$
| $\underline{2.39 \times 10^{-6} \text{ cm}^3/\text{atm.sec}}$

(B-5) $L_{u(mix)} = (F_c + F_m)(P_u - P_d)(P_a/P_u) \text{ cm}^3/\text{s}$ -- all parameters are listed above.

$$L_{u(mix)} = (2.017 \times 10^{-5} + 2.38 \times 10^{-6})(5.91 - 1.0)(3.46/5.91) = \\ (2.26 \times 10^{-5})(4.91)(0.586) = \underline{6.50 \times 10^{-5} \text{ cm}^3/\text{s}}$$

Calculation of Leak Rate for the Hydrogen Component of Gas Mixture

From the above calculation: $F_c = 2.017 \times 10^{-5} \text{ cm}^3/\text{atm.s}$, and $F_m = 2.39 \times 10^{-6} \text{ cm}^3/\text{atm.sec}$ ($0.239 \times 10^{-5} \text{ cm}^3/\text{atm.s}$), such that $F_c/F_m = 8.44$ (i.e., continuum flow dominates). Consequently the hydrogen is simply swept out with the overall flow as a component of the gas mixture (see section 7.2.1.5.1):

$$L_u = L_{u(mix)} \times \text{mole-fraction}_{\text{hydrogen}} = 6.50 \times 10^{-5} \text{ cm}^3/\text{s} \times 0.613 = \underline{3.99 \times 10^{-5} \text{ cm}^3/\text{s}}$$

For hydrogen, the issue is time to maximum acceptable hydrogen concentration in a CSB storage tube, consequently the result can either be expressed as moles of hydrogen released to the tube per unit of time, or as volumetric flow rate at the downstream pressure (P_d) and temperature (T_d). The spread sheet calculations include both values. Regardless of whether the flow is expressed in moles or liters, the calculation for time to reach the maximum hydrogen concentration limit requires that either the volumetric flow rate from the MCO or the molar contents of the tube be corrected to the worst case (maximum) gas temperature within the tube (T_d). For the purposes of this document, that temperature is conservatively taken as the upstream gas temperature (64°C or 337 K) per section 4.4.

$$(B-5) L_{d(mix)} = (F_c + F_m)(P_u - P_d)(P_a/P_d) = (2.26 \times 10^{-5})(4.91)(3.46/1) = \\ 38.39 \times 10^{-5} \text{ cm}^3/\text{s} = 3.84 \times 10^{-4} \text{ cm}^3/\text{s at 337 K}$$

Based on the above, the hydrogen flow is:

$$L_d = L_{d(mix)} \times \text{mole-fraction}_{\text{hydrogen}} = 3.84 \times 10^{-4} \text{ cm}^3/\text{s} \times 0.613 = 2.35 \times 10^{-4} \text{ cm}^3/\text{s} \\ = 2.35 \times 10^{-4} \text{ cm}^3/\text{s} \times 60 \text{ s/min} \times 60 \text{ min/hr} \times 24 \text{ hr/day} \times 1 \text{ L}/1000 \text{ cm}^3 \\ = \underline{0.020 \text{ L/day}}$$

The above result exactly matches that listed under the "H2 - CSB" column on the fifth sheet of Appendix A ("2.032E-02"), which confirms the spread sheet calculations for hydrogen release.

7.3 MAXIMUM STEADY STATE HYDROGEN CONCENTRATION IN CSB TUBES

The hydrogen release calculations summarized by the fifth spread sheet listing in Appendix A of this document conclude that it would take almost a year for the hydrogen concentration to reach 1 vol% within a sealed CSB tube containing two safety basis pressure, mechanically sealed MCOs. However, the current CSB design provides vented tube closures for all air-atmosphere tubes. This section documents the ability of the stagnant vent paths to limit steady state hydrogen concentrations within CSB tubes to acceptable levels. The goal is to demonstrate that the hydrogen concentration within a worst case tube will never exceed 1 vol% hydrogen (25% of the LFL).

7.3.1 Dilution by Barometrically Induced Breathing

This section calculates the worst case steady state hydrogen concentration that is ever expected to occur within any CSB tube, based on dilution of hydrogen within tubes as a result of "tube breathing" driven by barometric pressure variations alone. Breathing calculations are limited to barometric effects because thermal cycling within the CSB vault is not considered to be reliable for this purpose (there is no guarantee that all tubes would be subject to it).

7.3.1.1 Assumptions. The breathing calculations assume that, even in the case where a particular storage tube payload provides little or no heat to support a vertical thermal gradient within the tube, the air within that storage tube will be well mixed. This assumption is reasonable in view of the long time frame required for a completely sealed tube to reach 1 vol% hydrogen (over ten months).

These calculations also assume that the difference between the observed 1.69 atmosphere integrated annual barometric pressure variation (see section 7.3.1.2) and the more conservative value used for this calculation (1.25 atm) is sufficient to compensate for (among other things) volumetric hold-up within the vent paths, which is calculated to require a 0.01" Hg minimum sustained change (up or down) before any subsequent change will result in a net movement of air to or from the storage tube (see the 2nd paragraph of section 7.3.1.2).

7.3.1.2 Basis For Air-Exchange Rate. Local barometric effects have most recently been documented in *Barometric Pressure Variations* (WHC-EP-0651), which reports an integrated annual barometric pressure variation of 1.69 atmospheres (i.e., tube volumes). Table 6 of that report provides minimum, average, and maximum integrated short-term data for periods from one hour to one year. While daily pressure swings can approach zero for several consecutive days, the minimum value is within 75% of the average value for

periods on the order of one month or more. For time periods approaching one year, the minimum value is within 99% of the average value. In view of the fact that the worst case calculation in this document predicts that a completely sealed tube would not reach 1 vol% hydrogen during the first ten months of service, it should be sufficiently conservative to base a "breathing allowance" for vented tubes on a value that Table 6 [of WHC-EP-0651] describes as the minimum integrated pressure swing over a period of one month or less. That table lists the minimum integrated swing as 2.97 inches of mercury over a 696 hour period (less than one month), which is equivalent to 0.00427 inches of mercury per hour, or 37.38 inches of mercury per year. At 29.92 inches of mercury per atmosphere, this translates to 37.38/29.92, or 1.25 atm per year.

Finally, consideration must be given to the effects of hold-up within the tube's shield plug vent ports. The shield plug is provided with two identical vent ports, each of which consists of a 9" long 3/4" I.D. hole bored into the side of the shield plug at its upper end, and slanting upward to a point where it intersects a 2" deep vertical hole that has been bored into the upper face of the shield plug. The vertical hole is taped to receive a 2 1/2" long, 3/4" NPT pipe nipple. The vent port terminates with a 3/4" NPT pipe coupling and a small strainer fitting (the "breather vent assembly"). Based on a 170 cm³ estimate for the hold-up volume of each assembly, a total hold-up volume of 0.4 L should be conservative (see section 4.7 for the volume calculations).

Given a total net storage tube void volume of 1300 L for the worst case payload configuration (again, see section 4.7), the 0.4 L hold-up volume represents only about three hundredths of 1% (3.1×10^{-4}) of the worst case minimum tube volume. Consequently, a sustained barometric swing of 0.01 inches of Hg should be more than adequate to clear the ports of their 0.4 L hold-up volume and, thereby, allow any subsequent sustained swing (in either direction) to actually transfer gas to or from the storage tube:

$$29.92" \text{ Hg (equivalent to one tube volume)} \times 3.1 \times 10^{-4} = 0.0093" \text{ Hg.}$$

Based on all of the above, it should be both reasonable and conservative to assume that the air within vented CSB tubes will be exchanged at least 1.25 times per year, and that at least 10% of it will be exchanged per month, on average. And while it is possible that several days may go by without any exchange occurring, the calculated worst case daily hydrogen leakage is so low that any short term interruptions will not result in a significant short term hydrogen build up.

7.3.1.3 Material Balance Equations. Based on a worst case minimum net void volume of 1300 L for a CSB tube containing two mechanically sealed MCOs (see section 4.7), and based on a 7.31×10^{-4} mol/day per MCO worst case maximum hydrogen release rate (see the fifth spread sheet listing in Appendix A of this document), the following material balance equations apply:

Figure 7-2: Gas Exchange Through CSB Tube Plug Vents

$H = H_2 \text{ IN} = 2(7.31 \times 10^{-4} \text{ mol/day})(365 \text{ day/yr}) = 0.533 \text{ mol/yr}$ (see the last spread sheet listing in Appendix A of this document)

$V = 1300 \text{ L}$ (see section 4.7)

$T = 337 \text{ K}$ (see section 4.4)

$N = PV/RT = (1 \text{ atm})(1300 \text{ L})/((.08206 \text{ atm.L/mol.K})(337 \text{ K})) = 47.0 \text{ mol}$

$A = \text{Air IN (mol/yr) as barometric pressure increases}$

$G = \text{Total gas OUT (mol/yr) as barometric pressure decreases}$

Given a 1.25 atm annual integrated pressure variation,

$G = 1.25 N/\text{yr} = 58.8 \text{ mol/yr}$

Hydrogen Balance

In: H , mol H_2 /yr

Out: $Y_H G$ mol H_2 /yr -- Y_H = mole fraction H_2 , G = mol/yr total

Accumulation: $(PV/RT) dY_H/dt = N dY_H/dt$ gmol H_2 /yr ;

$$N dY_H/dt = H - (Y_H G) ;$$

$$dY_H/dt + (G/N)Y_H = H/N ;$$

The "integrating factor" $\mu = e^{\int G/N dt} = e^{G/N t} ;$

$$e^{G/N t} \times [dY_H/dt + (G/N)Y_H] = (H/N) \times e^{G/N t} ;$$

$$\int d(Y_H e^{G/N t}) = \int H/N e^{G/N t} dt ;$$

$$Y_H e^{G/N t} = H/N(N/G)e^{G/N t} + C ;$$

$$Y_H = (N/G) + C e^{-G/N t} ;$$

$$@ t = 0, Y_H = Y_H^0 ;$$

$$Y_H^0 = (H/G) + C, C = Y_H^0 - (H/G) ;$$

$$Y_H = (H/G) + [Y_H^0 - (H/G)e^{-G/N t}] = [Y_H^0 e^{-G/N t} + (1 - e^{-G/N t}) H/G] ;$$

As t approaches infinity, Y_H approaches H/G ;

Steady State Solution

$H = 0.533$ mol H_2 /yr (see above);

$N = 47.0$ mol (see above);

$G = 58.8$ mol/yr (see above);

At steady state, $Y_H = H/G = (0.533 \text{ mol/yr})/(58.8 \text{ mol/yr}) =$
0.0091, or 0.9 vol%

Hydrogen composition in CSB tube (time averaged atmospheric breathing)

CSB Tube Vol (L)	1300 (with 2 MCOs)
Pres (atm)	1 (nominal)
Temp (K)	337
R (atm-L/gmol-K)	0.082
Total Gas in Tube N (gmol)	47.04
Hydrogen Addition Rate H (gmol H ₂ /yr)	0.53
Exchange from Press Swings (tube vols/yr)	1.25
Gas discharge rate G (gmol/yr)	58.80
Initial Hydrogen mole fraction in tube	0

Transient hydrogen concentration:		
Time, yr	Y H ₂	mole % H ₂
0.0	0.0000	0.00
0.1	0.0011	0.11
0.2	0.0020	0.20
0.3	0.0028	0.28
0.4	0.0036	0.36
0.5	0.0042	0.42
0.6	0.0048	0.48
0.7	0.0053	0.53
0.8	0.0057	0.57
0.9	0.0061	0.61
1.0	0.0065	0.65
1.1	0.0068	0.68
1.2	0.0070	0.70
1.3	0.0073	0.73
1.4	0.0075	0.75
1.6	0.0078	0.78
1.8	0.0081	0.81
2.0	0.0083	0.83
2.2	0.0085	0.85
2.4	0.0086	0.86
2.6	0.0087	0.87
2.8	0.0088	0.88
3.0	0.0089	0.89
3.2	0.0089	0.89
3.4	0.0089	0.89
3.6	0.0090	0.90
3.8	0.0090	0.90
4.0	0.0090	0.90
∞	0.0091	0.91

Figure 7-3: Worst Case H₂ Concentration With Atmospheric Breathing

8.0 REFERENCES

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APPENDIX A: SPREAD SHEET CALCULATIONS

SPREAD SHEET VALIDATION CALCULATIONS (NOT CALCULATED FOR CURRENT MCO LEAK SPECS)									
The calculations for "Air (Lr)" reproduce results for 1E-3 cm and 2E-4 cm holes that are listed by Table B-2 of ANSI N14.5 1997 Draft J.									
		For 0.001 cm (10 microns) Hole Diameter			For 0.0002 cm (2 microns) Hole Diameter				
		Air (Lr)	He - Test			Air (Lr)	He - test		
Lu (cc/s @ Pupstrm)		7.94E-05	9.54E-05			2.04394E-07	3.61E-07		
La (cc/s @ Pavg)		1.57E-04	1.89E-04			4.05E-07	7.15E-07		
Ld (cc/s @ Pdnstrm)		0.007938	0.009543			2.04394E-05	3.61E-05		
D (hole dia -- cm)		1.00E-03	1.00E-03			2.00E-04	2.00E-04		
Rlrr (gas const L.atm)		8.21E-02	8.21E-02			8.21E-02	8.21E-02		
Ro (gas const ergs)		8.31E+07	8.31E+07			8.31E+07	8.31E+07		
Tu (upstrm temp K)		298	298			298	298		
Td (dnstrm temp K)		298	298			298	298		
M (g/mole)		29	4			29	4		
k (Cp/Cv)		1.4	1.66			1.4	1.66		
Pu (atm)		1	1			1	1		
Pd (atm)		0.01	0.01			0.01	0.01		
Pd/Pu		0.01	0.01			0.01	0.01		
Crit Ratio		0.528	0.487			0.528	0.487		
Fc (cc/atm.sec)		0.000135	0.000126			2.15351E-07	2.01E-07		
Fm (cc/atm.sec)		2.42E-05	6.51E-05			1.93479E-07	5.21E-07		
a (hole length -- cm)		1	1			1	1		
μ (cP)		0.0185	0.0198			0.0185	0.0198		
Pa (ave sys P -- atm)		0.505	0.505			0.505	0.505		
$r_f = F_c/F_m$		5.56525	1.93118			1.11305	0.38624		
Mole/Day		0.00028	0.000337			1.27565E-06	1.28E-06		
Ltrs/Day		0.006858	0.008244			3.11913E-05	3.12E-05		

HELIUM LOSS RATE CALCULATED FOR MAX-HYDROGEN SAFETY BASIS MCOS WITH RECOMMENDED MCO LEAK SPECS

The calculations on this sheet are based on a total gas inventory (96.7 mol) corresponding to Ti-040, case K-17, at 40 yrs, after addition of 0.7 mol of He and 0.2 mol of H₂. Of the 96.7 mol total, 31 moles are taken as He, and 65.7 moles are taken as hydrogen. The 337K MCO gas temperature is from Ti-40 case K-17, at 40 years. The 337K tube temperature is an arbitrary assumption, but has no impact on the He results.

[illegible]

The calculations on this sheet are based on a total gas inventory (92.8 mol) corresponding to the 65.7 mol maximum H₂ inventory from the previous sheet, plus the 26.1 mol minimum helium inventory (also from the previous sheet) calculated for a mechanically sealed MCO after 40 years of "staging," plus 1.0 mol of helium that will be under the weld cap when it is installed. The 337K MCO gas temperature is from TI-40 case K-17, at 40 yrs. The 337K tube temperature is an arbitrary assumption, but has no impact on the He results.

(The leak test acceptance criterion is 1E-7 std cc/s)

[illegible]

NOTE: This calculation is based on a 27.1 mol initial He inventory, which is the minimum amount that will remain after 40 years of mechanically sealed "straging" (26.1 mol), plus 1.0 mol that will be within the weld cap's void space when it is installed. Also note that the minimum acceptable He inventory of a welded MCO is 26.6 mol, as opposed to 25.2 mol for an un-welded MCO, because of the additional void space under the weld cap. Finally, this leak rate calculation assumes that pressures have equalized between the cover cap void space and the MCO proper, which is grossly conservative. However, it also assumes that the MCO pressure will remain constant after 40 years, although that is only slightly unconservative in light of the pressure curve's shape at that point in time (see page K-13 of TI-040).

MINIMUM HELIUM INVENTORY OF WORST-OXYGEN-CASE MCO AFTER 40 YEARS									
HELIUM LOSS RATE CALCULATED FOR WORST-OXYGEN-CASE (250W) BOUNDING LOW AREA/HIGH WATER, MINIMUM BACKFILL, MCO WITH MECHANICAL SEALS									
The calculations on this sheet are based on a total gas inventory (41.1 mol) corresponding to TI-040, case I-13, at 40 yrs, after addition of 0.7 moles of He and 0.2 moles of H ₂ . Of the 41.1 mol total, 31 moles are taken as He, and 10.1 moles are taken as hydrogen. The 304 K MCO gas temperature is the average fuel temperature from the same figure at 40 yrs. The 304 K tube temperature is an arbitrary assumption, but has no impact on the He results.									
The helium loss calculations cover flow ranges for mechanically sealed MCOs with a 1E-5 std cc/s leak test acceptance criterion. No helium loss calculations are provided for welded MCO's using this gas inventory because the oxygen gettering analysis is only affected by the He inventory of the MCO proper (vs the MCO + weld-cap).									
	Air (Lr)	He - Test	MIX - CSB	He - CSB					
Lu (cc/s @ Pupstrm)	1.00E-05	1.35E-05	1.64E-05						
La (cc/s @ Paverg)	1.99E-05	2.68E-05	2.21E-05						
Ld (cc/s @ Pdnstrm)	1.00E-03	1.35E-03	3.37E-05						
D (hole dia -- cm)	5.81E-04	5.81E-04	5.81E-04						
Rltr (gas const L.atm)	8.21E-02	8.21E-02	8.21E-02						
Ro (gas const ergs)	8.31E+07	8.31E+07	8.31E+07						
Tu (upstrm temp K)	298	298	304						
Td (dnstrm temp K)	298	298	304						
M (g/mole)	29	4	3.509						
k (Cp/Cv)	1.400	1.660	1.599						
Pu (atm)	1.000	1.000	2.051						
Pd (atm)	0.010	0.010	1.000						
Pd/Pu	0.010	0.010	0.488						
Crit Ratio	0.528	0.487	0.497						
Fc (cc/atm.sec)	1.53E-05	1.43E-05	1.65E-05						
Fm (cc/atm.sec)	4.74E-06	1.28E-05	4.56E-06						
a (hole length -- cm)	1	1	1						
μ (cP)	0.0185	0.0198	0.0172						
Pa (ave sys P -- atm)	0.5050	0.5050	1.5253						
rf = Fc/Fm	3.2334	1.1220	3.6129						
Mole/Year	0.0129	0.0175	0.0426	0.0321					
Helium inventory after 40 Years				29.7 Moles					
Note: The initial He inventory is taken as 31.0 gmol, i.e., adjusted downward from the 31.2 gmol minimum backfill inventory to account for impurities.									
The leftover 0.2 gmol is taken as hydrogen. Also note that the initial He inventory of an average MCO will be at least 32.8 gmol, based on the 11 psig nominal fill press, the 500 L minimum void, the 50 deg C worst case (high) fill temperature, and the 0.2 gmol deduction for impurities.									
This means that an average MCO will actually contain over 31.4 gmol (as opposed to 29.7) after 40 yrs.									

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HYDROGEN RELEASE RATE CALCULATED FOR MAX-PRESSURE SAFETY BASIS MCOs WITH RECOMMENDED MCO LEAK SPECS									
This sheet is based on the maximum He fill (41.1 g/mol) and an H2 inventory (65.5 + 0.2 = 65.7 g/mol) that corresponds to the max pressure listed in TI-40, plus 0.2 g/mol of backfill gas impurities. The 337K MCO gas temperature is from TI-40; the 337K tube temperature is a conservative assumption.									
The calculations below cover flow ranges for mechanically sealed MCOs (The leak test acceptance criterion is 1E-5 std cc/s)					The calculations below cover the flow range for welded MCOs. (The leak test acceptance criterion is 1E-7 std cc/s.)				
	Air (Lr)	He - Test	MIX - CSB	H2 - CSB	Air (Lr)	He - test	MIX - CSB	H2 - CSB	
Lu (cc/s @ Pupstrm)	1E-05	1.35E-05	6.47E-05		1E-07	1.86E-07	5.12E-07		
La (cc/s @ Pavg)	1.99E-05	2.68E-05	1.11E-04		1.99E-07	3.69E-07	8.76E-07		
Ld (cc/s @ Pdnstrm)	0.001004	0.001355	0.000382		1E-05	1.86E-05	3.02E-06		
D (hole dia -- cm)	5.81E-04	5.81E-04	5.81E-04		1.63E-04	1.63E-04	1.63E-04		
Ritr (gas const L atm)	8.21E-02	8.21E-02	8.21E-02		8.21E-02	8.21E-02	8.21E-02		
Ro (gas const ergs)	8.31E+07	8.31E+07	8.31E+07		8.31E+07	8.31E+07	8.31E+07		
Tu (upstrm temp K)	298	298	337		298	298	337		
Td (dnstrm temp K)	298	298	337		298	298	337		
M (g/mole)	29	4	2.770		29	4	2.770		
k (Cp/Cv)	1.4	1.66	1.506		1.4	1.66	1.506		
Pu (atm)	1	1	5.907		1	1	5.907		
Pd (atm)	0.01	0.01	1		0.01	0.01	1		
Pd/Pu	0.01	0.01	0.169		0.01	0.01	0.169		
Crit Ratio	0.528	0.487	0.512		0.528	0.487	0.512		
Fc (cc/atm.sec)	1.53E-05	1.43E-05	2.02E-05		9.55E-08	8.92E-08	1.26E-07		
Fm (cc/atm.sec)	4.74E-06	1.28E-05	2.39E-06		1.05E-07	2.83E-07	5.29E-08		
a (hole length -- cm)	1	1	1		1	1	1		
μ (cP)	0.0185	0.0198	0.01406		0.0185	0.0198	0.01406		
Pa (ave sys P -- atm)	0.505	0.505	3.453		0.505	0.505	3.453		
rf = Fc/Fm	3.23341	1.12201	8.453		0.90825	0.31517	2.374		
Mole/Day per MCO	3.55E-05	4.79E-05	0.00119	7.348E-04	3.54E-07	6.58E-07	9.45E-06	5.796E-06	
Ltrs/Day per MCO	0.000867	0.001171	0.0330	2.032E-02	8.66E-06	1.61E-05	0.000261	1.603E-04	
Tube Void Volume With One MCO - Liters				2500				2500	
Years to 1 % H2				3.4				427	
Tube Void Volume With Two MCOs - Liters				1300				1200	
Years to 1 % H2				0.9				103	

NOTE: These "Years to 1 % H2" estimates are based on sealed storage tubes -- see section 7.3, which shows that vented tubes will never exceed 1 %.

HYDROGEN RELEASE RATE CALCULATED FOR 530 L VOID MAX-PRESSURE SAFETY BASIS MCOs											
This sheet is based on the maximum MCO gas inventory (43.4 mol of He and 67.6 mol of H ₂ = 111.0 mol), MCO void volume (530 L), and temperature (329.3 K) used in Appdx N of T-040 to establish the project's 5.66 atm maximum safety basis pressure for any MCO. The 329.3 K tube temperature is conservative for H ₂ build-in calculations.											
The calculations below cover flow ranges for mechanically sealed MCOs (The leak test acceptance criterion is 1E-5 std cc/s)						The calculations below cover the flow range for welded MCOs. (The leak test acceptance criterion is 1E-7 std cc/s.)					
	Air (Lr)	He - Test	MIX- CSB	H ₂ - CSB		Air (Lr)	He - test	MIX- CSB	H ₂ - CSB		
Lu (cc/s @ Pupstrm)	1E-05	1.35E-05	6.17E-05			1E-07	1.86E-07	4.91E-07			
La (cc/s @ Paverl)	1.99E-05	2.68E-05	1.05E-04			1.99E-07	3.69E-07	8.34E-07			
Ld (cc/s @ Pdnstrm)	0.001004	0.001355	0.000349			1E-05	1.86E-05	2.78E-06			
D (hole dia -- cm)	5.81E-04	5.81E-04	5.81E-04			1.63E-04	1.63E-04	1.63E-04			
Rlrr (gas const L.atm)	8.21E-02	8.21E-02	8.21E-02			8.21E-02	8.21E-02	8.21E-02			
Ro (gas const ergs)	8.31E+07	8.31E+07	8.31E+07			8.31E+07	8.31E+07	8.31E+07			
Tu (upstrm temp K)	298	298	329.3			298	298	329.3			
Td (dnstrm temp K)	298	298	329.3			298	298	329.3			
M (g/mole)	29	4	2.782			29	4	2.782			
k (Cp/Cv)	1.4	1.66	1.508			1.4	1.66	1.508			
Pu (atm)	1	1	5.659			1	1	5.659			
Pd (atm)	0.01	0.01	1			0.01	0.01	1			
Pd/Pu	0.01	0.01	0.177			0.01	0.01	0.177			
Crit Ratio	0.528	0.487	0.511			0.528	0.487	0.511			
Fc (cc/atm.sec)	1.53E-05	1.43E-05	2.01E-05			9.55E-08	8.92E-08	1.25E-07			
Fm (cc/atm.sec)	4.74E-06	1.28E-05	2.44E-06			1.05E-07	2.83E-07	5.41E-08			
a (hole length -- cm)	1	1	1			1	1	1			
μ (cP)	0.0185	0.0198	0.01414			0.0185	0.0198	0.01414			
Pa (ave sys P -- atm)	0.505	0.505	3.330			0.505	0.505	3.330			
rf = Fc/Fm	3.23341	1.12201	8.221			0.90825	0.31517	2.309			
Mole/Day per MCO	3.55E-05	4.79E-05	0.00112	6.801E-04		3.54E-07	6.58E-07	8.88E-06	5.410E-06		
Ltrs/Day per MCO	0.000867	0.001171	0.0302	1.838E-02		8.66E-06	1.61E-05	0.00024	1.462E-04		
Tube Void Volume With One MCO - Liters				2500		Tube Void Volume With One MCO - Liters				2500	
Years to 1 % H ₂				3.7		Years to 1 % H ₂				469	
Tube Void Volume With Two MCOs - Liters				1300		Tube Void Volume With Two MCOs - Liters				1200	
Years to 1 % H ₂				1.0		Years to 1 % H ₂				112	

NOTE: These "Years to 1 % H₂" estimates are based on sealed storage tubes -- see section 7.3, which shows that vented tubes will never exceed 1%.

APPENDIX B: THE NFPA 69 EXPLOSION PREVENTION STANDARD

THE NFPA 69 EXPLOSION PREVENTION STANDARD

The stated purpose of NFPA 69 is to prevent explosions in enclosures that contain combustible gases, mists, or dusts. An explosion is defined by the standard as "The bursting or rupture of an enclosure or a container due to the development of internal pressure from a deflagration." A deflagration is defined as "Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium." Paragraph 1-1.2 of the standard specifically states that it does not apply to devices or systems designed to protect against detonations, which it defines as "Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium." It also excludes, among other things, unconfined deflagrations and the design, construction, and installation of deflagration vents.

The standard recognizes two general classes of techniques for preventing explosions. One class is based on combustion prevention while the other is based on preventing or limiting damage from combustion.

Four methods are recognized for limiting or preventing damage from combustion: 1) deflagration suppression, 2) deflagration pressure containment, 3) spark extinguishing, and 4) isolation. Because hydrogen is very easy to ignite over a wide range of hydrogen and oxygen concentrations, and because it would be very difficult to demonstrate that a hydrogen burn could not result in a detonation, as opposed to a deflagration, none of these methods appears to apply (one possible exception would be to demonstrate adequate deflagration pressure containment, based on a limited oxygen concentration -- see section 5.1.2.2.1). This is not to say that the MCO, shipping cask, MCO Handling Machine (MHM) cask, or storage tube designs will not require analysis to demonstrate capability to withstand a detonation with no unacceptable consequences. However, if it were necessary to perform such an analysis, it would not be performed to any requirement of NFPA 69.

Two methods are recognized for preventing combustion: 1) oxidant concentration reduction, and 2) combustible concentration reduction.

Chapter 2 of the standard covers application of the oxidant reduction technique. Paragraph 2-7.2 provides the operating limits and instrumentation requirements for systems that will be operated below the Limiting Oxidant Concentration (LOC). See section 5.1.1.1 for additional detail regarding the specific operating limits and instrumentation requirements that are invoked by the standard.

Chapter 3 covers application of the combustible reduction technique. Paragraph 3-3 provides design and operating requirements for systems that will be operated below the Lower Flammable Limit (LFL). Paragraph 3-3.1 requires that the combustible concentration be maintained at or below 25% of the LFL (i.e., 25% of 4 vol% for hydrogen in air = 1 vol%). An exception is provided to allow combustible concentrations up to 60% of the LFL for systems that have the capability to automatically shut off the source of combustible material or otherwise prevent a combustion event (automatic activation of quenching systems, etc.) by means of instrumentation with safety interlocks.

Finally, NFPA 69 addresses situations where it is either impossible or inappropriate to meet any or all of the detailed requirements that it invokes. Paragraph 1-1.3 of NFPA 69 states that "Nothing in this standard shall be intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, fire resistance, effectiveness, durability, and safety over those prescribed by this standard, provided technical documentation is made available to the authority having jurisdiction to demonstrate equivalency and the system, method, or device is approved for the intended purpose."

APPENDIX C: ALTERNATE CALCULATION FOR SECTION 7.3

LOSS OF HYDROGEN FROM CSB TUBES VIA DIFFUSION

Whereas the calculations and results in section 7.3 are based on dilution of hydrogen by barometrically induced atmospheric breathing alone, the attached alternate calculation is based on loss of hydrogen from the tubes via diffusion alone, with no allowance for any mass flow of gas to or from the tubes. And, whereas the calculations in section 7.3 are based on complete mixing of the air and hydrogen within each tube, this alternate calculation limits that assumption to the void space between the bottom of the tube plug and the upper surface of the top MCO. All other void spaces, including the vent penetrations/lines and the annular space between the bottom of the tube plug and the bottom of each vent penetration, are assumed to be stagnate. As shown on the last page of the attached hand written sheets, the diffusion calculation predicts that, based on the diffusion mechanism alone, the maximum steady state hydrogen concentration will not exceed 0.7 vol%.

Considering that both mechanisms (breathing and diffusion) are shown to result in maximum steady state hydrogen concentrations that are well below 1 vol% (0.9 vol%, based on breathing alone, and 0.7 vol%, based on diffusion alone) along with the fact that both mechanisms will actually be active at the same time, the overall conclusion is that no vented CSB tube will ever even approach 1 vol% hydrogen (let alone the 4 vol% LFL) unless it contains an MCO with a defective seal.

ANALYTICAL CALCULATIONS

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SEE Pg 9 FOR RESULTS SUMMARY

$$N = \frac{\dot{n}}{A_1} = \frac{\dot{n}}{A_2}$$

$$N \frac{\text{SMOL}}{\text{CM}^2 \cdot \text{YR}} = \frac{C D_{AB}}{(z_2 - z_1)} \ln \left(\frac{1 - y_2}{1 - y_1} \right)$$

$$\frac{\dot{n}}{A_2} = \frac{D_{AB} P}{RT(z_2 - z_1)} \ln \left(\frac{1 - y_2}{1 - y_1} \right)$$

AND

$$\frac{\dot{n}}{A_1} = \frac{D_{AB} P}{RT(z_1 - z_0)} \ln \left(\frac{1 - y_1}{1 - y_0} \right)$$

EQU 26.5 FOR
DIFFUSION THROUGH
A STAGNANT GAS
(CONSTANT AREA) IN
WILTY, WICKS & WILSON (1969)

FOR TOP REGION

$$\frac{\dot{n}}{A_2} = \frac{D_{AB} P}{RT(z_2 - z_1)} \ln \left(\frac{1 - y_2}{1 - y_1} \right) = \frac{D_{AB} P}{RT(z_2 - z_1)} \ln \left(\frac{1}{1 - y_1} \right)$$

$$\frac{\dot{n} RT(z_2 - z_1)}{A_2 D_{AB} P} = -\ln(1 - y_1)$$

$$\exp \left\{ \frac{\dot{n} RT(z_2 - z_1)}{A_2 D_{AB} P} \right\} = (1 - y_1)$$

$$y_1 = 1 - \exp \left\{ -\frac{\dot{n} RT(z_2 - z_1)}{A_2 D_{AB} P} \right\}$$

1969,
REF: WILTY, J.R., G.E. WICKS AND R.E. WILSON, "FUNDAMENTALS OF
MOMENTUM, HEAT AND MASS TRANSFER, JOHN WILEY & SONS INC.
NEW YORK, NEW YORK.

ANALYTICAL CALCULATIONS

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Subject H₂ DIFFUSION IN CSB TUBE WITH 2 MKDS
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FOR BOTTOM REGION:

$$\frac{\dot{n} RT(z_1 - z_0)}{A_1 D_{AB} P} = \ln \left(\frac{1 - y_1}{1 - y_0} \right)$$

$$\exp \left\{ \frac{\dot{n} RT(z_1 - z_0)}{A_1 D_{AB} P} \right\} = \left(\frac{1 - y_1}{1 - y_0} \right)$$

$$(1 - y_0) \exp \left\{ \frac{\dot{n} RT(z_1 - z_0)}{A_1 D_{AB} P} \right\} = (1 - y_1)$$

$$\exp \left\{ \frac{\dot{n} RT(z_2 - z_1)}{A_2 D_{AB} P} \right\} \cdot \exp \left\{ \frac{\dot{n} RT(z_1 - z_0)}{A_1 D_{AB} P} \right\} = \left(\frac{1 - y_0}{1 - y_1} \right)$$

$$y_0 = 1 - \exp \left\{ - \frac{\dot{n} RT(z_2 - z_1)}{A_2 D_{AB} P} - \frac{\dot{n} RT(z_1 - z_0)}{A_1 D_{AB} P} \right\}$$

$$= 1 - \exp \left\{ - \frac{\dot{n} RT}{D_{AB} P} \left(\frac{z_2 - z_1}{A_2} + \frac{(z_1 - z_0)}{A_1} \right) \right\}$$

BASE A_2 ON 2 - 3/4" BY 12" LONG OPENINGS + 12" FOR MISC. EQUIPMENT

$$A_2 = 2 \times \frac{\pi}{4} \left(\frac{3}{4} \times 2.54 \right)^2 = 5.7 \text{ cm}^2$$

$$(z_2 - z_1) = 24 \times 2.54 = 61 \text{ cm}$$

BASE A_1 ON ANNULUS 2 ft IN DIAMETER, 1/2" THICK & 36" LONG

$$A_1 = \pi (2 \cdot 12 \cdot 2.54) \left(\frac{1}{2} \cdot 2.54 \right) = 243 \text{ cm}^2$$

$$(z_1 - z_0) = 36 \times 2.54 = 91.5 \text{ cm}$$

FROM PERRY'S 5TH ED PG 3-222, TABLE 3-299

$$D_{AB} P \text{ FOR H}_2 \text{ IN AIR @ 0°C} = 0.611 \frac{\text{cm}^2 \cdot \text{atm}}{\text{SEC}}$$

ANALYTICAL CALCULATIONS

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Subject H₂ DIFFUSION IN CSB TUBE WITH 2 MCOS
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$$D_{AB} P = 0.611 \left(\frac{T}{273} \right)^{1.5} \frac{\text{cm}^2 \cdot \text{atm}}{\text{SEC}} \left(3000 \frac{\text{SEC}}{\text{HR}} \right) \left(24 \frac{\text{HR}}{\text{DAY}} \right) \left(365 \frac{\text{DAY}}{\text{YR}} \right)$$

$$= 1.93 \times 10^7 \left(\frac{T}{273} \right)^{1.5} \frac{\text{cm}^2 \cdot \text{atm}}{\text{YR}}$$

For 2 MCOS, $\dot{n} = 0.54 \frac{\text{SMOL H}_2}{\text{YR}}$, $R = 82.06 \frac{\text{cm}^3 \cdot \text{atm}}{\text{SMOL} \cdot \text{K}}$

At $T = 337 \text{ K}$, $D_{AB} P = 2.65 \times 10^7 \frac{\text{cm}^2 \cdot \text{atm}}{\text{YR}}$

$$Y_1 = 1 - \exp \left\{ - \frac{\dot{n} R T (z_2 - z_1)}{A_2 D_{AB} P} \right\}$$

$$= 1 - \exp \left\{ - \frac{(0.54)(82.06)(337)(61)}{(5.7)(2.65 \times 10^7)} \right\}$$

$$= 1 - 0.994$$

$$= 0.006$$

$$Y_0 = 1 - \exp \left\{ - \frac{\dot{n} R T}{D_{AB} P} \left(\frac{(z_2 - z_1)}{A_2} + \frac{(z_1 - z_0)}{A_1} \right) \right\}$$

$$= 1 - \exp \left\{ - \frac{(0.54)(82.06)(337)}{(2.65 \times 10^7)} \left(\frac{61}{5.7} + \frac{91.5}{243} \right) \right\}$$

$$= 1 - 0.9938$$

$$= 0.0062$$

ANALYTICAL CALCULATIONS

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FOR MORE CONSERVATIVE ANALYSIS OF ANNULUS, ASSUME
ZONES OF STAGNANT CONCENTRATIONS -

CHANGE IN CROSS SECTION AREA IS

$$S = A_2 - \frac{(A_2 - A_1)}{z_1} z \quad \text{LET } \frac{(A_2 - A_1)}{z_1} = \alpha$$

$$= A_2 - \alpha z$$

AT SS,

$$\lim_{\Delta z \rightarrow 0} \frac{SN|_{z+\Delta z} - SN|_z}{\Delta z} = 0$$

$$\frac{d}{dz} (SN) = 0$$

OR

$$SN = C, \text{ A CONST}$$

$$@ z=0, S=A_2$$

$$N = \frac{\dot{n}}{A_2}$$

$$\therefore A_2 \left(\frac{\dot{n}}{A_2} \right) = C$$

$$\text{OR}$$

$$\dot{n} = C$$

$$\therefore N = \frac{\dot{n}}{S} = \frac{\dot{n}}{A_2 - \alpha z}$$

ANALYTICAL CALCULATIONS

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$$N = - \frac{C D_{AB}}{1-y} \frac{dy}{dz} = \frac{\dot{n}}{A_2 - \alpha z} \quad \text{Eqn 26-3 from Werry, Wicks & Wilson (1969)}$$

$$- \frac{C D_{AB}}{\dot{n}} \int_{y_0}^{y_1} \frac{dy}{1-y} = \int_0^{z_1} \frac{dz}{A_2 - \alpha z}$$

$$- \frac{C D_{AB}}{\dot{n}} \left(-\ln(1-y) \right) \Big|_{y_0}^{y_1} = - \frac{1}{\alpha} \left(\ln(A_2 - \alpha z) \right) \Big|_0^{z_1}$$

$$\frac{C D_{AB}}{\dot{n}} \ln \left(\frac{1-y_1}{1-y_0} \right) = - \frac{1}{\alpha} \ln \left(\frac{A_2 - \alpha z_1}{A_2} \right)$$

$$\alpha z_1 = \frac{(A_2 - A_1)}{z_1} z_1 = (A_2 - A_1)$$

$$\ln \left(\frac{1-y_1}{1-y_0} \right) = - \frac{\dot{n}}{C D_{AB} \alpha} \ln \left(\frac{A_1}{A_2} \right)$$

$$\begin{aligned} \left(\frac{1-y_1}{1-y_0} \right) &= \left(\frac{A_1}{A_2} \right)^{-\frac{\dot{n} RT}{P D_{AB} \alpha}} \quad C = \frac{P}{RT} \\ &= \left(\frac{A_1}{A_2} \right)^{-\frac{\dot{n} RT z_1}{D_{AB} P (A_2 - A_1)}} \end{aligned}$$

$$\frac{3 \text{ mol}}{\text{hr}} \cdot \frac{46 \text{ g}}{\text{mol}} \cdot \frac{1 \text{ hr}}{3600 \text{ s}} \cdot \frac{1 \text{ kg}}{1000 \text{ g}} = \frac{3 \cdot 46}{3600 \cdot 1000} \text{ kg/s}$$

ANALYTICAL CALCULATIONS

Page 6 of 9Subject H₂ DIFFUSION IN CSB TUBE WITH 2 MCOSOriginator AL PATTERSONDate 1/18/99

Checker _____

Date _____

SOLVING FOR y_0 ,

$$y_0 = 1 - (1 - y_1) \left(\frac{A_1}{A_2} \right)^{\frac{\dot{n} R T z_1}{D_{H_2} P (A_2 - A_1)}}$$

FROM P₃ 3, $y_1 = 0.003$, USE SYMMETRY TO MAKE SOLUTION APPLICABLE, I.E.

$$A_1 = \frac{243}{2} = 121.5 \text{ cm}^2 \quad z_1 = 91.5 \text{ cm}$$

$$A_2 = \frac{5.7}{2} = 2.85 \text{ cm}^2$$

$$R = 82.06 \frac{\text{atm} \cdot \text{cm}^3}{\text{gmol} \cdot \text{K}}$$

$$\dot{n} = \frac{0.54}{2} = 0.27 \frac{\text{gmol H}_2}{\text{yr}}$$

$$T = 337 \text{ K}$$

$$D_{H_2} P = 2.65 \times 10^{-7} \frac{\text{cm}^2 \cdot \text{atm}}{\text{yr}}$$

$$y_0 = 1 - (1 - 0.006) \left(\frac{121.5}{2.85} \right)^{\frac{(0.27)(82.06)(337)(91.5)}{(2.65 \times 10^{-7})(2.85 - 121.5)}}$$

$$= 1 - (1 - 0.006) \left(42.63 \right)^{-2.17 \times 10^{-4}}$$

$$= 1 - 0.9992$$

$$= \underline{\underline{0.0068}}$$

COMPARED TO 0.0062 ASSUMING
CONSTANT AREA.

ANALYTICAL CALCULATIONS

Page 7 of 9

Subject H_2 DIFFUSION IN CSB TUBE WITH 2 MCOS
 Originator AL PATUNAN Date 1/12/99
 Checker _____ Date _____

FOR LOWER SECTION OF CSB TUBE, ASSUME WELL MIXED
 BETWEEN TOP MCO AND TUBE PLUG

$$N = \frac{\dot{n}}{A'} = \frac{C D_{AB}}{z'} \ln \left(\frac{1-y_0}{1-y_1} \right)$$

$$\frac{\dot{n}}{A'} = \frac{P D_{AB}}{RT z'} \ln \left(\frac{1-y_0}{1-y_1} \right)$$

$$\ln \left(\frac{1-y_0}{1-y_1} \right) = \frac{\dot{n} RT z'}{A' P D_{AB}}$$

ANALYTICAL CALCULATIONS

Page 8 of 9

Subject H₂ DIFFUSION IN CSB TUBE WITH 2 MGUS
 Originator AL PAJUNEN Date 1/18/99
 Checker _____ Date _____

$$(1 - y_0) \exp\left\{-\frac{\dot{n}RTz'}{A'D_{AB}P}\right\} = 1 - y'$$

$$y' = 1 - (1 - y_0) \exp\left\{-\frac{\dot{n}RTz'}{A'D_{AB}P}\right\}$$

FOR THIS SECTION

$$\dot{n} = \frac{0.54}{2} = 0.27 \frac{\text{SMOL H}_2}{\text{H}}$$

$$D_{AB}P = 2.65 \times 10^7 \frac{\text{cm}^2 \cdot \text{atm}}{\text{H}}$$

$$T = 337 \text{ K}$$

$$A' = \pi (24 \times 2.54)(1 \times 2.54) = 486 \text{ cm}^2 \quad R = 82.06 \frac{\text{atm} \cdot \text{cm}^3}{\text{SMOL} \cdot \text{K}}$$

$$z' = 16 \times 12 \times 2.54 = 488 \text{ cm} \quad y_0 = 0.0068 \text{ FROM A 6}$$

$$y' = 1 - (1 - 0.0068) \exp\left\{-\frac{(0.27)(82.06)(337)488}{(486)(2.65 \times 10^7)}\right\}$$

$$= 1 - (1 - 0.0068) 0.9957$$

$$= 0.0071$$

ANALYTICAL CALCULATIONS

Page 4 of 9

Subject *H₂ DIFFUSION IN CSB TUBE WITH 2 MCDs*
 Originator *AL PATUNGA* Date *1/18/99*
 Checker _____ Date _____

SUMMARY OF RESULTS
(MOST CONSERVATIVE METHOD)

APPENDIX D: INDEPENDENT REVIEW

REVIEW PLAN

NOTE: Reviews requiring OCRWM QARD Document Review compliance, or OCRWM QARD Peer Review compliance shall complete all applicable sections of this plan.

1. PROJECT: SNF Project

2. SUBJECT OF REVIEW: The document under review (HNF-2155) establishes leak test acceptance criteria and helium backfill criteria for multi-canister overpacks (MCO) to support the SNF Project's combustible gas management strategy.

3. DOCUMENTS TO BE REVIEWED:

Document Title	Document Number	Rev. No. and Date
Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria (OCRWM)	HNF-2155	Rev 2, June 2000

4. SCOPE OF REVIEW: Check the appropriate review criteria boxes.

NOTE: All asterisk (*) criteria items SHALL be considered for reviews requiring OCRWM QARD Document Review compliance. All triangle (▼) items SHALL be included, as appropriate, for reviews requiring OCRWM QARD Peer Review compliance.

☒ Applicability*	☒ Documented and soundly based inferences and conclusions**
☒ Correctness*	☒ Uncertainty of results and impact if wrong**
☒ Technical adequacy*	☒ Consistent with and traceable to data
☒ Completeness*	☒ Data traceable to its origin
☒ Accuracy*	☒ Documentation being reviewed internally consistent
☒ Compliance with established requirements*	☐ Documentation being reviewed consistent with other documents listed for review
☒ Documented and soundly based assumptions**	☒ Correct application of software
☒ Alternate interpretations**	☐ List follow up reviews that may be needed
☒ Adequacy of requirements and criteria**	☒ Software verification documents
☒ Appropriateness and limitations of the methods and implementing documents used to complete the work under review**	☒ Software validation documents
☒ Adequacy of application**	☒ Adequacy of applicable codes and standards
☒ Accuracy of calculations**	

5. PURPOSE OF REVIEW: (List objectives to be achieved by this review.) In addition to providing an independent review of the overall document, the OCRWM QARD Document Review covered by this plan is intended to confirm that the leak test acceptance criteria, helium backfill criteria, and supporting calculations are adequate to ensure that the minimum amount of helium remaining within any MCO after 40 years of interim storage is adequate to maintain a positive pressure within that MCO at temperatures down to -31C.

Type of Review: Based on evaluation of the subject document against the criteria listed in Section 5.0 of AP 6-009-00, the document meets criteria (Sec 5.1.1.c and Sec 5.1.3) requiring an OCRWM QARD Document Review. Based on the criteria in Section 5.2 of the AP, the additional rigor of an OCRWM QARD Peer Review is not required.

6. REVIEWERS: Reviews requiring OCRWM QARD Document Review compliance shall attach a summary of each reviewer(s) experience. Add reviewer(s) technical qualifications and credentials that are recognized and verifiable to this summary for OCRWM QARD Peer Review compliance.

	Reviewer Name	Technical Expertise	Expected Level of Effort	Charge Code	Special Instructions
1	REVIEWER: Y. Justin Liu	Safety Analysis	As Required	N/A	Review includes all aspects of entire document, with exception that review of mathematical derivations is optional.
2	REVIEWER: M. J. Packer	Process Analysis	As Required	N/A	Review limited to mathematical derivations for Sec 7.3, Apndx C, and Apndx G.

7. REVIEW REQUIREMENTS: List all requirements applicable to the reviewer. NOTE: All reviews requiring OCRWM QARD Document or Peer Review compliance comments shall document comments on a RCR (A-6400-090.1).

In addition to providing comments on an RCR form, each reviewer is also required to complete a standard review checklist form (e.g., A-6002-359). Note that Mr. Liu is required to address all of the items on the checklist with the exception of the mathematical derivations, which are optional for him, whereas Mr. Packer is only required to address the mathematical derivations. Also note that Mr. Packer may confirm the mathematical derivations by any means he deems appropriate, including alternate calculations.

Sponsoring Manager Approval of Review Plan

Design Authority Concurrence of Review Plan

(Sign and date) J. R. Frederickson

6/2/2000

(Sign and date) L. H. Goldmann

I have read this review plan and confirm that my review addressed the scope/requirements listed in sections 6 & 7 above.

Y. Justin Liu Date 10/2/00

M. J. Packer Date 9/2/2000

1. Date September 27, 2000	2. Review No. na
3. Project No. na	4. Page 1 of 1

9. Location/Phone

MO-725, RM 104
372-0126

11. CLOSFD

Reviewer Point of Contact

Reviewer/Point of Contact
[Signature]
Author/Editor/Reviewer

[illegible]

REVIEW CHECKLIST

Document Reviewed:

HNF-2155, REV 2

MULTI-CANISTER OVERPACK COMBUSTIBLE GAS MANAGEMENT LEAK TEST ACCEPTANCE CRITERIA

Scope of Review:

THE SCOPE OF THE REVIEW IS DEFINED IN THE ATTACHED OCRWM QARD DOCUMENT REVIEW PLAN PER SECTION 4 (SCOPE OF REVIEW), PER THE SPECIAL INSTRUCTIONS LISTED IN ITEM 1 OF SECTION 6 (REVIEWS), AND PER THE REQUIREMENTS LISTED FOR MR. LIU IN SECTION 7 (REVIEW REQUIREMENTS).

Yes	No	NA	
☐	☐	☒	* Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☒	☐	☐	Problem completely defined.
☒	☐	☐	Accident scenarios developed in a clear and logical manner.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☒	☐	☐	Computer codes and data files documented.
☒	☐	☐	Data used in calculations explicitly stated in document.
☒	☐	☐	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivation checked including dimensional consistency of results.
☒	☐	☐	Models appropriate and used within range of validity or use outside range of established validity justified.
☒	☐	☐	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
☐	☐	☒	Software input correct and consistent with document reviewed.
☐	☐	☒	Software output consistent with input and with results reported in document reviewed.
☒	☐	☐	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
☒	☐	☐	Safety margins consistent with good engineering practices.
☒	☐	☐	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.
☒	☐	☐	Format consistent with appropriate NRC Regulatory Guide or other standards.
☐	☐	☒	* Review calculations, comments, and/or notes are attached.
☒	☐	☐	Document approved.

Y. JUSTIN LIU

Reviewer (Printed Name and Signature)

Date

*Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

REVIEW COMMENT RECORD (RCR)

1. Date	2. Review No.
September 27, 2000	na
3. Project No.	4. Page
na	1 of 1

5. Document Number(s)/Title(s) HNF-2155, Rev 2 (ECN 658200) <i>Multi-Canister Overpack Combustible Gas Management Leak Test Acceptance Criteria</i>	6. Program/Project/ Building Number Spent Nuclear Fuel	7. Reviewer M.J. Packer	8. Organization/Group Process Engineering	9. Location/Phone MO-285, RM B112 376-6625
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17. Comment Submittal Approval:

10. Agreement with indicated comment disposition(s)

11. CLOSED

Organization Manager (Optional)

Date

9/27/00

Reviewer/Print of Contact

Author/Originator

Date

9/27/00

Reviewer/Print of Contact

Author/Originator

12. Item

13. Comment(s)/Discrepancy(s) (Provide technical justification for the comment and detailed recommendation of the action required to correct/ resolve the discrepancy/problem indicated.)

14. Hold Point

15. Disposition (Provide justification if NOT accepted.)

16. Status

1

The subject document was reviewed per Section 4 (*Scope of Review*). per the special instructions listed in Item 2 of Section 6 (*Reviewers*), and per the requirements listed for Mr. Packer in Section 7 (*Review Requirements*) of the attached OCRM QARD Document Review Plan. In accordance with those instructions and requirements, Mr. Packer's review was limited to confirmation of the mathematical derivations via alternate calculations. The alternate calculations have been submitted to the SNF Project File under EDI 629044, *Review for HNF-2155, Rev. 2*. Results from the alternate calculations were in agreement with those of the subject document and no problems were identified.

Accepted

closed

9/27/00

REVIEW CHECKLIST

Document Reviewed:

HNF-2155 : MULTI-CANISTER OVERPACK COMBUSTIBLE GAS
MANAGEMENT LEAK TEST ACCEPTANCE CRITERIA

Scope of Review:

The scope of this review is limited to checking mathematical derivations, as noted below. See Appendix D for the overall document review.

Yes No NA

☐	☐	☒	* Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☐	☐	☒	Problem completely defined.
☐	☐	☒	Accident scenarios developed in a clear and logical manner.
☐	☐	☒	Necessary assumptions explicitly stated and supported.
☐	☐	☒	Computer codes and data files documented.
☐	☐	☒	Data used in calculations explicitly stated in document.
☐	☐	☒	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivation checked including dimensional consistency of results.
☐	☐	☒	Models appropriate and used within range of validity or use outside range of established validity justified.
☐	☐	☒	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
☐	☐	☒	Software input correct and consistent with document reviewed.
☐	☐	☒	Software output consistent with input and with results reported in document reviewed.
☐	☐	☒	Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
☐	☐	☒	Safety margins consistent with good engineering practices.
☐	☐	☒	Conclusions consistent with analytical results and applicable limits.
☐	☐	☒	Results and conclusions address all points required in the problem statement.
☐	☐	☒	Format consistent with appropriate NRC Regulatory Guide or other standards.
☐	☐	☒	* Review calculations, comments, and/or notes are attached.
☒	☐	☐	Document approved.

Review calculations/notes are documented on EDT 628529.

M. J. Packer
Reviewer (Printed Name and Signature)

2/01/00
Date

*Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

| APPENDIX E: ADDITIONAL REVIEW OF APPENDIX G

The helium temperature calculations of Appendix G were checked using a spreadsheet. The spreadsheet used a trapezoidal integration with the allowed temperature range divided into 80 equal steps. The graphs are shown below. They agree well with the calculated values presented in Appendix G.

Wall Temperature is 14 C

Paul R. Rasmussen
1-10-00

Wall Temperature is 26 C

APPENDIX F: MCO COOL DOWN ANALYSIS

SIMULATION OF MCO COOLDOWN AT CVDF

Mel Piepho, Ph.D.
Fluor Daniel Northwest, Inc.
Richland, Washington

Nov. 15, 1999

INTRODUCTION

The fuel and gas temperatures within a bounding MCO (bounding decay heat, surface reaction area and oxidation rate multipliers) during its cooldown period after drying at CVDF were calculated with version 1.3.2 of the HANSF code (SNF-3650, SNF-5226). The QA for this application of the HANSF code is attached, and the general QA is included in SNF-5226. The thermal model used is briefly described in the next section. The temperature and pressure plots for the cooldown period are attached.

THERMAL MODEL

As previously stated, the HANSF computer code (SNF-3650) was used to model the MCO's fuel and gas temperatures during the cooldown period. This time period takes place after the MCO passes the twenty-hour proof test for dryness that is required for a single scrap basket MCO (as opposed to the less conservative eight-hour proof test for an all fuel basket MCO). During the proof test, the fuel and gas temperatures increase over time due to the decay heat and low gas conductivity under vacuum conditions; hence, the fuel and gas are hotter at twenty hours than at eight hours. Although the bounding decay power (776 W) is only possible within MCOs that contain five fuel baskets of Mark IV fuel and no scrap baskets, the bounding decay heat MCO modeled for this evaluation contains one scrap basket and four fuel baskets. The bounding power of 776 W per MCO (HNF-SD-SNF-TI-015) is equivalent to about 155.2 W per fuel basket. The decay power of the scrap basket was adjusted upwards from 120 W to 155.2 W to match that of a maximum decay heat fuel basket. Furthermore, the extra heat capacity of the fuel basket compared to a scrap basket is added to the scrap basket. Hence, even though the simulations included the geometry and surface areas of a scrap basket, the decay heat and heat capacity of the scrap fuel basket was the same as for a fuel basket. In order to be conservative, the maximum gas temperature of the hottest fuel basket, which is the top fuel basket, was used to determine if the gas temperature of the MCO is cool enough ($< 50^{\circ}\text{C}$) after five hours.

The thermal model in the code includes thermal radiation, conduction, and natural convection heat transfer processes. The heat from the fuel inside the MCO transfers through the MCO wall to cooler water in the annulus between the cask and MCO. The fuel has decay heat, but very little chemical heat since the internal MCO water is essentially gone. The cask wall is stainless steel, about 7 in. thick. The annulus gap between the cask and MCO is about 0.6 in. wide and contains water until the cask is ready to be shipped from the CVDF to the CSB. In the fuel baskets, each fuel assembly has its own radiation view factor to other fuel assemblies, to the MCO wall, and to the center post of the MCO, for thermal radiation heat transfer. Micro convection heat transfer is also included in the thermal model, for heat transfer between each inner and outer fuel element of each fuel assembly, and between the fuel assemblies themselves. The scrap basket heat transfer model includes conduction and radiation in the scrap fuel, conduction from the scrap fuel to the copper fin, micro convection and radiation heat transfer from the outer fin to the MCO wall. The model also includes radiation and natural convection heat transfer from the top and bottom baskets to the inner MCO shield plug (lid) and to the MCO floor (bottom), respectively.

Since very little water (< 200 g) remains within a dry MCO, very little chemical heat is present. This analysis assumes 200 g of free water is still in the MCO in the cracks of fuel and cladding. This water is assumed to evaporate at a rate of 0.4 mg/s which is conservatively based on a vapor pressure increase of 0.4 kPa per hour. This represents the maximum acceptable rate of pressure rise (3 torr/hr) during the first pressure rebound test, per section 3.4.16 of the CVDF operations manual (SNF-2356). In addition, the helium gas supply is assumed to be contaminated with 0.5 vol% water vapor per the helium supply specification in the CVDF design requirements document (HNF-SD-SNF-DRD-002), which is conservative because the 0.5 vol% impurity inventory is more likely to be moist air than pure water vapor. The water vapor will chemically react with uranium and produce more heat, which will increase the cooling time.

Bounding MCO properties are documented in the project's technical databook (HNF-SD-SNF-TI-015). The most important thermal parameters for a dry MCO being cooled are:

- 1) decay power of 776 watts;
- 2) residual heat (heat capacity) in the fuel, MCO, and, cask;
- 3) annulus water temperature and flow rate.

The heat capacity (a measure of residual heat) is summarized below for each residual heat source included in the model.

Table 1: Heat Capacity Summary

Residual Heat Source	Heat Capacity (Joules/°C)
Cask Wall and Floor	7.78×10^6
Uranium Fuel and Cladding	9.03×10^5
Shield Plug and MCO Floor	3.95×10^5
MCO wall	3.30×10^5
Center Post, Long Access Tube, Support Posts, Basket Bottom Plates	2.92×10^5
Copper Scrap Basket Fins	2.56×10^4
TOTAL MCO & CASK	9.73×10^6

The cask wall and floor dominate the heat capacity of the combined MCO and cask. The uranium fuel and cladding dominate the combined mass, but represent less than 10% of the total heat capacity. The heat capacity of the support posts and basket bottom plates (2.5×10^5 J/°C), which are not explicitly defined in the model, has been conservatively added to the heat capacity of the center post and long access tube (4.2×10^4 J/°C). The center post and long access tube are located in the hottest and most difficult area of the MCO to cool. The heat capacity of the scrap basket fuel has also been increased to match the heat capacity of the fuel and cladding in a fuel basket as previously discussed.

The temperature of the cooling water in the analysis is 17°C at the point it enters the cask-MCO annulus, and the flow rate is 15 gpm. The flow rate is not a sensitive parameter and is not as important as the water temperature. If faster cooling rates are desired, the most effective way to achieve faster cooling is to lower the temperature of the cooling water. For example, increasing the flow rate from 15 gpm to 20 gpm would not increase cooling rates to any appreciable extent, but lowering the temperature from 17°C to 12°C would be very effective.

The annulus is modeled as five reservoirs of water containing a total of about 125 liters of water. All five reservoirs are initially at 50°C, which is the maximum annulus water temperature allowed (HNF-3553, Annex B). Water is injected into the bottom reservoir, located between the outside of MCO bottom and top part of cask floor, at about 15 gpm and 17°C. The bottom reservoir of water is connected to the reservoir between the MCO wall and cask wall by the bottom fuel basket. The next (third) reservoir is next to the fourth fuel basket, the fourth reservoir is next to the third fuel basket, and the fifth and last reservoir is next to the second fuel basket and scrap basket and is the largest reservoir in the model. Multiple reservoirs of the annulus water were modeled so that the axial temperature effects of the annulus are included. The top fuel basket will have warmer annulus water than the lower fuel baskets or MCO bottom. The water in each reservoir is uniformly mixed at all times. However, each reservoir is hotter than the preceding reservoir due to the annulus water heating up as it travels through the annulus. Since the annulus water is changed over about every 2 minutes with 17°C water, the axial temperature gradient along the height of the MCO annulus is fairly small after the first hour. The difference between the maximum (top) reservoir temperature and the inlet temperature is less than 3 C° after the first half (2.5 hours) of the minimum five hour time period required for the cool-down operation, and about 1.5 C° during the fifth and last hour of cooling operation.

SCENARIO BOUNDARY and INITIAL CONDITIONS

The bounding MCO is vacuum dried, which takes less than 20 hours, and then experiences a vacuum with no helium flow for another 20 hours, which is the proof of dryness test. After the proof test, cool water (17°C) is pumped into the MCO-cask annulus, which still contains water at 50°C. The flow rate of the cooling water is assumed to be 15 gpm. The process bay temperature is assumed to be very hot at 45.6°C (114°F) such that the cool flowing annulus water is the only effective cooling mechanism. The operations manual (SNF-2356) requires that a 15 gpm minimum flow rate be maintained, at a 15°C maximum chiller discharge temperature (to the cask/MCO supply piping), for a minimum of five hours. The slightly higher temperature of 17°C for the incoming cooling water used in the simulation provides an allowance for instrument error and temperature rise between the chiller discharge and the cask-MCO inlet.

RESULTS OF COOLING CASE

The scrap basket has the coolest fuel and gas of all the baskets in the MCO, even though it was given the same decay heat and heat capacity of a fuel basket. The scrap basket is cooler due to the copper fins, which have a high thermal conductivity, and due to thermal radiation losses to the MCO lid above it.

Since the scrap basket has cooler gas temperatures than the fuel baskets, the maximum fuel basket gas temperature was used as the performance measure for cooling in order to be conservative. The maximum and minimum fuel basket gas temperatures are shown in Table 2 for each hour of the five-hour cooling period. The hottest fuel basket is the top fuel basket (below the scrap basket) and coolest fuel basket is the bottom fuel basket. If the scrap basket were a fuel basket, it would not be hotter than the current top fuel basket due to radiation cooling to the MCO lid. Furthermore, five fuel baskets would have cooler initial temperatures due to only eight hours of proof test instead of twenty hours. The gas temperatures (and some fuel temperatures) for all MCO baskets are shown continuously versus time in Figures 1 and 2 for eight hours of cooling, even though only six hours have been allocated to the overall cool-down operation by the CVDF

operations manual (SNF-2356). The cooling performance period in this bounding analysis stops at five hours, which is necessary because the operations manual only requires that the minimum flow rate and maximum temperature discharge temperature be maintained for at least five of the six hours allocated to the cool-down operation. The MCO pressure, which is elevated due to applied helium pressure, is also shown in Figure 2. The heat transfer rate out of the MCO and the total (decay and chemical heat) heat rate generated within the MCO are plotted versus time in Figure 1. Most of the heat generation rate is the decay heat rate which is around 776 W with the chemical heat adding very little extra to achieve a heat rate slightly over 800 W (see Figure 1). The cooling rate is greater than 2000 W during the first hour of cooling and greater than 1300 W after around five hours. The heat rate out will be greater than the heat rate generated until the entire MCO is cooled to 17 °C, the temperature of the incoming annulus water.

Table 2: MCO Gas Temperatures Versus Time

Time (hrs)	Maximum Gas Temperature (°C) (Top Fuel Basket Temperature)	Minimum Gas Temperature (°C) (Bottom Fuel Basket Temperature)
0	67.0	66.2
2	59.8	58.2
3	53.1	53.3
4	50.7	48.9
5	48.8	47.1

After five hours of cooling with 17°C cooling water at 15 gpm, the maximum gas temperature (top fuel basket) is 48.8°C, the minimum gas temperature (bottom fuel basket) is 47.1°C. The average fuel basket gas temperature (for four fuel baskets) is about 48.2°C.

CODE QUALITY ASSURANCE

As mentioned previously, the general HANSF QA is documented in SNF-5226. However, the simulation here uses cooling water flowing in the annulus directly, whereas the general QA used either fixed temperature boundary conditions or stationary fluids (air or water) in the annulus. Hence, additional checking was performed and documented on the heat transfer effects of flowing annulus water. This work was performed by Fauske and Associates, Inc. (see Attachment 1). Based on this additional check and the general QA, the HANSF code was accepted for this cooling analysis with flowing cooling water entering the MCO-cask annulus.

Figure 1: Selected MCO Parameters Versus Time During Cooldown Process

COOLHXM: 17C-oxc.15gpm flow, 4 psigHE+.5% H_2O , 114 F Boy, 200 gm H_2O , 1LAW=3

Figure 2: Selected MCO Parameters Versus Time During Cooldown Process (cont.)

COOLHXHM: 17C-oxc.15gpm flow.4 psigHE+.5% H_2O . 114 F Boy. 200 gm H_2O . 1LAM=3

REFERENCES

HNF-3553, Annex B, 1999, *Cold Vacuum Drying Facility Final Safety Analysis Report*, Rev. 0, Fluor Daniel Hanford, Incorporated, Richland, WA.

SNF-5226, 1999, *Comparison Cases Simulated with HANSF 1.3.2 to Supplement Thermal Analyses Documented in HNF-SD-SNF-CN-023*, Rev 0, Fluor Daniel Hanford, Richland, WA.

HNF-SD-SNF-TI-015, 1998, *Spent Nuclear Fuel Project Technical Databook*, Rev 6, Fluor Daniel Hanford, Richland, WA.

HNF-SD-SNF-DRD-002, 1999, *Spent Nuclear Fuel Project Cold Vacuum Drying Facility Design Requirements*, Rev 4, Numatec Hanford Corporation, Richland, WA.

SNF-2356, 1999, *Spent Nuclear Fuel Project Cold Vacuum Drying Facility Operations Manual*, Rev 2, Numatec Hanford Corporation, Richland, WA.

SNF-3650, 1999, *HANSF 1.3.2 User's Manual*, Rev 2, Fluor Daniel Hanford, Richland, WA.

ATTACHMENT 1

Check on Validity of Heat Transfer Effects of Flowing Annulus Water With HANSF Code.

Fauske & Associates, Inc.

DATE: May 14, 1999

TO: Darrel R. Duncan, Dennis L. Sherrell, Melvin G. Piepho,
Martin G. Plys, Boro Malinovic

FROM: Sung Jin Lee

SUBJECT: Heat Transfer Coefficient for the Annulus Cooling Water

Laminar Flow

A 15 °C cooling water is introduced into the bottom of the annulus between the MCO wall and the cask at a rate of 0.94 Liter per second. The annulus water exits at the top of the MCO.

The hydraulic diameter is given by,

$$D_h = 2(r_o - r_i) = 2(0.3199m - 0.3046m) = 0.0306m$$

Flow area of the annulus is given by,

$$A = \pi(0.3199^2 - 0.3046^2) = 0.0300 m^2$$

Therefore, the velocity of the flow is given by,

$$V = \frac{0.94 \times 10^{-3} m^3/s}{0.0300 m^2} = 0.0313 m/s$$

The Reynolds number of the annulus flow is given by,

$$Re = \frac{D_h V}{\nu} = \frac{0.0306m \times 0.0313m/s}{\{1.6e-7@15^\circ C, 55.4e-8@50^\circ C\} m^2/s} = \{826@15^\circ C, 1729@50^\circ C\}$$

Since the Reynolds number is well below 2300, the flow is clearly a laminar flow.

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Laminar Flow Heat Transfer Coefficient

For a laminar flow through an annulus when the inner tube alone is heated, the corresponding Nusselt number is given by (W.M. Kays & M.E. Crawford, *Convective Heat and Mass Transfer*, second edition, McGraw-Hill, Inc., 1980, pp.98-101)

$$Nu = 5.43$$

Therefore, the corresponding heat transfer coefficient is given by

$$h = \frac{Nu \, k}{D_h} = \frac{5.43 \{0.591 @ 15^\circ C, 0.640 @ 50^\circ C\} W/m-K}{0.0306 m} = \{105, 114\} W/m^2-K$$

Thus, the average heat transfer coefficient is 110 W/m²-K.

HANSF Code Uses Natural Convection Heat Transfer Coefficient

Currently, the code considers only natural convection heat transfer between the MCO wall and the annulus coolant. The Nusselt number for a natural convection heat transfer is given by

$$Nu = 0.12 Pr^{0.33} Gr^{0.33}$$

where

$$Pr = \frac{\mu c_p}{k}$$

$$Gr = \frac{g \beta \Delta T L^3}{\nu^2}$$

The corresponding heat transfer coefficient is given by

$$h = \frac{Nu \, k}{L}$$

where L is the characteristic height of the wall.

For the COOLHX sequence, it was found that the natural convection heat transfer coefficient calculated by the code was about three times larger than the theoretical laminar flow heat transfer coefficient. The calculated temperature difference between the coolant in the annulus and the MCO wall was between one and two degrees K.

Multiplier to the Coolant Conductivity to Mimic Laminar Flow Convective Heat Transfer

Since the natural convection heat transfer coefficient is proportional to (conductivity)^{0.66}, a multiplier was applied to the conductivity so that the code calculated heat transfer coefficient is

close to $110 \text{ W/m}^2\text{-K}$. A multiplier of 0.055 seems to produce the desired heat transfer coefficient over the range of the entire cooling transient as following.

Time since the cooling started	Annulus water temperature	MCO wall temperature	Gr	Heat transfer coefficient
1 hr.	18.7°C	21.2°C	$0.16\text{e}12$	$121 \text{ W/m}^2\text{-K}$
2 hr.	17.5°C	19.7°C	$0.15\text{e}12$	$116 \text{ W/m}^2\text{-K}$
3 hr.	16.8°C	18.8°C	$0.13\text{e}12$	$113 \text{ W/m}^2\text{-K}$
4 hr.	16.3°C	18.2°C	$0.13\text{e}12$	$111 \text{ W/m}^2\text{-K}$
5 hr.	16.0°C	17.8°C	$0.12\text{e}12$	$109 \text{ W/m}^2\text{-K}$

Limitation of the Approach

The laminar flow convective heat transfer was fairly well simulated in HANSF code by applying appropriate multiplier to the coolant conductivity. However, the assumption that the coolant has uniform temperature distribution in the annulus might not be a good one since the axial height of the MCO spans almost 4 m. The coolant enters the bottom of the annulus at 15°C , but by the time it reaches the top it will get significantly warmer, reducing its effectiveness to cool the top scrap basket. In order to model it accurately, the annulus needs to be axially nodalized to represent different coolant temperatures at various elevations.

| **APPENDIX G: MINIMUM REQUIRED BACKFILL GAS EQUILIBRATION TIME**

CALCULATION OF MINIMUM TIME REQUIRED FOR HELIUM TO REACH THE ALLOWABLE BACKFILL TEMPERATURE RANGE

INTRODUCTION

A concern has been expressed that, unless a substantial process hold time is imposed between the final helium backfill gas addition and measurement of the backfill pressure, or unless the temperature of the CVDF's helium supply piping is controlled within some specified range, or both, the backfill helium may be introduced into the MCO at temperatures that are significantly hotter or colder than the average fuel temperature within the MCO, resulting in erroneous pressure readings that are either higher or lower (most probably lower) than they would be after the helium's temperature had time to equilibrate with MCO internals. Depending on: 1) fuel temperatures within a given MCO immediately after the final backfill gas addition, 2) the amount of helium that was already within the MCO prior to the final backfill gas addition, 3) the temperature of the helium that is delivered to the MCO through the facility piping, and 4) the required degree of temperature approach, it might, or might not, be necessary to trace heat the helium supply piping and/or impose a process hold between introduction of the backfill helium and measurement of the final backfill pressure in order to ensure that the temperature of the freshly introduced helium is within the allowable range when the final backfill pressure is measured and recorded.

SUMMARY OF CURRENT REQUIREMENTS

Based on sections 4.3, 4.4, 5.1.1.1.3, 5.1.1.1.4, 7.1.2, and Appendix F of this document (HNF-2155) the following requirements apply to the MCO cooldown and backfill operations.

Backfill Gas Temperature

The backfill temperature requirement is that the average gas temperature within the MCO can be proven to have been somewhere between 0°C and 50°C at the time the backfill pressure was measured.

The CVDF is not required to measure MCO temperatures during the cooldown operation. The worst case low end of the allowable range was taken as 0°C because it is impossible to circulate colder water without adding antifreeze. The worst case high gas temperature was determined analytically (see Apndx F), based on completion of the cooldown procedure specified in the operations manual (SNF-2356). The cooldown analysis predicts a 48°C average gas temperature, which is then rounded up to 50°C. The room temperature is taken as the worst case high temperature (114°F) listed for the site (PNNL-11471).

The following process conditions must be met to support the cooldown analysis:

- 1) The MCO must be refilled with helium (following the final pressure rise test) and maintained at a positive gage pressure (14.7 psia or higher);
- 2) Cooling water must be circulated at a minimum flow rate of 15 gpm;
- 3) The tempered water discharge temperature must be maintained at or below 15 °C [the analysis conservatively assumes a 17°C maximum Cask/MCO annulus inlet temperature]; and
- 4) The above conditions must be maintained for at least five hours (not required to be contiguous) of the six hour period that the operations manual allocates to cooldown.

Backfill Gas Pressure

The backfill pressure requirement is that the actual backfill pressure (not the gage reading) can be proven to have been somewhere between 9.5 psig and 12.5 psig, after all corrections for precision, calibration errors and/or drift that may be discovered after the fact, etc.

The CVDF operations manual (SNF-2356) ensures that the above requirement will be met by stipulating that the MCO be backfilled to 11 ± 0.5 psig.

ANALYTICAL STRATEGY

The following rational and associated calculations assume that the helium temperature will NOT be controlled as it is supplied to the MCO. Note that it would probably be possible to perform alternate calculations to show that helium could not possibly be delivered to MCOs at temperatures outside of the acceptable backfill range, based on a worst case high flow rate through the CVDF's piping system, and given an appropriate range of possible CVDF building temperatures.

Instead, the strategy is to determine how much time, if any, must be allowed for the temperature of the freshly introduced helium to approach MCO temperatures before the final backfill pressure is recorded. The attached analysis is very simplified and, therefore, very conservative in order to avoid expending the time and money that would be required to develop a detailed analytical model (typical of that used for Appendix F) and run it for all of the possible cases. For instance, instead of looking at what would happen to the helium on its way through all the building plumbing, the attached analysis simply assumes a -31°C worst case low helium inlet temperature that is based on the worst case low temperature for the Hanford site (PNNL-11471). And instead of having it flow down through the MCO's long dip tube (as it must), the analysis has it instantaneously materialize inside the MCO.

Helium Inlet Temperature Range: -31°C to 100°C

The -31°C worst case low helium inlet temperature is the worst case low (-23°F) listed for the Hanford site (PNNL-11471), with no credit taken for heat from the piping.

The 100°C worst case high helium inlet temperature is assumed because that is plainly conservative. While helium will gain some heat as it expands from the tube trailer into the CVDF's distribution piping, that would only translate into an additional 10 to 15°C, depending on tube trailer pressure. The additional heat accrues from the fact that the tube trailer's -31°C worst case low temperature is well above helium's Joule-Thomson inversion temperature.

Maximum Allowable Approach Temperature Differential: 50 C Deg

In order to determine how much equilibration time must be allowed, it is first necessary to establish an acceptable temperature range for the freshly introduced helium at the time the pressure is measured (i.e., to establish the required "approach"). The following calculations are based on a 50 C deg approach: 1) because the maximum and minimum helium inventories developed in sections 7.1.2.3.1 and 7.1.2.1.1 of this document (HNF-2155) are based on a 0°C to 50°C range for the average gas temperature within the MCO at the time the backfill pressure is measured; and 2) because it would be impossible for the average gas temperature within the MCO to fall outside of that temperature range if the freshly introduced gas has at least achieved a sufficient approach to make it into that range, even though it's temperature may still differ from the average gas temperature by up to 50 C° (i.e., the difference between 0°C new gas and 50°C existing gas, or conversely, between 50°C new gas and 0°C existing gas.)

Given the above 50 C° approach criterion, it doesn't matter that the "true" backfill pressure might have been higher or lower if sufficient hold time were to have been allowed for the fresh gas to come completely into equilibrium with the rest of the MCO before the backfill pressure was measured. The backfill pressure reading will automatically be valid, as long as the fresh helium has made it into the range between 0°C and 50°C by the time the pressure is measured

Heat Transfer Surfaces: MCO Wall Only

The calculations are based on a simplified model that only takes credit for the surface area of the MCO wall, which constitutes only a small fraction of the surface area within an MCO. This approach is particularly conservative with respect to the warmup time for very cold helium, which happens to be the limiting case (25 seconds for the minimum warmup time, versus under 15 seconds for the minimum cooldown time).

MCO Wall Temperature for Warming -31°C Helium: 7°C

The 7°C wall temperature used to calculate the time required to warm -31°C helium up to the 0°C minimum allowable backfill temperature is based on a zero decay heat MCO supplied with cooling water at a temperature of 7°C, which is itself conservatively based on the 45°F (7.2°C) setpoint of the CVDF's Chilled Water System (SNF-3086), which supplies chilled water to the secondary side(s) of the Tempered Water System's heat exchanger(s). The 7°C worst case low wall temperature is conservative because it includes no allowance for decay heat or room heat input to the chilled water piping, tempered water piping, and cask.

MCO Wall Temperature for Cooling 100°C Helium: 33°C

The 33°C wall temperature used to calculate the time needed to cool the 100°C helium down to the 50°C maximum allowable backfill temperature is based on the 20°C wall temperature predicted by the calculations in Appendix F, with an additional 13°C allowed. This provides the overall analysis with a $\pm 13^\circ\text{C}$ range on either side of the predicted 20°C wall temperature.

Helium Inventory Already Within MCO Prior to Backfill Operation: 22.6 mol

No MCO will contain less than 22.6 mol of helium prior to conduct of the MCO backfill operation. The 22.6 mol initial helium inventory is based on a 500 L MCO that is maintained at a minimum pressure of 1.2 atmospheres (3 psig) during the five hour cooldown operation, as specified by the CVDF Operations Manual (SNF-2356), and on the 50°C worst case high average MCO gas temperature calculated for the backfill operation (see Appendix F of this document):

$$PV = nRT; n_{\text{pre-backfill}} = PV/RT = \text{minimum gas inventory prior to backfill, mol};$$

$$n_{\text{pre-backfill}} = (1.2 \text{ atm})(500 \text{ L}) / [(0.08206 \text{ L atm/mol K})(323 \text{ K})] = 22.6 \text{ mol}.$$

While this analysis conservatively takes no credit for the heat capacity of the helium that is already within the MCO (i.e., it assumes the MCO is completely evacuated and then has the backfill gas instantly "materialize" within the MCO), it does take credit for the initial inventory to the extent that it only adds the molar equivalent of 1 atm to the MCO, whereas the

minimum backfill pressure is 1.65 atm and the maximum backfill pressure is 1.85 atm. However, this approach would still be conservative even if the analysis did take credit for the heat capacity of the pre-backfill helium inventory because the final pressure would be 1.2 atm (initial) plus 1 atm (added) = 2.2 atm, which exceeds the 1.85 atm maximum allowable backfill pressure and, therefore, represents a larger quantity of helium than could possibly be introduced during any acceptable backfill operation.

RESULTS AND CONCLUSIONS

The attached calculations predict a 25 second warmup time for -31°C helium. The predicted cooldown time for 100°C helium is under 15 seconds. While the calculations do indicate the need for a 25 sec (worst case) process hold time for freshly introduced helium, there is no need to officially impose a hold time for the following reasons:

- 1) per the MCO cooldown procedure specified in the operations manual (SNF-2356), 2/3 of the final backfill inventory will already have been in place for hours by the time the final backfill pressure is established (the procedure maintains the MCO at 3 psig, or 1.2 atm);
- 2) it will probably take longer than 25 seconds to achieve the final backfill pressure (despite the fact that the pressure reading is recorded automatically every second or so) because the physical arrangement of the MCO's helium supply requires that the last few portions of the backfill gas be added in small increments to avoid overshoot. The MCO is restricted to one open port and one particular leg of the CVDF helium supply piping at this point in the process, which, for a number of reasons, makes it difficult to remove excess helium.

REFERENCES

- PNNL-11471, *Hanford Site Climatological Data Summary 1996 With Historical Data*, Pacific Northwest National Laboratory, (1996).
- SNF-2356, Rev. 3, *Spent Nuclear Fuel Project Cold Vacuum Drying Facility Operations Manual*, Fluor Hanford, Inc., Richland, WA, 2000.
- SNF-3086, Rev 1, *Cold Vacuum Drying Facility Chilled Water System Design Description*, DE&S Hanford Inc., Richland, WA, 1999.
- Welty, James R., Charles E. Wicks, and Robert E. Wilson, *Fundamentals of Momentum, Heat and Mass Transfer*, John Wiley & Sons, Inc. New York, NY, 1969.

HELIUM TEMPERATURE IN AN MCO

DIMENSIONLESS PARAMETERS

$$Nu_L = \text{AVERAGE NUSSLETT NUMBER} = \frac{hL}{K} \quad \text{SUCH THAT } q = hA(T_w - T_G)$$

$$Gr_L = \text{AVERAGE GRASHOF NUMBER} = \frac{g L^3 (T_w - T_G)}{\nu^2 T_G} \quad \frac{\frac{\text{ft}}{\text{sec}^2} \frac{\text{ft}^3}{\text{sec}^2} \frac{^\circ\text{R}}{\text{ft}^2}}{\frac{\text{ft}^4}{\text{sec}^2} \frac{^\circ\text{R}}{\text{ft}^2}}$$

Pr : PRANDTL NUMBER ~ 0.7 FOR He AT 0 TO 300 $^\circ\text{F}$.

For He @ 1 atm (APPENDIX I of WILSON, WICKS & WILSON)

$T(^{\circ}\text{F})$	$C_p (\text{BTU/lbm}^{\circ}\text{F})$	$\nu (\text{ft}^2/\text{sec})$	$K (\frac{\text{BTU}}{\text{in}^2\text{-ft}^{\circ}\text{F}})$
0	1.24	1.03×10^{-3}	0.0784
30	1.24	1.14×10^{-3}	0.0818
60	1.24	1.25×10^{-3}	0.0852
80	1.24	1.32×10^{-3}	0.0872
100	1.24	1.41×10^{-3}	0.0892
150	1.24	1.63×10^{-3}	0.0937

WELF, WICKS & WILSON (P. 339, Eqs. 20-15 & 20-16) PROVIDES A CORRELATION FOR HEAT TRANSFER FROM VERTICAL SURFACES OF

$$Gr_L Pr < 10^9 \quad Nu_L = 0.555 (Gr_L Pr)^{1/4}$$

$$Gr_L Pr > 10^9 \quad Nu_L = 0.0210 (Gr_L Pr)^{2/5}$$

T_b ANALYZE, ASSUME $\nu \sim \text{CONST} = 1.25 \times 10^{-3} \text{ ft}^2/\text{sac}$

$$\Rightarrow \text{SAMPLE } Gr_L Pr = \frac{g L^3 (T_w - T_b)}{\nu^2 T_b} Pr$$

$$\text{IF } T_w = 25^\circ\text{C} = 77^\circ\text{F} = 587^\circ\text{R}$$

$$T_b = 0^\circ\text{C} = 32^\circ\text{F} = 492^\circ\text{R}$$

$$= \frac{(32.2 \text{ ft/sac}^2) (13 \text{ ft})^3 (45 \text{ R})}{(1.25 \times 10^{-3})^2 (492 \text{ R})} (0.7)$$

$$= 2.9 \times 10^9 \Rightarrow \text{TURBULENT FLOW REGIME, BUT REDUCES TO LAMINAR REGIME AS } T_b \rightarrow T_w.$$

START BY ASSUME ALWAYS IN LAMINAR REGIME FOR MOST CONSERVATIVE ESTIMATE OF HEAT TRANSFER RATE.

$$hA(T_w - T_b) = \dot{m} c_p \frac{dT_b}{dx}$$

$$\frac{hL}{k} = 0.555 (Gr_L Pr)^{1/4}$$

$$h = 0.555 \frac{k}{L} Pr^{1/4} \left(\frac{g L^3 (T_w - T_b)}{\nu^2 T_b} \right)^{1/4}$$

$$= 0.555 \frac{k}{L} \left(Pr \frac{g L^3}{\nu^2} \right)^{1/4} \left(\frac{T_w - T_b}{T_b} \right)^{1/4}$$

$$= a$$

$$a \left(\frac{T_w - T_c}{T_c} \right)^{1/4} A (T_w - T_c) = M_g C_p \frac{dT_c}{dt}$$

$$n = \frac{PV}{RT}$$

$$\frac{a A}{M_g C_p} \int_0^t dt = \int_{T_0}^{T_c} \frac{T_c^{1/4}}{(T_w - T_c)^{5/4}} dT_c$$

$$t = \frac{M_g C_p}{a A} \int_{T_0}^{T_c} \frac{T_c^{1/4}}{(T_w - T_c)^{5/4}} dT_c$$

For Gas Cooling

$$h A (T_c - T_w) = M_g C_p \left(- \frac{dT_c}{dt} \right)$$

$$h = a \left(\frac{T_c - T_w}{T_c} \right)^{1/4}$$

$$a \left(\frac{T_c - T_w}{T_c} \right)^{1/4} A (T_c - T_w) = M_g C_p \left(- \frac{dT_c}{dt} \right)$$

$$t = - \frac{M_g C_p}{a A} \int_{T_0}^{T_c} \frac{T_c^{1/4}}{(T_c - T_w)^{5/4}} dT_c$$

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS

Estimate of Helium gas heating in an MCO with Constant Wall Temperature
Laminar Convective Heat Transfer Regime

Helium properties:

Plotting Points: $i := 0..35$

$$Pr := 0.7 \quad v := 0.00125 \text{ ft}^2/\text{sec} \quad Cp := 1.24 \text{ BTU/lbm-F}$$

$$k := 0.085 \text{ BTU/hr-ft-F}$$

MCO geometry:

$$P := 1 \text{ atm} \quad Vol := 500 \text{ L} \quad T_{mass} := 0 + 273 \text{ K}$$

$$M_{he} := 4 \cdot \frac{(P \cdot Vol)}{(0.082 \cdot T_{mass} \cdot 454)} \quad M_{he} = 0.197 \text{ lbm}$$

$$D := 2 \text{ ft}$$

$$L_{mco} := 13 \text{ ft}$$

$$A_{mco} := \pi \cdot D \cdot L_{mco} \quad A_{mco} = 81.681 \text{ ft}^2$$

$$g_{cnst} := 32.2 \text{ ft/sec}^2$$

$$a := 0.555 \cdot \frac{k \cdot \left[\frac{Pr \cdot (g_{cnst} \cdot L_{mco}^3)}{v^2} \right]^{\frac{1}{4}}}{L_{mco}} \quad a = 1.531 \text{ BTU/hr-ft}^2\text{-F}$$

$$T_{wallC} := 7 \text{ C} \quad T_{wall} := 1.8 \cdot T_{wallC} + 492 \quad T_{wall} = 504.6 \text{ R}$$

$$T_{0C} := -31 \text{ C} \quad T_0 := 1.8 \cdot T_{0C} + 492 \quad T_0 = 436.2 \text{ R}$$

$$TGC_i := T_{0C} + i$$

$$TG_i := 1.8 \cdot TGC_i + 492$$

$$f(T) := \frac{T^{\frac{1}{4}}}{(T_{wall} - T)^{\frac{5}{4}}}$$

$$Int_i := \int_{T_0}^{TG_i} f(T) dT$$

$$timehr_i := \frac{[M_{he} \cdot Cp \cdot (Int_i)]}{a \cdot A_{mco}} \text{ hr}$$

$$timesec_i := 3600 \cdot timehr_i \text{ sec}$$

Helium Gas Heating in an MCO based on Constant MCO Wall Temperature
MCO Wall at 7 C and Initial Gas Temperature at -31 C, Assumes Laminar
Free Convection at MCO Wall.

Estimate of Helium gas cooling in an MCO with Constant Wall Temperature
Laminar Convective Heat Transfer Regime

Helium properties:

Plotting Points: $i := 0..65$

$$Pr := 0.7 \quad \nu := 0.00125 \text{ ft}^2/\text{sec} \quad Cp := 1.24 \text{ BTU/lbm-F}$$

$$k := 0.085 \text{ BTU/hr-ft-F}$$

MCO geometry:

$$P := 1 \text{ atm} \quad Vol := 500 \text{ L} \quad T_{mass} := 50 + 273 \text{ K}$$

$$M_{he} := 4 \cdot \frac{(P \cdot Vol)}{(0.082 \cdot T_{mass} \cdot 454)} \quad M_{he} = 0.166 \text{ lbm}$$

$$D := 2 \text{ ft}$$

$$L_{mco} := 13 \text{ ft}$$

$$A_{mco} := \pi \cdot D \cdot L_{mco} \quad A_{mco} = 81.681 \text{ ft}^2$$

$$g_{cnst} := 32.2 \text{ ft/sec}^2$$

$$a := 0.555 \cdot \frac{k \cdot \left[Pr \cdot \frac{(g_{cnst} \cdot L_{mco}^3)}{\nu^2} \right]^{\frac{1}{4}}}{L_{mco}} \quad a = 1.531 \text{ BTU/hr-ft}^2\text{-F}$$

$$T_{wallC} := 33 \text{ C} \quad T_{wall} := 1.8 \cdot T_{wallC} + 492 \quad T_{wall} = 551.4 \text{ R}$$

$$T_{0C} := 100 \text{ C} \quad T_0 := 1.8 \cdot T_{0C} + 492 \quad T_0 = 672 \text{ R}$$

$$TGC_i := 100 - i$$

$$TG_i := 1.8 \cdot TGC_i + 492$$

$$f(T) := \frac{T^{\frac{1}{4}}}{(T - T_{wall})^{\frac{5}{4}}}$$

$$Int_i := \int_{T_0}^{TG_i} f(T) dT$$

$$timehr_i := \frac{-[M_{he} \cdot Cp \cdot (Int_i)]}{a \cdot A_{mco}} \text{ hr}$$

$$timesec_i := 3600 \cdot timehr_i \text{ sec}$$

Helium Gas Cooling in an MCO based on Constant MCO Wall Temperature
MCO Wall at 33 C and Initial Gas Temperature at 100 C, Assumes Laminar
Free Convection at MCO Wall.

| **APPENDIX H: INDEPENDENT REVIEWER RESUMES**

YIH JUSTIN LIU
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Professional Experience:

XWEST COMPANY, Richland, WA

1998 - Present

Consulting Engineer (1998 - Present)

- Develop Safety Analysis Reports and Topical Report for Hanford Spent Nuclear Fuel Project.
- Perform facility hazard assessment, and safety analysis.
- Develop fault trees and event trees for accident frequency determination.

PACIFIC GAS AND ELECTRIC COMPANY, San Francisco, CA

1980 - 1998

Consulting Engineer (1997 - 1998)

- Provide consulting services in the areas of engineering, problem solving, licensing, and project management in Nuclear Power Generation.
- Responsible for dose analysis and shielding calculations.
- Participated in a design basis reconstruction project.
- Performed assessment as required by the NRC of the effectiveness of engineering support activities.
- Westinghouse Owners Group (WOG) Analysis Subcommittee member.

Assistant Project Developer (1996 - 1997)

- Developed a 2 x 750 MW power plant.
- Coordinated the Feasibility Study.
- Developed the Construction Plan and the Environmental Impact Statement for the plant.
- Negotiated and developed the Power Purchase Agreement with the power company.

Senior Mechanical Engineer (1993 - 1996)

- Managed the Nuclear Analysis Group of seven people with responsibility for developing and performing deterministic steady state and transient analyses which include nuclear analysis, fuel performance analysis, core thermal hydraulic analysis, system analysis and containment analysis.
- WOG Analysis Subcommittee member.
- Electric Power Research Institute (EPRI) Severe Accident Program Committee member.
- American Nuclear Society Reactor Safety Program Committee member.

Senior Nuclear Generation Engineer (1990 - 1993)

- Managed the Integrated Safety Assessment Group of 15 people with responsibility for: (1) coordinating the performance of all safety analysis and maintaining the plant safety analysis design basis, (2) performing deterministic analysis and probabilistic risk assessment, and (3) performing integrated safety reviews.
- EPRI Safety & Reliability Task Force member.

Nuclear Generation Engineer (1987 - 1990)

- Responsible for developing and conducting the safety analysis training programs.
- Developed safety analysis procedures which include computer code v&v procedures, and interface procedures.
- Resolved safety valve issues.
- Participated in the negative flux rate trip elimination program.
- Performed power uprating study.
- Provided responses to generic letters on IPE and loss of RHR.
- Emergency Response analytical support manager.

YIH JUSTIN LIU

Page Two

Acting Senior Engineer (1986 - 1987)

- Managed Analysis Group of 20 people responsible for in-house reload design development.
- Provided analytical responses to anomalous plant conditions and to emergency situations such as mid-loop operation and plant cooldown transient.
- Provided technical support for plant operations such as PORV stroke time relaxation, Appendix G curve update, emergency drill scenario development, and simulator benchmark.
- Performed and coordinated analyses for engineering design such as BIT elimination, accident analyses for PRA, criticality calculations LOCA and SGTR analyses, and trip reduction study.

Nuclear Generation Engineer (1981 - 1986)

- Developed safety analysis capabilities which include core thermal hydraulic and NSSS computer models, comparison of code results with plant data, and sensitivity study.
- Determined RCP trip setpoint.
- Performed thermal-hydraulic analysis to predict startup test.
- Developed various department procedures.

Nuclear Generation Engineer (1980 - 1981)

- Coordinated specialized studies relating to operation and licensing such as radiation shielding review and degraded core rule-making issue.
- Provided staff support to the VP of Nuclear Power Generation.

COMBUSTION ENGINEERING, INC., Windsor, CT

1979 - 1980

Senior Nuclear Engineer

- Engaged in new plant design and licensing.
- Performed reload safety calculations.
- Responsible for the development of on-line monitoring/protection thermal hydraulic software for San Onofre-2.
- Developed statistical analysis methods for identifying thermal margins.

NORTHEAST UTILITIES SERVICE COMPANY, Hartford, CT

1977 - 1979

Nuclear Engineer

- Engaged in operating plant technical support activities to resolve regulatory, design, safety, and operational issues.
- Scope included core thermal hydraulic and neutronic analysis as well as fuel performance and NSSS safety analysis.
- Developed in-house safety and fuel performance analysis capabilities.

STONE AND WEBSTER ENGINEERING CORPORATION, Boston, MA

1974 - 1977

Mechanical Engineer

- Engaged in the Millstone and PECO nuclear power plant projects.
- Responsible for the pipe rupture accident analysis and stress analysis.

Education:

Massachusetts Institute of Technology, Cambridge, MA

Engineer's Degree in Nuclear Engineering, 1977

Master of Science Degree in Nuclear Engineering, 1977

Research Assistant - Developed methods for steady state thermal hydraulic analysis.

Tufts University, Medford, MA

Master of Science Degree in Engineering Design, 1976

National Taiwan University, Taipei, Taiwan

Bachelor of Science Degree in Mechanical Engineering, 1970

Professional Registration:

Professional Engineer, Engineering, Connecticut

Michael Packer, PE

EXPERIENCE

Engineer I, Spent Nuclear Fuel Project: Oct 1996/Oct 2000

DUKE ENGINEERING & SERVICES/ FLUOR HANFORD, INC., RICHLAND, WASHINGTON

Full-time employee for the spent nuclear fuel cleanup project. Provided design analysis and technical support for dry, highly radioactive fuel storage, radioactive sludge characterization, and water treatment system safety efforts.

Sludge characterization efforts included calculations of radionuclide activities and chemical constituent mass amounts in the sludge expected to be fed to a nitric acid dissolution process. Provided detailed heat transfer analysis of storing heat generating radioactive sludge in a water-submerged basin pit area.

Dry fuel storage efforts included calculations to determine oxygen, helium, and hydrogen gas concentrations in vessels during assorted treatment processes.

Senior Engineer, Spent Nuclear Fuel Project: March 1994/Oct 1996

WESTINGHOUSE HANFORD COMPANY, RICHLAND, WASHINGTON

Full-time employee for the spent nuclear fuel cleanup project. Provided design and development work for radioactive sludge retrieval processes. Designed a new manual system to retrieve radioactive sludge from the basin floor.

Developed and tested an eductor system to optimize a sludge pump system destined for submerged basin area. This eductor system is the precursor of the automated system eventually destined to be installed in the year 2000.

Project Engineer, Projects Department: July 1989/March 1994

WESTINGHOUSE HANFORD COMPANY, RICHLAND, WASHINGTON

Managed Plutonium Finishing Plant construction projects including design, procurement, construction, scheduling and estimating.

EDUCATION

B. S. Chemical Engineering, 1988

WASHINGTON STATE UNIVERSITY, PULLMAN, WASHINGTON

M. S. Chemical Engineering, 1997

WASHINGTON STATE UNIVERSITY, PULLMAN, WASHINGTON

State of Washington Professional Engineer License No. 37081

COMPUTER SKILLS

Experienced user with MacIntosh, UNIX, and IBM platforms. Software experience includes DOS, EXCEL, FORTRAN, MATHCAD and MATLAB.

PUBLICATIONS

Master's Thesis: Multivariate Statistical Process Monitoring Using Principal Components Analysis in Plasma Etch Process.