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ENGINEERING CHANGE NOTICE

Page 1 of 2

1. ECN 637183

Proj. ECN

2. ECN Category (mark one)	3. Originator's Name, Organization, MSIN, and Telephone No.	4. USQ Required?	5. Date
Supplemental [ ] Direct Revision [x] Change ECN [ ] Temporary [ ] Standby [ ] Supersedure [ ] Cancel/Void [ ]	M.G. Piepho, Nuclear Safety, R3-26, 372-8009	[ ] Yes [X] No	7/17/98
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[ ] Yes (fill out Blk. 12b) [X] No (NA Blks. 12b, 12c, 12d)	N/A	N/A Design Authority/Cog. Engineer Signature & Date	N/A Design Authority/Cog. Engineer Signature & Date

13a. Description of Change

13b. Design Baseline Document? [X] Yes [ ] No

Total rewrite to incorporate new Cold Vacuum Drying Facility and Multicanister Overpack design, new data, new model, and new cases.

14a. Justification (mark one)

Criteria Change	[X]	Design Improvement	[ ]	Environmental	[ ]	Facility Deactivation	[ ]
As-Found	[ ]	Facilitate Const	[ ]	Const. Error/Omission	[ ]	Design Error/Omission	[ ]

14b. Justification Details

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16. Design Verification Required
[ ] Yes
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17. Cost Impact

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Additional	[ ] $	Additional	[ ] $
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18. Schedule Impact (days)
Improvement [ ]
Delay [ ]

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.

SDD/DD	[] N/A	Seismic/Stress Analysis	[] N/A	Tank Calibration Manual	[]
Functional Design Criteria	[]	Stress/Design Report	[]	Health Physics Procedure	[]
Operating Specification	[]	Interface Control Drawing	[]	Spares Multiple Unit Listing	[]
Criticality Specification	[]	Calibration Procedure	[]	Test Procedures/Specification	[]
Conceptual Design Report	[]	Installation Procedure	[]	Component Index	[]
Equipment Spec.	[]	Maintenance Procedure	[]	ASME Coded Item	[]
Const. Spec.	[]	Engineering Procedure	[]	Human Factor Consideration	[]
Procurement Spec.	[]	Operating Instruction	[]	Computer Software	[]
Vendor Information	[]	Operating Procedure	[]	Electric Circuit Schedule	[]
OM Manual	[]	Operational Safety Requirement	[]	ICRS Procedure	[]
FSAR/SAR	[]	IEFD Drawing	[]	Process Control Manual/Plan	[]
Safety Equipment List	[]	Cell Arrangement Drawing	[]	Process Flow Chart	[]
Radiation Work Permit	[]	Essential Material Specification	[]	Purchase Requisition	[]
Environmental Impact Statement	[]	Fac. Proc. Samp. Schedule	[]	Tickler File	[]
Environmental Report	[]	Inspection Plan	[]		[]
Environmental Permit	[]	Inventory Adjustment Request	[]		[]

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
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21. Approvals

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Cog. Mgr.	R.P. Omberg	7/17/98	QA		
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Thermal Analysis of Cold Vacuum Drying of Spent Nuclear Fuel

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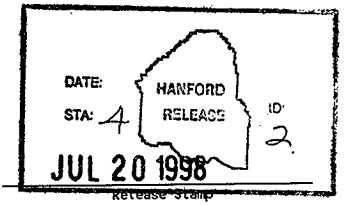
Abstract: The thermal analysis examined transient thermal and chemical behavior of the Multicanister Overpack (MCO) container for a broad range of cases that represent the Cold Vacuum Drying (CVD) processes. The cases were defined to consider both normal and off-normal operations at the CVD Facility for an MCO with Mark IV N Reactor spent fuel in four fuel baskets and one scrap basket. This analysis provides the basis for the MCO thermal behavior at the CVD Facility for its Phase 2 Safety Analysis Report (revision 4).



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THERMAL ANALYSIS OF COLD VACUUM DRYING OF SPENT NUCLEAR FUEL

HNF-SD-SNF-CN-023
Revision 1

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Richland, Washington

Prepared for

DE&S Hanford, Incorporated
Richland, Washington

July 1998

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THERMAL ANALYSIS OF COLD VACUUM DRYING OF SPENT NUCLEAR FUEL

EXECUTIVE SUMMARY

This report documents the analysis of transient thermal and chemical behavior of the multi-canister overpack (MCO) for a broad range of cases postulated to occur during cold vacuum drying. To perform this analysis, the HANSF code[1] and its previous input[2] were updated and new models were developed for both normal operation and off-normal operation of the cold vacuum drying processes. More off-normal cases were run than normal operation cases in order to determine the effectiveness of the MCO thermal design for bounding parameter values under off-normal conditions.

CONCLUSIONS

The following conclusions have been drawn from the thermal analysis.

1. **Vacuum drying is inherently stable**. Vacuum drying with no helium purge is inherently stable forever for all annulus water conditions including the hot (85 °C) annulus water and loss of coolant (annulus water) cases. Radiative heat transfer is

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[1]Plys, M. G., S. J. Lee, B. Malinovic, and M. Epstein, 1998, *Hanford Spent Nuclear Fuel Safety Analysis Model HANSF 1.2: User's Manual*, FAI/98-40, Rev. 0, Fauske & Associates, Incorporated, Burr Ridge, Illinois.

[2]Duncan, D. R., and D. E. Ball, 1997, *Thermal Analysis of Cold Vacuum Drying of Spent Nuclear Fuel*, HNF-SD-SNF-CN-023, Rev. 0A, Fluor Daniel Hanford, Incorporated, Richland, Washington.

sufficient under vacuum to remove enough heat to maintain stable fuel temperatures. Even for air ingress scenarios, the fuel temperatures are stable under vacuum except for the hot annulus water and loss of coolant cases. However, even for these major features of the tempered water (annulus) system, the fuel temperatures are stable for more than 2 days. Vacuum drying is the most inherently stable physical process occurring at the Cold Vacuum Drying Facility.

2. **Helium purge is stable under normal conditions**. The helium purge only (i.e., no vacuum) process has stable temperatures for the normal (50 °C) annulus water and loss of annulus water flow cases, but it is not stable for the hot annulus water and loss of coolant cases. The helium purge only process is not stable for air ingress cases with bounding hydrides, which have unstable scrap fuel temperatures in less than 2 hours primarily because of the large bounding hydride mass.

3. **Open MCOs are stable under most conditions**. An open MCO with no vacuum and no helium purge is stable forever for the normal annulus water and loss of annulus water flow cases, but it is very unstable (fuel temperature > 1,000 °C) for the hot annulus water and loss of coolant cases after 30 hours if enough residual water is available.

4. **Closed MCOs with bounding parameter values take a long time to pressurize under most conditions**. A closed (isolated) MCO will pressurize and eventually reach the rupture disk burst pressure for all annulus water conditions, but reaching the rupture disk burst pressure will take 3 days for the normal (50 °C) annulus water case and 6 days for the loss of annulus water flow case (stationary annulus water is cooler than 50 °C because of the lower room temperature of the process bay and the

good thermal conductivity of water). If no rupture disk were used, very high fuel temperatures (>900 °C) would result for the hot annulus water and loss of coolant cases after 30 hours if enough residual water were available.

5. **Closed MCOs with nominal parameter values are inherently stable**. A closed MCO with nominal parameter values for decay heat, chemical reaction rates, and reaction surface area pressurizes very slowly for the loss of coolant case. The MCO gas pressure and the temperatures in the bottom fuel basket are shown in Figure ES-1 for both the bounding MCO and nominal MCO under loss of coolant conditions (with no rupture disk included). Clearly, even under loss of coolant conditions, the nominal MCO does not heat up or pressurize very much in 2 days, whereas the bounding MCO reaches very high pressures and temperatures in less than 2 days.

6. **Introducing water into the annulus can prevent bursting of the rupture disk**. For the bounding MCO under loss of coolant conditions, the MCO pressurization can be stopped very quickly (less than 60 seconds) by introducing 25 °C water into the annulus. The cool water injected into the annulus cools the stainless steel MCO wall and bottom very quickly, and the water vapor inside the MCO starts to condense on the cooler MCO wall and bottom immediately. The condensation of water vapor lowers the gas pressure immediately and prevents the pressure from reaching the rupture disk burst pressure, as shown in Figure ES-2. Figure ES-2 also shows that the inner fuel element temperature does not decrease immediately; it takes about 2 hours to show a significant decrease in temperature. Nevertheless, the water vapor condensing on the cooler MCO wall and bottom keeps the MCO pressure below the rupture disk burst pressure for as long as 8 hours if the annulus

water is stationary and more than 24 hours if the annulus water is flowing. Furthermore, the MCO wall temperature is only about 85 °C when the MCO pressure reaches rupture disk burst pressure, 11.2 atm (150 lb/in^2 gauge), so there is no danger of the water flashing or boiling when introduced into the annulus.

7. **Favorable annulus water conditions promote stability for all operating conditions**. The normal annulus water condition (50 °C and flowing) and the loss of annulus water flow condition result in stable temperatures forever for all normal and off-normal conditions analyzed. The loss of annulus water flow condition promotes lower fuel temperatures than the 50 °C annulus water condition.

8. **Scrap fuel is generally cooler than fuel elements**. The scrap basket design with compartments created by copper fins is efficient for heat removal purposes. Most of the off-normal cases that resulted in high temperatures had higher fuel element temperatures than scrap fuel temperatures, except for the helium purge only off-normal cases. The helium purge only cases with unfavorable annulus conditions have high fuel-water (steam) reaction rates in the scrap fuel because water vapor is blown from the fuel baskets into the scrap basket, which has a high surface area to volume ratio, causing the maximum scrap fuel temperature to be greater than the maximum fuel element temperature. Also, the latest scrap basket design,[3] which does not have copper fin spokes in the fine scrap portion, causes even higher scrap temperatures for off-normal helium purge only cases than the design used in the previous thermal analysis,[2] which included copper fin spokes in the fine scrap portion.

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[3]Smith, K. E., 1998, *Multi-Canister Overpack Design Report*, HNF-SD-SNF-DR-003, Rev. 0C, Fluor Daniel Hanford, Incorporated, Richland, Washington.

In summary, the results of this analysis show that the bounding MCO has stable temperatures for all cold vacuum drying processes after draining if the annulus water is kept at 50 °C or cooler by the tempered water (annulus) system, or if the annulus water is stationary (not flowing).

Figure ES-1. Thermal Runaway Reaction with Nominal and Bounding Values Caused by Loss of Coolant Condition and Closed Multi-Canister Overpack.

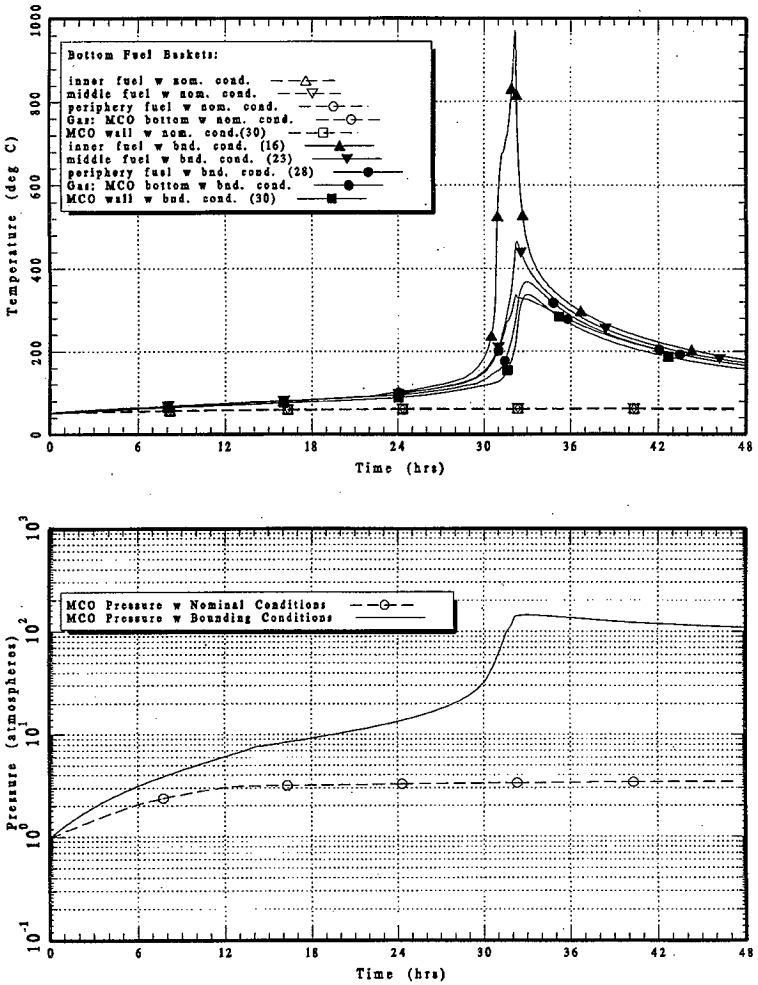
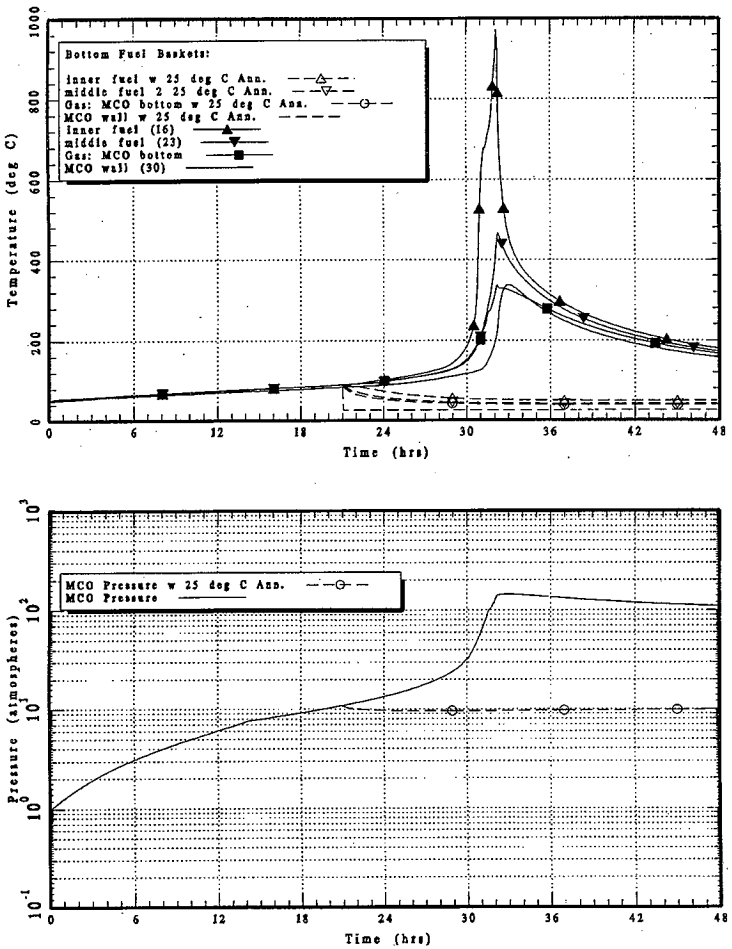


Figure ES-2. Thermal Runaway Reaction Caused by Loss of Coolant Condition and Closed Multi-Canister Overpack with Annulus Water Recovery.



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CONTENTS

CONTENTS (Continued)

APPENDIXES

LIST OF FIGURES

LIST OF TABLES

LIST OF TERMS

CSB	Canister Storage Building
CVDF	Cold Vacuum Drying Facility
MCO	multi-canister overpack
TWS	tempered water (annulus) system

THERMAL ANALYSIS OF COLD VACUUM DRYING OF SPENT NUCLEAR FUEL

1.0 INTRODUCTION

This report documents the analysis of transient thermal and chemical behavior of the multi-canister overpack (MCO) for a broad range of cases postulated to occur during the cold vacuum drying process. The analysis supports the Cold Vacuum Drying Facility (CVDF) Safety Analysis Report (Pili-Vincens 1998), and the safety analysis documentation (Crowe et al. 1998) associated with it. To perform the analysis, the HANSF code (Plys et al. 1998) was updated and models were developed that support both normal and off-normal operation of the cold vacuum drying processes. More off-normal than normal operation cases were run in order to determine the effectiveness of the MCO thermal design with bounding parameter values under off-normal conditions.

The cold vacuum drying processes and models are described in Section 2.0; the cases that were analyzed are presented in Section 3.0 with the key input for them presented in Section 4.0. The results of the cases are described in Section 5.0, and the conclusions are discussed in Section 6.0. Appendix A shows all of the plots from the cases. Appendix B provides a representative input file. The input files are too large to include all of them in Appendix B, so a list of the differences between the representative input file and the others is provided. Key input parameters used in this analysis are provided in Appendix C, and the derivation of the view factors for the radiative thermal model is provided in Appendix D. Quality assurance for the HANSF code at the Hanford Site is handled in Appendix E.

2.0 COLD VACUUM DRYING PROCESSES AND MODELS

2.1 COLD VACUUM DRYING PROCESSES

The basic cold vacuum drying process involves receipt of a fuel-loaded, water-flooded MCO confined within a shipping cask. The MCO is drained of most of the free water it contains and then dried under vacuum, with and without helium purge cycles and with some helium purge only cycles (Irwin et al. 1998). During the multistep drying process, the temperature of the MCO and fuel is controlled by the tempered water (annulus) system (TWS), which circulates tempered water in the annulus between the MCO and the shipping cask, and by the helium purge system, which pushes helium into the bottom of the MCO (via the long process tube) and out through the high-efficiency particulate air filter at the top of the MCO. There is also a safety-class helium purge system, which would only be used under certain off-normal conditions (Pili-Vincens 1998). After several drying cycles, the MCO is tested for dryness (Pajunen 1998a); if the drying tests are satisfactory, the MCO is prepared for shipment to the Canister Storage Building (CSB).

2.2 CONCEPTUAL AND NUMERICAL MODELS

The conceptual model for the cold vacuum drying process needs to incorporate heat and mass transfer mechanisms that include (1) thermal conduction in solids, liquids, and gas mixtures, (2) radiative heat transfer from solid to solid, (3) convection of gases, (4) water evaporation and condensation, (5) dynamic gas-solid chemical reactions in confined spaces, and (6) thermal decomposition of hydrates.

The primary heat sources for the MCO at the CVDF are the decay heat of the spent fuel and the chemical heat from (1) the main fuel-water reaction, $U + 2H_2O \rightarrow UO_2 + 2H_2 + heat$, (2) the main uranium hydride-water reaction, $UH_3 + 2H_2O \rightarrow UO_2 + 3.5H_2 + heat$, and (3) the thermal decomposition of uranium hydrates, $UO_3 \cdot 2H_2O \rightarrow UO_3 \cdot 1H_2O + H_2O + heat \rightarrow UO_3 \cdot 0.5H_2O + 1.5H_2O + heat \rightarrow UO_3 + 2H_2O + heat$. The primary function of the TWS is to remove heat from the MCO, but it also serves to add heat to the MCO for the predraining heatup process, which is not modeled here, and for the vacuum drying process, which cools the fuel by evaporation.

Air ingress into the MCO, an off-normal process, is included in the conceptual model for this report. If the fuel in the MCO contacts air because of some off-normal event or process, the MCO will gain heat from the main fuel-oxygen reaction, $U + O_2 \rightarrow UO_2 + heat$, the main hydride-oxygen reaction, $2UH_3 + 3.5O_2 \rightarrow 2UO_2 + 3H_2O + heat$, and the fuel-nitrogen reaction (only at very high temperatures), $2U + 1.5N_2 \rightarrow U_2N_3 + heat$.

The chemical reactions listed above (both water and gas types of reactions) are the primary reactions occurring at the temperatures of interest during cold vacuum drying, but they certainly are not the only ones. For example, another hydride-oxygen reaction is $UH_3 + O_2 \rightarrow UO_2 + 1.5H_2 + heat$, but this reaction is believed to be secondary (Plys et al. 1998). All of the fuel reaction rates depend on the fuel surface temperature and the exposed surface area. The evaporation, condensation, and hydrate decomposition rates depend not only on the surface temperature and area of the solid (not just the fuel), but also on the composition and temperature of the gas around the surface of the solid.

On the relatively short time scales of interest (less than a week) at CVDF, radiolysis, which is a very slow reaction, was considered unimportant and not included in the conceptual model. Also, the free water in particulate-filled cracks in the fuel was not included in the model. The free water in particulate-filled cracks will evaporate more slowly than free water on a surface. Furthermore, the hydrogen gettering by fuel reaction, $U + 1.5H_2 \rightarrow UH_3 + heat$, also was not included in the conceptual model because oxygen, and then water, will react with the fuel first and block out the fuel-hydrogen reaction (Baker et al. 1966). All the cases analyzed here have water, oxygen, or both present initially. The isolated MCO cases eventually run out of water, have no oxygen, and have lots of hydrogen, but the peak containment pressure and temperature and the times to reach the peak pressure and temperature were the main outputs of interest. In such cases, hydrogen gettering, if included, would cause a more rapid decrease in pressure, which is already decreasing because of the absence of water and the lower chemical heat.

The HANSF code, version 1.2 (Plys et al. 1998), is a computer code that numerically and/or analytically solves all of the mathematical equations used to model the physical processes in the conceptual model described above. The code has gone through a validation exercise (Plys et al. 1998) that compared specific code results to experimental results and/or analytical solutions (see Appendix E). The HANSF code is very fast, and as a result, many cases having long time periods of interest could be simulated.

2.3 DIFFERENCES BETWEEN THIS REPORT AND EARLIER VERSIONS

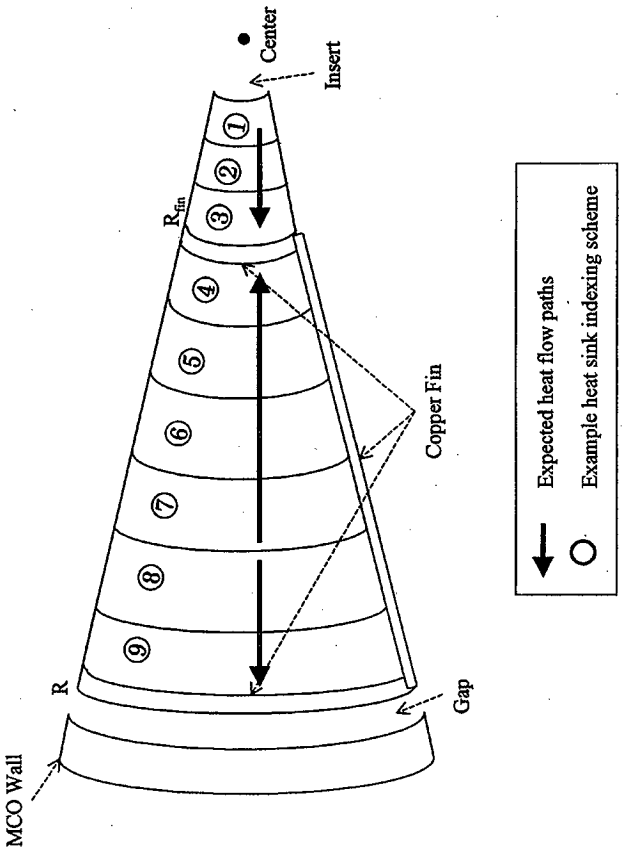
The main differences between this analysis and the earlier revision (Duncan and Ball 1997) of this report are listed below. This analysis includes

- Lower bounding decay heat
- Heat capacity of free residual water
- Lower cladding emissivity for fuel element instead of higher uranium emissivity
- No copper fin spokes in fine portion of scrap basket
- Mass-based, instead of mole-based, evaporation and condensation rates
- Uranium hydrides.

The first two differences result in slower increases of temperature with the current analysis. The use of the lower cladding emissivity for fuel elements results in higher fuel temperatures. The mass-based evaporation and condensation rates result in a hydrogen blanket that is less effective in slowing down the evaporation rate. The addition of uranium hydrides to the model results in higher hydrogen generation rates and higher fuel temperatures. The exclusion of the copper fin spokes in the fine scrap portion of the scrap basket results in higher temperatures for the fine scrap in some cases. The new scrap basket model with no copper fins in the fine scrap portion is described in HNF-2256, *Simulation of Normal and Off-Normal Multi-Canister Overpack Behavior* (Plys and Duncan 1998). A schematic of the new scrap basket model is shown in Figure 1.

The reaction surface area for scrap fuel and fuel elements and the free residual water mass after draining are lower in HNF-2256 (Plys and Duncan 1998), which looks at two scrap baskets per MCO, than the surface area used in this report for one scrap basket per MCO. The higher reaction surface areas in this report provide an extra margin of safety and are consistent with HNF-SD-SNF-TI-015, *Spent Nuclear Fuel Project Technical Databook* (Reilly 1998), and HNF-SD-SNF-SAR-002, *Safety Analysis Report for the Cold Vacuum Drying Facility, Phase 2, Supporting Installation of Processing Systems* (Pili-Vincens 1998).

Figure 1. Schematic of Thermal Scrap Basket Model.



2.4 MODEL AND CODE LIMITATIONS

Since all models are simpler than the real physical and chemical processes, there must be limitations on all models. The following paragraphs discuss the limitations for the current model and code.

The axial dependence of temperature and thermal conduction is ignored, with only the radial direction of heat transfer considered. However, the emissivity of the upper shield plug was increased to enhance the heat transfer rate from the scrap basket to the shield plug. Flow paths in the axial direction, with counter-current flow, are included in order to model the changing gas compositions and temperatures in the axial direction.

The heat capacity of the stainless steel inside the MCO (i.e., baskets, support rods, long process tube) is excluded from the model, which promotes more rapid temperature increases and is considered conservative. The heat capacity (or specific heat) of the inner stainless steel is relatively small compared to the heat capacity of the fuel, shield plug, MCO wall and bottom, and the cask wall. In the future, the long process tube and insert casing should be added to the input, but their effects are not expected to be significant.

The solid material properties are constant over time (i.e., the material properties are independent of temperature during the simulation). Most of the material property values were chosen at a reference temperature of 100 °C. Since the thermal conductivity of uranium and stainless steel increases with temperature, it is conservative to use the lower temperature values.

The effects of fuel damage are not considered. Most of the off-normal conditions do not result in temperatures high enough to cause fuel damage. The calculation of very high temperatures (>1,000 °C) for the extreme off-normal cases is not accurate because the data taken from RD/B/6231/R89, *A Review of the Rates of Reaction of Unirradiated Uranium in Gaseous Atmospheres* (Pearce 1989), are only good up to 1,000 °C. For fuel temperatures above 1,000 °C, the reaction rates are calculated higher than reality, which is conservative. The thermal conductivity of uranium and stainless steel is also held to its lower value at 100 °C, which makes the calculations at high temperatures more conservative. The extreme off-normal cases, which do result in very high temperatures, are prevented by safety-class and safety-significant systems (Pili-Vincens 1998, Chapter 3.0).

Gaseous diffusion is not included. The gases are homogeneous over each volume in the model and are assumed to instantaneously mix all incoming and outgoing sources in each volume and flows between volumes. For cases with no induced convection between volumes and with the bottom fuel baskets wetter than the upper scrap basket (i.e., not the vacuum or purge cases), this assumption may not be conservative because it reduces the water vapor transfer rate into the scrap basket. If diffusion were included, it might enhance the transfer of water vapor to the dry scrap basket. In conjunction with diffusion, the effects of hot and cold surfaces on convection (i.e., heat-induced flow) between volumes also is excluded from the model. However, with copper fins included in the scrap basket (Smith 1998), the scrap basket is cooler, or has better heat transfer ability, than the fuel baskets for most, but not all, scenarios or

cases. Hence, having more water vapor with the hotter fuel elements is more conservative for those cases.

In summary, most of the current model's limitations are conservative or not important to the concerns of interest. However, improvements to the current model can be made and will be considered in the future, especially for the limitations that are not conservative.

3.0 COLD VACUUM DRYING PROCESSING CASES ANALYZED

Forty-two different cold vacuum drying processing cases, case numbers 1 through 42 in Table 1, have been analyzed; most of these cases are for off-normal conditions. These 42 cases are divided into 6 groups and described briefly in Table 1.

- Group I, Vacuum Drying and Helium Purge with Normal Annulus Water

  Cases 1 through 4 include the main vacuum drying processes of vacuum only, vacuum with helium purge, helium purge only, and a vacuum only case with 75 kg of residual water. The annulus water temperature is 50 °C and flowing for all the cases. The orifice used in the model is 0.00635 m (0.25 in.) in diameter.

- Group II, Vacuum Drying and Helium Purge with Hot Annulus Water

  Cases 5 through 7 look at vacuum drying processes with a major failure of the TWS. These cases include the vacuum only, vacuum with helium purge, and helium purge only cases with the annulus water heated to 85 °C and flowing. Other major failures of the TWS are covered in Group III. In the case names, the word HOT refers to the annulus water temperature of 85 °C. The orifice is 0.00635 m (0.25 in.) in diameter.

- Group III, Vacuum Drying and Helium Purge with Major Flow Failures of the Tempered Water (Annulus) System

  Cases 8 through 13 look at loss of annulus water flow and loss of coolant (annulus water), which are considered major failures of the TWS. These cases include vacuum drying with loss of annulus flow for initial annulus temperatures of 50 °C and 85 °C, and with loss of coolant). This group also includes a vacuum drying with helium purge and loss of coolant case and two helium purge only cases, one with loss of flow and one with loss of coolant. The orifice is 0.00635 m (0.25 in.) in diameter. The letters LOF (loss of flow) and LOC (loss of coolant) appear in the appropriate case names.

Table 1. Brief Descriptions of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Residual free water mass	CVDF process	Annulus water			Notes
					Flow	Temperature	Lost	
COMPLETE NORMAL OPERATIONS AFTER DRAINING AT CVDF: Bounding MCO and nominal hydrides (2.4 kg)								
0	NORMAL	Complete CVDF cycle after draining and before shipping to CSB	26.5 kg	CVDF drying operations	Normal conditions throughout normal drying			See Table 3
I. VACUUM DRYING AND HELIUM PURGE: Bounding MCO and nominal hydrides (2.4 kg)								
1	VACUUM (CVD3B)	Vacuum drying	26.5 kg	Vacuum	Yes	50 °C	No	CVD3B in Rev. 0A
2	VAC75KG (CVD3C)	Vacuum drying - 75 kg free water	75 kg	Vacuum	Yes	50 °C	No	CVD3C in Rev. 0
3	VACPUR	Vacuum drying - helium purge	26.5 kg	Vacuum and helium purge	Yes	50 °C	No	Purge is 1.6 scfm
4	PURGE (CVD2A)	Helium purge	26.5 kg	Helium purge	Yes	50 °C	No	Purge is 1.6 scfm CVD2A in Rev. 0A
II. VACUUM DRYING, HELIUM PURGE, WITH HOT ANNULUS WATER: Bounding MCO and nominal hydrides (2.4 kg)								
5	VACHOT	Vacuum drying - hot annulus water without helium purge	26.5 kg	Vacuum	Yes	85 °C	No	--
6	VPURHOT	Vacuum drying - hot annulus water with helium purge	26.5 kg	Vacuum and helium purge	Yes	85 °C	No	--
7	PURHOT	Helium purge - hot annulus water	26.5 kg	Helium purge	Yes	85 °C	No	Purge is 1.6 scfm
III. VACUUM DRYING WITH MAJOR FLOW FAILURE OF TEMPERED WATER (ANNULUS) SYSTEM: Bounding MCO and nominal hydrides (2.4 kg)								
8	VACLOF	Vacuum drying - no annulus flow	26.5 kg	Vacuum	No	50 °C initially	No	--
9	VLOFHOT	Vacuum drying - no annulus flow and hot annulus water	26.5 kg	Vacuum	No	85 °C initially	No	--
10	VACLOC	Vacuum drying - loss of coolant (annulus water)	26.5 kg	Vacuum	Air	50 °C initially	Yes	--
11	VPURLOC	Vacuum - loss of coolant with helium purge	26.5 kg	Vacuum and helium purge	Air	50 °C initially	Yes	Purge is 1.6 scfm

Table 1. Brief Descriptions of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Residual free water mass	CVDF process	Annulus water			Notes
					Flow	Temperature	Lost	
12	PURLOF (CVD2B)	Helium purge - no annulus water	26.5 kg	Helium purge	No	50 °C initially	No	Purge is 1.6 scfm CVD2B in Rev. 0
13	PURLOC (CVD2C)	Helium purge - loss of coolant	26.5 kg	Helium purge	Air	--	Yes	Purge is 1.6 scfm CVD2C in Rev. 0
IV. DRAINING STOP AND GAS BLOCKAGE: Bounding MCO and nominal hydrides (2.4 kg)								
14	DSTOP (CVD2A)	Draining and gas blockage - normal annulus water	26.5 kg	Drain and closed MCO	Yes	50 °C	No	CVD2A in Rev. 0A
15	DS75KG	Draining and gas blockage - normal annulus water, 75 kg residual water	75 kg	Drain and closed MCO	Yes	50 °C	No	--
16	DSTOPOV	Draining and gas blockage - normal annulus water, with open vent	26.5 kg	Drain with open vent	Yes	50 °C	No	--
17	DSLOF (CVD1F)	Draining and gas blockage - loss of annulus water flow	26.5 kg	Drain and closed MCO	No	50 °C initially	No	CVD1F in Rev. 0A
18	DLOF75KG	Draining and gas blockage - loss of annulus water flow, 75 kg residual water	75 kg	Drain and closed MCO	No	50 °C initially	No	--
19	DSLOFOV	Draining and gas blockage - loss of annulus water flow, with open vent	26.5 kg	Drain with open vent	No	50 °C initially	No	--
20	DSLOC (CVD1C)	Draining and gas blockage - loss of coolant	26.5 kg	Drain and closed MCO	Air	-	Yes	CVD1C in Rev. 0A
21	DLOC75KG	Draining and gas blockage - loss of coolant, 75 kg residual water	75 kg	Drain and closed MCO	Air	-	Yes	--
22	DSLOCNOM	Draining and gas blockage - loss of coolant	26.5 kg	Drain and closed MCO	Air	-	Yes	Nominal MCO
23	DSLOCREC	Draining and gas blockage - recovery from loss of coolant	23.7 kg at restart	Closed MCO recovery from loss of coolant	Yes	25 °C at restart	Restored	Flowing annulus recovery at 21 hours
24	DSLOCRE2	Draining and gas blockage - recovery from loss of coolant	23.7 kg at restart	Closed MCO recovery from loss of coolant	No	25 °C at restart	Restored	Stationary annulus recovery at 21 hours

Table 1. Brief Descriptions of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Residual free water mass	CVDF process	Annulus water			Notes
					Flow	Temperature	Lost	
25	DSLOCOV	Draining and gas blockage - loss of coolant	26.5 kg	Drain with open vent	Air	-	Yes	--
26	DS46DEG	Draining and gas blockage - 46 °C annulus	26.5 kg	Drain and closed MCO	Yes	46 °C	No	--
27	DS55DEG	Draining and gas blockage - 55 °C annulus	26.5 kg	Drain and closed MCO	Yes	55 °C	No	--
28	DS75DEG	Draining and gas blockage - 75 °C annulus	26.5 kg	Drain and closed MCO	Yes	75 °C	No	--
29	DSHOT	Draining and gas blockage - hot annulus water	26.5 kg	Drain and closed MCO	Yes	85 °C	No	--
30	DHOT75KG	Draining and gas blockage - hot annulus water, 75 kg residual water	75 kg	Drain and closed MCO	Yes	85 °C	No	--
31	DSHOTOV	Draining and gas blockage - hot annulus water, with open vent	26.5 kg	Drain with open vent	Yes	85 °C	No	--
V. VACUUM DRYING AND HELIUM PURGE WITH AIR INGRESS. Bounding MCO and bounding hydrides (14.6 kg)								
32	VACAIRI	Vacuum drying - air ingress and bounding hydrides	26.5 kg	Vacuum	Yes	50 °C	No	--
33	VAIRIHOT	Vacuum drying - air ingress, bounding hydrides, and hot annulus water	26.5 kg	Vacuum	Yes	85 °C	No	--
34	VAIRILOC	Vacuum drying - air ingress, bounding hydrides, and loss of coolant	26.5 kg	Vacuum	No	50 °C initially	Yes	--
35	PURAIRI	Helium purge - air ingress, bounding hydrides	26.5 kg	Helium purge	Yes	50 °C	No	--
36	PAIRIHOT	Helium purge - air ingress, bounding hydrides, and hot annulus water	26.5 kg	Helium purge	Yes	85 °C	No	--
37	VACAIRI2	Vacuum drying - air ingress without hydrides	26.5 kg	Vacuum	Yes	50 °C	No	--

Table 1. Brief Descriptions of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Residual free water mass	CVDF process	Annulus water			Notes
					Flow	Temperature	Lost	
VI. CVDF SAFETY ANALYSIS REPORT CASES								
38	DSLOCSA4	High-pressure thermal runaway (drain interrupt and gas blockage) - loss of coolant	35.5 kg	Drain interrupt and closed MCO	Air	50 °C	yes	Reaches burst pressure at 21 hours
39	BLOW4N	Blowdown of high-pressure thermal runaway at 11.2 atm (150 lb/in^2 gauge)	32.6 kg at restart	Rupture disk opens releasing gas and particulate	Air	64 °C at restart	yes	Restart at 21 hours
40	DSSA4REC	Recovery of high-pressure thermal runaway - stationary annulus water	32.6 kg at restart	Closed MCO recovery from loss of coolant	No	25 °C at restart	restored	Stationary annulus recovery at 21 hours
41	BLOWREOV	Recovery of low-pressure thermal runaway after blowdown occurs	31.7 kg at restart	Open MCO blowdown with recovery from loss of coolant	No	25 °C at restart	restored	Stationary annulus recovery at 22 hours
42	DSLOCOV2	Low-pressure thermal runaway (drain interrupt with loss of coolant and open vent)	35.5 kg	Drain interrupt with open vent	Air	50 °C	yes	Filtered release

CSB = Canister Storage Building.
CVDF = Cold Vacuum Drying Facility.
MCO = multi-canister overpack.
scfm = standard cubic feet per minute.

- Group IV, Draining Stop and Gas Blockage

  Cases 14 through 31 all involve an isolated (closed) MCO, which allows gas pressure to increase, or an open MCO with only an open vent (i.e., no vacuum or helium purge), or a closed MCO with a recovery from the loss of coolant condition (i.e., annulus water is restored). The isolated MCO cases include normal and off-normal TWS conditions, including 85 °C annulus water, loss of flow and loss of coolant conditions. The time to reach the rupture disk burst pressure of 11.2 atmospheres (150 lb/in^2 gauge) is the main output of interest for the closed MCO cases, and the fuel temperatures versus time are the key outputs of interest for the open MCO cases. These cases demonstrate the importance of the TWS in keeping the MCO fuel temperatures stable under the off-normal cold vacuum drying conditions of no vacuum drying and no helium purge, with large amounts of free water. These cases also demonstrate the importance of the MCO valves in keeping the MCO open under off-normal TWS conditions.

- Group V, Vacuum Drying and Helium Purge with Air Ingress

  Cases 32 through 37 include the vacuum drying and helium purge processes with air ingress at the bottom of the MCO (via the long process tube) for normal and off-normal annulus conditions. The main outputs of interest are the hydrogen generation rates and fuel temperatures versus time. These cases also have increased hydride loads, which are considered bounding here. The orifice is 0.00635 m (0.25 in.) in diameter. The letters AIRI, which stand for air ingress, appear in all of the air ingress case names.

- Group VI, CVDF Safety Analysis Report Cases

  Cases 38 through 42 include the cases used for Revision 4 of the CVDF Safety Analysis Report (Pili-Vincens 1998) and for the accident analysis documentation supporting it (Crowe et al. 1998). The primary case, case 38, is an isolated MCO with a loss of coolant condition after a drain interrupt; as a result of the drain interrupt, there is 35.5 kg of free residual water available instead of 26.5 kg, which is the bounding free water after a normal drain. Case 39 simulates both the actual blowdown resulting from the rupture disk opening and the fuel-water reactions after the blowdown. The rupture disk opening used in the model is 0.0254 m (1.0 in.) in diameter. Cases 40 and 41 simulate a recovery of the loss of coolant condition by restoring stationary water into the annulus at 21 hours, just before the rupture disk bursts open (case 40), and at 22 hours, one hour after the rupture disk bursts open (case 41). The purpose of the two recovery cases is to show the effectiveness of restoring the annulus water just before the blowdown and one hour after the blowdown. The last case, case 42, looks at the temperature behavior of the an open MCO with 35.5 kg of residual water and a loss of coolant condition.

All of the cases above, except the CVDF safety analysis report cases, have either the bounding amount of free water, 26.5 kg (Duncan and Ball 1997) after normal draining, or a larger free water mass of 75 kg, representing an incomplete drain or drain interrupt. All cases use bounding parameter values except for case 22 (DSLOCNOM), which uses nominal parameter values. Every case includes the uranium hydride mass, nominal for most cases and bounding for the air ingress cases, except case 37 (VACAIRI2), which is a vacuum case with air ingress and no hydride loading. The key parameter values are described in Section 4.0. All of the simulation times are long enough to show when the peak temperatures of scrap and fuel elements occur. Most of the cases have simulation times extended to 1 week in order to show long-term effects, even though such long times are not anticipated or expected for any cold vacuum drying process.

In addition to the six groups of cases, a suite of 13 cases was connected in time to simulate all the primary normal vacuum drying processes from the end of draining until the MCO is ready for shipment to the CSB, a total time period of 53.25 hours. This suite is called the 'normal' case and is identified in Table 1 as case 0. The complete set of processes includes the helium purge only, vacuum only, vacuum with helium purge processes, the rebound and proof tests for water content, the cooling down process and the preparation for CSB shipment process. Altogether, 13 different processes or steps were identified in the normal vacuum drying sequence after draining (Crowe et al. 1998, Chapter 2.0), requiring one distinct run for each case, and resulting in a total of 13 different runs. A detailed description of all of the processes is available in the CVDF operations manual (Irwin et al. 1998). These cases are itemized later in Section 5.0.

4.0 KEY INPUT PARAMETERS

This analysis was based upon key input parameters and specific process and equipment designs. Some of the postulated processing cases require operator actions within a reasonable time to maintain safe conditions. Most of the simulated cases exclude any operator intervention in order to estimate the behavior of an off-normal case based on just the physics and chemistry of the MCO under the off-normal condition.

The most important input parameters affecting the thermal analysis of the MCO during CVDF processing are the ones pertaining to the uranium-water reaction rate, the rate of heat removal from the MCO, and the decay heat. The parameters affecting the chemical reaction rate are the reaction surface area and the reaction rate multiplier. All but one of the cases use bounding values for chemical reaction rates and decay heat because a thermal design that is good enough for the bounding MCO will be good enough for all MCOs. The effects of uranium hydride were included in the thermal analysis because uranium hydride reacting with water or oxygen will generate heat and hydrogen. All of the cases include a large nominal value of initial uranium hydride (2.4 kg) except for the air ingress cases, which include a very large bounding value of initial hydride (14.6 kg). These hydride mass loadings have been compared to

preliminary data from some damaged fuel elements (Appendix C, Note 4). The values used in this report are much larger than those observed and, hence, contain some margin of safety.

The thermal analysis used only Mark IV fuel because the Mark IV fuel conservatively bounds the Mark IA fuel from a thermal perspective. The Mark IV fuel element mass per MCO is 25% larger than the Mark IA fuel element mass per MCO. The Mark IV scrap basket has a maximum load of 980 kg, whereas the Mark IA has a maximum load of 575 kg (Kessler and Peck 1998) because of criticality concerns. There are also fewer Mark IA fuel elements (and mass) per basket, therefore there is less decay heat per basket (and element), a smaller reaction area per basket, and a shorter conduction distance from the inner to outer regions; all of which make the Mark IA fuel more favorable in regards to thermal behavior in the MCO.

The key input parameters used in the analysis for the bounding and nominal MCO with one scrap basket and four Mark IV fuel baskets are shown in Table 2 and in Appendix C.

5.0 RESULTS OF CASES ANALYZED

The results of the cases analyzed are discussed in this section. All of the cases involving vacuum drying or helium purge processes are restarted from an initialization run that includes the first 0.42 hour after draining and a helium purge rate of 1.6 standard ft^3/min for 0.33 hour after that, for a total time of 0.75 hour after draining. The time of the maximum hydrogen generation rate does not include this 0.75 hour for the initialization run, but the dry out time does include the 0.75 hour.

5.1 NORMAL COLD VACUUM DRYING OPERATIONS SUITE OF RUNS (CASE 0)

For the series of normal vacuum drying steps, the MCO is completely dry about 20.5 hours after draining is completed. This dry-out time is longer than the dry-out time realized with only the vacuum drying process or the vacuum with helium purge process (for details see Section 5.2) because the helium purge only process is not an effective drying process. This is because the pressure in the MCO is greater than atmospheric pressure and prevents any boiling or rapid evaporation. However, the helium purge only process may be necessary to keep the free water from freezing for fuel with a much lower decay heat rate than the bounding decay rate (740.8 W per MCO [Table 2]).

The particulate (UO_2) generated during the entire suite of cold vacuum drying operations after draining is 5.15 kg (for a time period of 53.25 hours, see Table 3). Most of the particulate (80%) is generated during the first 20.5 hours when free water is still present in the MCO. The rest of the particulate (about 20%) is generated from the uranium hydrate water, which decomposes because the fuel temperature increases after the free water is gone. The initial

Table 2. Key Input Parameters for Bounding and Nominal Multi-Canister Overpack. (2 sheets)

Parameter	Value	Reference
HEAT GENERATION PARAMETERS: Power, reaction area, reaction rate		
Bounding decay power (776 W for five fuel baskets)	740.8 W per MCO	Reilly 1998 Note 1, Appendix C
Nominal decay power (403 W for five fuel baskets)	384.7 W per MCO	Reilly 1998 Note 2, Appendix C
Scrap fuel reaction surface area	6 m^2 - bounding 1.7 m^2 - nominal	Reilly 1998
Fuel reaction area	7 m^2 - bounding 0.3 m^2 - nominal	Reilly 1998
Reaction rate multiplier	10 - bounding 3 - nominal	Reilly 1998
Nominal effective rate multiplier for hydrides (nominal hydride mass)	13.7 - fuel basket 13.7 - scrap basket (2.4 kg per MCO)	Plys and Duncan1998 Note 3, Appendix C
Bounding effective rate multiplier for hydrides (bounding hydride mass)	59.2 - fuel basket 111 - scrap basket (14.6 kg per MCO)	Plys and Duncan1998 Note 4, Appendix C
RADIATION HEAT TRANSFER PARAMETERS: Emissivity, view factors		
Scrap fuel emissivity	0.7	Reilly 1998
Cladding emissivity	0.43	Scott 1965 Note 5, Appendix C
Inner shield plug emissivity	1.0	Plys et al. 1998 Note 6, Appendix C
MCO wall emissivity	0.3	Reilly 1998
Cask, MCO bottom, and outer shield plug emissivity	0.25	Plys et al. 1998 Note 7, Appendix C
View factors between fuel rods and MCO wall	8 x 8 matrix	Plys et al. 1998 Note 8, Appendix C
CONDUCTION HEAT TRANSFER PARAMETERS: Mass, conductivity, specific heat		
Effective fuel–cladding mass density	18,573.3 kg/m^3	Note 9, Appendix C
Uranium (scrap) mass density at 100 °C	19,000 kg/m^3	Holden 1958 Note 10, Appendix C
Stainless steel mass density at 100 °C	8,000 kg/m^3	ORNL 1987 Note 11, Appendix C

Table 2. Key Input Parameters for Bounding and Nominal Multi-Canister Overpack. (2 sheets)

Parameter	Value	Reference
Maximum fuel mass load (Mark IV fuel)	980 kg - scrap basket 1,268 kg - fuel basket 6,052 kg per MCO	Reilly 1998
Effective fuel/clad thermal conductivity	24.2 W/m/K	Note 12, Appendix C
Stainless steel thermal conductivity	16.0 W/m/K	ORNL 1987
Effective fuel–cladding and uranium specific heat	122.67 J/kg/K	Note 13, Appendix C
Stainless steel specific heat	500.0 J/kg/K	ORNL 1987
Free residual water after draining (1.5 kg per scrap basket, 6.0 kg per fuel basket, 1.0 kg per bottom)	26.5 kg per MCO	Duncan and Ball 1997
Water in uranium hydrates, $UO_3 \cdot 2H_2O$	1.16 kg (0.72 kg)*	Note 14, Appendix C
Helium purge and process bay temperature	26.7 °C (80 °F)	Irwin et al. 1998
Normal annulus water temperature	50 °C	Irwin et al. 1998
CONVECTION HEAT AND MASS TRANSFER PARAMETERS Gas volume, flow area, flow rate		
Scrap basket gas volume	0.153 m^3	Note 15, Appendix C
Upper fuel (2 fuel baskets) volume	0.186 m^3	Note 16, Appendix C
Lower fuel (2 fuel baskets) volume	0.199 m^3	Note 17, Appendix C
Fine scrap porosity	0.40	Note 18, Appendix C
Course scrap porosity	0.7392	Note 19, Appendix C
Flow area in scrap basket bottom	0.013 m^2	Note 20, Appendix C
Vacuum pumping rate	0.01416 m^3/s (30 scfm)	Irwin et al. 1998
Base helium mass purge rate	1.23 E-04 kg/s (1.6 scfm)	Irwin et al. 1998

* The hydrate water mass for case 0 (NORMAL) is 0.72 kg

MCO = multi-canister overpack.

amount of hydrate water is 0.72 kg for these normal operations. This is enough to produce about 20% of the particulate over the complete 53.25-hour cycle, but also enough to keep the MCO from passing the pressure rebound tests (Pajunen 1998a). Not passing the rebound tests because of hydrate water is not a safety concern because so little of the hydrate water is available. However, the hydrates will tend to lengthen the vacuum drying operations time at the CVDF for the MCOs with high decay heat.

The maximum hydrogen generation rate is 3 mg/sec, which occurs during the first purge right after draining and during the early stages of the first vacuum with helium purge process (see Table 3). This rate exceeds the design criteria of 2.4 mg/sec (Pajunen 1998b). As a result, the hydrogen concentration reaches about 1.25% of the gas space during the early stages after draining, which is more than one-quarter of the hydrogen flammability limit of 4%. However, the maximum hydrogen concentration (1.25%) is still less than one-third of the hydrogen flammability limit. The helium purge rate for this early time period is 1.6 standard ft^3/min.

The hydrogen generation rates and particulate generated during normal cold vacuum drying conditions are summarized in Table 3. Table 3 shows annulus water temperature, helium purge rate, calculated maximum hydrogen generation rate, and generated particulate mass for each of the 13 cases identified as being part of normal operations.

5.2 GROUP I, VACUUM DRYING AND HELIUM PURGE WITH NORMAL ANNULUS WATER (CASES 1 THROUGH 4)

These four cases show the MCO is completely dry from free water in a little more than 14 hours for the indefinite vacuum only process (case 1, VACUUM), a little more than 16 hours for the vacuum with helium purge process (case 3, VACPUR), and about 3 days for the helium purge only process (case 4, PURGE) (see Appendix A, Figures A-1 through A-4). As discussed previously, the helium purge only case (case 4, PURGE) takes much longer to dry the MCO because the pressure during purge is slightly above atmospheric pressure, so no boiling or rapid evaporation occurs. The scrap fuel and fuel elements are dry in about 7 hours and 31 hours, respectively, but the MCO wall and bottom are not dry for 3 days for case 4, PURGE. This is because the fuel temperature rises above 50 °C after 16 hours, which causes the free water to evaporate from the fuel and condense on the cooler MCO wall (50 °C). When 75 kg of free water (case 2, VAC75KG) is present, instead of 26.5 kg, for vacuum drying, the inner fuel temperature drops to 0 °C after 3 days because of the extra cooling supplied by the extra 48.5 kg of evaporating water. Case 2 (VAC75KG) indicates the importance of having good thermal conduction from the MCO wall to the inner fuel assemblies in order to prevent the freezing of free water. The helium purge gas is expected to provide this good conduction and prevent the water from freezing for conditions involving very high amounts of free water or low decay heat. However, this issue needs more investigation and quantification.

Table 3. Hydrogen Generation Rates and Particulate Formation under Normal Cold Vacuum Drying Operations for Bounding Multi-Canister Overpack with Nominal Hydrides.

Cold vacuum drying operation on bounding MCO	Case	Duration of operation	Total elapsed time	Annulus temperature	Helium purge rate	Final MCO pressure	Max H_2 gen. rate	UO2 generated	Cumulative UO2 generated
MCO drained with 26.5 kg free water remaining	Name	hours	hours	°C	standard ft^3/min	kPa	mg/sec	grams	grams
Line flush (with helium)	PURGEH0	0.42	0.42	50.0	0	101.3	3.0	366	366
Helium purge following MCO drain		0.33	0.75	50.0	1.6	101.8			
Vacuum purge with NPV checks[a]	VACPUR1	7.50	8.25	50.0	1.6	10.4	3.0	1,651	2,017
Helium purge (thermal reset)	PURGE2	4.00	12.25	50.0	1.6	101.6	1.5	878	2,895
Helium purge (minimum purge reset)	PURGE3	0.50	12.75	50.0	4.0	103.3	1.5	145	3,040
Vacuum purge with NPV checks[a]	VACPUR4	3.50	16.25	50.0	1.6	7.4	1.5	607	3,647
Helium purge (thermal reset)	PURGE5	4.00	20.25	50.0	1.6	101.5	0.80	546	4,193
Helium purge (minimum purge reset)	PURGE6	0.50	20.75	50.0	4.0	102.5	0.56	30	4,223
Vacuum purge with NPV checks[a]	VACPUR7	1.00	21.75	50.0	1.6	5.6	0.18	21	4,244
Pressure rebound test	REBND8	1.00	22.75	50.0	0	7.3 (55 torr)	0.20	27	4,271
Proof test	PROOF	19.00	41.75	50.0	0	0.14 (1 torr)	0.36	644	4,915
Second rebound test	REBND10	1.00	42.75	50.0	0	1.72 (13 torr)	0.37	35	4,950
Cool MCO to 25 °C	COOL	3.00	45.75	25.0	0.5	101.3	0.31	79	5,029
Ready for CSB[b]	READY	7.50	53.25	25.9	0[b]	105.5[b]	0.21	125	5,154
TOTALS			53.25					5,154	5,154

[a]NPV checks are not included in simulations since they take up so little time.
[b]Helium pressurization is excluded from simulation, otherwise pressure would be around 150 kPa with the extra helium.

CSB = Canister Storage Building.
MCO = multi-canister overpack.
NPV = no purge vacuum.

The fuel temperatures are stable for all four cases, with the scrap fuel being cooler than the fuel elements. The scrap fuel holds less water (1.5 kg) than the fuel baskets (6 kg per fuel basket) for the bounding MCO. Hence, the scrap fuel dries out first and starts to heat up after the water evaporates. With water vapor from the fuel baskets flowing through the scrap fuel, the scrap fuel has the potential to reach high temperatures. However, the scrap fuel basket has fins that make the heat removal in the scrap basket very good and better than the heat removal from the fuel baskets. Hence, if the top fuel basket had very little free residual water at the beginning of vacuum drying, it would dry early, be fed by water vapor from the lower fuel baskets and wall, and heat up more than the dry scrap fuel because heat removal for the fuel basket is not as good as heat removal for the scrap basket. The fuel temperatures in the upper fuel baskets for such a scenario could reach 200 °C if more than 50 kg of residual water existed at the bottom of the MCO.

The maximum hydrogen generation rate among the four cases is 3.2 mg/sec for the helium purge only case (case 4, PURGE). The maximum rate occurs about 40 seconds after the helium purge only process begins. The maximum hydrogen generation rate for the vacuum and vacuum with helium purge processes (case 1, VACUUM, and case 3, VACPUR) is 3.0 mg/sec at about 90 seconds after the start of these processes (see Table 4 for details).

The vacuum only case (case 1, VACUUM) compares well to case CVD3B in the previous revision of this document (Duncan and Ball 1997). Case CVD3B dries out in about 14 hours, which is a little sooner than for case 1 (VACUUM). Case 2 (VAC75KG) is similar to case CVD3C (Duncan and Ball 1997) except that the fuel reaches 0 °C in case 2 (VAC75KG) but not in case CVD3C. It is not clear why the two cases differ at this time. Case 4 (PURGE) is not really comparable to case CVD2A (Duncan and Ball 1997) since case CVD2A starts with a helium purge after 8 hours of vacuum drying. Hence, case CVD2A starts with less water than case 4 (PURGE), which starts 45 minutes after draining and has almost 26.5 kg of residual water.

5.3 GROUP II, VACUUM DRYING AND HELIUM PURGE WITH HOT ANNULUS WATER (CASES 5 THROUGH 7)

These three cases show that if the TWS overheats the annulus water to 85 °C, fuel temperatures will remain stable as long as the vacuum process is operational (see Appendix A, Figures A-5 through A-7). The vacuum only (case 5, VACHOT) and vacuum with helium purge (case 6, VPURHOT) processes provide stable fuel temperatures, but the helium purge only (case 7, PURHOT) process does not keep the fuel temperature stable in the inner parts of the fine and coarse scrap fuel regions. The helium purge only process feeds the scrap basket with water vapor at about 41 kPa of pressure. This high water vapor pressure causes the reaction rate to be higher than the reaction rates under vacuum or under vacuum with helium purge (about 5 kPa of water vapor) processes.

5.4 GROUP III, VACUUM DRYING AND HELIUM PURGE WITH MAJOR FLOW FAILURES OF THE TEMPERED WATER (ANNULUS) SYSTEM (CASES 8 THROUGH 13)

The cases in this group represent a major failure in the TWS in providing annulus water flow (see Appendix A, Figures A-8 through A-13). In other words, this group of cases includes the loss of coolant failure and the loss of flow failure.

The loss of flow failure, resulting in a stationary annulus water condition, is rather benign because the process bay cools the stationary annulus water below 50 °C. The thermal conductivity of the stationary annulus water also is good enough to transfer the heat from inside the MCO, to the cask, and to the process bay at a high rate under vacuum only and helium purge only conditions (case 8, VACLOF, and case 12, PURLOF). Even if the loss of flow failure occurs after the annulus has been heated up to 85 °C, the results are benign for the vacuum only condition (case 9, VLOFHOT) with fuel temperatures staying below 76 °C.

The loss of coolant (annulus water) failure, resulting in air filling the annulus between the MCO and the cask, is a severe degradation of the heat transfer or heat removal capability of the annulus. Air is a poor thermal conductor, so heat from the MCO is not transferred to the cask and process bay very quickly. However, even with severe degradation of the cooling annulus, the fuel temperatures are stable for the vacuum only (case 10, VACLOC) and vacuum with helium purge (case 11, VPURLOC) processes. Fuel temperatures are not stable in the scrap basket, especially the inner fine scrap portion, for the helium purge only process (case 13, PURLOC). For the helium purge only case (case 13, PURLOC), the inner fine scrap basket temperature stays below 100 °C for up to 1 day but reaches a peak of about 330 °C in less than 2 days. Hence, even for the worst cold vacuum drying operations case, which is the helium purge only case (case 13, PURLOC) for the loss of coolant condition, the fuel temperatures are stable for up to 1 day. Comparing the vacuum only case (case 10, VACLOC) with the vacuum with helium purge case (case 11, VPURLOC) shows that the scrap basket temperature is cooler (64 °C versus 70 °C) for the vacuum with helium purge case, which demonstrates the better thermal conductivity effects of the helium gas (see Appendix A, Figures A-10 and A-11).

Case 12 (PURLOF) is similar to case CVD2B in the previous revision of this document (Duncan and Ball 1997) but not really comparable because case CVD2B starts after 8 hours of vacuuming and case 12 (PURLOF) starts 45 minutes after draining. The same is true for case 13 (PURLOC) and CVD2C (Duncan and Ball 1997).

5.5 GROUP IV, DRAINING STOP AND GAS BLOCKAGE (CASES 14 THROUGH 31)

This group of 18 cases could perhaps have been divided into smaller groups, but all these cases share the characteristic of having no vacuum drying or helium purge processes included. Most of the cases include an isolated or closed MCO, but some cases have an open MCO with no vacuum or helium purge taking place. All of the annulus conditions, both normal and

off-normal, are incorporated into this group of cases. Every case in this group is off-normal even though some of the annulus conditions are normal. The main output of interest for the isolated MCO cases is the time that it takes the pressure to reach 11.2 atm (150 lb/in^2 gauge), which is the burst pressure of the rupture disk.

The first case (case 14, DSTOP) in this group is an isolated MCO with normal annulus water (50 °C and flowing). The pressure reaches 11.2 atm about 3 days after the MCO is closed. The fuel temperatures remain below 80 °C forever because the heat removal rate is greater than the heat generation rate after 2.5 days. The next case (case 15, DS75KG) is the same except that 75 kg of free water remains after draining instead of 26.5 kg. The extra 48.5 kg of free water is placed in the bottom fuel basket. This case takes longer (3.5 days instead of 3 days) for the pressure to reach 11.2 atm than case 14 (DSTOP) takes. The temperature increase is smaller than in case 14 (DSTOP) because of the additional heat capacity provided by the extra 48.5 kg of free water. Eventually the temperatures rise to about the same levels and are stable. The next case (case 16, DSTOPOV) is the same as case 14 (DSTOP), except that the MCO is not isolated because a valve is open. Case 16 (DSTOPOV) has no pressure increase due to the open valve, but the temperatures are higher than the temperatures of the two previous cases with isolated MCOs (see Appendix A, Figures A-14, A-15, and A-16). This is because the pressure builds up in isolated MCOs as the hydrogen builds up, slows down the evaporation rate, and provides a better thermal conductor to the MCO wall than steam containing low hydrogen content. Hence the MCO with an open valve reaches higher temperatures, but the temperatures are still stable and below 105 °C. The scrap fuel temperatures are lower than the innermost fuel element temperature for all of the cases discussed in this paragraph.

The next three cases (case 17, DSLOF; case 18, DLOF75KG; and case 19, DSLOFOV) are the same as the previous three cases except that the annulus water is stationary (not flowing). Since the stationary annulus water is cooled by the process bay, which has a low gas temperature (26.7 °C), these cases are more benign than the previous cases with normal flowing annulus water (see Appendix A, Figures A-17 to A-19). The time required for the pressure to reach 11.2 atm is 6 days for case 17 (DSLOF), and a little more than 6 days for case 18 (DLOF75KG), which has 75 kg of free water. The fuel temperatures are below 71 °C forever because the heat removal rate is greater than the heat generation rate after a couple of days. The case with an open MCO (case 19, DSLOFOV) has stable fuel temperatures that are higher than the fuel temperatures in an isolated MCO (80 °C versus 71 °C). Case 17 (DSLOF) differs from the corresponding case CVD1F in the previous revision of this document (Duncan and Ball 1997) by having much lower fuel temperatures and a much slower rise in pressure (6 days to 11.2 atm versus 20.5 hours to 11.2 atm in case CVD1F). The lower decay heat used in case 17 (DSLOF) and the inclusion of the heat capacity of the residual water and annulus water in case 17 (DSLOF) are certainly factors that would cause such a difference. Also, the thermal conductivity of the annulus water is more accurate for case 17 (DSLOF).

The next six cases involve a loss of coolant (annulus water) failure.

- Case 20 (DSLOC) is an isolated MCO with a loss of coolant failure in which air takes the place of the flowing water in the annulus. The gas pressure reaches

11.2 atm in a little more than 21 hours when the maximum fuel temperature is still only 95 °C. If there is no rupture disk, then the maximum fuel temperature reaches about 900 °C in about 32 hours. The MCO pressurizes more slowly (21 hours to 11.2 atm) in case 20 (DSLOC) than in case CVD1C (approximately 18 hours to 11.2 atm) in the previous revision of this document (Duncan and Ball 1997). This is primarily because the decay heat is lower and the heat capacity of the residual water is included in case 20 (DSLOC).

- Case 21 (DLOC75KG) is the same as case 20 (DSLOC), except that 75 kg of free water is present at the time of the cooling failure. The pressure reaches 11.2 atm in about 25 hours, which is longer than in the previous case because the extra 48.5 kg of free water provides added heat capacity and causes a lower rate of temperature increase (see Appendix A, Figures A-20 and A-21). However, the peak fuel temperature is greater than 1,000 °C, which is greater than the peak fuel temperature in case 20 (DSLOC) because of the extra free water.

- Case 22 (DSLOCNOM) is the same as case 20 (DSLOC), except that it simulates an MCO with nominal parameter values (see Table 2) instead of bounding parameter values. The hydride loading (2.4 kg), free water (26.5 kg), and hydrate water (1.16 kg) are the same as in previous cases. Basically, the results are very benign, with a very slow pressure increase and temperature rise compared to the same case with an MCO with bounding parameter values (case 20, DSLOC). See Appendix A, Figure A-22, which shows both cases (case 22, DSLOCNOM and case 20, DSLOC).

- Case 23 (DSLOCREC) examines a recovery of the loss of coolant failure by restoring flowing annulus water at a cooler temperature of 25 °C at 21 hours after failure, which is just before the pressure reaches the rupture disk burst pressure. Since the water in the annulus cools down the MCO wall very quickly, the water vapor or steam starts to condense almost immediately on the cooler MCO wall and bottom, which are in contact with the annulus water. The condensing steam reduces the number of gas molecules in the MCO, and the pressure decreases. The pressure stays below the pressure at the time of the recovery (21 hours) for at least 24 hours (see Appendix A, Figure A-23).

- Case 24 (DSLOCRE2) is the same as the previous recovery case, except that the recovery consists of filling the annulus with stationary water at a cooler temperature of 25 °C. The effects of the cooler annulus are the same as in the previous case, except that the stationary annulus water heats up over time and the MCO pressure exceeds the pressure at the time of recovery (21 hours) in about 8 hours (see Appendix A, Figure A-24 for both case 24, DSLOCRE2, and case 20, DSLOC). If the recovery can take place earlier, then it will take the pressure longer to reach 11.2 atm. In other words, the recovery from the TWS failure is only minutes before the rupture disk would burst open for the two recovery cases. If the recovery were one hour or more before blowdown instead of few minutes, then the pressure would take a much longer time to reach the burst pressure.

- Case 25 (DSLOCOV) is the same as case 20 (DSLOC), except that a valve remains open at the time of the loss of coolant failure. As expected, the fuel temperatures are larger (>900 °C) than the temperatures in case 20 (DSLOC) and the peak occurs later, at more than 36 hours, instead of at 32 hours (see Appendix A, Figures A-25 and A-20).

The next four cases analyze the effects of different temperatures of annulus water on an isolated MCO. The annulus water temperatures are 46 °C for case 26 (DS46DEG), 55 °C for case 27 (DS55DEG), 75 °C for case 28 (DS75DEG), and 85 °C for case 29 (DSHOT). The time for the pressure to reach 11.2 atm is plotted in Figure 2, which clearly shows the nonlinear effects of temperature on the pressurization time.

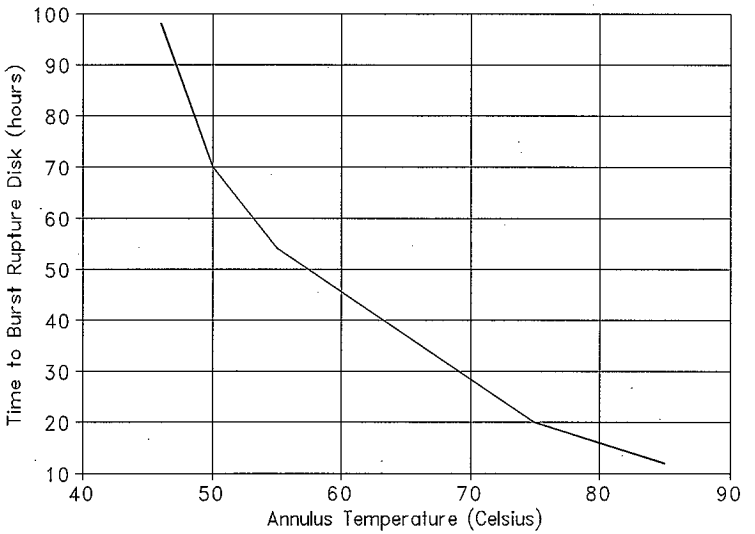
Case 30 (DHOT75KG) is the same as case 29 (DSHOT with an 85 °C annulus), except that 75 kg of free residual water, instead of 26.5 kg, is available at the time of TWS failure. Because of the hot annulus, the residual water is heated up quickly and the pressure reaches 11.2 atm in slightly less time, 11.5 hours, than the time realized (12 hours) in case 29 (DSHOT) (see Appendix A, Figures A-30 and A-29). Normally, the additional heat capacity of the extra 48.5 kg of water slows down the temperature increase and the resulting pressure increase. However, a hot annulus (85 °C) supplies more heat to the lower temperature MCO, and this extra heat more than makes up for the extra heat capacity. This phenomenon is different for the loss of coolant cases (case 20, DSLOC, and case 21, DLOC75KG) because the annulus water in those cases does not supply heat to the MCO but, instead, slows down the heat removal rate, which makes the extra heat capacity more noticeable (see Appendix A, Figures A-20 and A-21). It should be noted that the 85 °C annulus acts as a heater in the early stages of the thermal runaway reaction but acts as a coolant in the later stages of the thermal runaway reaction with the peak fuel temperatures being much lower (<215 °C) than the peak temperature (>900 °C) for the thermal runaway reaction with loss of coolant condition (case 20, DSLOC).

Case 31 (DSHOTOV), the last case in this group, is the same as case 29 (DSHOT), except that a valve is open at the time of the TWS temperature failure. Hence, this case does not have an isolated MCO like case 29 (DSHOT). As expected, the fuel temperatures are higher (>1,000 °C) than they are in case 29 (DSHOT) (<215 °C), and the peak temperature occurs later in time (see Appendix A, Figures A-31 and A-29).

5.6 GROUP V, VACUUM DRYING AND HELIUM PURGE WITH AIR INGRESS (CASES 32 THROUGH 37)

This group of cases examines the effects of air ingress during the vacuum drying processes. Air is assumed to enter the MCO through a very small hole (0.1 cm^2) (Plys et al. 1997), so the operators cannot detect it by observing an increase in pressure during the vacuum drying processes. Major TWS failures — loss of coolant and a hot (85 °C) annulus — are included with the air ingress effects. Since the hydrides reacting with air (oxygen) can be significant in contributing heat to the fuel, the hydride loading for the air ingress case was increased from 2.4 kg to 14.6 kg (9.0 kg for the scrap basket, 5.6 kg for four fuel baskets). This higher hydride loading results in an effective reaction rate multiplier of 111 for the scrap fuel and 59.2 for the fuel elements (see Appendix C, Note 4).

Figure 2. Time to Reach Rupture Disk Burst Pressure versus Temperature of Annulus Water.



The drying time of the MCO for the vacuum only process (case 32, VACAIRI) is longer with air ingress than without it (19 hours for case 32, VACAIRI, versus 14 hours for case 1, VACUUM). This is because the fuel-air reaction rates are lower than the fuel-water reaction rates and less heat is generated as a result. With less heat, the fuel temperatures and evaporation and boiling rates are lower, and the dryout time is longer (see Appendix A, Figure A-32). However, the helium purge only process (case 35, PURAIRI) with air ingress is not stable. The fuel temperatures for this case stay below 105 °C, but the innermost fine scrap fuel temperature reaches 700 °C in less than 1.4 hours. This peak temperature lasts only for a few minutes and is due to the high hydride mass loading on the scrap fuel (see Appendix A, Figure A-35). The scrap fuel temperatures are expected to be stable for the helium purge only process with the large nominal value of 1.1 kg for hydrides in the scrap instead of the bounding value of 9.0 kg as in this case.

The hot water annulus (85 °C) and loss of coolant conditions under vacuum processes (case 33, VAIRIHOT , and case 34, VAIRILOC) produce very unstable temperatures (>900 °C), after 2.5 days for case 33 (VAIRIHOT), and after 4 days for case 34 (VAIRILOC). In all the vacuum only cases, the fuel heats up after the free water is gone. Combining air ingress with

poor heat removal conditions causes the fuel temperature to increase greatly and react with the incoming oxygen continuously at increasing reaction rates. The temperatures eventually become very unstable after a couple of days. However, when free water is present, the cooling effects of evaporation keep the fuel temperatures low as long as the free water is available, and it takes more than a day after the free water is gone to start reaching high fuel temperatures (see Appendix A, Figures A-33 and A-34). For the helium purge only process (case 36, PAIRIHOT) with the hot annulus condition, the inner fine scrap fuel becomes unstable very quickly (<1 hour), but the temperatures of the fuel elements remain stable and stay below 115 °C.

The maximum hydrogen generation rates for these cases are higher than the corresponding cases with no air ingress. The main reason for this is the increased bounding hydride loading used in the air ingress cases compared to the other cases with nominal hydride loading. An air ingress case with no hydrides for the vacuum only process (case 37, VACAIRI2) was simulated to show the effects of hydrides on the hydrogen generation rate during air ingress. The maximum hydrogen generation rate for this case is only 1.9 mg/sec compared to 21.2 mg/sec for the same case with bounding hydrides (case 32, VACAIRI). Hence, the bounding hydrides with air produce about 11.2 times as much hydrogen as the uranium-air reaction produces during the initial stage of vacuum drying with air ingress. The maximum hydrogen generation rate was 3.0 mg/sec for the vacuum only case (case 1, VACUUM) with no air ingress and 2.4 kg of hydrides (see Appendix A, Figures A-32 and A-1). Hence, the amount of hydrides is a very important factor in hydrogen production and scrap fuel temperature stability.

5.7 GROUP VI, COLD VACUUM DRYING FACILITY SAFETY ANALYSIS REPORT CASES (CASES 38 THROUGH 42)

The CVDF Safety Analysis Report (Pili-Vincens 1998) included a high-pressure thermal runaway scenario with the MCO rupture disk bursting open at a pressure of 11.2 atm (150 lb/in^2 gauge). The blowdown release of particulate and the continuous release of particulate following the blowdown were included in the Safety Analysis Report (Pili-Vincens 1998) in order to estimate the dose to people at onsite and offsite locations. The only difference between the primary SAR case, case 38 (DSLOCSA4), and case 20 (DSLOC) is that 35.5 kg of free residual water, instead of 26.5 kg, is present when the loss of coolant failure occurs. An extra 9 kg of free water was postulated to exist between the bottom of the lowest fuel basket and the surface of MCO bottom (a 1.5-in. gap). This extra water can be caused by a drain interrupt or a blockage of the long process tube intake at the bottom of the MCO.

The high-pressure thermal runaway scenario (case 38, DSLOCSA4) reaches the rupture disk burst pressure of 11.2 atm in a little more than 21 hours after the loss of coolant failure. The maximum fuel temperature at this point in time is only about 95 °C. If there were no rupture disk in the MCO (there is none in case 38, DSLOCSA4), the pressure would start to increase very rapidly 30 hours after the loss of coolant condition. The pressure peaks at around 230 atm at 32 hours (assuming no pressure relief), and the inner fuel temperatures peak above 1,000 °C at about the same time. The pressures and temperatures would continue to increase after 32 hours except that all of the free water and all of hydrate water are consumed. Hence, there are no more

oxidants left for the fuel after the water is depleted. Hydrogen gettering was not included in the case but would take place mainly after the water is consumed and would lower the pressure more quickly than illustrated in Appendix A, Figure A-38. Since the main interest in this case was to provide the conditions for the blowdown release, which occurs around 21 hours, hydrogen gettering was not important to this scenario.

The blowdown release, the continuous release, and the reactions after the blowdown are included is case 39 (BLOW4N). The free water and hydrated water are depleted about 16 hours after the blowdown (about 37 hours after the loss of coolant failure) although there is a small amount (0.037 kg) of hydrate water left on the scrap fuel because the scrap fuel is not hot enough to decompose the last water molecule in a hydrate molecule. The inner fuel element temperature surpasses 1,000 °C about 15 hours after the blowdown (36 hours after the loss of coolant failure [see Appendix A, Figure A-39]). After the water is gone, the fuel continues to react with the air constituents (oxygen, water vapor, and nitrogen) that enter the MCO through the rupture disk orifice. Since air outside the MCO is cooler and more dense than the hot MCO gases exiting the orifice, a small amount of the air will flow counter to the exiting gases. After the water is depleted, the MCO will cool down and draw in more air at a faster rate. Since some of the fuel elements are hot (<700 °C), nitrogen will react with the hot fuel to form uranium nitride. However, only about 0.55 kg of nitride is formed during the entire 24-hour time period after the blowdown, whereas about 250 kg of UO_2 is generated over the same 24-hour time period. Less than 22 kg of particulate is generated after draining and before the blowdown at 21 hours.

Since the recovery of the loss of coolant failure is of interest, two recovery cases were analyzed. One recovery case takes place 21 hours after the loss of coolant condition (case 40, DSSA4REC) and just before the rupture disk bursts open. The recovery consists of restoring the annulus water with stationary (not flowing) water that is around room temperature (25 °C). The result of the recovery that the MCO gas pressure quickly decreases because of the water vapor (steam) condensing on the cooler MCO wall. The gas pressure stays below the rupture disk burst pressure for another 8 hours, thus preventing the blowdown release for at least that long (see Appendix A, Figure A-40). If the annulus water is recovered sooner than just before the blowdown, the blowdown will be prevented for more than 24 hours. The second recovery case (case 41, BLOWREOV) investigated the effect of restored annulus water after the blowdown had occurred (which includes an opened rupture disk). The stationary annulus water is put in place 1 hour after the blowdown release (22 hours after loss of coolant condition). The result is stable fuel temperatures forever. The cooler annulus causes condensation of steam on the cooler MCO wall, which lowers the water vapor pressure and the ensuing reaction rates. With lower reaction rates and good heat transfer from the MCO to the cask and process bay, the fuel temperatures stay stable and lower than they were initially at the time of recovery (see Appendix A, Figure A-41). Furthermore, the amount of particulate generated for 24 hours after the blowdown is only about 2.5 kg, compared with 250 kg when there is no recovery (case 39, BLOW4N). Hence, the recovery of the lost annulus water by filling the annulus with stationary water is very effective in preventing the blowdown (case 40, DSSA4REC) and reducing the continuous release after the blowdown by a factor of 10 (case 41, BLOWREOV).

Table 4. Results Summary of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Annulus water description	Maximum H_2 generation rate (mg/sec) and time of maximum	Results summary; highlights
COMPLETE NORMAL OPERATIONS AFTER DRAINING AT CVDF: Bounding MCO and nominal hydrides (2.4 kg)					
0	NORMAL	Complete CVDF cycle after draining and before shipping to CSB	Normal: 25 to 50 °C and flowing	3.0 at 0.78 hour	See Table 3 Dry in 20.5 hours
I. VACUUM DRYING AND HELIUM PURGE: Bounding MCO and nominal hydrides (2.4 kg)					
1	VACUUM (CVD3B)	Vacuum drying	50 °C and flowing	3.0 at 80 sec	Dry in 14+ hours Fuel temperature <82 °C forever
2	VAC75KG (CVD3C)	Vacuum drying - 75 kg free water	50 °C and flowing	2.9 at 85 sec	Dry in 3 days Maximum fuel temperature = 140 °C in 3+ days
3	VACPUR	Vacuum drying - helium purge	50 °C and flowing	3.0 at 95 sec	Dry in 16+ hours Fuel temperature <85 °C forever
4	PURGE (CVD2A)	Helium purge	50 °C and flowing	3.2 at 40 sec	MCO dry in 3 days, fuel dry in 31 hours Fuel temperature <104 °C forever
II. VACUUM DRYING, HELIUM PURGE, HOT ANNULUS WATER: Bounding MCO and nominal hydrides (2.4 kg)					
5	VACHOT	Vacuum drying with hot annulus water without helium purge	85 °C and flowing	5.1 at 1 sec	Dry in 12+ hours Fuel temperature <115 °C forever
6	VPURHOT	Vacuum drying with hot annulus water with helium purge	85 °C and flowing	5.1 at 1 sec	Dry in 12+ hours Fuel temperature <115 °C forever
7	PURHOT	Helium purge with hot annulus water	85 °C and flowing	300 at 14 hours	Dry in 20+ hours Scrap fuel temperature > 500 °C in 8 hours
III. VACUUM DRYING WITH MAJOR FLOW FAILURE OF TEMPERED WATER (ANNULUS) SYSTEM: Bounding MCO and nominal hydrides (2.4 kg)					
8	VACLOF	Vacuum drying - no annulus flow	50 °C initially and not flowing	3.0 at 1 sec	Dry in 15+ hours Fuel temperature <72 °C forever
9	VLOFHOT	Vacuum drying - no annulus flow and hot annulus water	85 °C initially and not flowing	5.1 at 1 sec	Dry in 12 hours Fuel temperature <76 °C forever
10	VACLOC	Vacuum drying - loss of coolant (annulus water)	Water lost, air in annulus	2.9 at 1 sec	Dry in 14+ hours Fuel temperature <115 °C forever

Table 4. Results Summary of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Annulus water description	Maximum H_2 generation rate (mg/sec) and time of maximum	Results summary; highlights
11	VPURLOC	Vacuum drying - loss of coolant with helium purge	Water lost, air in annulus	2.9 at 1 sec	Dry in 16+ hours Fuel temperature <120 °C forever
12	PURLOF (CVD2B)	Helium purge - no annulus water	50 °C initially and not flowing	3.0 at 1 sec	Dry in almost 6 days Fuel temperature <82 °C forever
13	PURLOC (CVD2C)	Helium purge - loss of coolant	Water lost, air in annulus	22 at 14 hours	Dry in 2 days Maximum scrap fuel temperature = 330 °C in 2 days
IV. DRAINING STOP AND GAS BLOCKAGE: Bounding MCO and nominal hydrides (2.4 kg)					
14	DSTOP (CVD2A)	Draining and gas blockage - normal annulus water	50 °C and flowing	3.1 at 1.2 hours	Gas pressure = 11.2 atm in 3 days Fuel temperature <80 °C forever
15	DS75KG	Draining and gas blockage - normal annulus water, 75 kg free water	50 °C and flowing	3.1 at 1.2 hours	Gas pressure = 11.2 atm in 3.5+ days Fuel temperature <80 °C forever
16	DSTOPOV	Draining and gas blockage - normal annulus water, with open vent	50 °C and flowing	3.2 at 0.7 hour	Fuel temperature <105 °C forever
17	DSLOF (CVD1F)	Draining and gas blockage - loss of annulus water flow	50 °C initially and not flowing	3.1 at 0.6 hour	Gas pressure = 11.2 atm in 6 days Fuel temperature <71 °C forever
18	DLOF75KG	Draining and gas blockage - loss of annulus water flow, 75 kg free water	50 °C initially and not flowing	3.1 at 0.6 hour	Gas pressure = 11.2 atm in 6+ days Fuel temperature <71 °C forever
19	DSLOFOV	Draining and gas blockage - loss of annulus water flow, with open vent	50 °C initially and not flowing	3.1 at 0.5 hour	Fuel temperature <80 °C forever
20	DSLOC (CVD1C)	Draining and gas blockage - loss of coolant	Water lost, air in annulus	540 at 32 hours	Gas pressure = 11.2 atm in 21 hours Maximum fuel temperature > 900 °C in 32 hours
21	DLOC75KG	Draining and gas blockage - loss of coolant, 75 kg free water	Water lost, air in annulus	163,000 at 40 hours	Gas pressure = 11.2 atm in 25 hours Maximum fuel temperature >1,000 °C in 39+ hours
22	DSLOCNOM	Draining and gas blockage - loss of coolant	Water lost, air in annulus	2.1 at 5.5 hours	Gas pressure <3.5 atm for 2 days Fuel temperature <77 °C for 2 days
23	DSLOCREC	Draining and gas blockage - loss of coolant recovery	25 °C and flowing at restart	6.0 at 21 hours	25 °C flowing annulus water in 21 hours prevents blowdown release and cools down fuel

Table 4. Results Summary of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Annulus water description	Maximum H_2 generation rate (mg/sec) and time of maximum	Results summary; highlights
24	DSLOCRE2	Draining and gas blockage - loss of coolant recovery	Stationary and 25 °C at 21 hours	6.0 at 21 hours	Stationary annulus recovery at 21 hours delays blowdown for 14 hours
25	DSLOCOV	Draining and gas blockage - loss of coolant	Water lost, air in annulus	8,100 at 32 hours	Maximum fuel temperature >900 °C in 36+ hours
26	DS46DEG	Draining and gas blockage - 46 °C annulus	46 °C and flowing	3.1 at 120 sec	Gas pressure = 11.2 atm in 4+ days Fuel temperature <76 °C forever
27	DS55DEG	Draining and gas blockage - 55 °C annulus	55 °C and flowing	4.0 at 2.3 hours	Gas pressure = 11.2 atm in 2+ days Fuel temperature <85 °C forever
28	DS75DEG	Draining and gas blockage - 75 °C annulus	75 °C and flowing	8.6 at 3.8 hours	Gas pressure = 11.2 atm in 20+ hours Fuel temperature <120 °C forever
29	DSHOT	Draining and gas blockage - hot annulus water	85 °C and flowing	25 at 4.9 hours	Gas pressure = 11.2 atm in 12 hours Fuel element temperature <151 °C forever Maximum scrap fuel temperature = 215 °C in 5 hours
30	DHOT75KG	Draining and gas blockage - hot annulus, water 75 kg free water	85 °C and flowing	24 at 4.9 hours	Gas pressure = 11.2 atm in 11.5 hours Fuel element temperature <157 °C forever Maximum scrap fuel temperature = 210 °C in 5 hours
31	DSHOTOV	Draining and gas blockage - hot annulus water, with open vent	85 °C and flowing	13,600 at 29 hours	Fuel temperature >1,000 °C in 28+ hours
V. VACUUM DRYING AND HELIUM PURGE WITH AIR INGRESS Bounding MCO and bounding hydrides (14.6 kg)					
32	VACAIRI	Vacuum drying - air ingress and bounding hydrides	50 °C and flowing	21.2 at 1 sec	Dry in 19 hours Fuel temperature <120 °C forever
33	VAIRIHOT	Vacuum drying - air ingress, bounding hydrides, and hot annulus water	85 °C and flowing	49 at 1 second	Dry in 16 hours Fuel temperature >900 °C in 2.5 days
34	VAIRILOC	Vacuum drying - air ingress, bounding hydrides, and loss of coolant	Water lost, air in annulus	49 at 108 hours	Dry in 20 hours Fuel temperature >900 °C in 4+ days

Table 4. Results Summary of Simulated Cases. (4 sheets)

Case number	Case name	Operating mode description	Annulus water description	Maximum H_2 generation rate (mg/sec) and time of maximum	Results summary; highlights
35	PURAIRI	Helium purge - air ingress and bounding hydrides	50 °C and flowing	2,390 at 1.4 hours	Dry in 3+ days Fuel temperature < 105 °C forever Maximum scrap fuel temperature > 700 °C in 1.4 hours
36	PAIRIHOT	Helium purge - air ingress, bounding hydrides, and hot annulus water	85 °C and flowing	8,670 at 0.9 hour	Dry in 19+ hours Fuel temperature < 115 °C forever Maximum scrap fuel temperature > 750 °C in 0.9 hour
37	VACAIRI2	Vacuum drying - air ingress without hydrides	50 °C and flowing	1.9 at 1 sec	Dry in 20 hours Fuel temperature < 115 °C forever
VI. CVDF SAFETY ANALYSIS REPORT CASES					
38	DSLOCSA4	High-pressure thermal runaway (drain interrupt and gas blockage) - loss of coolant	Water lost: air at 50 °C initially	1,600 at 32 hours	Gas pressure = 11.2 atm in 21+ hours Fuel temperature > 1000 °C in 32 hours, 22 kg of UO_2 generated in 21 hours after loss of coolant
39	BLOW4N	Blowdown of high-pressure thermal runaway at 11.2 atm (150 lb/in^2 gauge)	Air at 64 °C initially at restart at 21 hours	35,800 at 36 hours	Fuel temperature > 1000 °C in 36 hours, ~250 kg of UO_2 generated in 24 hours after rupture disk opens
40	DSSA4REC	Recovery of high-pressure thermal runaway - stationary annulus water	25 °C and not flowing at restart at 21 hours	6.2 at 21 hours	Stationary annulus recovery delays blowdown release 8 hours and keeps fuel temperature < 100°C forever
41	BLOWREOV	Recovery of low-pressure thermal runaway after blowdown occurs	25 °C and not flowing at 21 hours	1,000 at 22 hours	Stationary annulus water keeps fuel temperatures < 100°C after blowdown
42	DSLOCOV2	Low-pressure thermal runaway (drain interrupt with loss of coolant and open vent)	Annulus water lost: air at 50 °C initially	35,600 at 37+ hours	Fuel temperature > 1000 °C in 37+ hours

CSB = Canister Storage Building.
CVDF = Cold Vacuum Drying Facility.
MCO = multi-canister overpack.

Case 42 (DSLOCOV2) is the last case included in this report. This case is the same as case 25 (DSLOCOV), except that the free residual water is 35.5 kg instead of 26.5 kg. Both cases look at the thermal behavior of an open MCO (not isolated and no vacuum or purge processes) with a loss of coolant condition. As expected, the fuel temperatures in case 42 (DSLOCOV2) are unstable and are greater than 1,000 °C in a little more than 37 hours after the loss of coolant condition. The fuel temperatures are larger than those in case 25 (DSLOCOV) because more free water is available for the fuel-water reactions (see Appendix A, Figures A-42 and A-25).

6.0 CONCLUSIONS

The following conclusions, which are also presented in the Executive Summary, can be drawn from the thermal analysis.

1. **Vacuum drying is inherently stable**. Vacuum drying with no helium purge is inherently stable forever for all annulus water conditions including the hot (85 °C) annulus water and loss of coolant (annulus water) cases. Radiative heat transfer is sufficient under vacuum to remove enough heat to maintain stable fuel temperatures. Even for air ingress scenarios, the fuel temperatures are stable under vacuum except for the hot annulus water and loss of coolant cases. However, even for these major failures of the tempered water (annulus) system, the fuel temperatures are stable for more than 2 days. Vacuum drying is the most inherently stable physical process occurring at the Cold Vacuum Drying Facility.

2. **Helium purge is stable under normal conditions**. The helium purge only (i.e., no vacuum) process has stable temperatures for the normal (50 °C) annulus water and loss of annulus water flow cases, but it is not stable for the hot annulus water and loss of coolant cases. The helium purge only process is not stable for air ingress cases with bounding hydrides, which have unstable scrap fuel temperatures in less than 2 hours primarily because of the large bounding hydride mass.

3. **Open MCOs are stable under most conditions**. An open MCO with no vacuum and no helium purge is stable forever for the normal annulus water and loss of annulus water flow cases, but it is very unstable (fuel temperature > 1,000 °C) for the hot annulus water and loss of coolant cases after 30 hours if enough residual water is available.

4. **Closed MCOs with bounding parameter values take a long time to pressurize under most conditions**. A closed (isolated) MCO will pressurize and eventually reach the rupture disk burst pressure for all annulus water conditions, but reaching the rupture disk burst pressure will take 3 days for the normal (50 °C) annulus water case and 6 days for the loss of annulus water flow case (stationary annulus water is

cooler than 50 °C because of the lower room temperature of the process bay and the good thermal conductivity of water). If no rupture disk were used, very high fuel temperatures (>900 °C) would result for the hot annulus water and loss of coolant cases after 30 hours if enough residual water were available.

5. **Closed MCOs with nominal parameter values are inherently stable**. A closed MCO with nominal parameter values for decay heat, chemical reaction rates, and reaction surface area pressurizes very slowly for the loss of coolant case. The MCO gas pressure and the temperatures in the bottom fuel basket are shown in Appendix A, Figure A-22 for both the bounding MCO and nominal MCO under loss of coolant conditions (with no rupture disk included). Clearly, even under loss of coolant conditions, the nominal MCO does not heat up or pressurize very much in 2 days, whereas the bounding MCO reaches very high pressures and temperatures in less than 2 days.

6. **Introducing water into the annulus can prevent bursting of the rupture disk**. For the bounding MCO under loss of coolant conditions, the MCO pressurization can be stopped very quickly (less than 60 seconds) by introducing 25 °C water into the annulus. The cool water injected into the annulus cools the stainless steel MCO wall and bottom very quickly, and the water vapor inside the MCO starts to condense on the cooler MCO wall and bottom immediately. The condensation of water vapor lowers the gas pressure immediately and prevents the pressure from reaching the rupture disk burst pressure, as shown in Appendix A, Figure A-23. Figure A-23 also shows that the inner fuel element temperature does not decrease immediately; it takes about 2 hours to show a significant decrease in temperature. Nevertheless, the water vapor condensing on the cooler MCO wall and bottom keeps the MCO pressure below the rupture disk burst pressure for as long as 8 hours if the annulus water is stationary and more than 24 hours if the annulus water is flowing. Furthermore, the MCO wall temperature is only about 85 °C when the MCO pressure reaches rupture disk burst pressure, 11.2 atm (150 lb/in^2 gauge), so there is no danger of the water flashing or boiling when introduced into the annulus.

7. **Favorable annulus water conditions promote stability for all operating conditions**. The normal annulus water condition (50 °C and flowing) and the loss of annulus water flow condition result in stable temperatures forever for all normal and off-normal conditions analyzed. The loss of annulus water flow condition promotes lower fuel temperatures than the 50 °C annulus water condition.

8. **Scrap fuel is generally cooler than fuel elements**. The scrap basket design with compartments created by copper fins is efficient for heat removal purposes. Most of the off-normal cases that resulted in high temperatures had higher fuel element temperatures than scrap fuel temperatures, except for the helium purge only off-normal cases. The helium purge only cases with unfavorable annulus conditions have high fuel-water (steam) reaction rates in the scrap fuel because water vapor is blown from the fuel baskets into the scrap basket, which has a high surface area to

volume ratio, causing the maximum scrap fuel temperature to be greater than the maximum fuel element temperature. Also, the latest scrap basket design (Smith 1998), which does not have copper fin spokes in the fine scrap portion, causes even higher scrap temperatures for off-normal helium purge only cases than the design used in the previous thermal analysis (Duncan and Ball 1997), which included copper fin spokes in the fine scrap portion.

In summary, the results of this analysis show that the bounding MCO has stable temperatures for all cold vacuum drying processes after draining if the annulus water is kept at 50 °C or cooler by the tempered water (annulus) system, or if the annulus water is stationary (not flowing). Air ingress with bounding hydride loadings (9.0 kg) in the scrap fuel results in unstable scrap fuel temperatures for the helium purge only process but not for the vacuum only process unless the TWS has major failures lasting for more than 2 days.

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APPENDIX A

HANSF OUTPUT PLOTS

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TABLE OF FIGURES

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Figure A-1 VACUUM: Indefinite Vacuum with 50 °C Annulus

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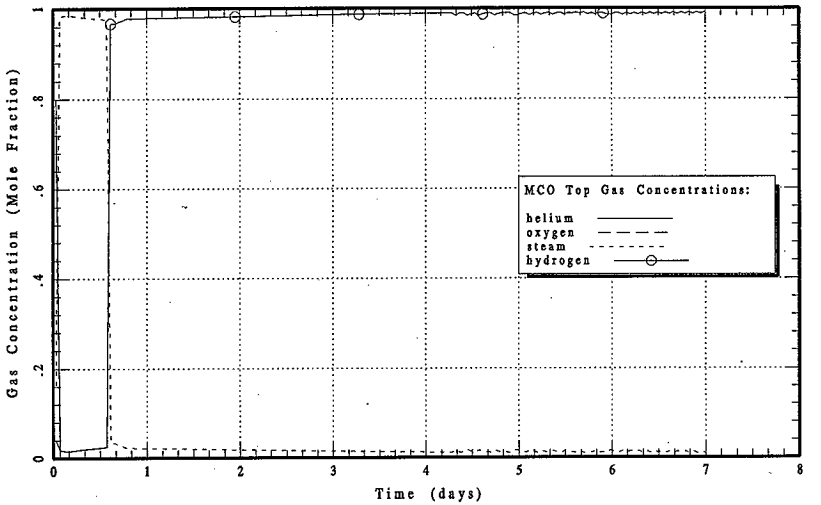
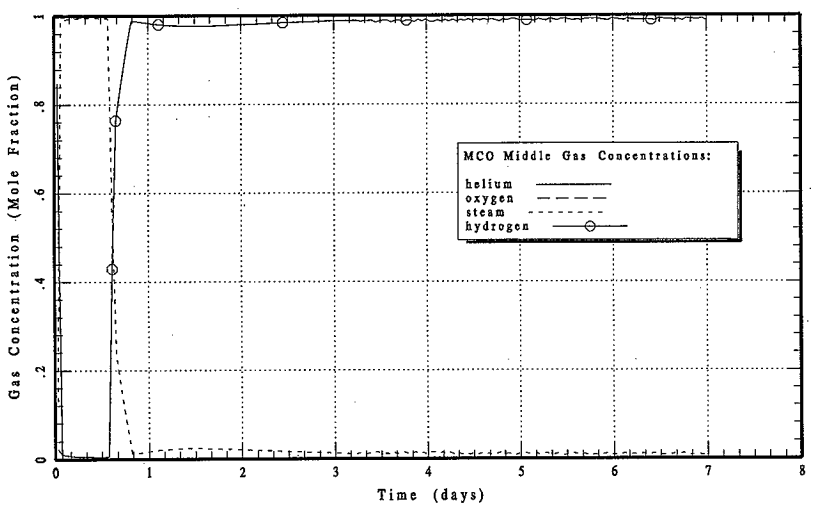
VACUUM: INDEFINITE VACUUM w 50 Deg C Annulus





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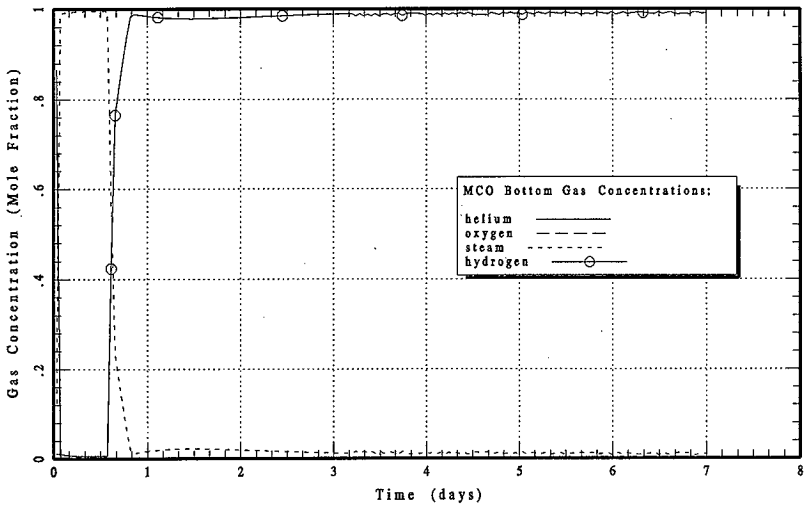

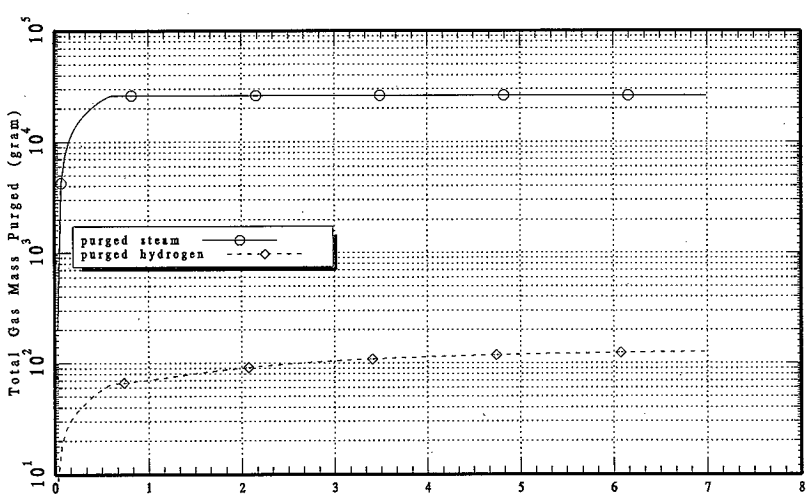

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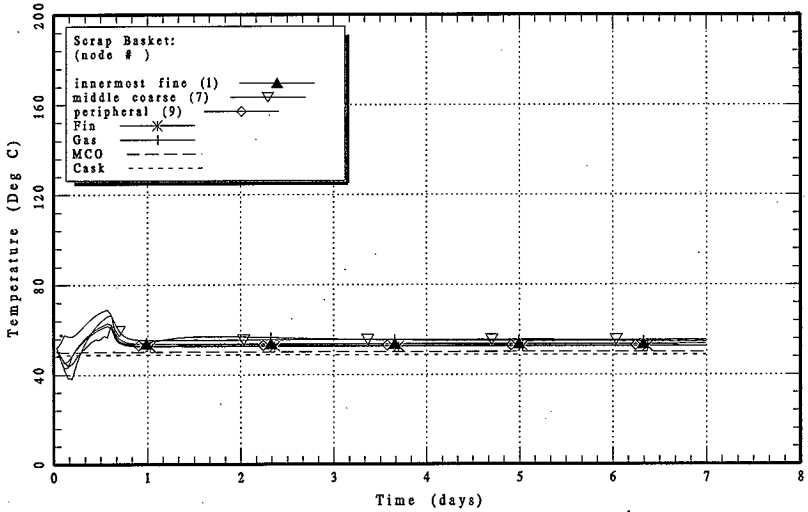

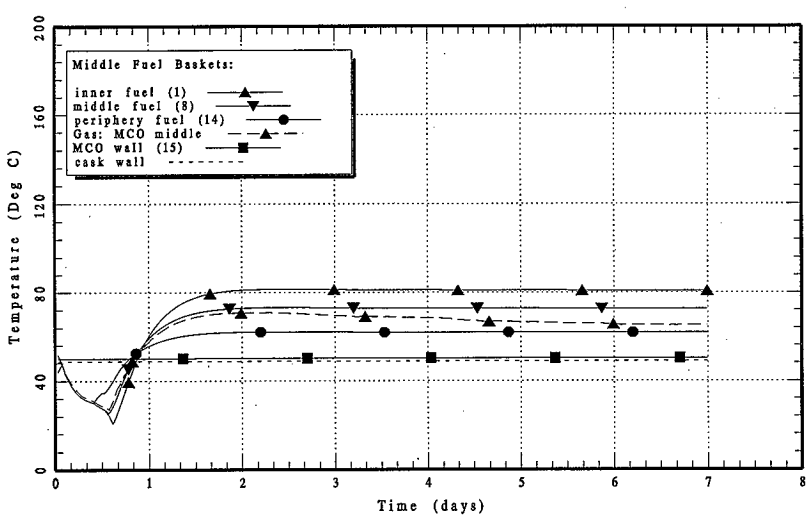

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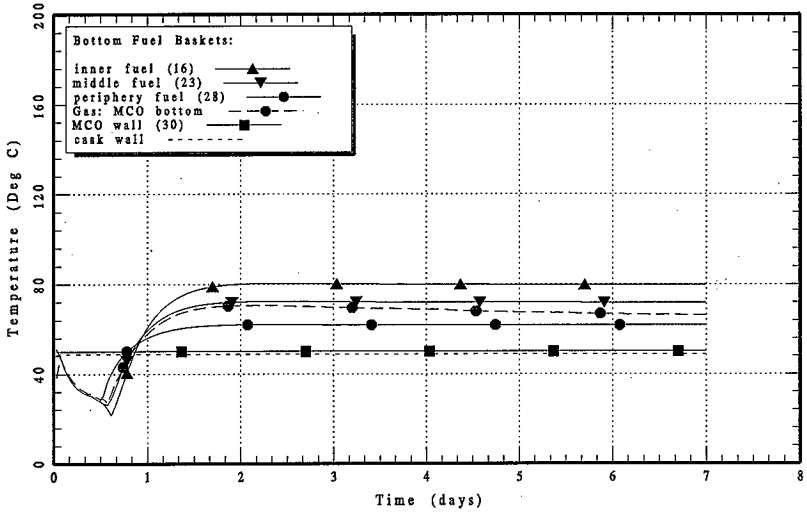

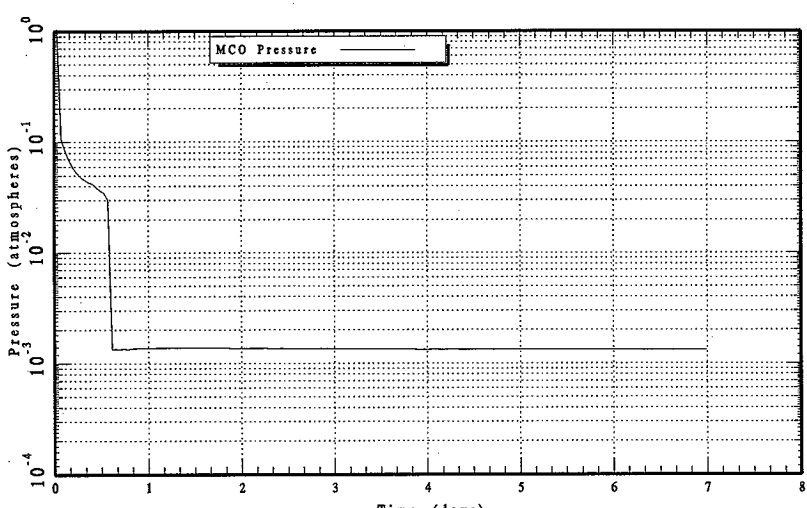

Figure A-2 VAC75KG: Indefinite Vacuum with 75 Kg Water and 50 °C Annulus

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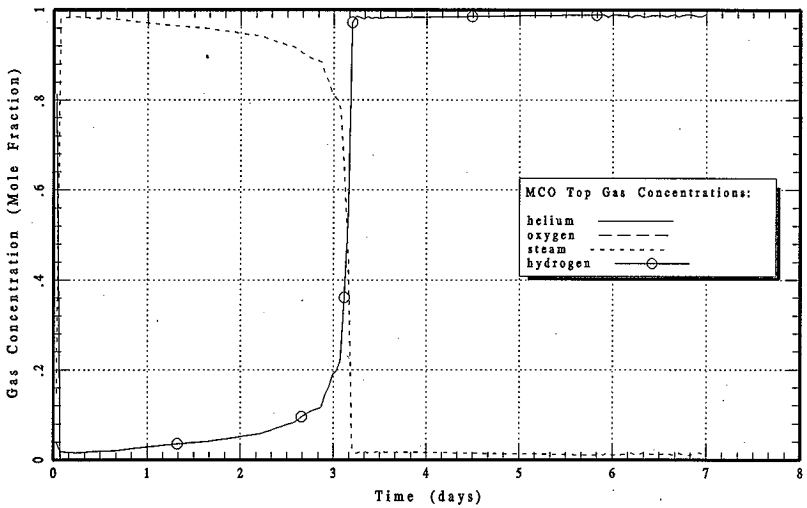
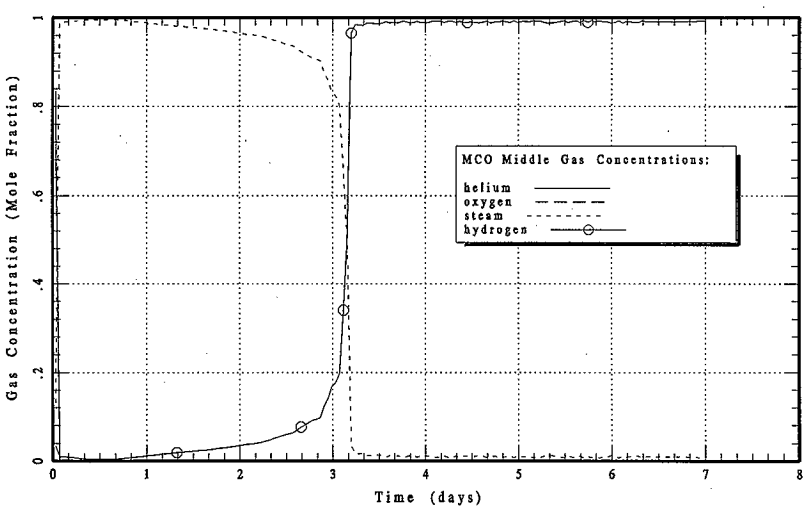
VAC75KG: INDEFINITE VACUUM w 75 Kg Water & 50 Deg C Annulus





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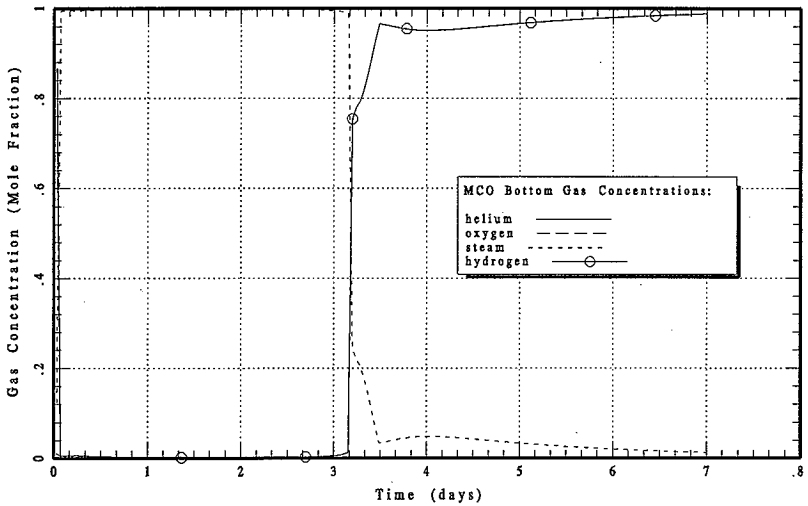

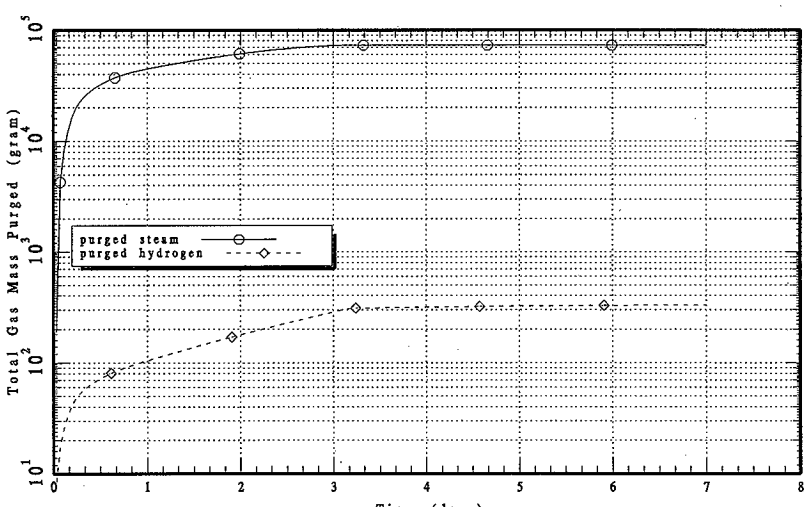

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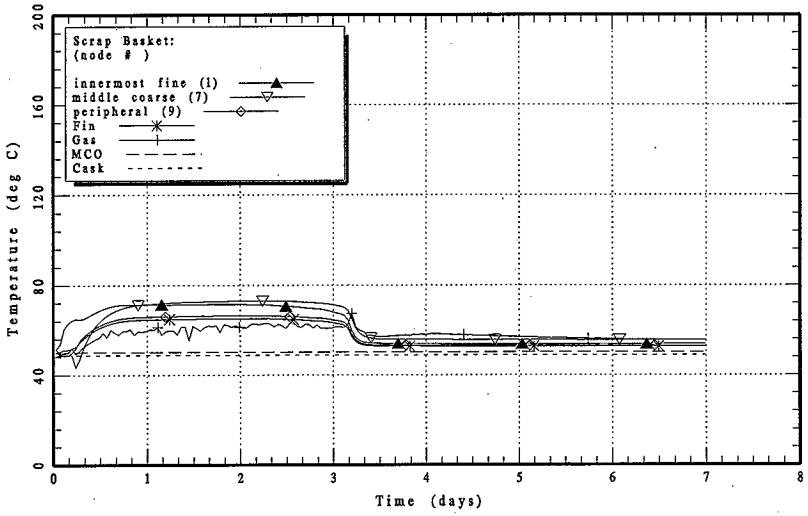

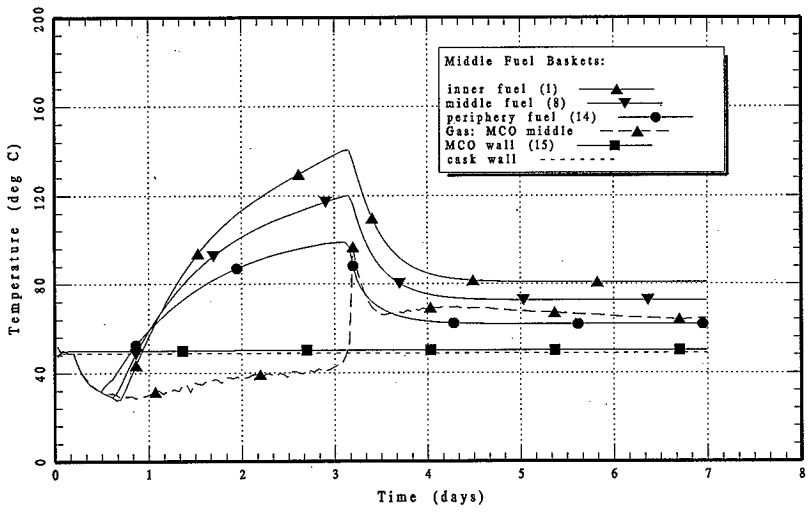

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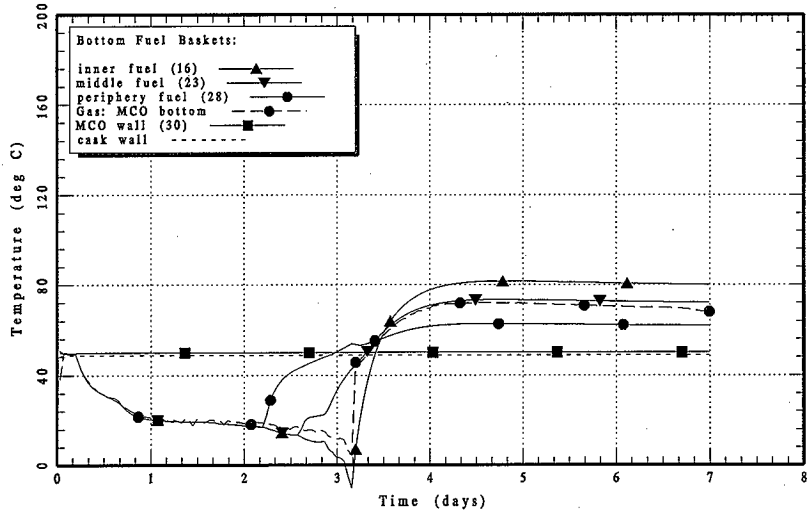

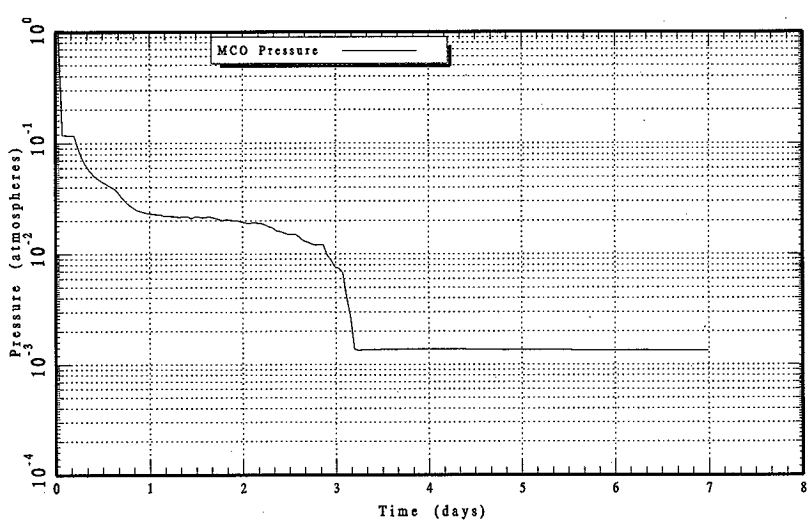

Figure A-3 VACPUR: Vacuum with Helium Purge with 50 °C Annulus

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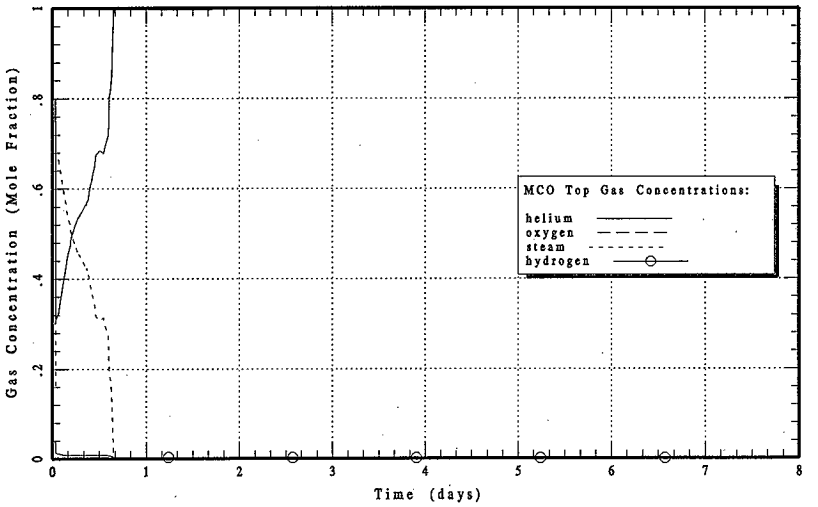
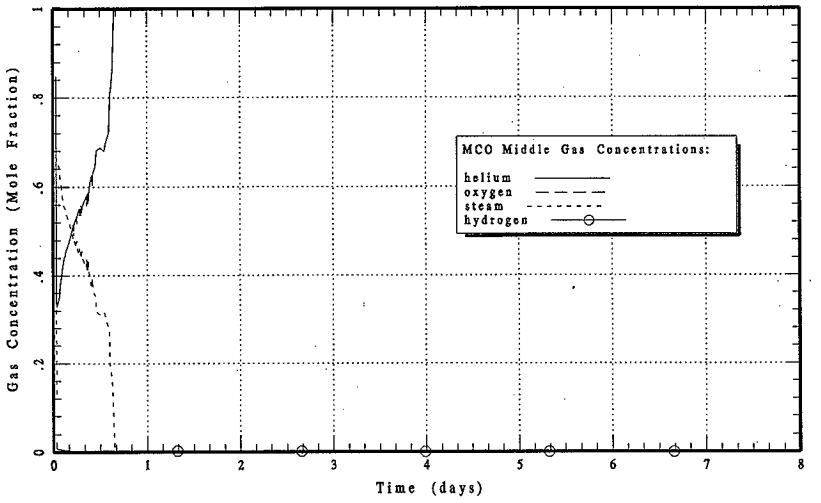
VACPUR: VACUUM w HELIUM PURGE w 50 Deg C Annulus





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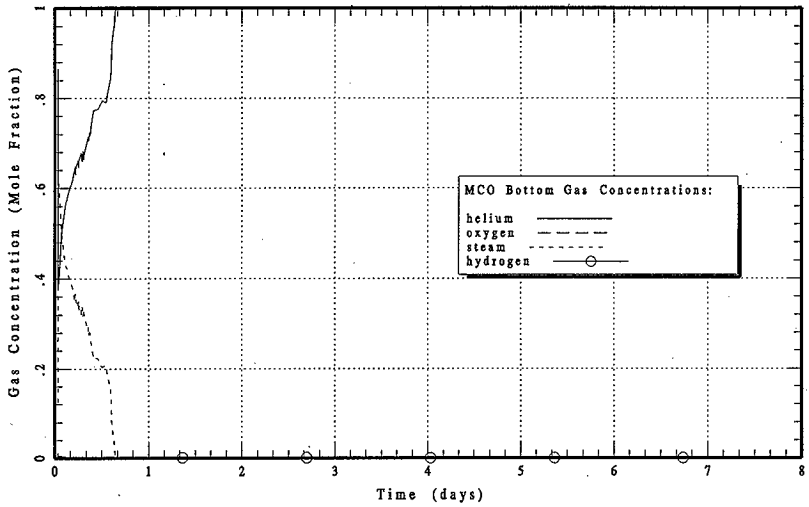

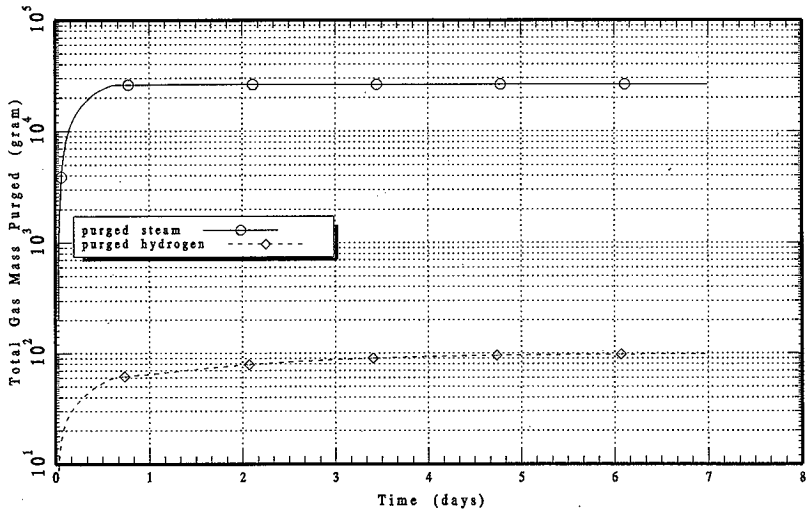

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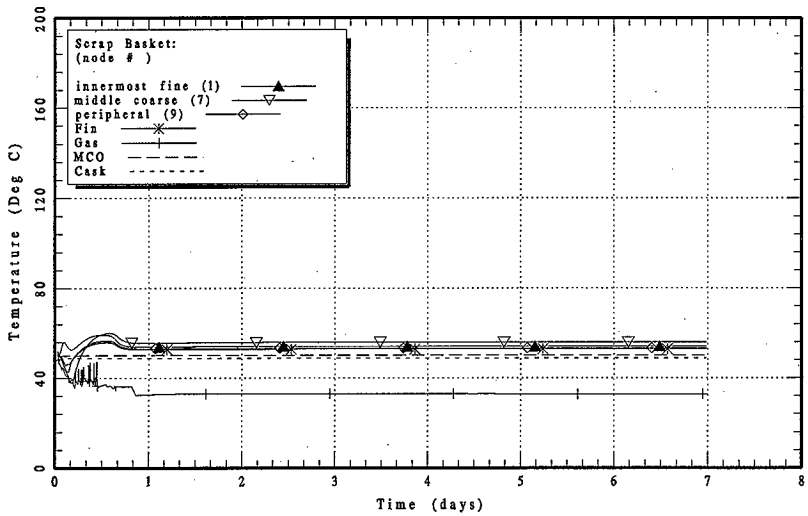

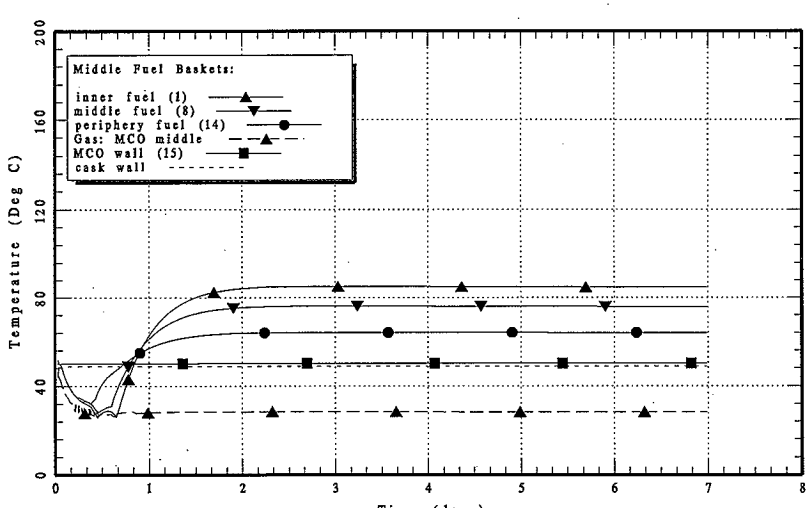

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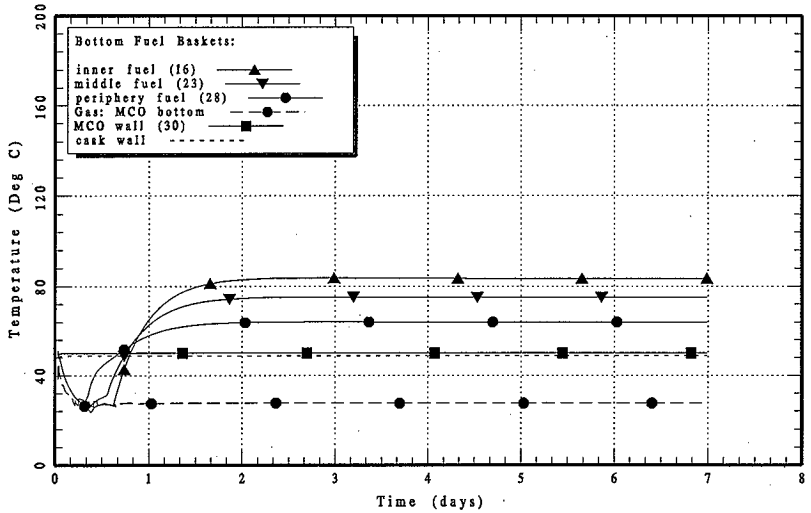

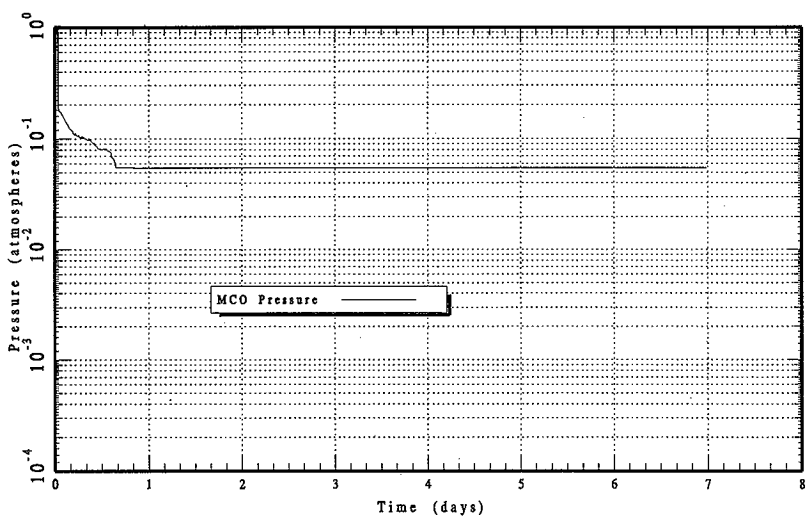

Figure A-4 PURGE: Helium Purge with 50 °C Annulus Water

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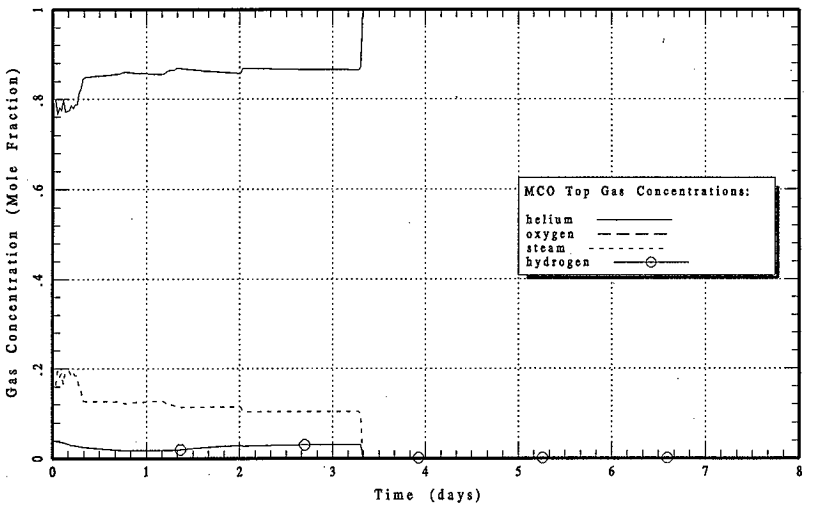
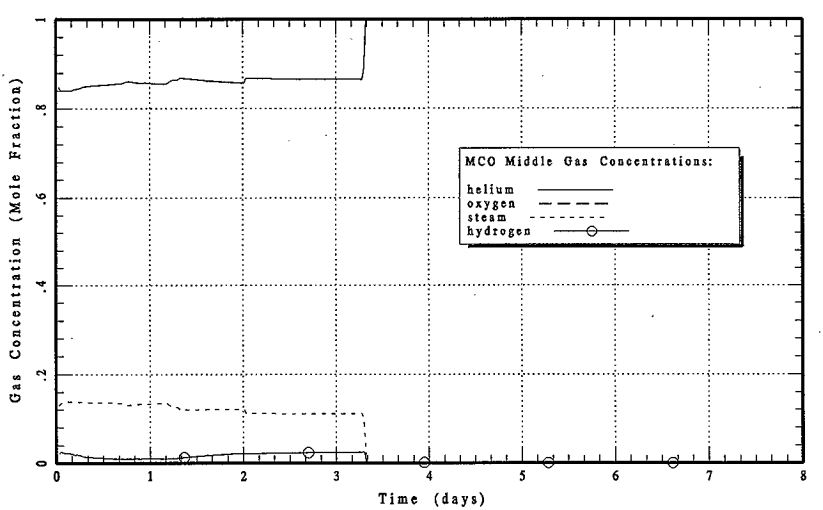
PURGE: HELIUM PURGE w 50 Deg C Annulus Water





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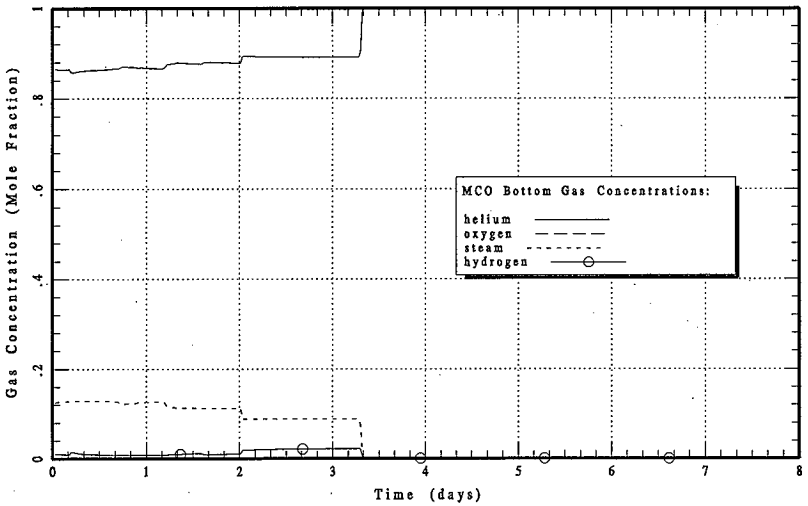

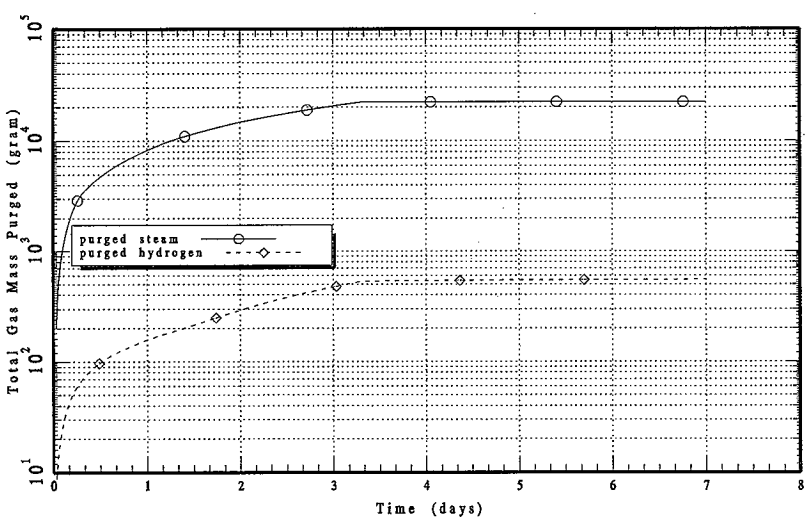

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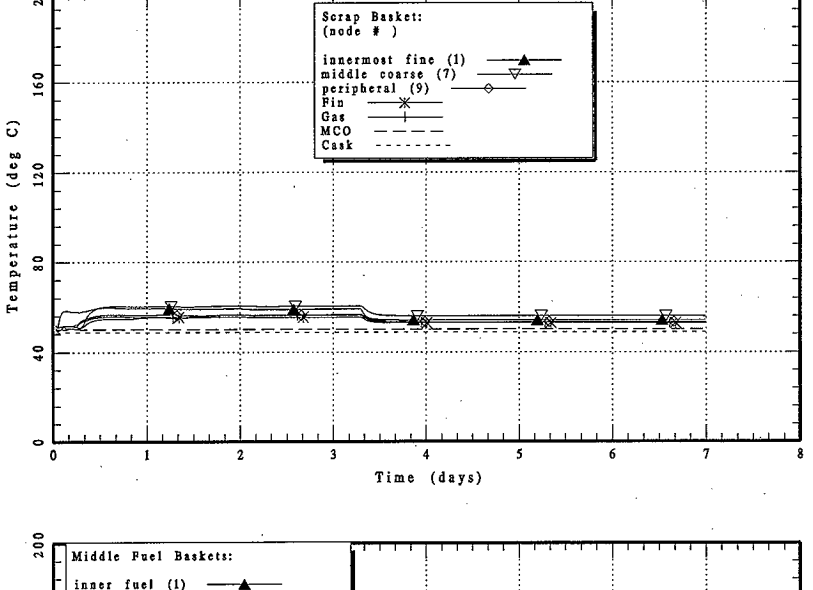

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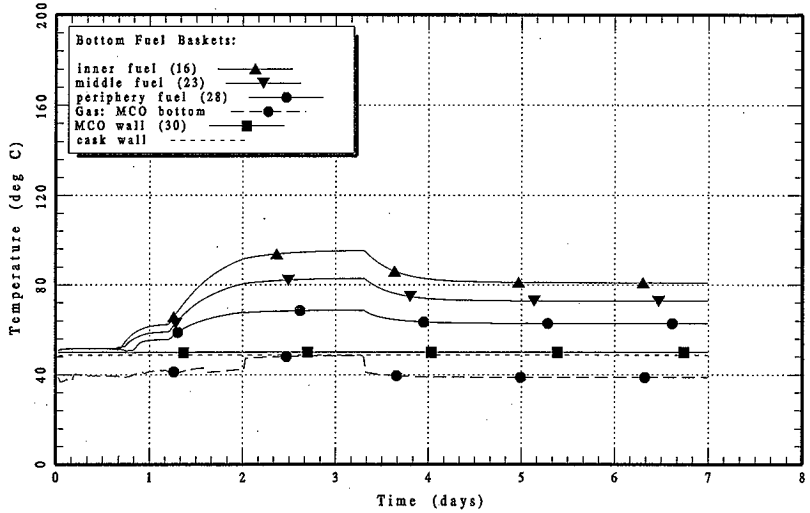

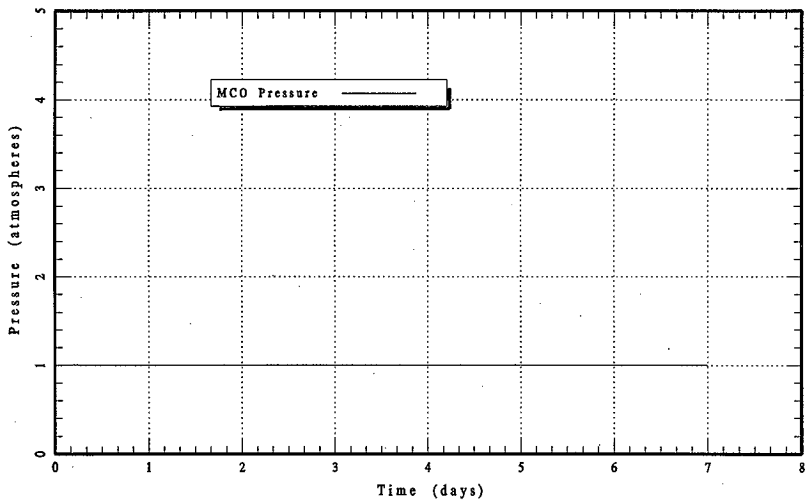

Figure A-5 VACHOT: Indefinite Vacuum with 85 °C Annulus

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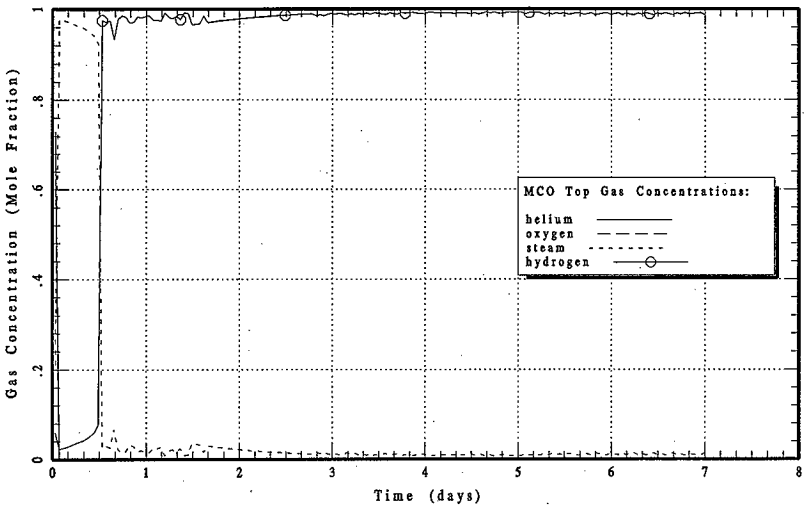
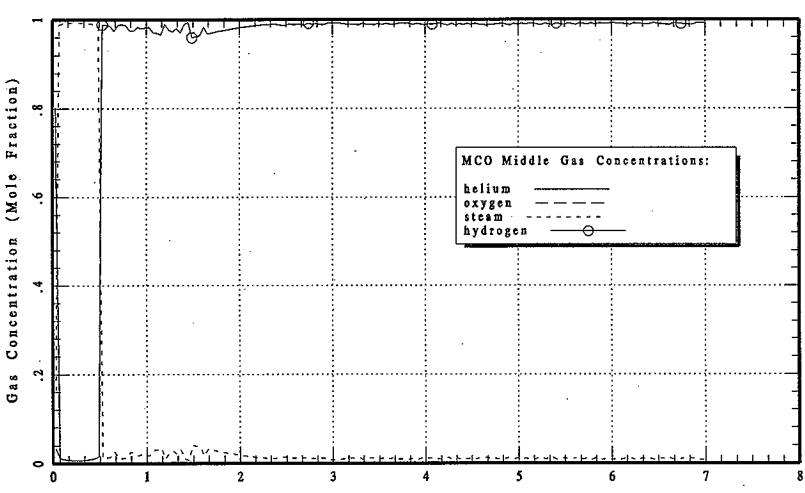
VACHOT: INDEFINITE VACUUM w 85 Deg C Annulus





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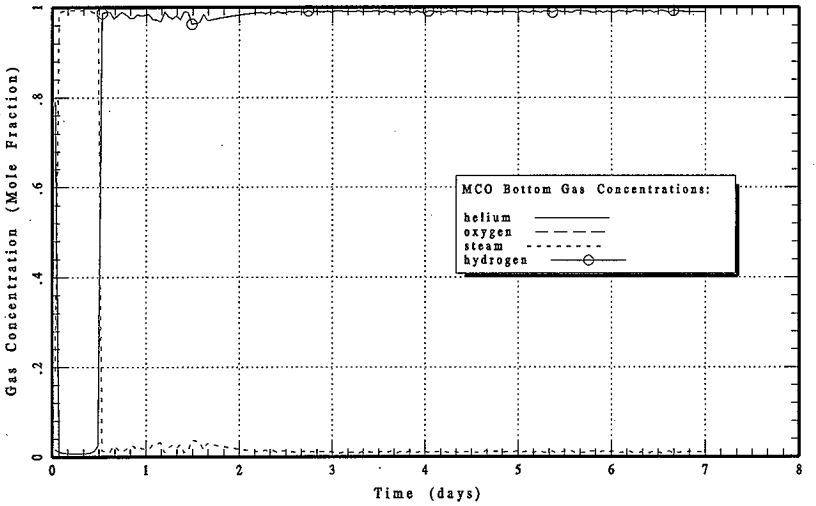
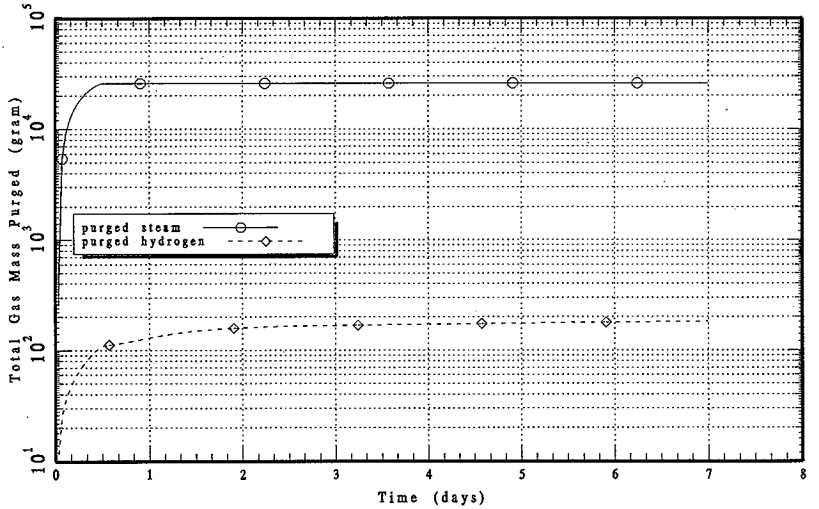
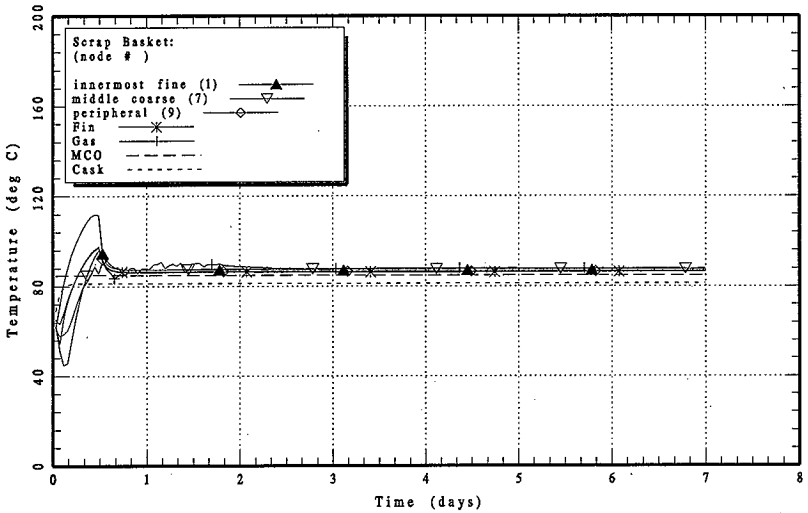
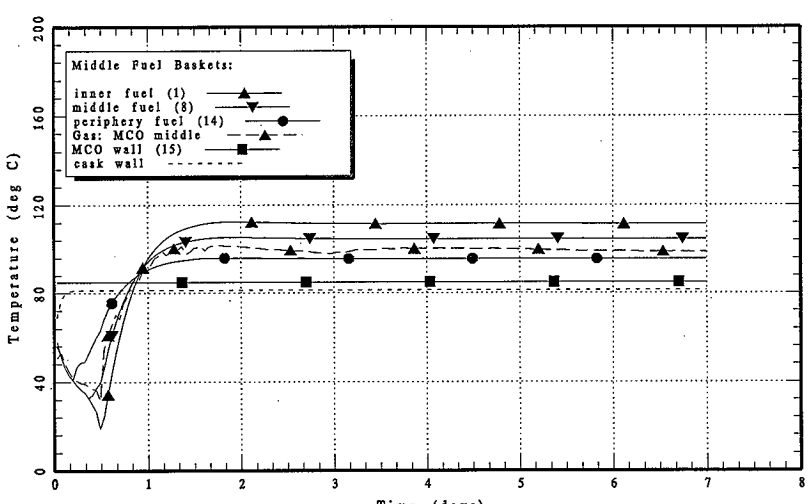


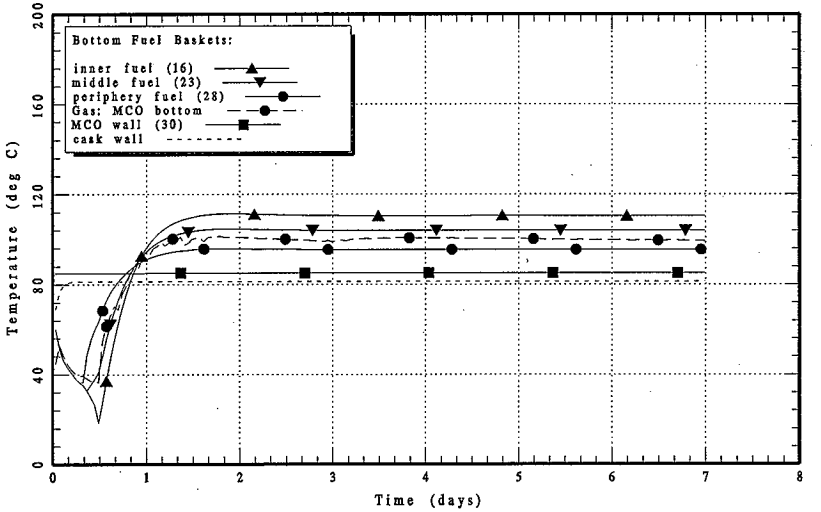


VACHOT: INDEFINITE VACUUM w 85 Deg C Annulus





VACHOT: INDEFINITE VACUUM w 85 Deg C Annulus



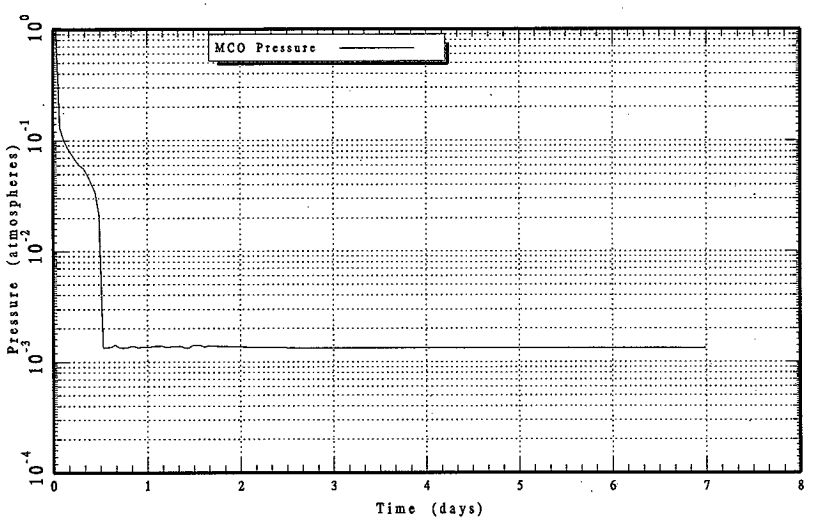


Figure A-6 VPURHOT: Vacuum with Helium Purge with 85 °C Annulus

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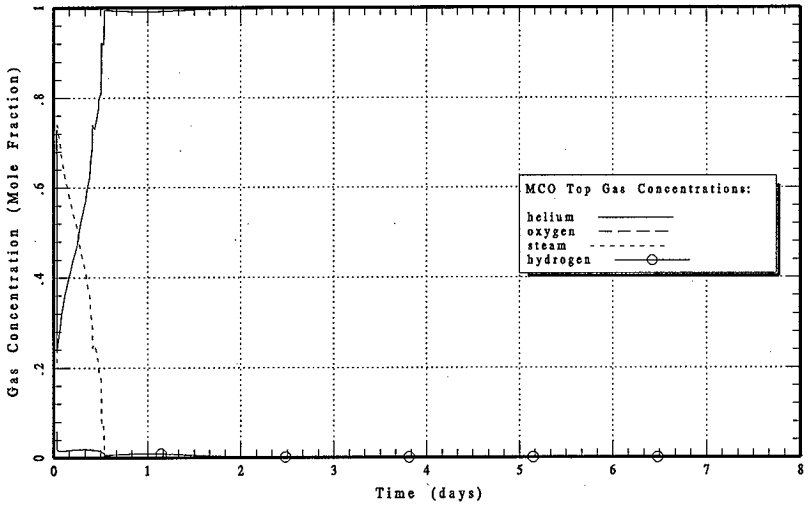
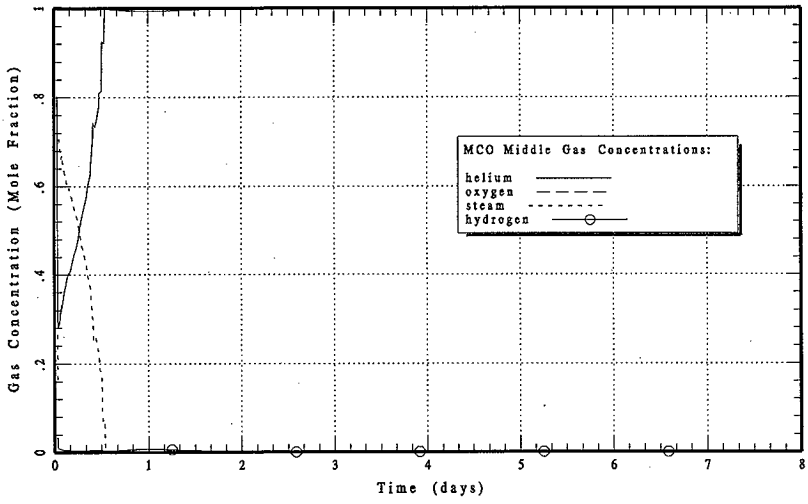
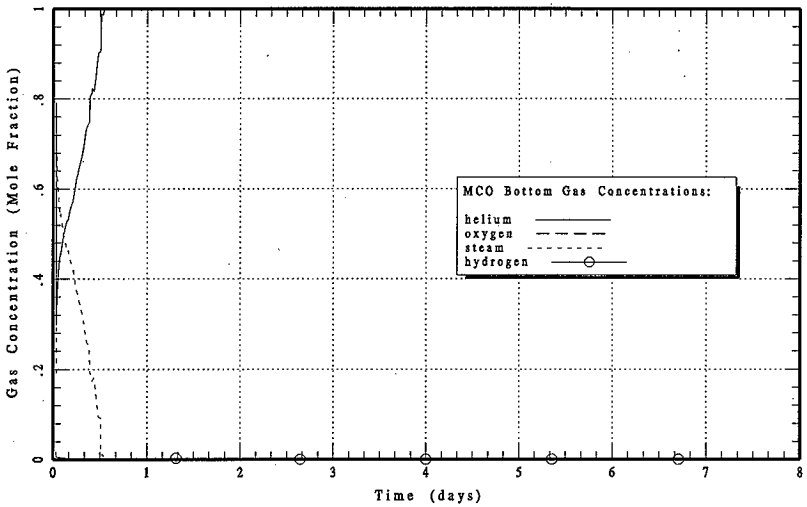
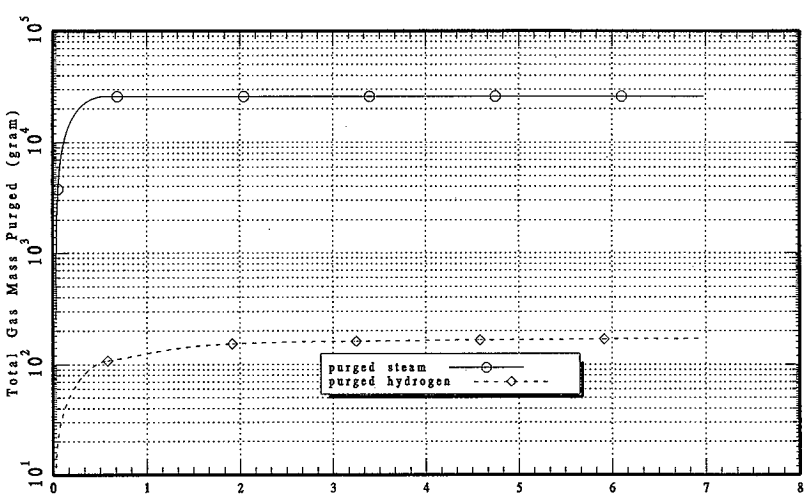
VPURHOT: VAC w Helium Purge w 85 Deg C Annulus



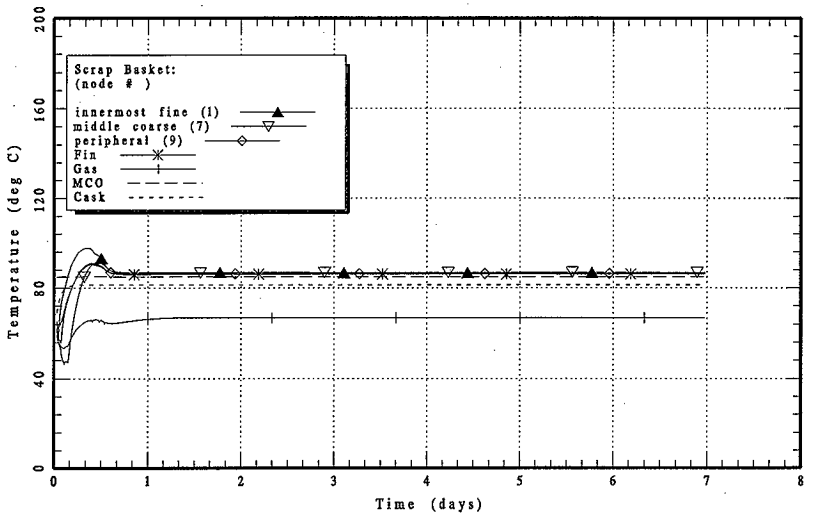


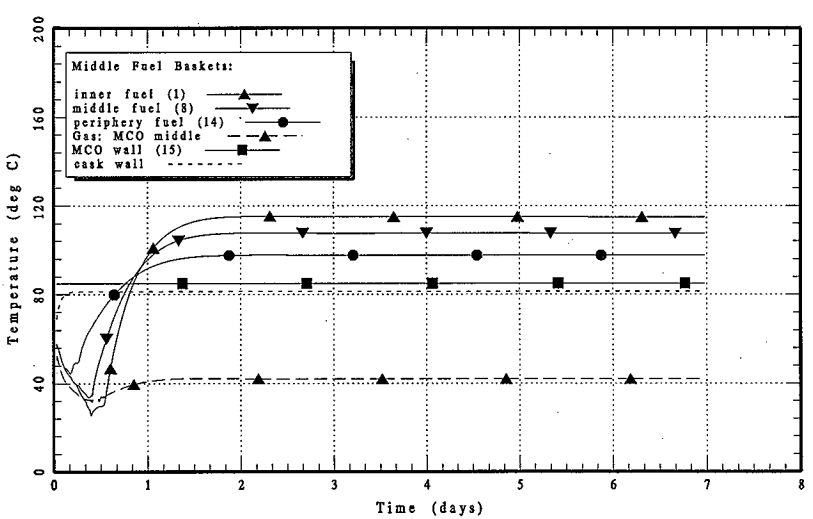
VPURHOT: VAC w Helium Purge w 85 Deg C Annulus

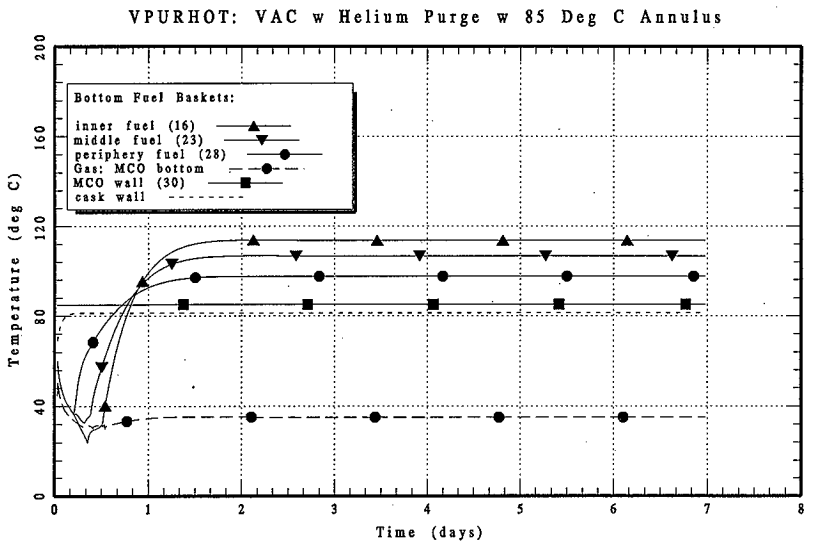




VPURHOT: VAC w Helium Purge w 85 Deg C Annulus






VPURHOT: VAC w Helium Purge w 85 Deg C Annulus
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (deg C)
Time (days)

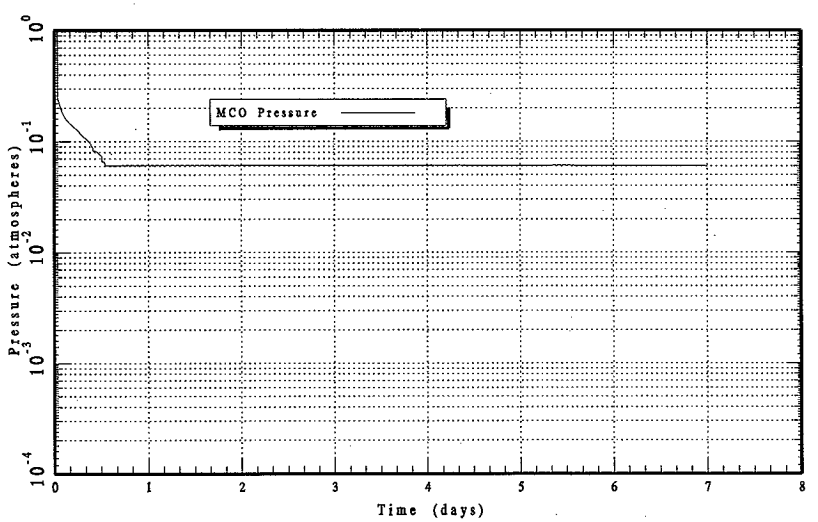

MCO Pressure
Pressure (atmospheres)
Time (days)

Figure A-7 PURHOT: Helium Purge with 85 °C Annulus Water

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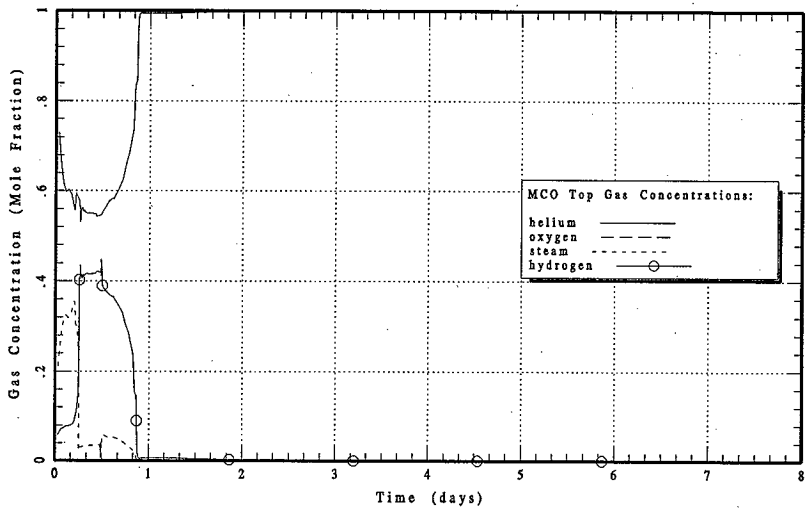
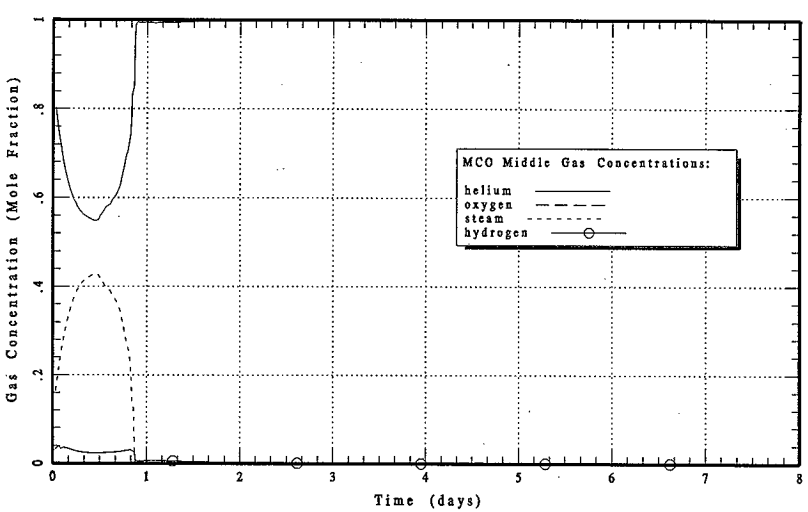
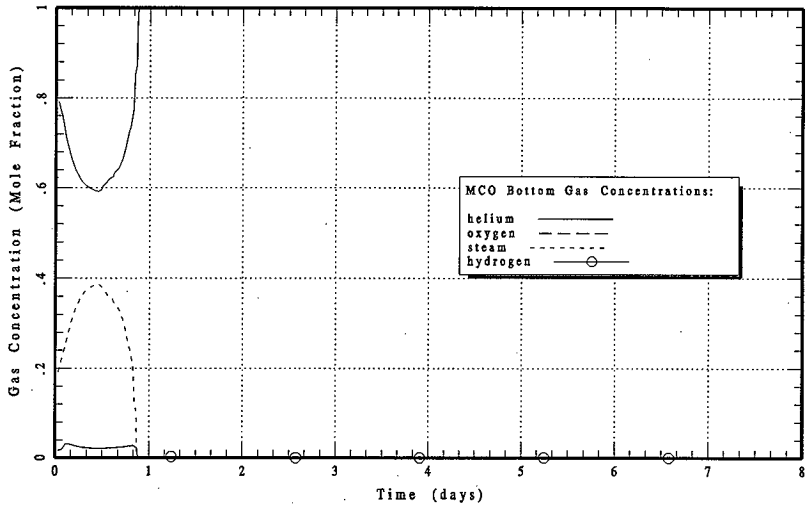
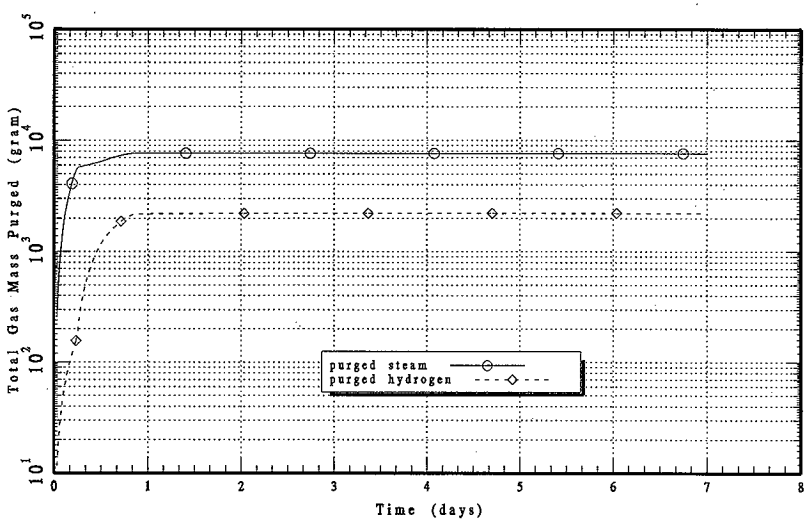
PURHOT: HELIUM PURGE w 85 Deg C Annulus Water



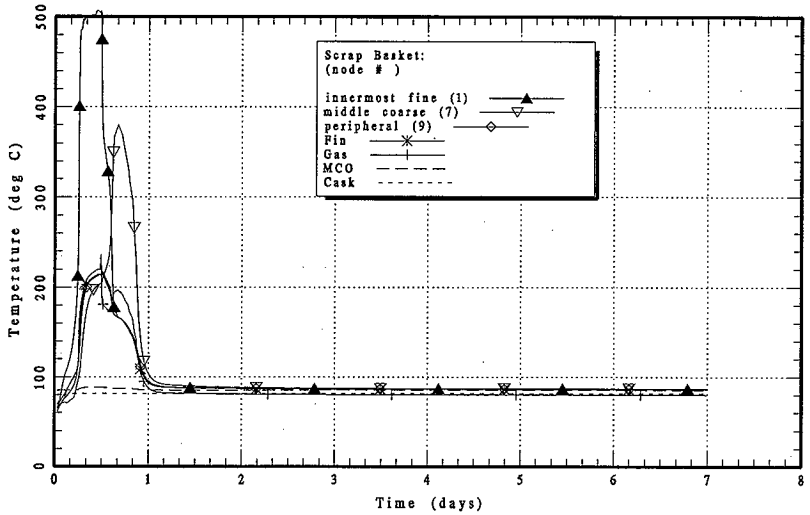


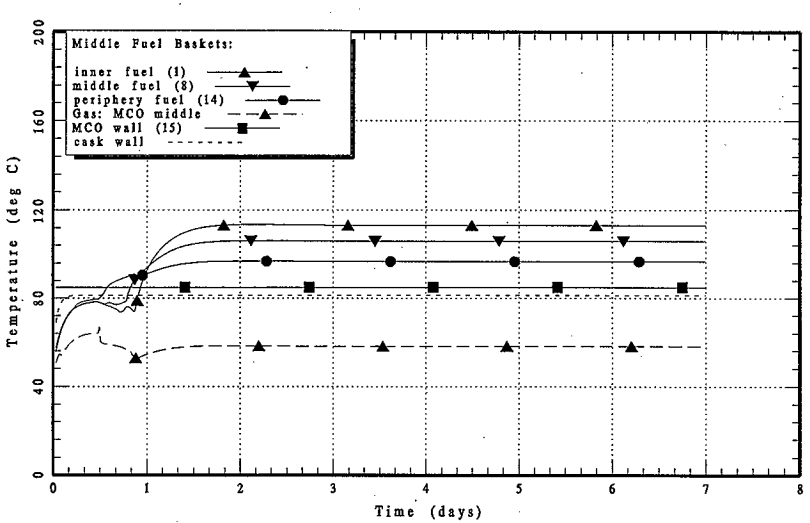
PURHOT: HELIUM PURGE w 85 Deg C Annulus Water



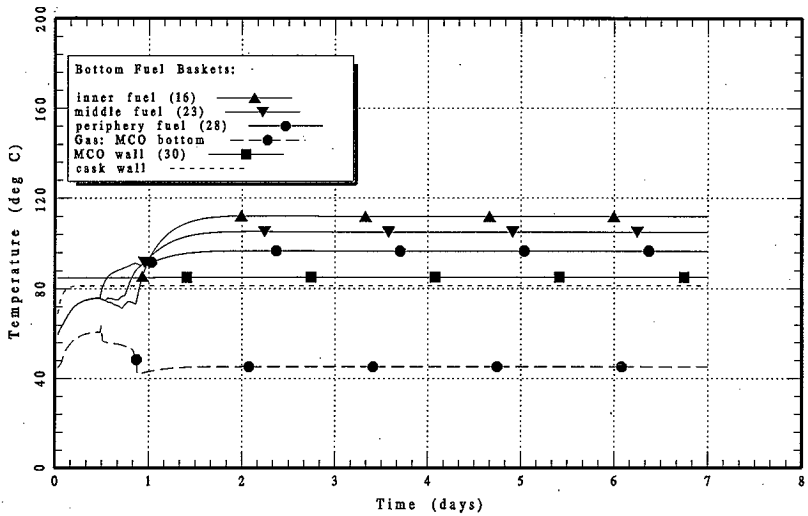


PURHOT: HELIUM PURGE w 85 Deg C Annulus Water





PURHOT: HELIUM PURGE w 85 Deg C Annulus Water



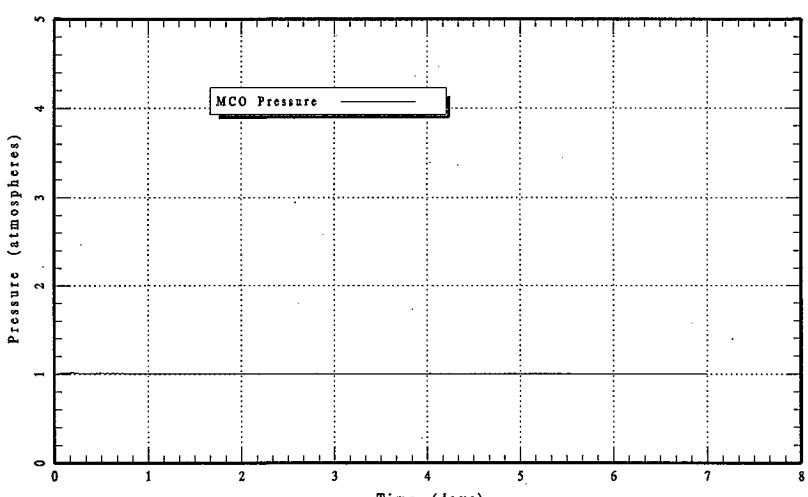


Figure A-8 VACLOF: Indefinite Vacuum with Loss of Flow in Annulus

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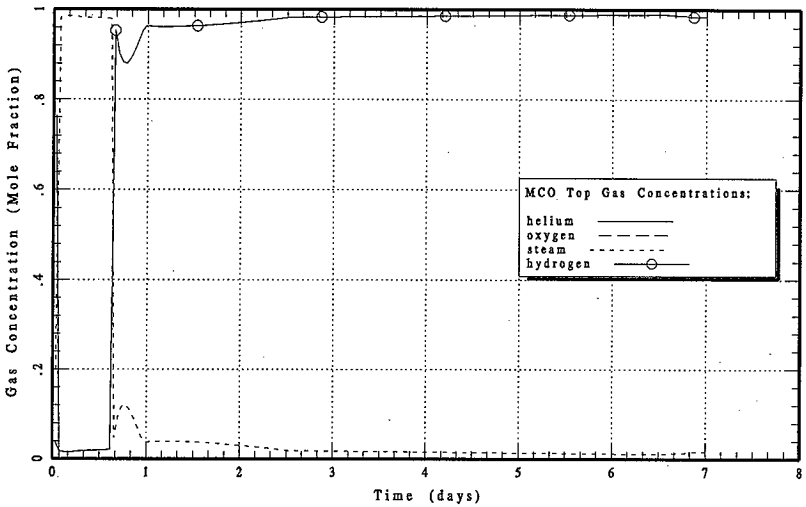
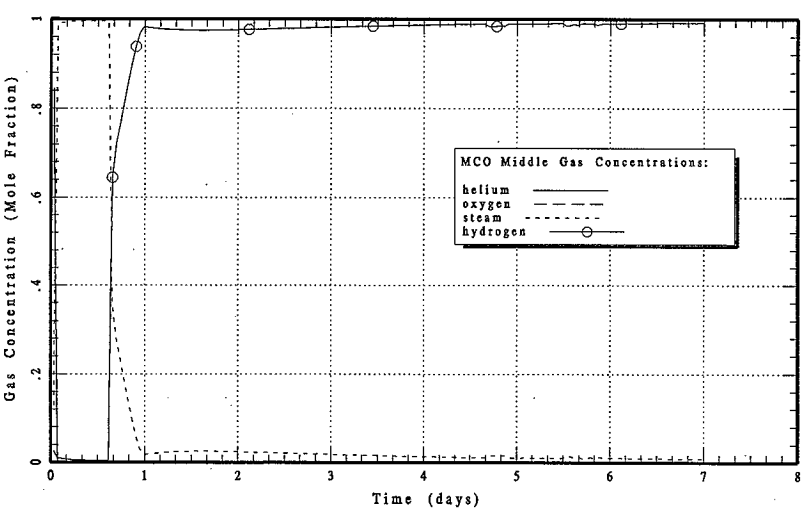
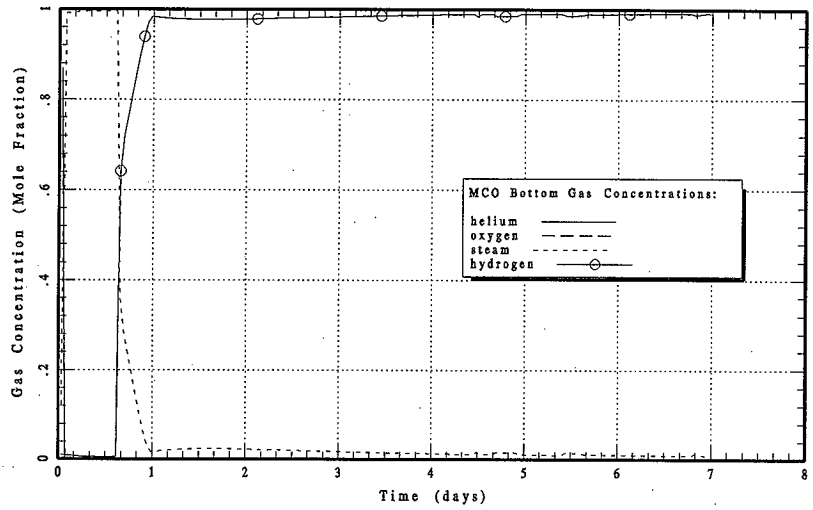
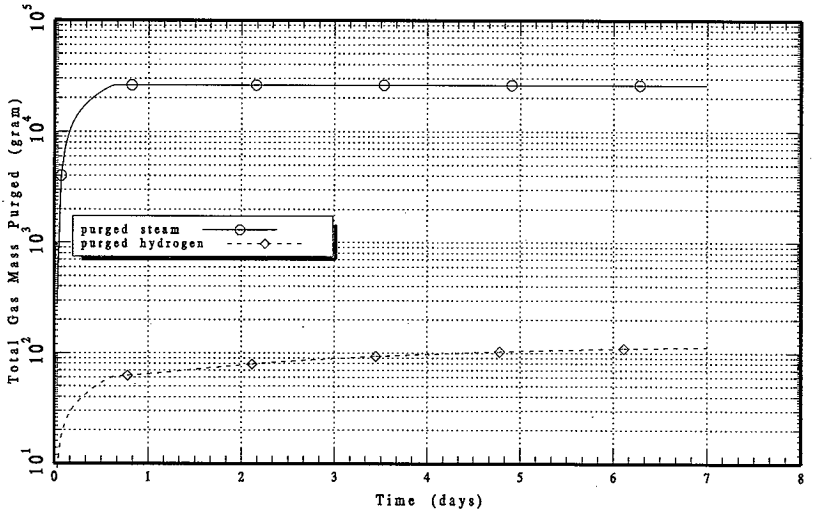
VACLOF: INDEFINITE VACUUM w Loss of Flow in Annulus



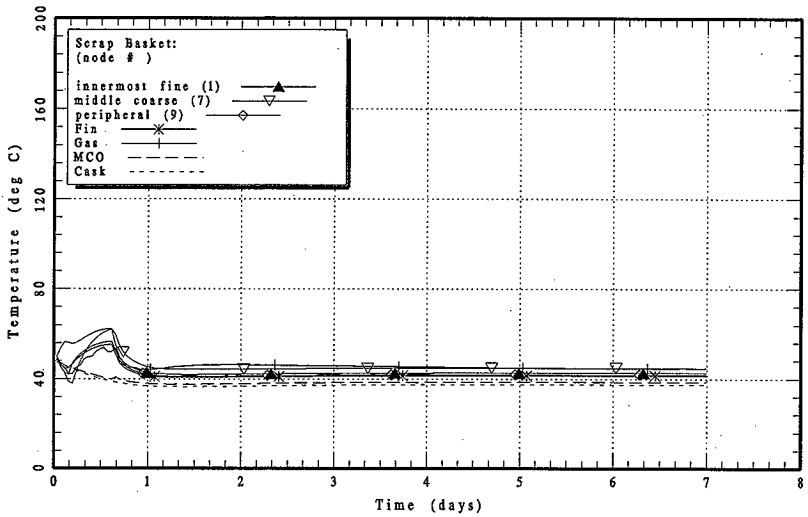


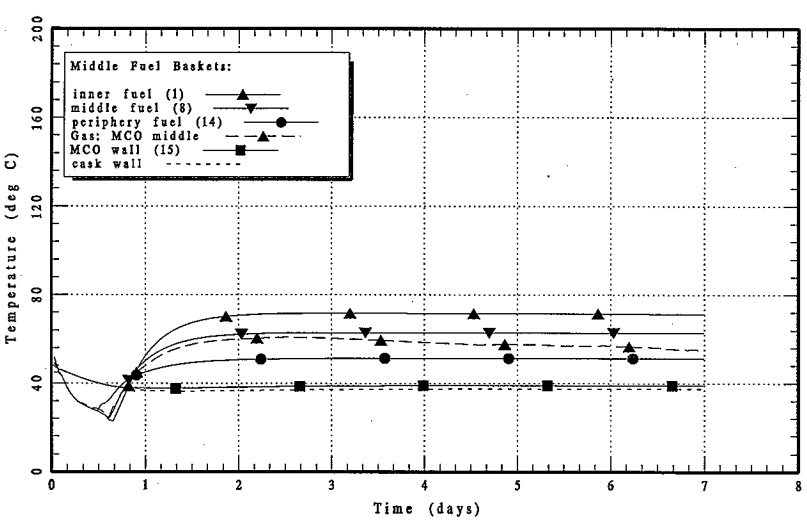
VACLOF: INDEFINITE VACUUM w Loss of Flow in Annulus



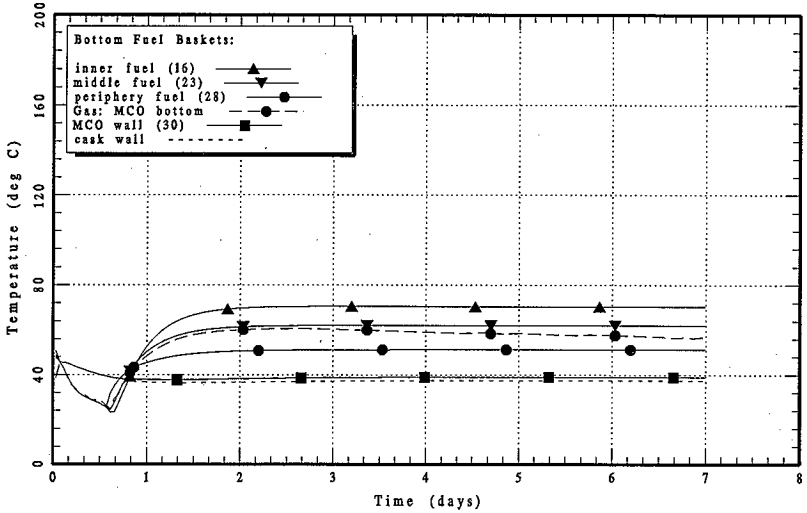


VACLOF: INDEFINITE VACUUM w Loss of Flow in Annulus





VACLOF: INDEFINITE VACUUM w Loss of Flow in Annulus



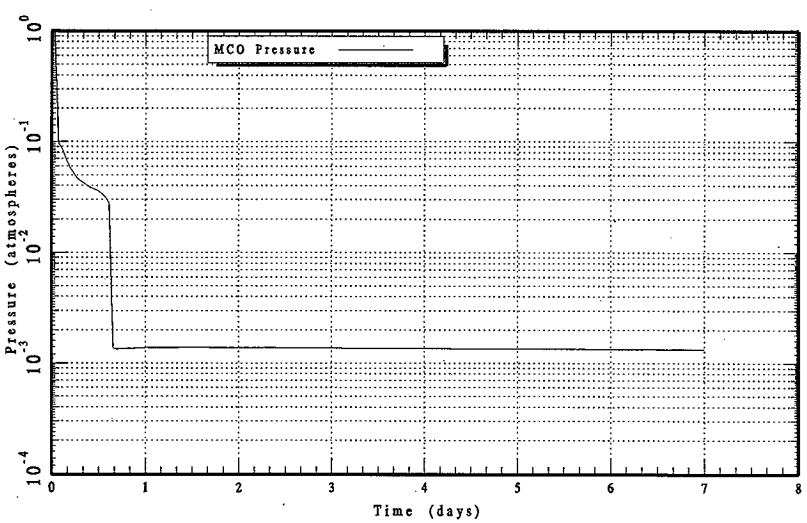


Figure A-9 VLOFHOT: Vacuum with Loss of Flow in Annulus at 85 °C

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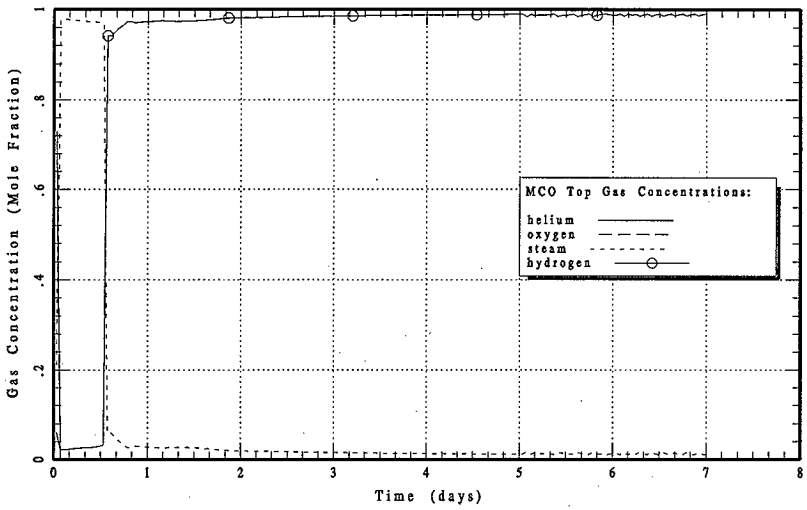
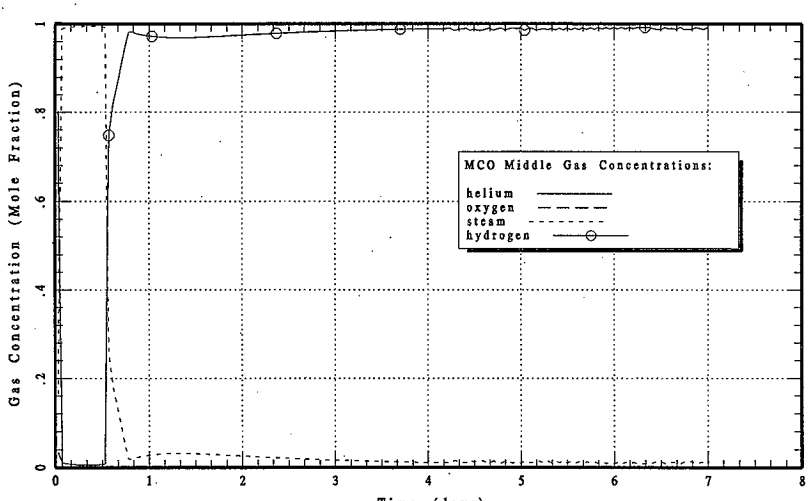
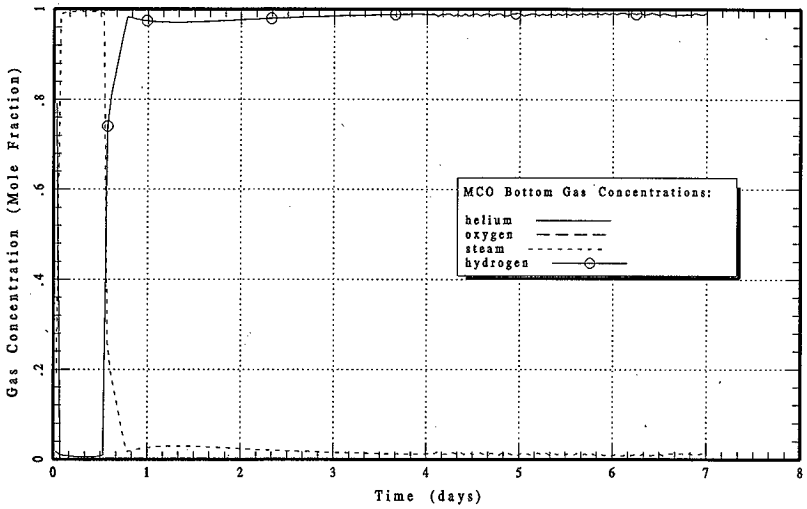
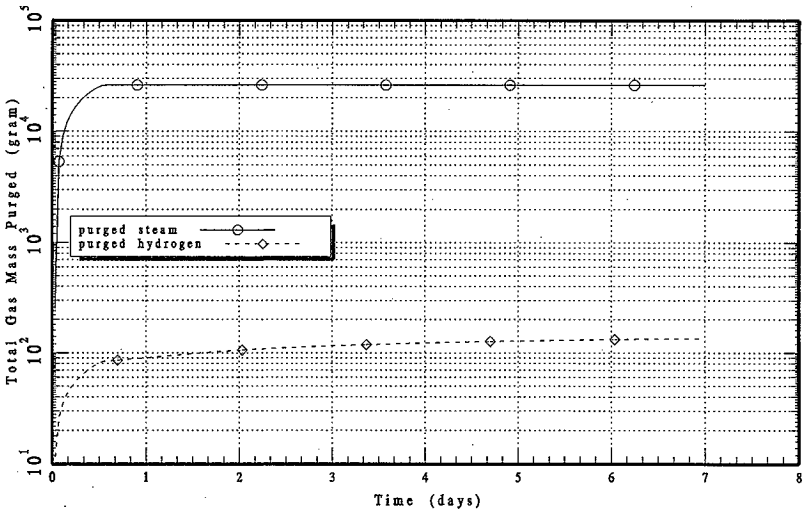
VLOFHOT: VACUUM w Loss of Flow in Annulus @ 85 deg C



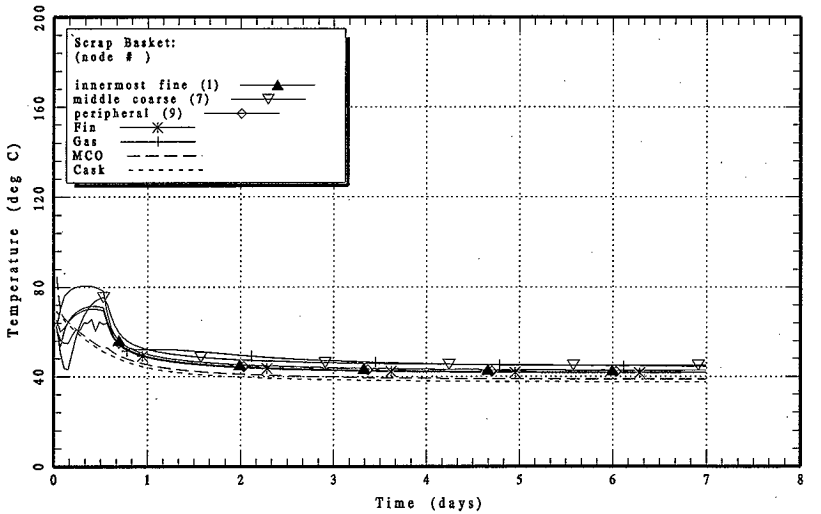


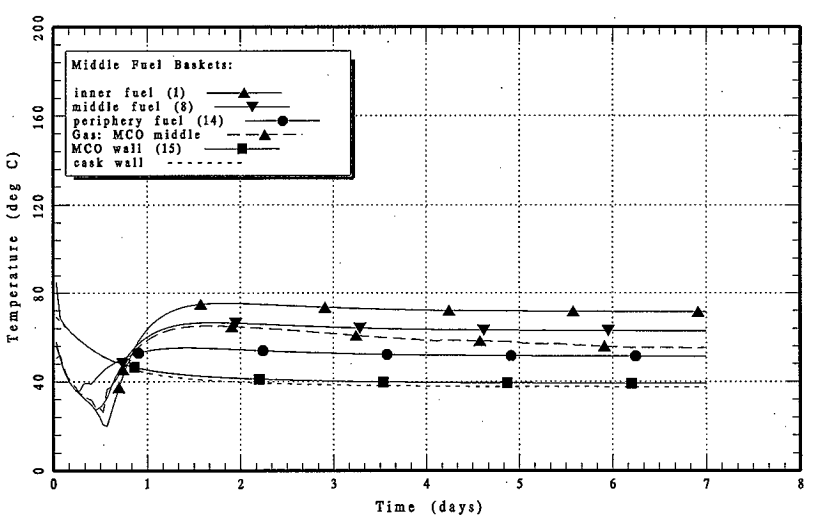
VLOFHOT: VACUUM w Loss of Flow in Annulus @ 85 deg C



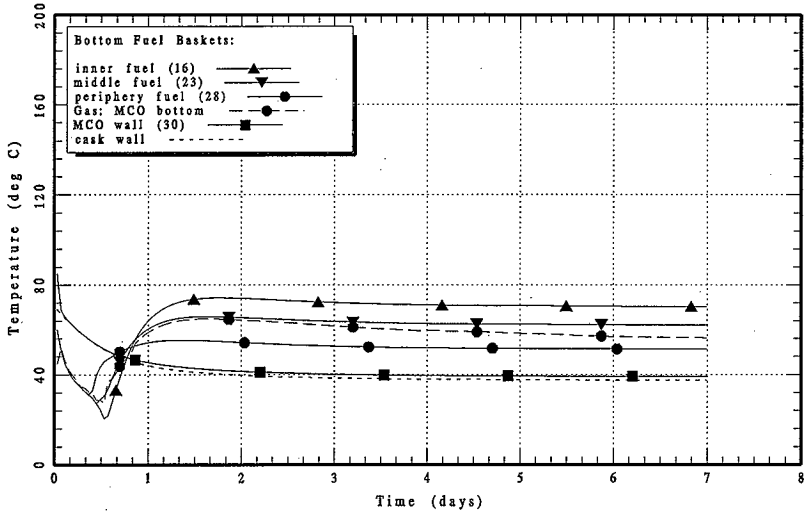


VLOFHOT: VACUUM w Loss of Flow in Annulus @ 85 deg C





VLOFHOT: VACUUM w Loss of Flow in Annulus @ 85 deg C



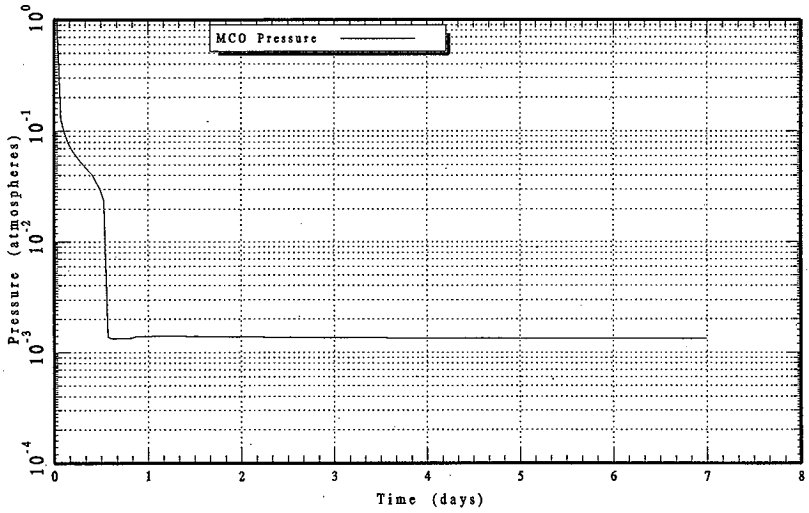


Figure A-10 VACLOC: Indefinite Vacuum with Loss of Coolant (LOC) in Annulus

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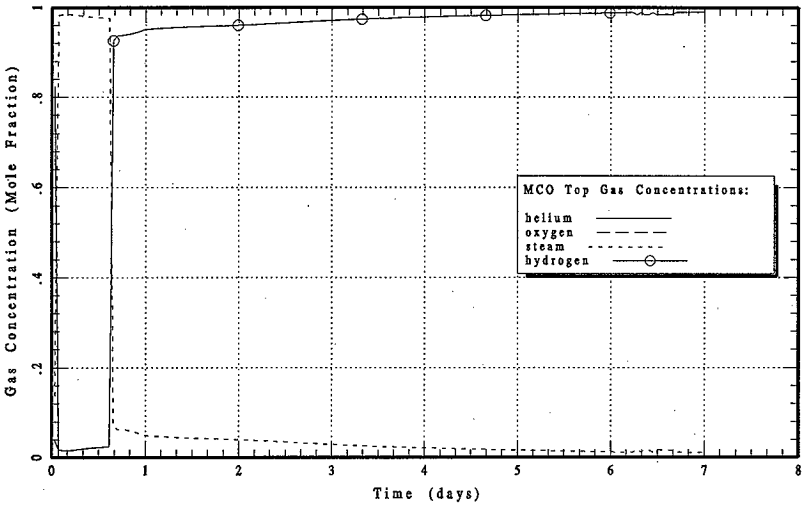
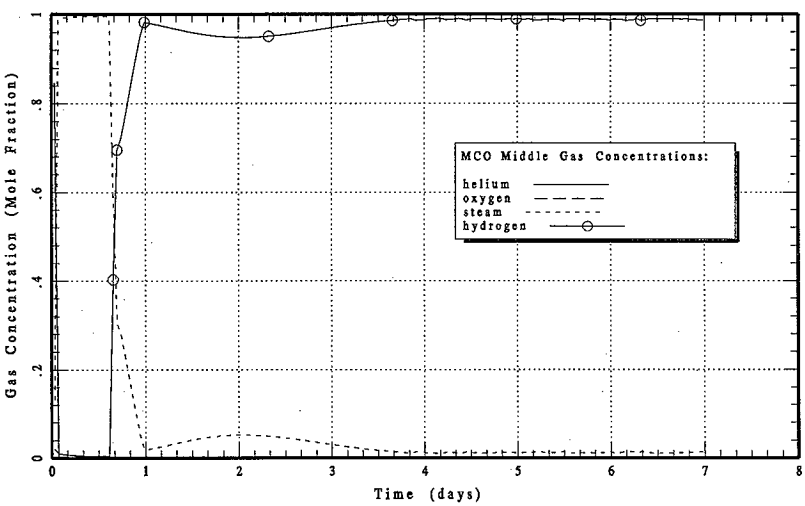
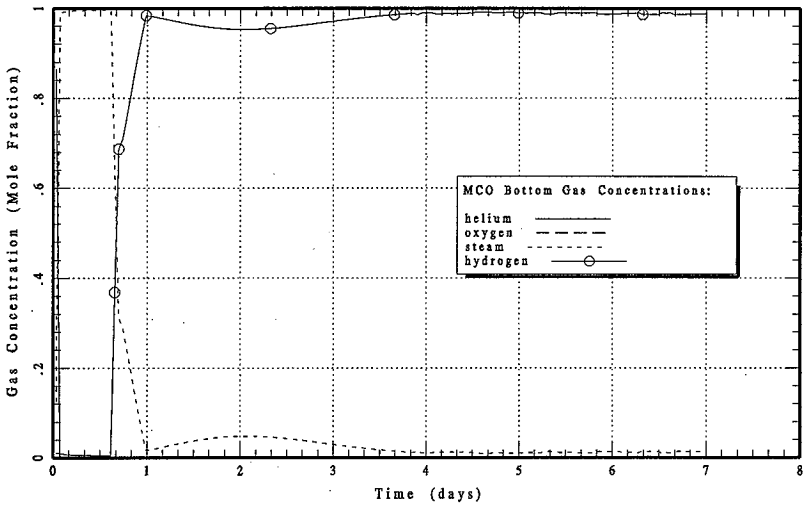
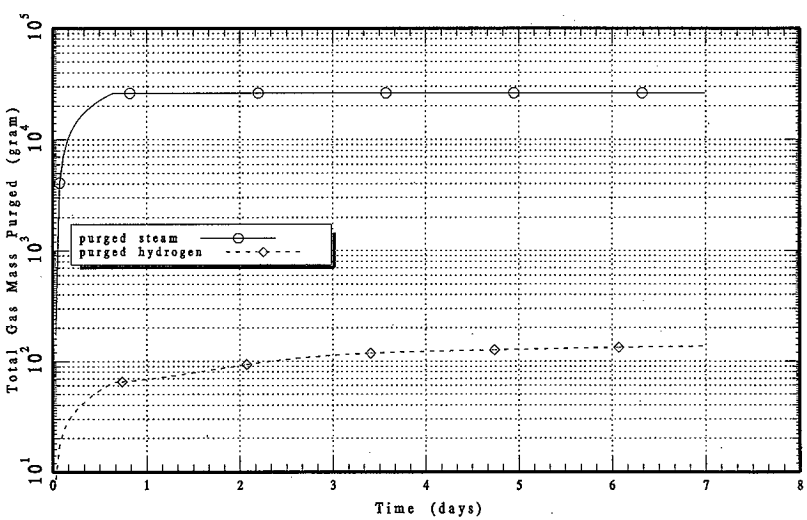
VACLOC: INDEFINITE VACUUM w Loss of Coolant in Annulus

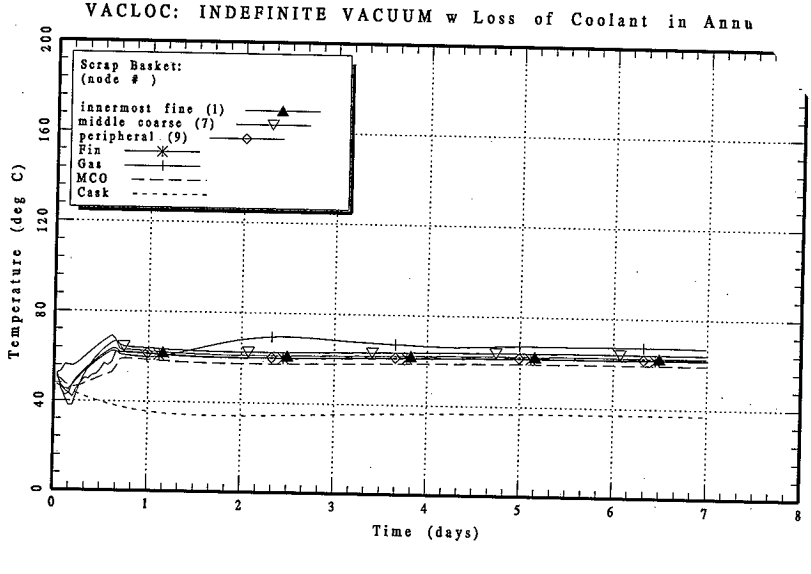


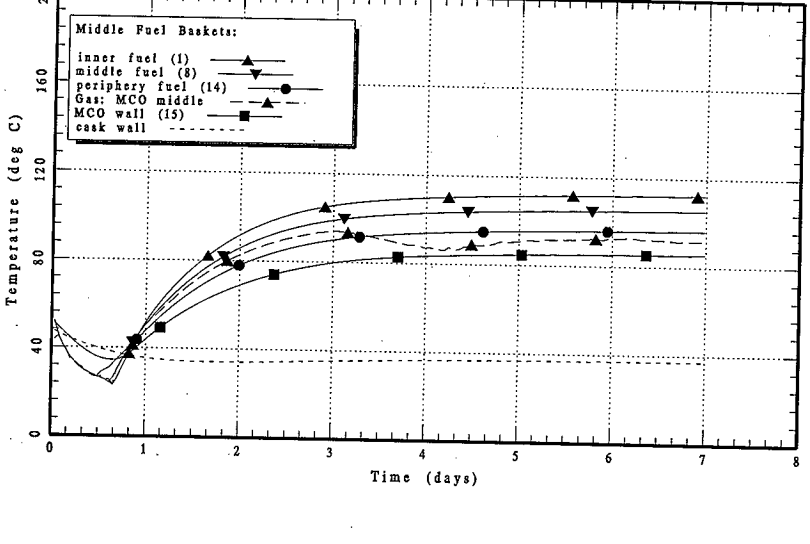


VACLOC: INDEFINITE VACUUM w Loss of Coolant in Annulus

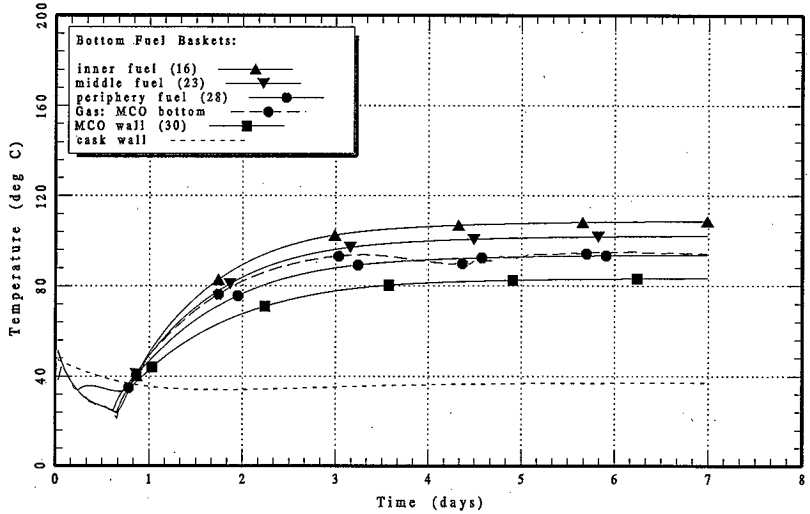





VACLOC: INDEFINITE VACUUM w Loss of Coolant in Annu
Scrap Basket:
(node #)
innermost fine (1)
middle coarse (7)
peripheral (9)
Fin
Gas
MCO
Cask
Temperature (deg C)
Time (days)
0
40
80
120
160
200
1
2
3
4
5
6
7
8


Middle Fuel Baskets:
inner fuel (1)
middle fuel (8)
periphery fuel (14)
Gas: MCO middle
MCO wall (15)
cask wall
Temperature (deg C)
Time (days)
0
40
80
120
160
200
1
2
3
4
5
6
7
8

VACLOC: INDEFINITE VACUUM w Loss of Coolant in Annulus



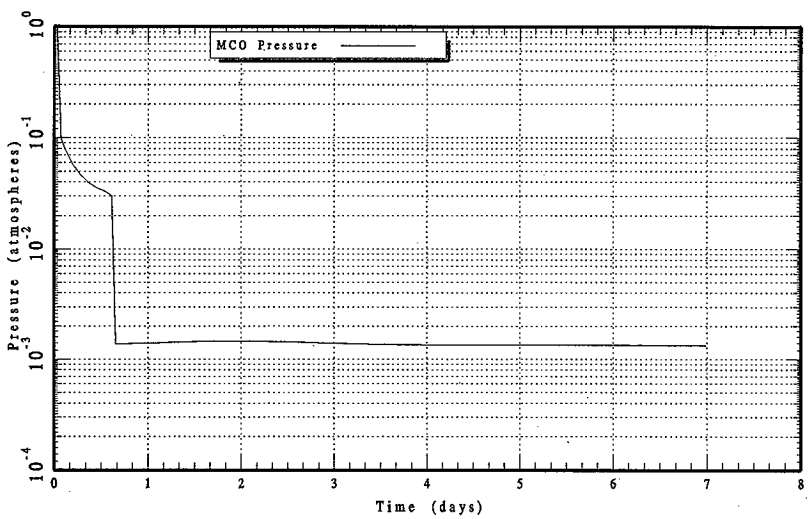


Figure A-11 VPURLOC: Vacuum and Helium Purge with Loss of Coolant (LOC)

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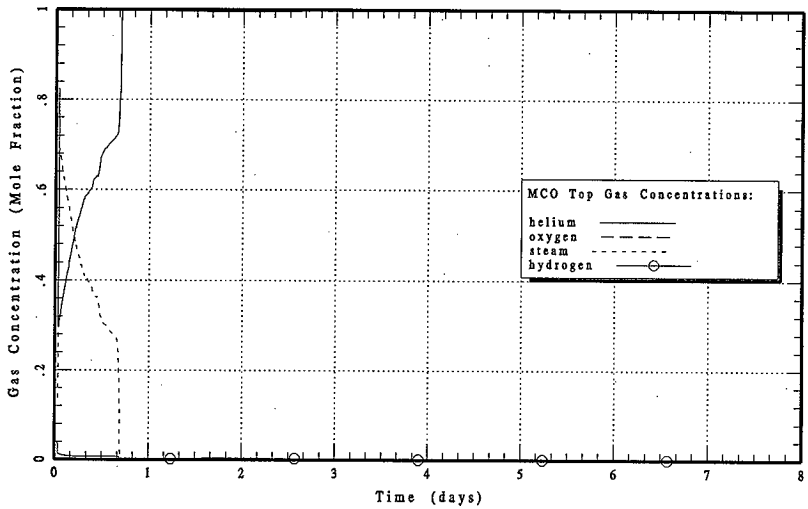
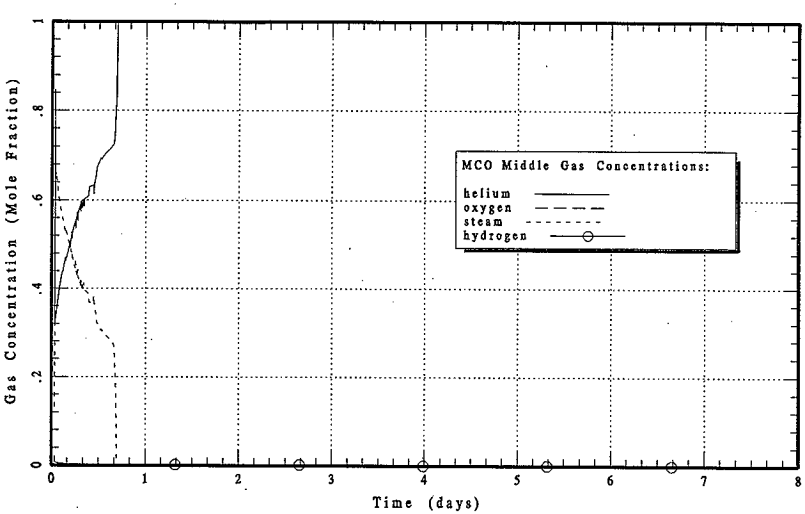
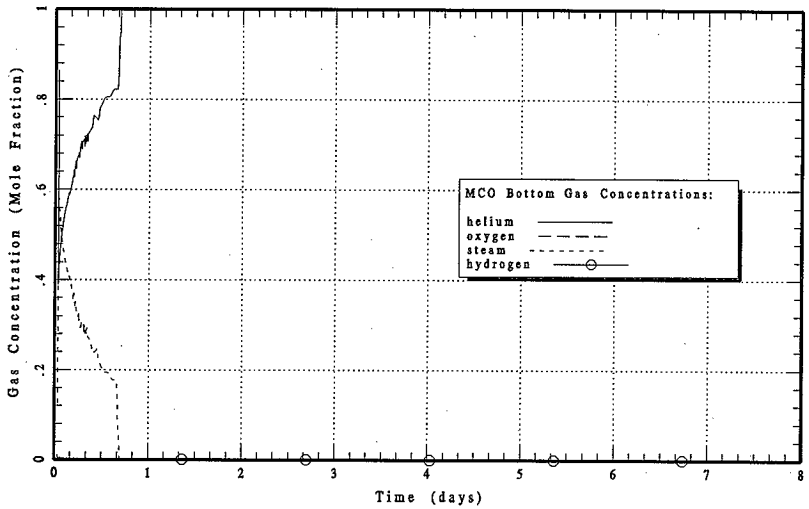
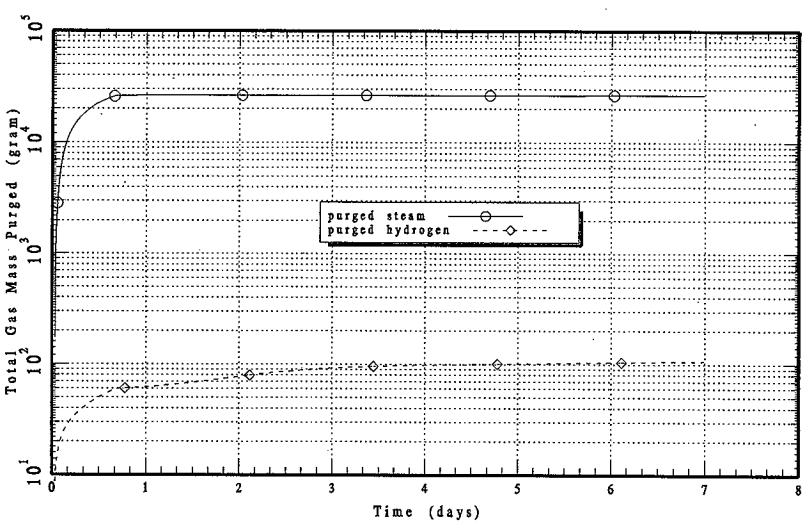
VPURLOC: VAC and Helium Purge w Loss of Coolant



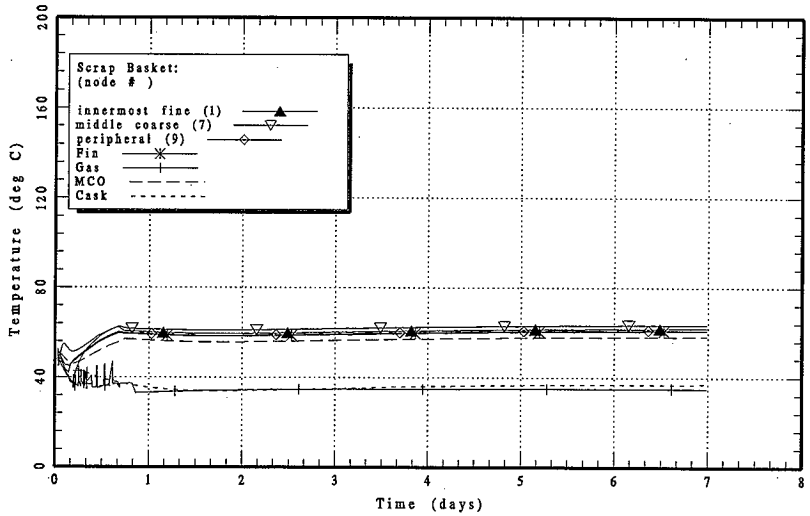


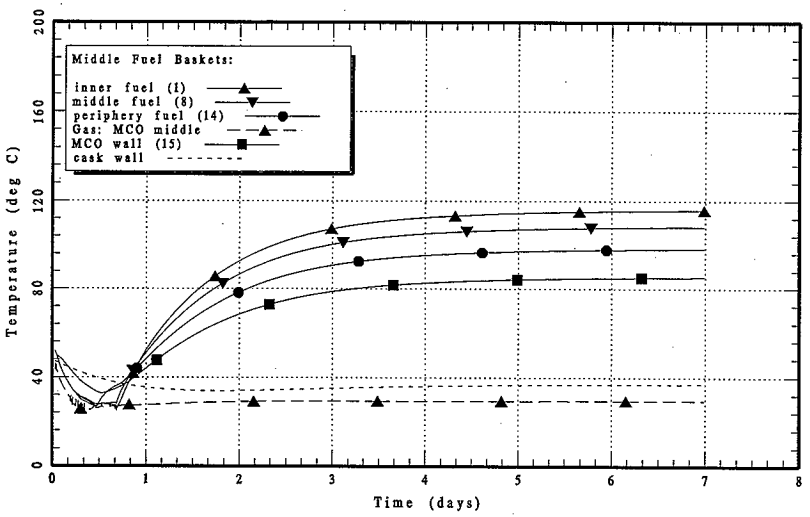
VPURLOC: VAC and Helium Purge w Loss of Coolant



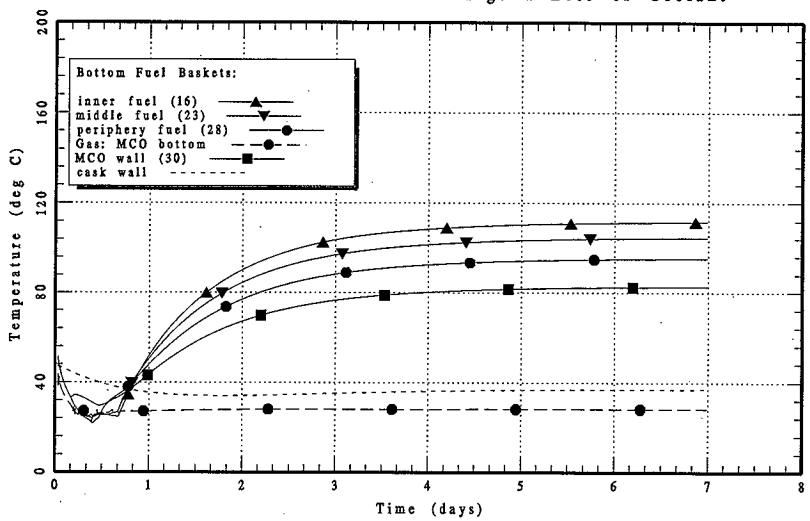


VPURLOC: VAC and Helium Purge w Loss of Coolant





VPURLOC: VAC and Helium Purge w Loss of Coolant



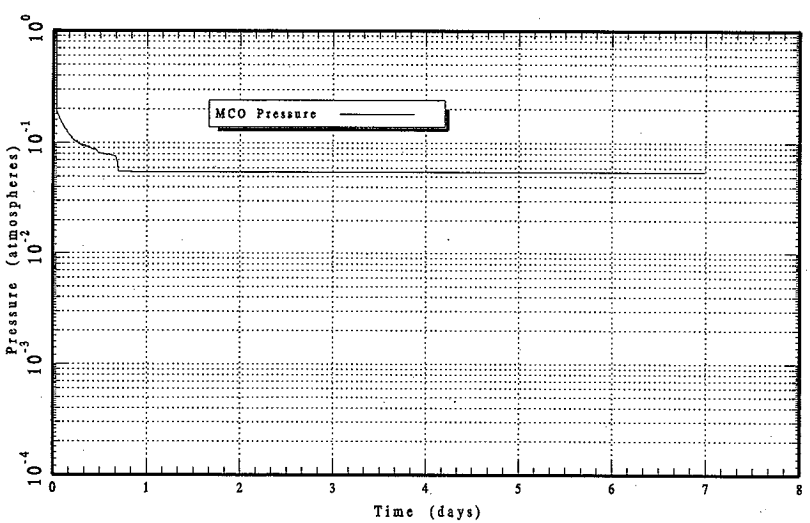


Figure A-12 · PURLOF: Helium Purge with Loss of Flow in Annulus

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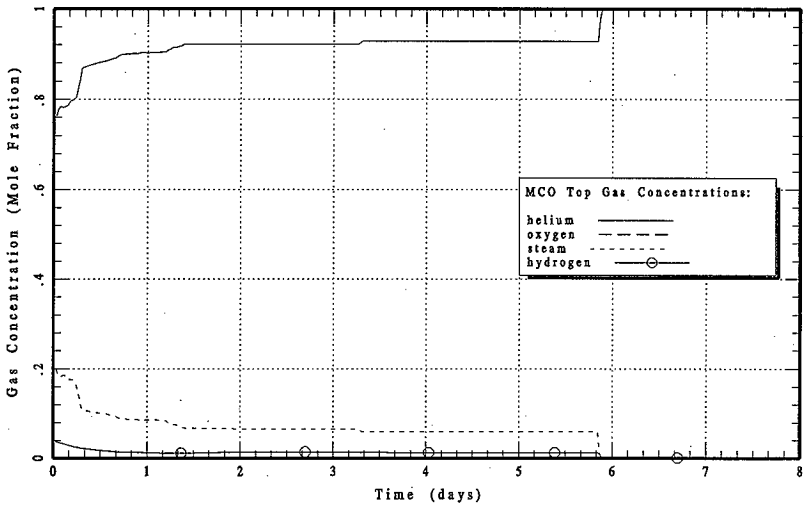
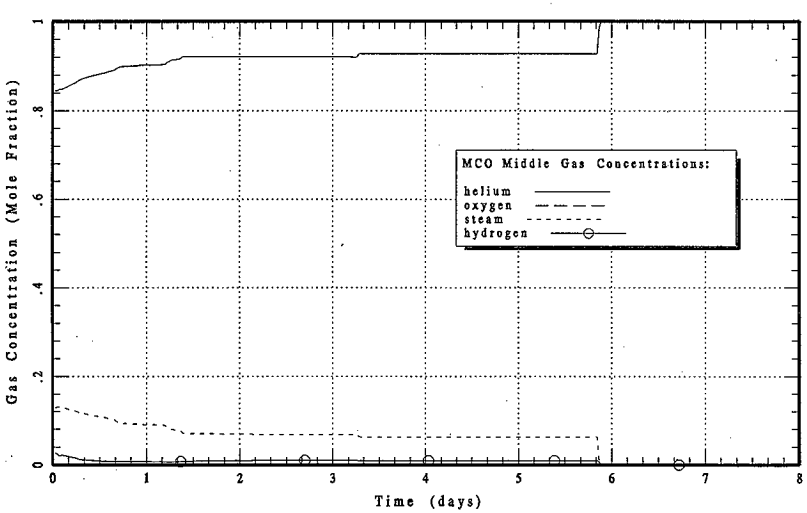
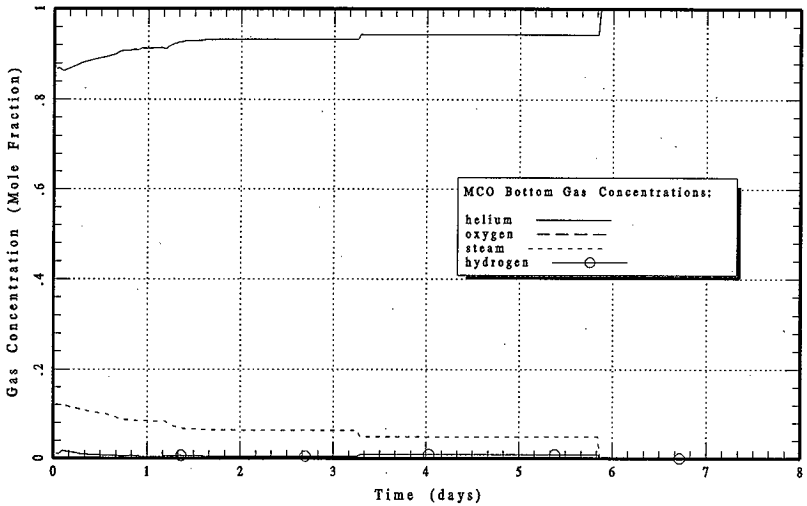
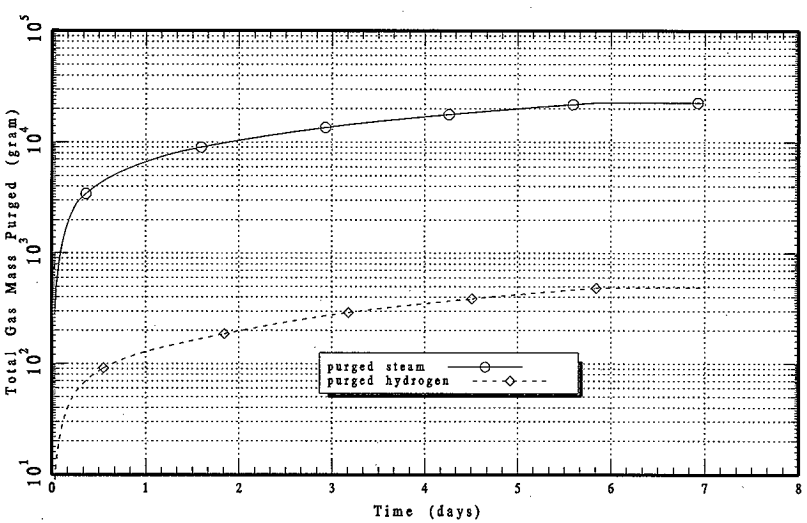
PURLOF: HELIUM PURGE w Loss of Flow in Annulus



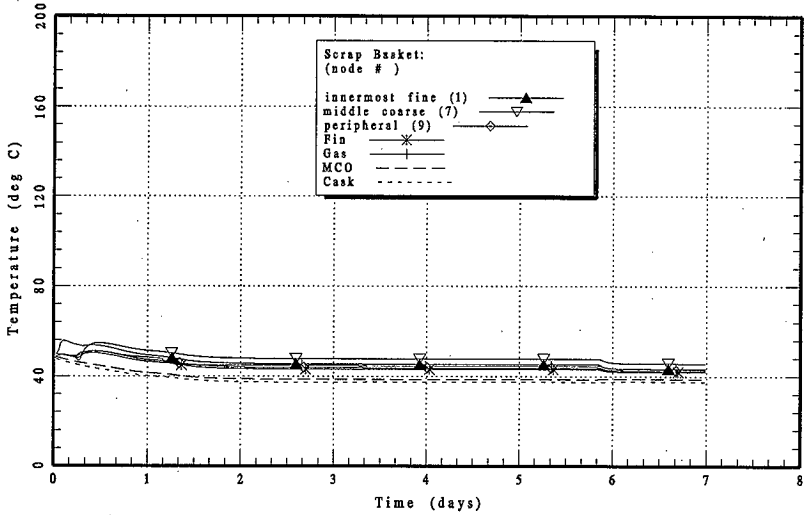


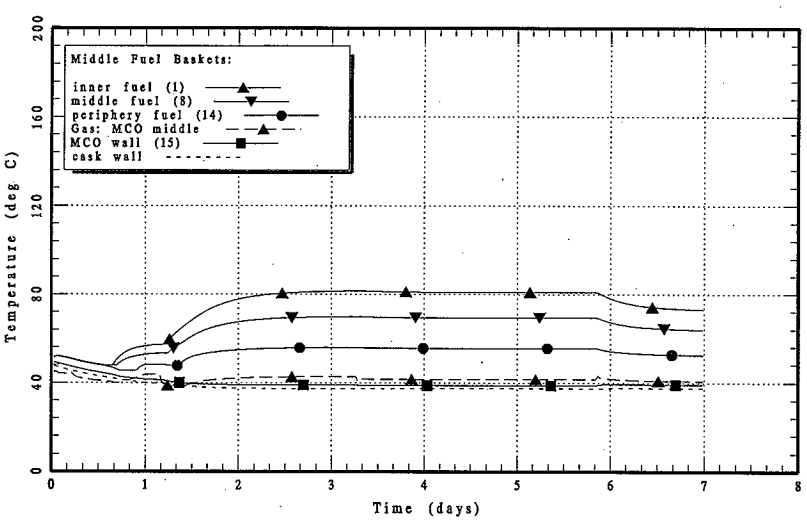
PURLOF: HELIUM PURGE w Loss of Flow in Annulus



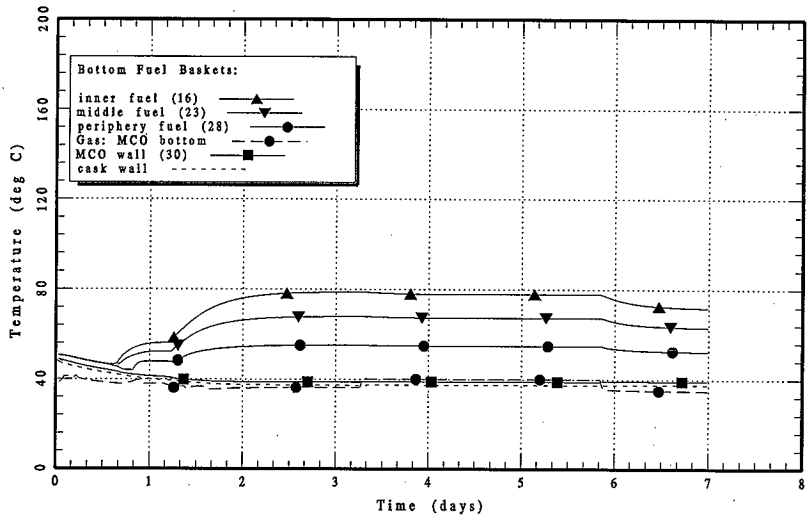


PURLOF: HELIUM PURGE w Loss of Flow in Annulus





PURLOF: HELIUM PURGE w Loss of Flow in Annulus



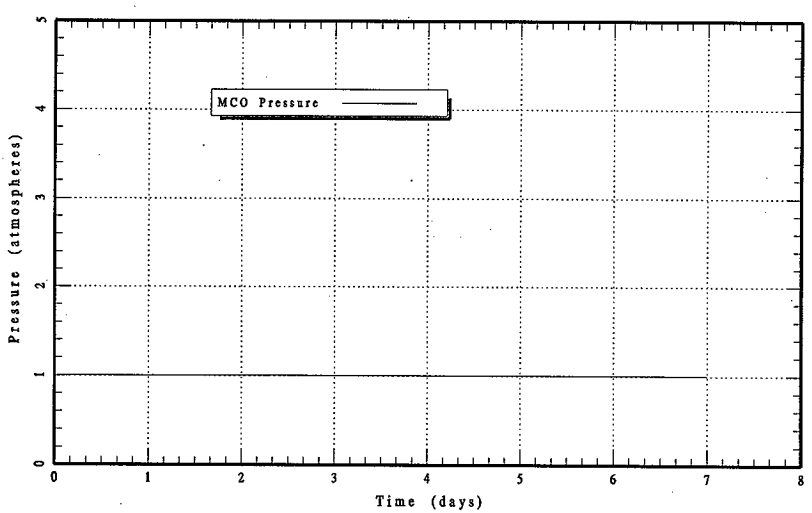


Figure A-13 PURLOC: Helium Purge with Loss of Coolant (LOC) - Annulus Water

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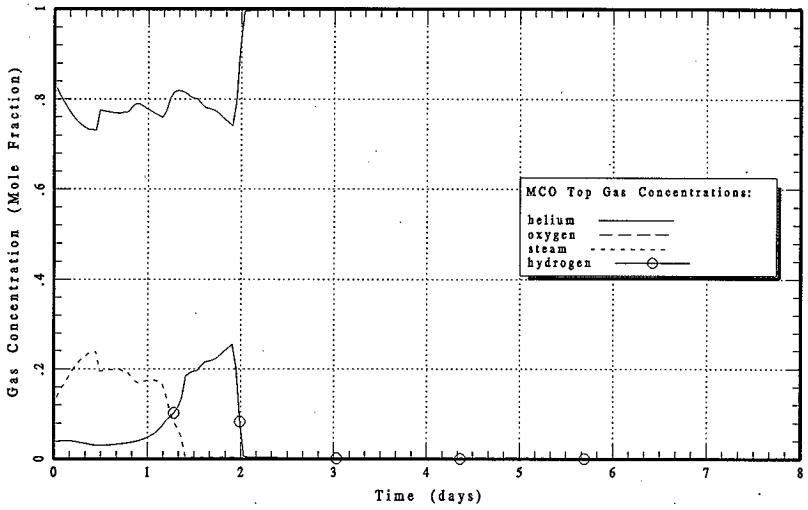
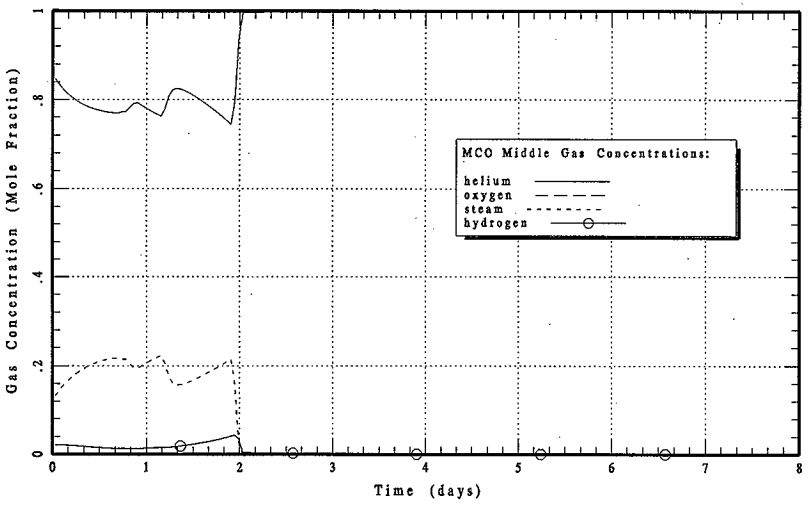
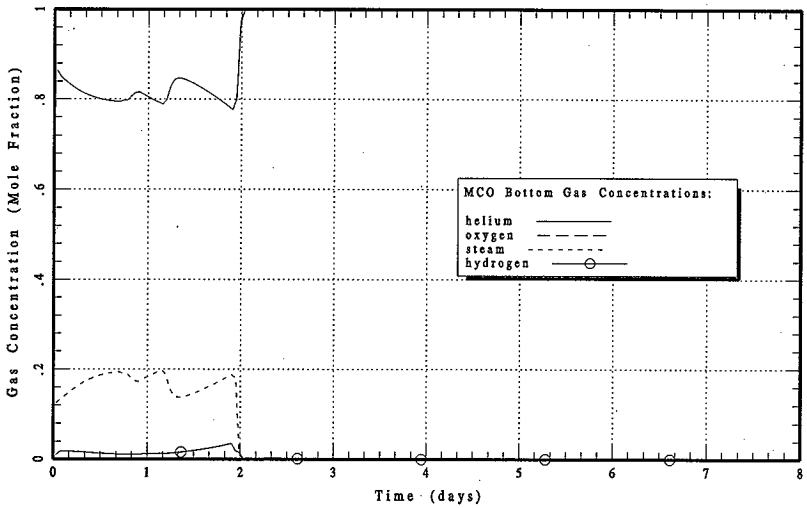
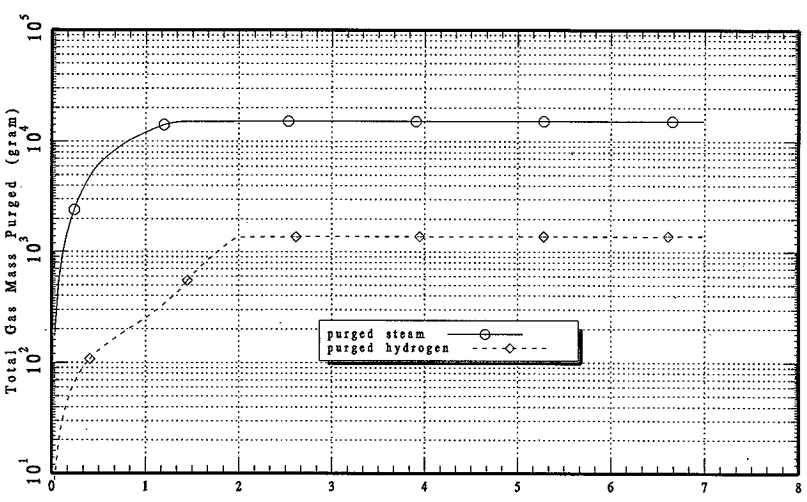
PURLOC: HELIUM PURGE w Loss of Coolant - Annulus Water



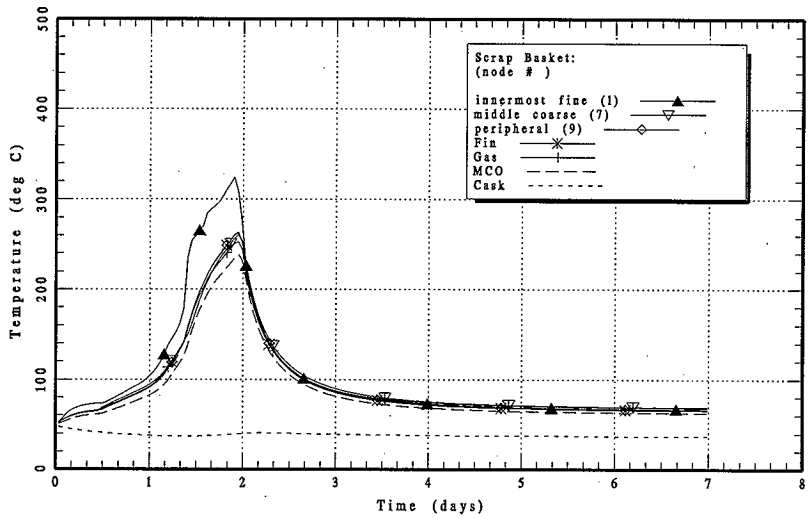


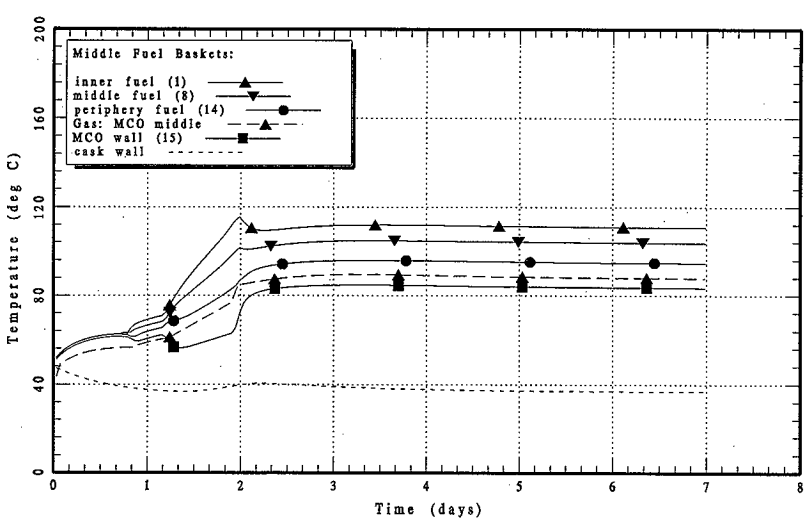
PURLOC: HELIUM PURGE w Loss of Coolant - Annulus Water



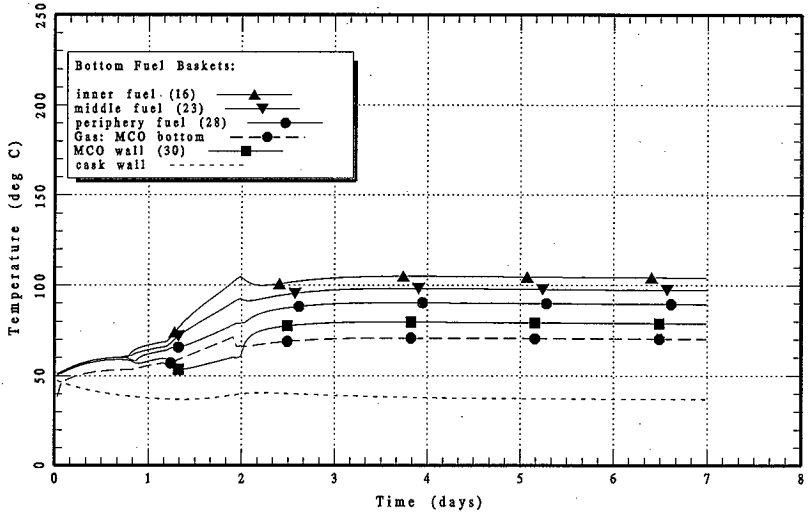


PURLOC: HELIUM PURGE w Loss of Coolant - Annulus Water





PURLOC: HELIUM PURGE w Loss of Coolant - Annulus Water



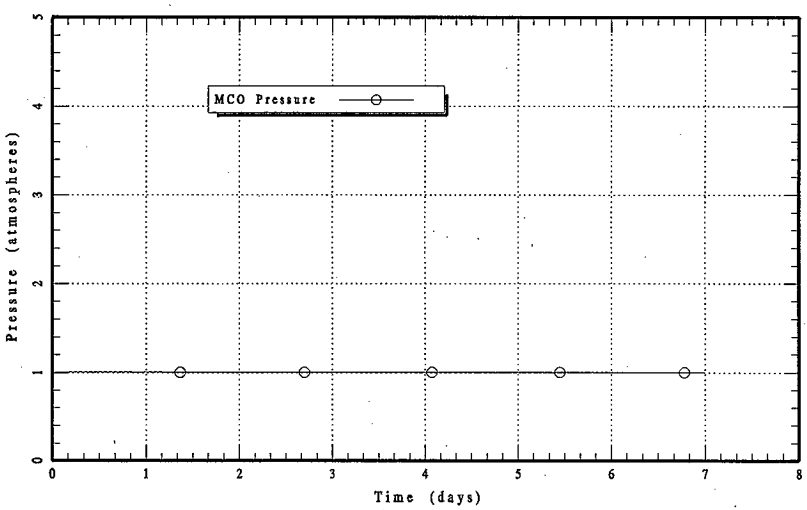


Figure A-14 DSTOP: High-Pressure Thermal Runaway with 50 °C Annulus

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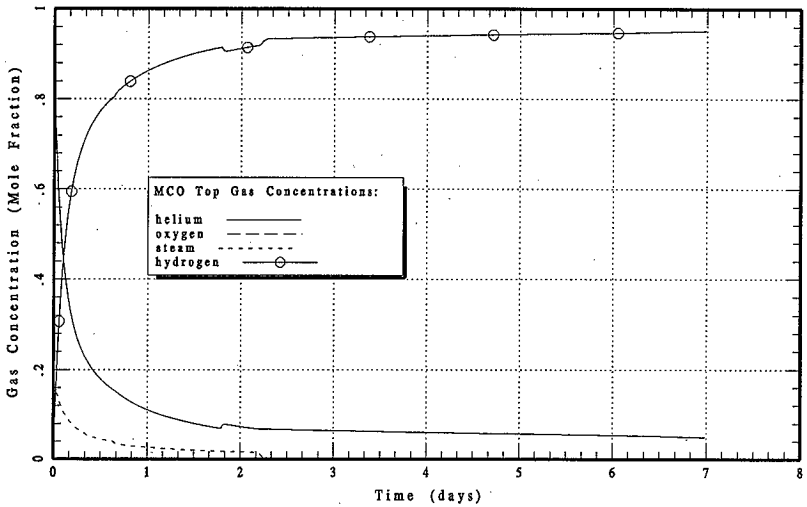
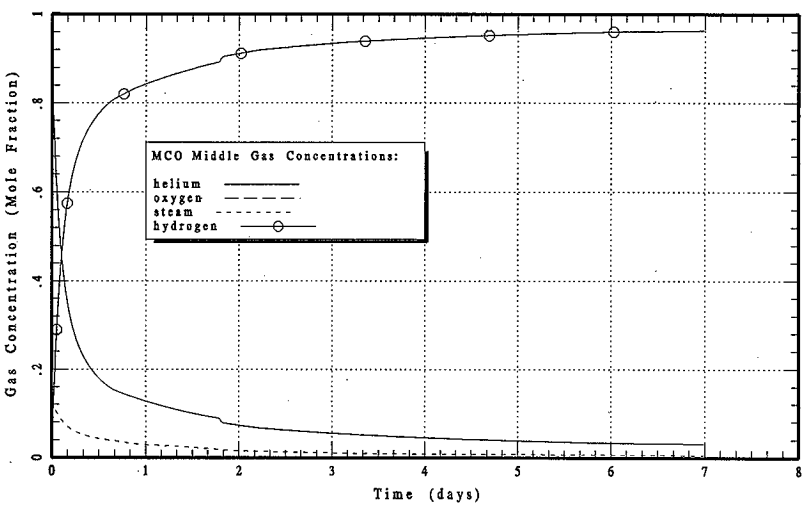
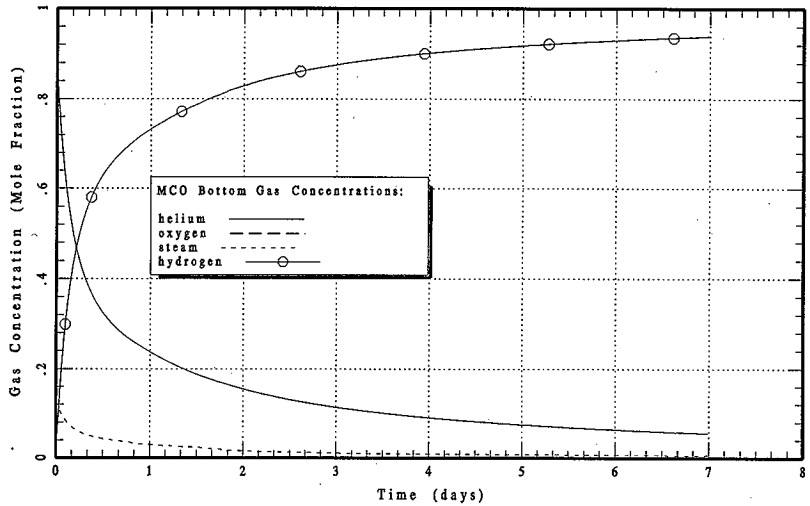
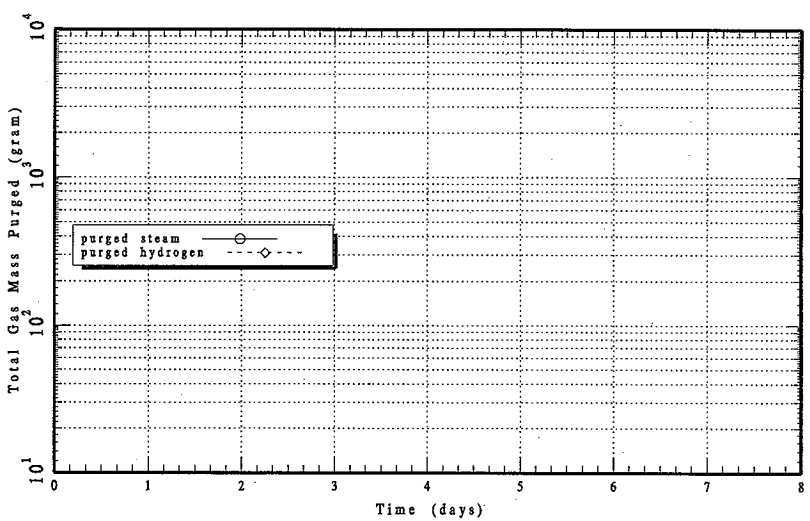
DSTOP: HIGH-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus

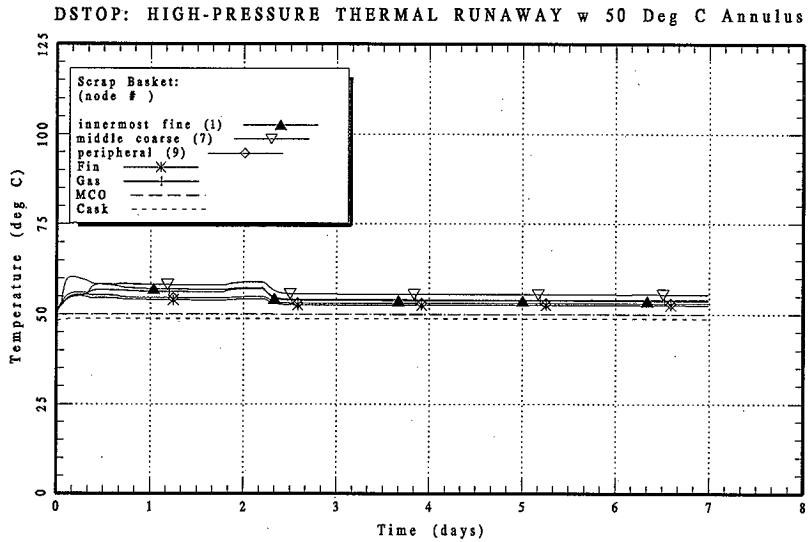


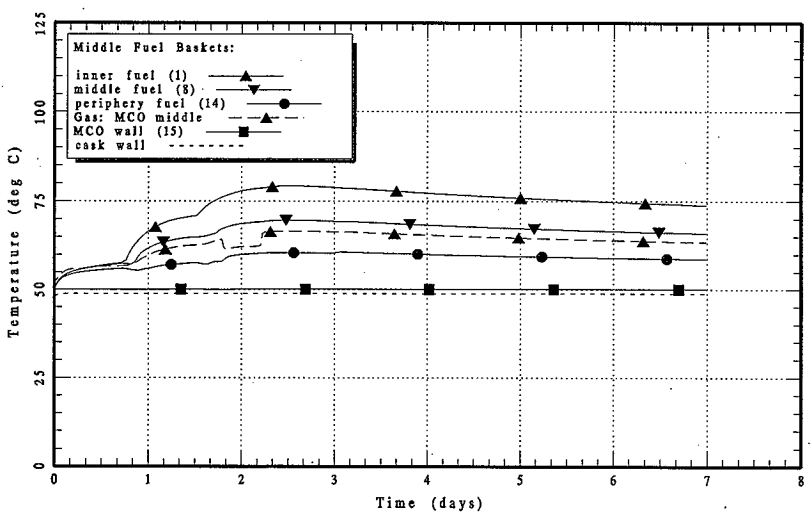


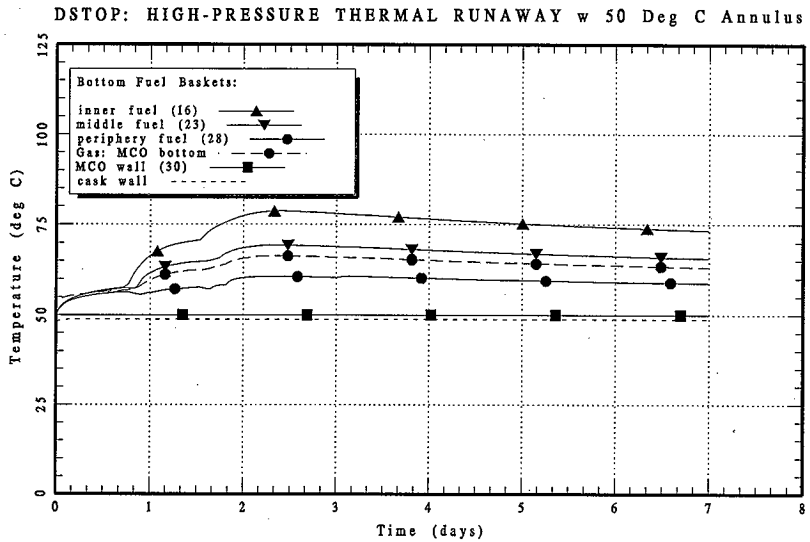
DSTOP: HIGH-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus






DSTOP: HIGH-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus
Scrap Basket:
(node #)
innermost fine (1)
middle coarse (7)
peripheral (9)
Fin
Gas
MCO
Cask
Temperature (deg C)
Time (days)
0
25
50
75
100
125
1
2
3
4
5
6
7
8


Middle Fuel Baskets:
inner fuel (1)
middle fuel (8)
periphery fuel (14)
Gas: MCO middle
MCO wall (15)
cask wall
Temperature (deg C)
Time (days)
0
25
50
75
100
125
1
2
3
4
5
6
7
8


DSTOP: HIGH-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (deg C)
Time (days)

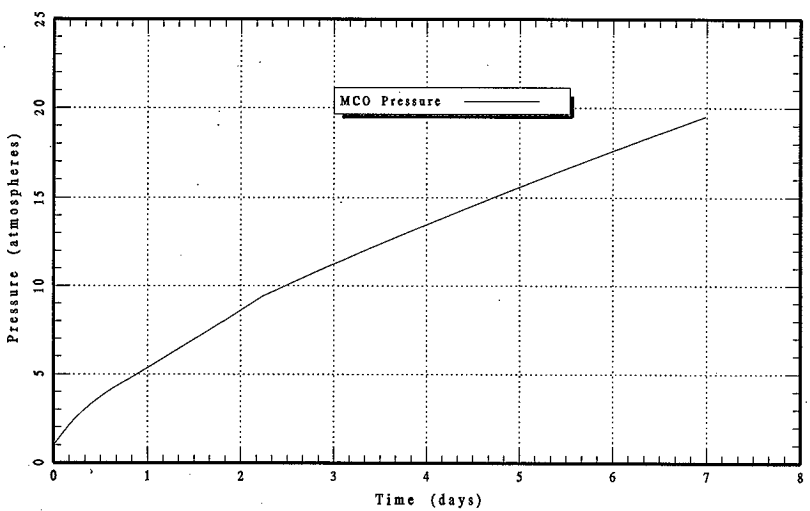

MCO Pressure
Pressure (atmospheres)
Time (days)

Figure A-15 DS75KG: High-Pressure Thermal Runaway with 75 Kg Water and 50 °C Annulus

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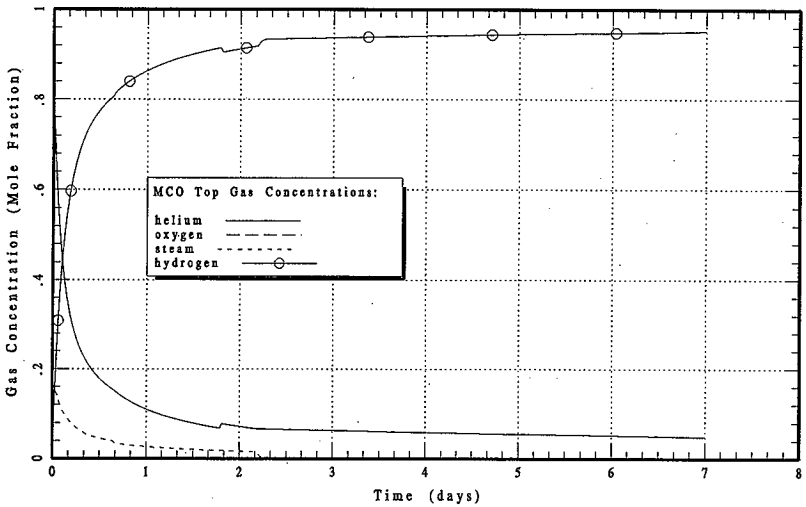
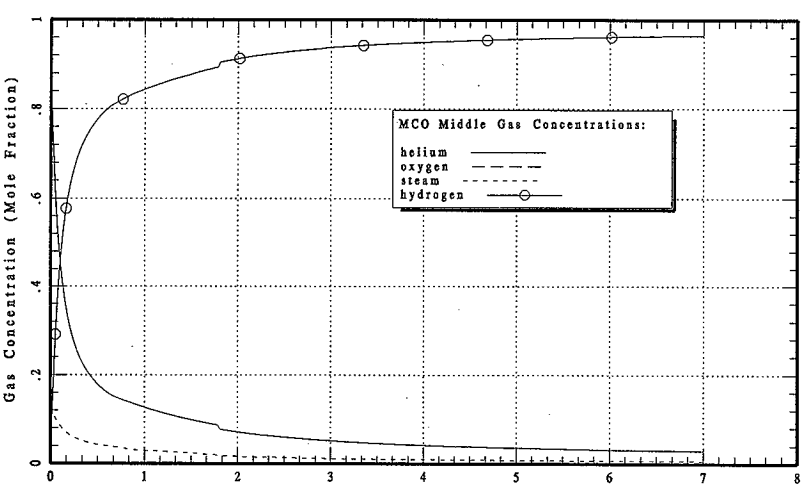
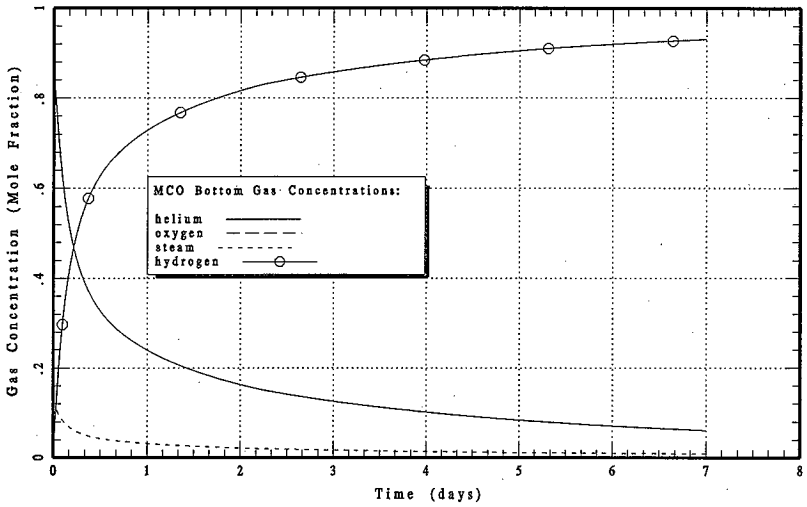
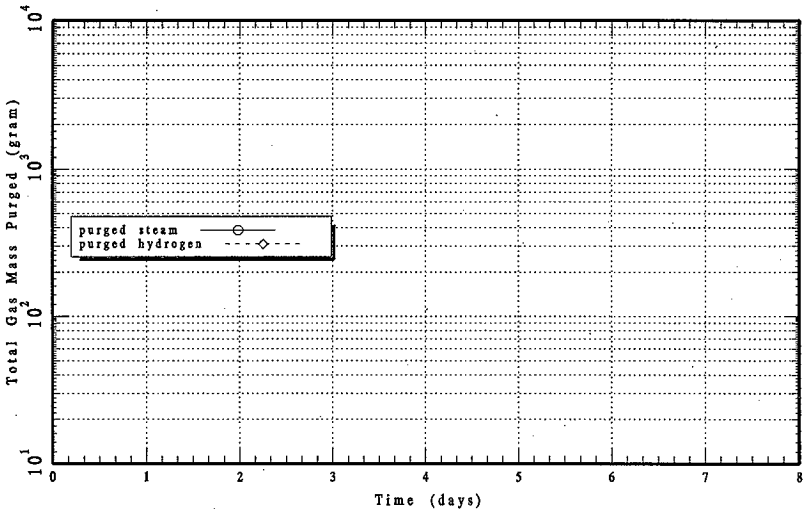
DS75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 50 Deg C Annulus



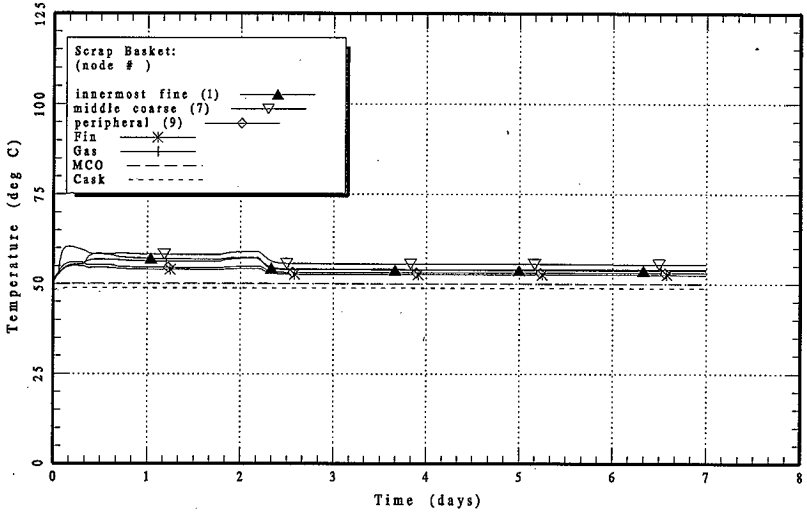


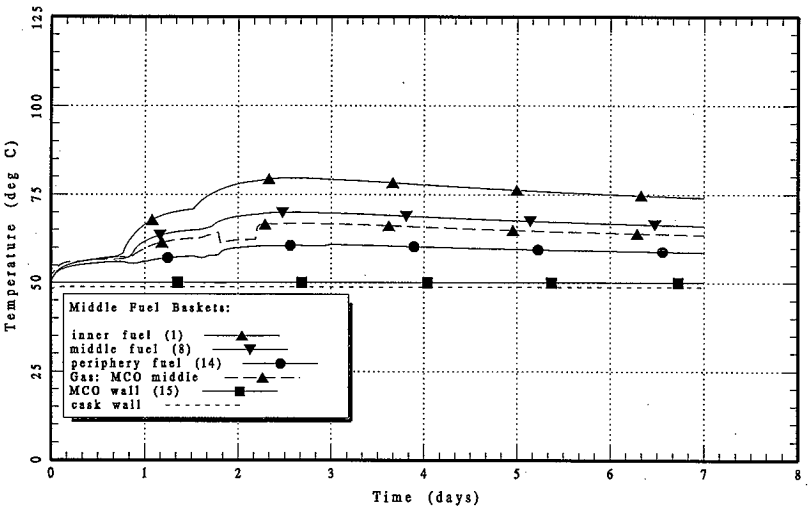
DS75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 50 Deg C Annulus



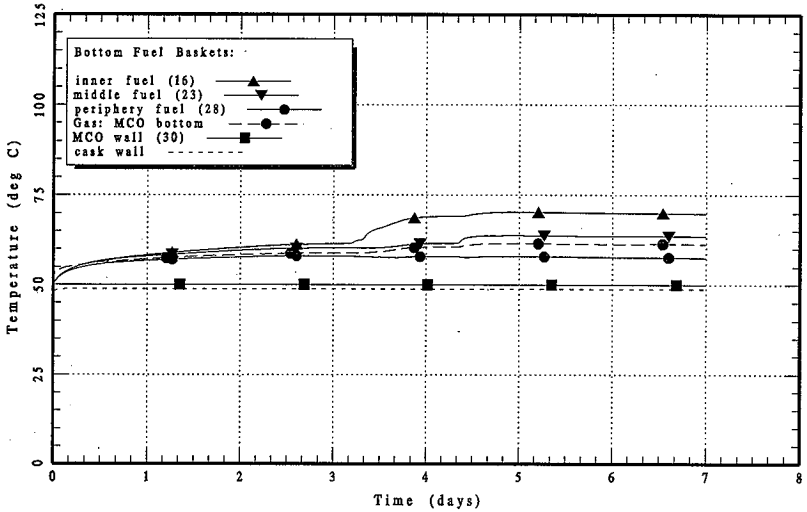


DS75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 50 Deg C Annulus





DS75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 50 Deg C Annulus



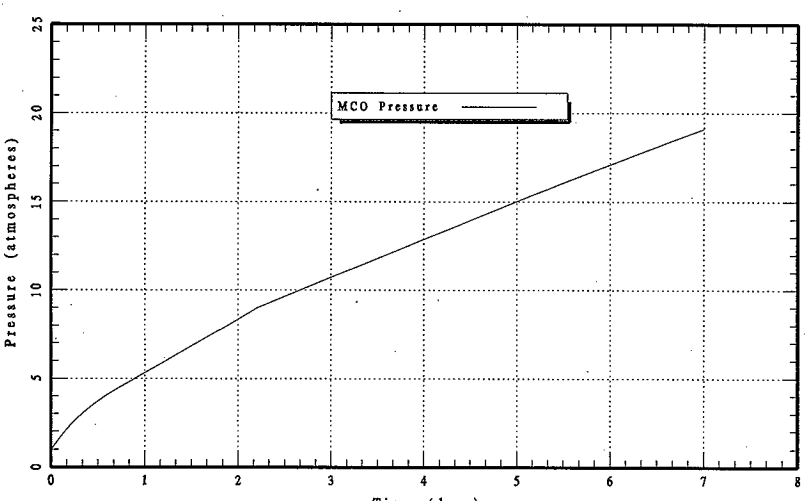


Figure A-16 DSTOPOV: Low-Pressure Thermal Runaway with 50 °C Annulus

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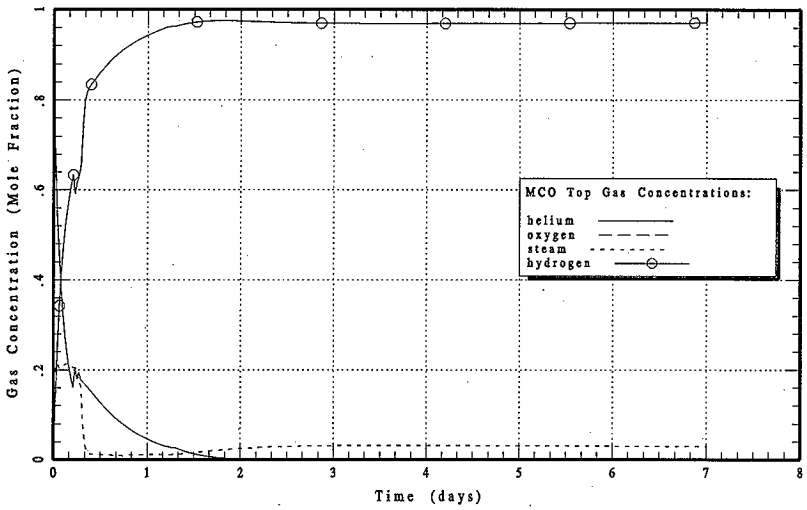
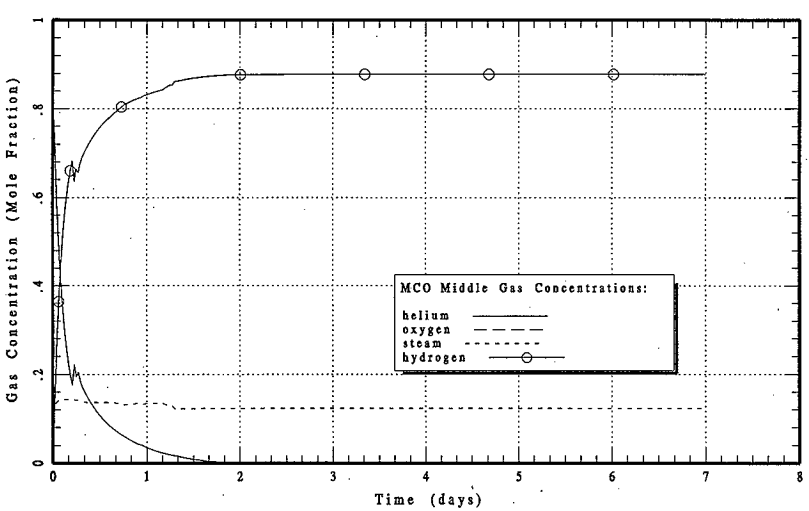
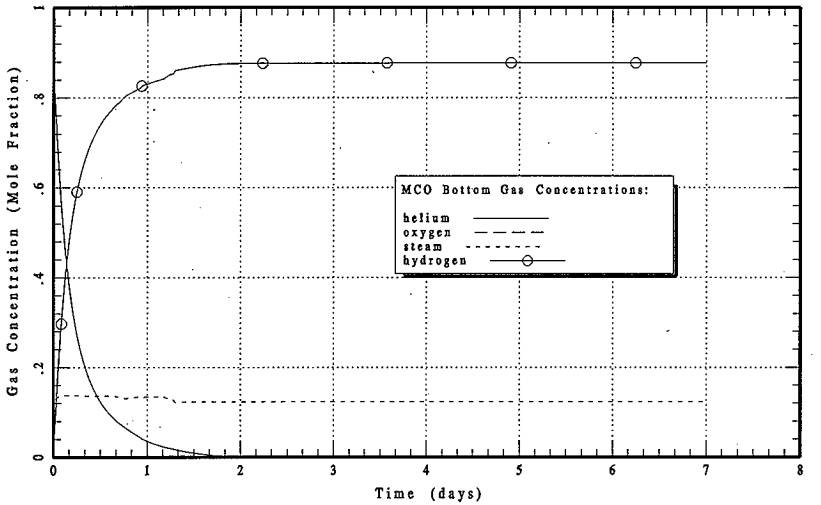
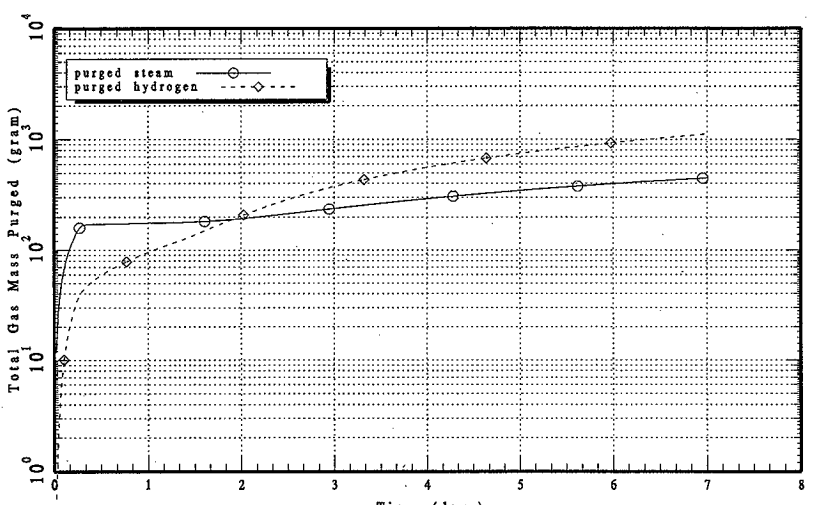
DSTOPOV: LOW-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus



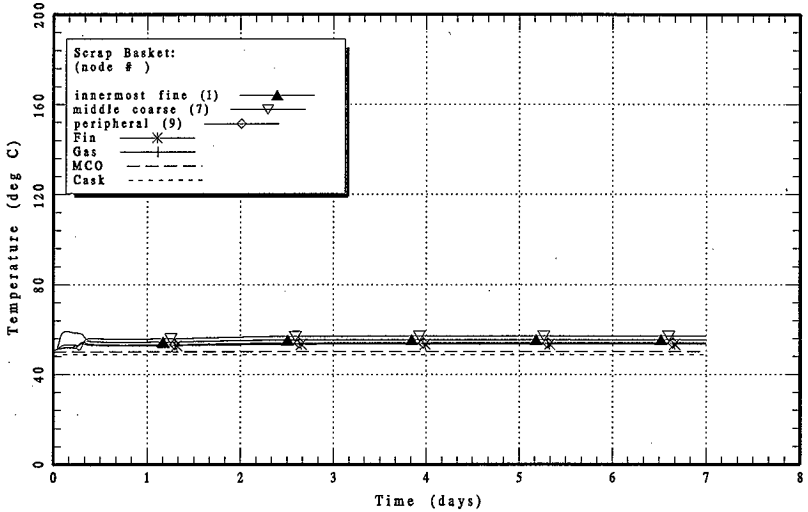


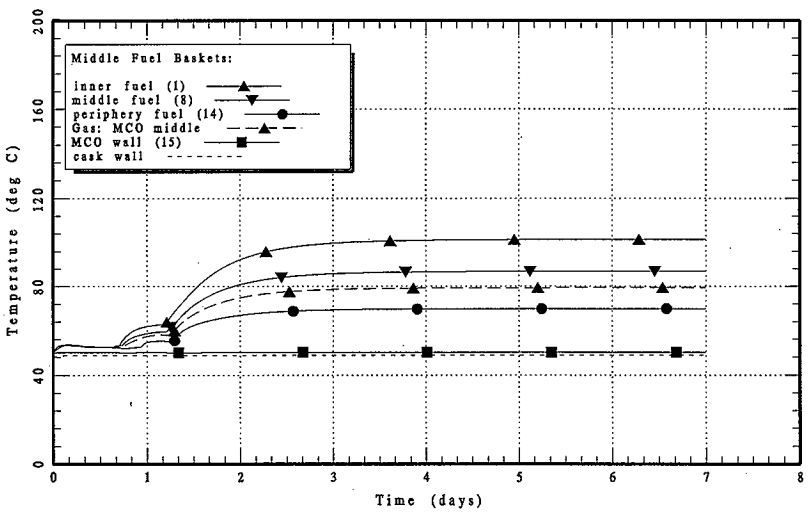
DSTOPOV: LOW-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus



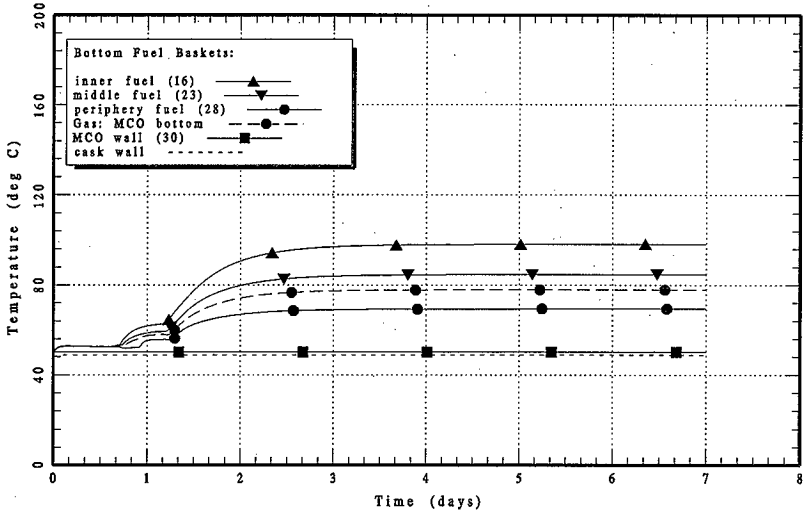


DSTOPOV: LOW-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus





DSTOPOV: LOW-PRESSURE THERMAL RUNAWAY w 50 Deg C Annulus



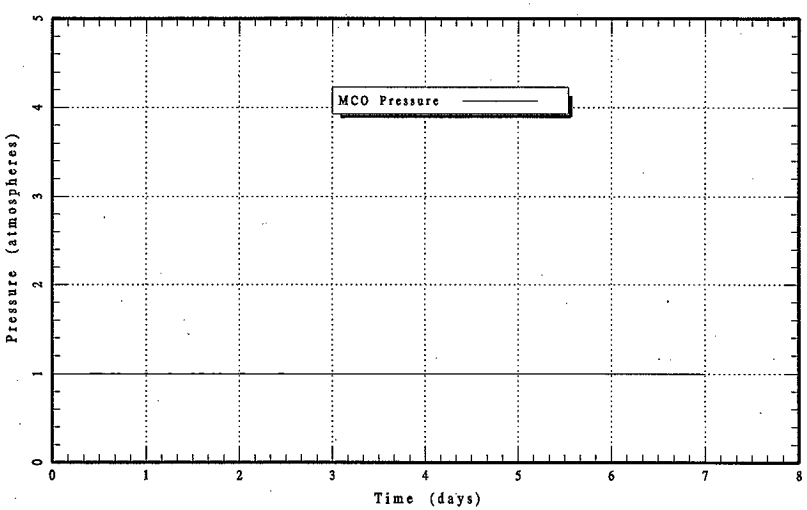


Figure A-17 DSLOF: High-Pressure Thermal Runaway with Loss of Flow in Annulus

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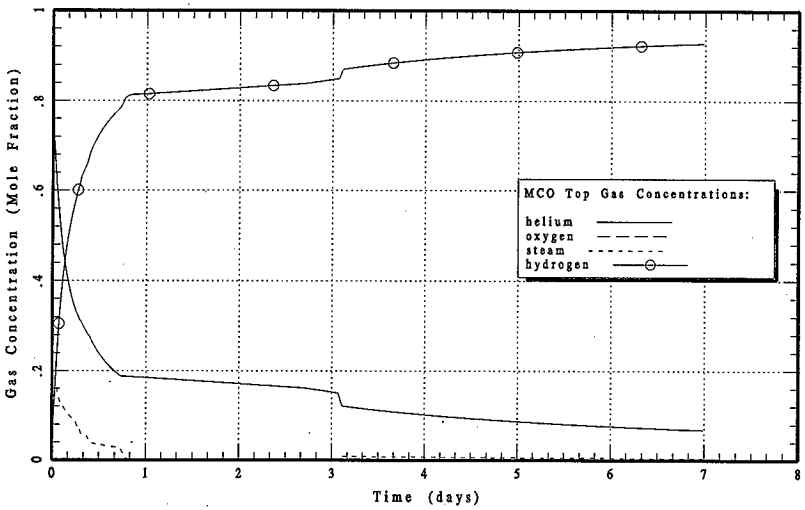
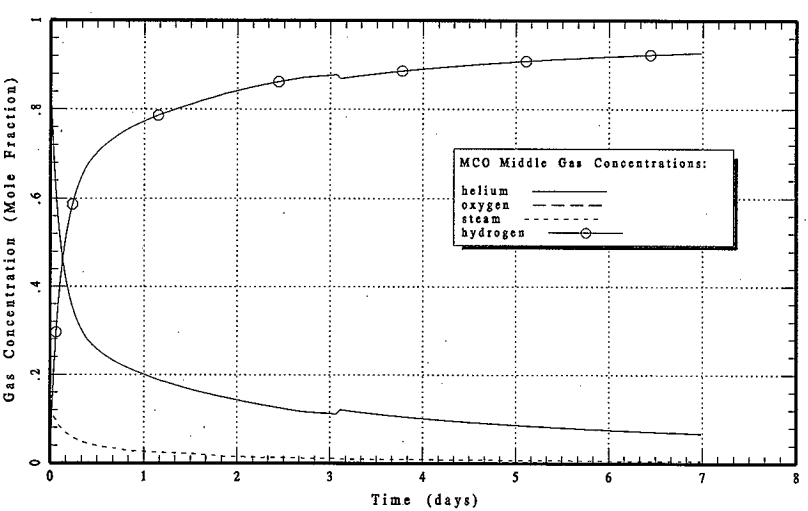
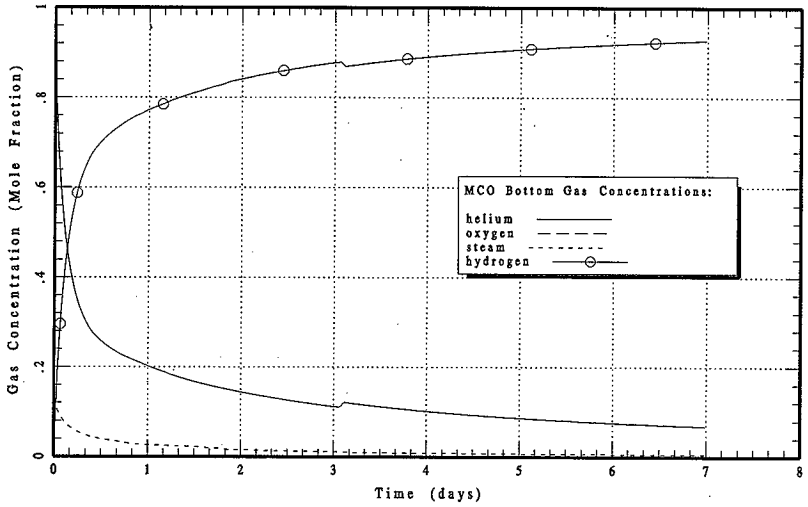
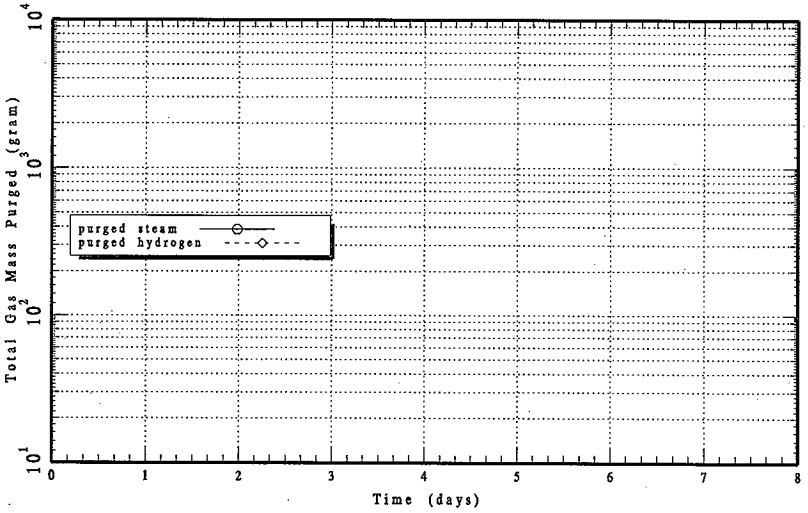
DSLOF: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



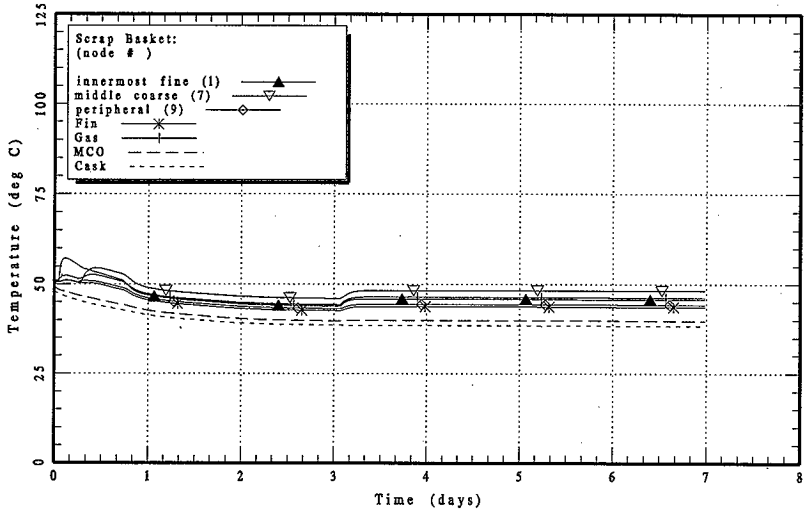


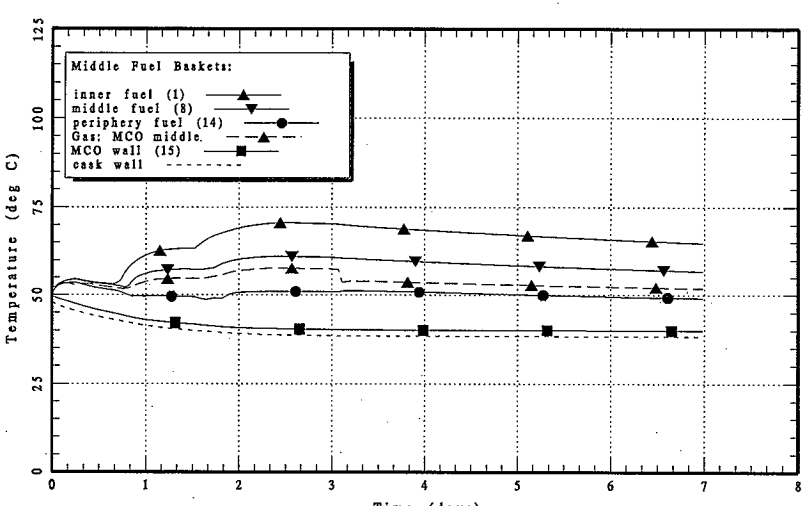
DSLOF: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



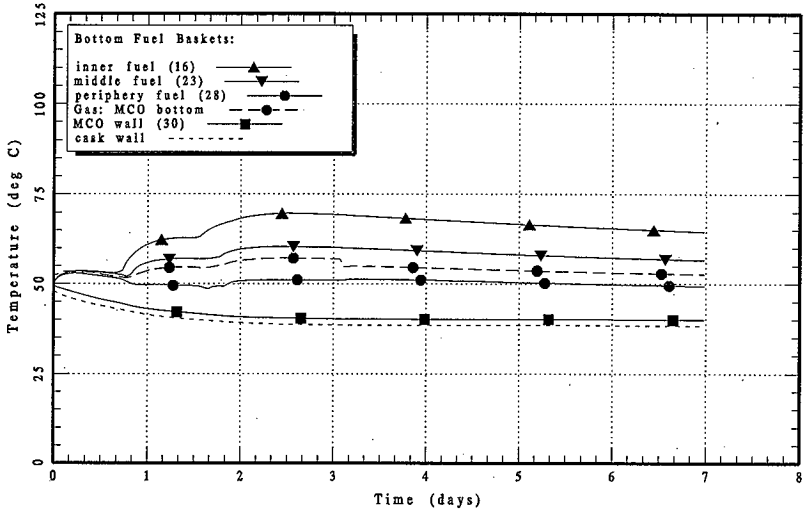


DSLOF: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus





DSLOF: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



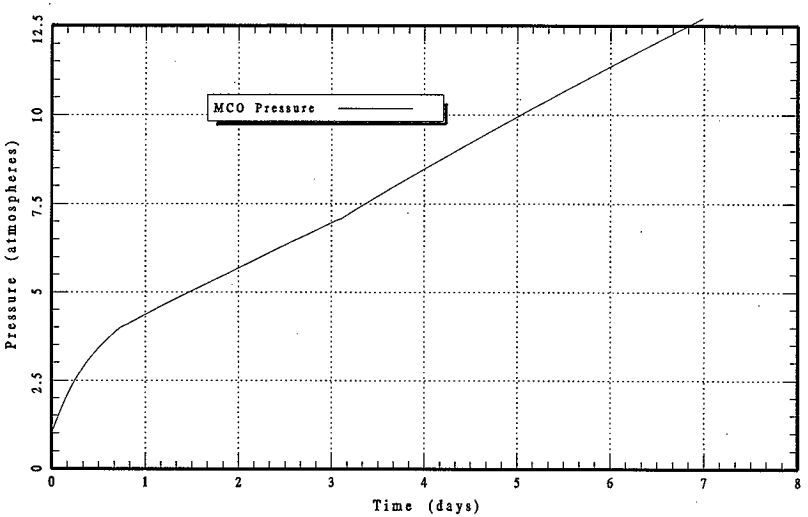


Figure A-18 DLOF75KG: High-Pressure Thermal Runaway with 75 Kg Water and Loss of Flow in Annulus

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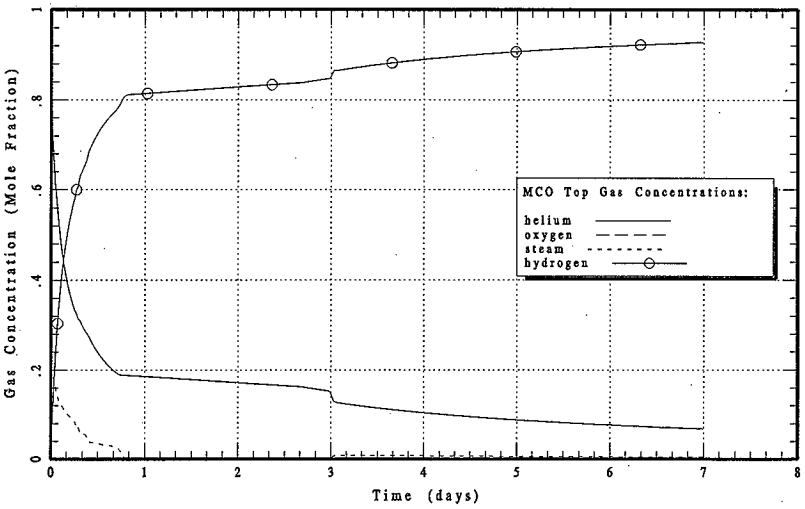
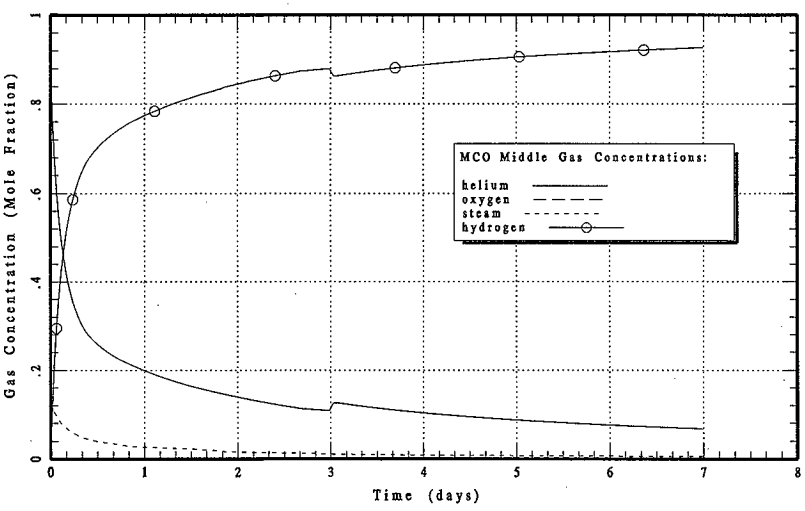
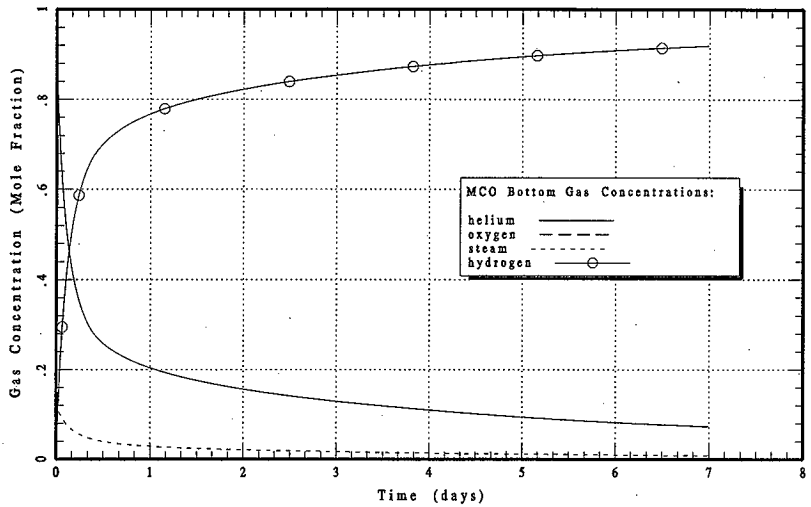
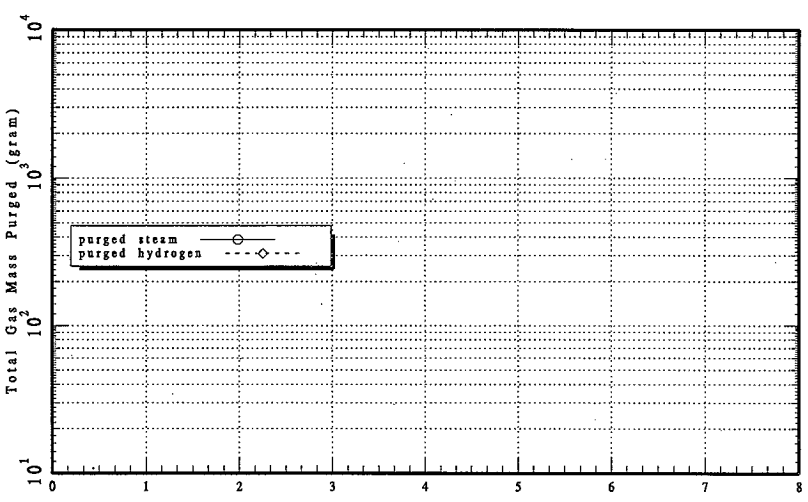
DLOF75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Flow in Annulus



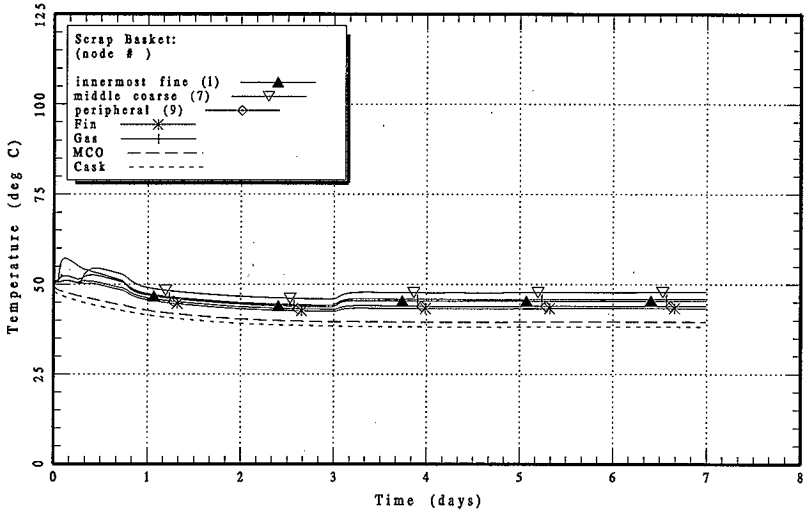


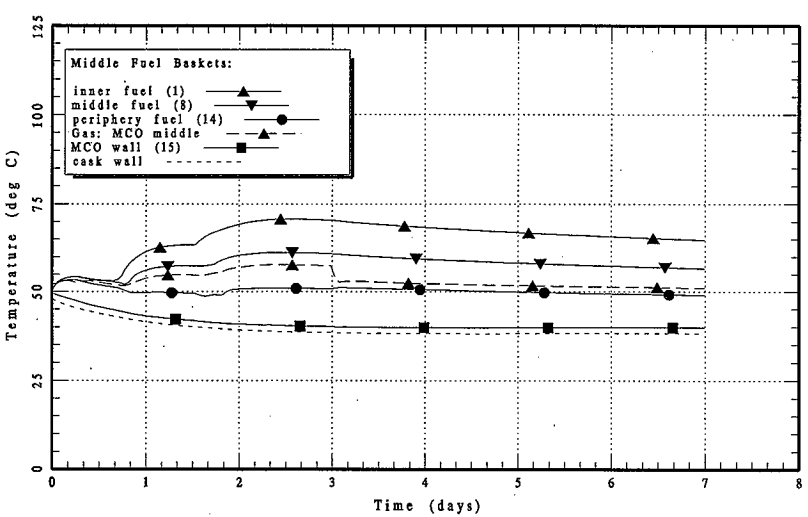
DLOF75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Flow in Annulus



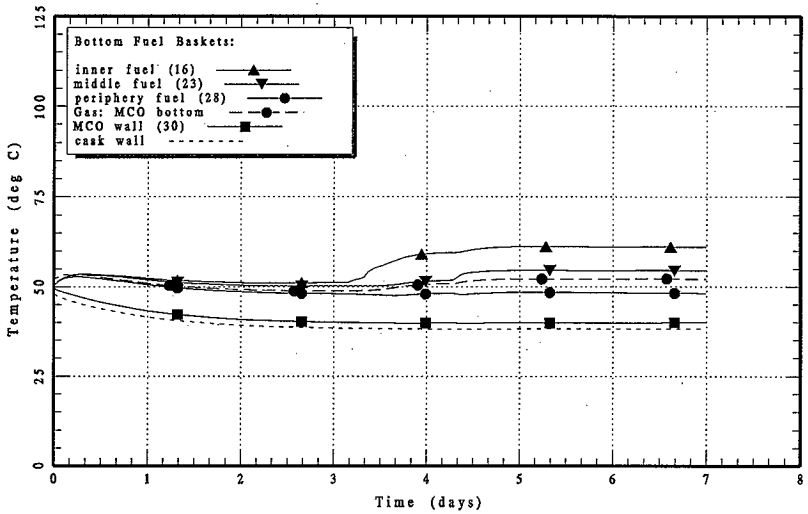


DLOF75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Flow in Annulus





DLOF75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Flow in Annulus



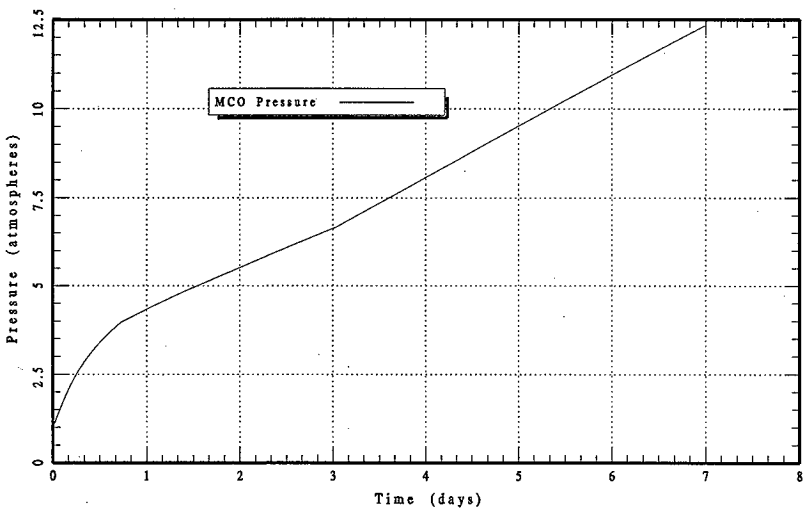


Figure A-19 DSLOFOV: Low-Pressure Thermal Runaway with Loss of Flow in Annulus

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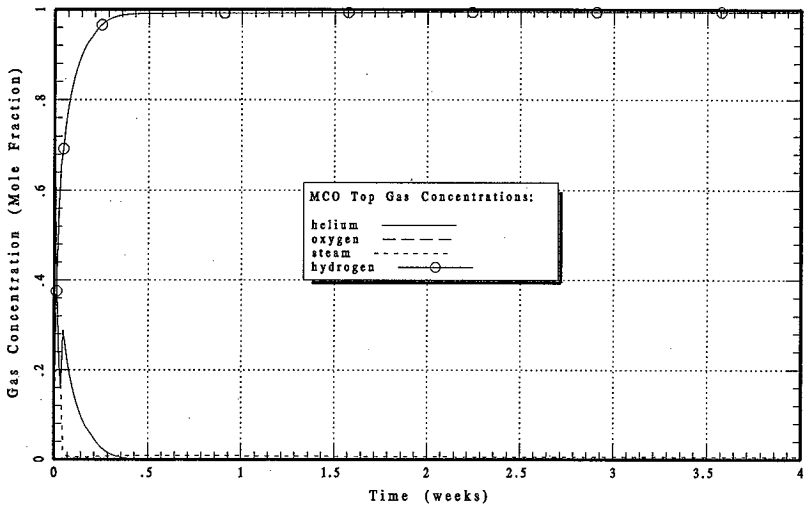
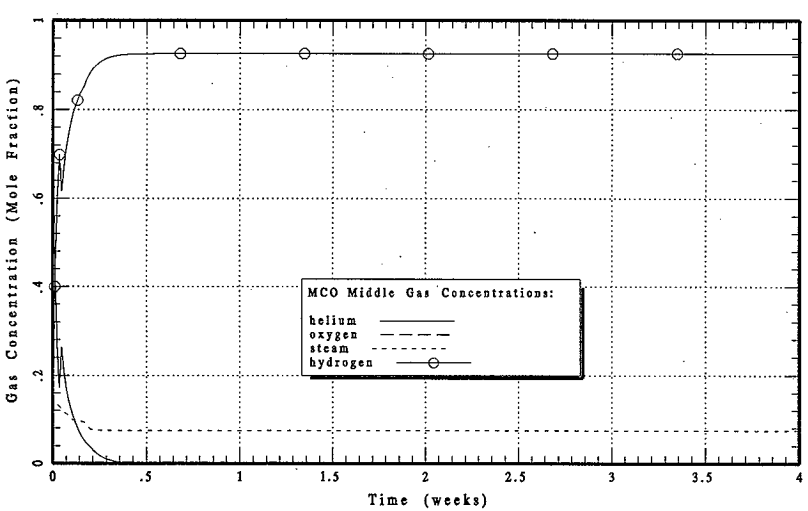
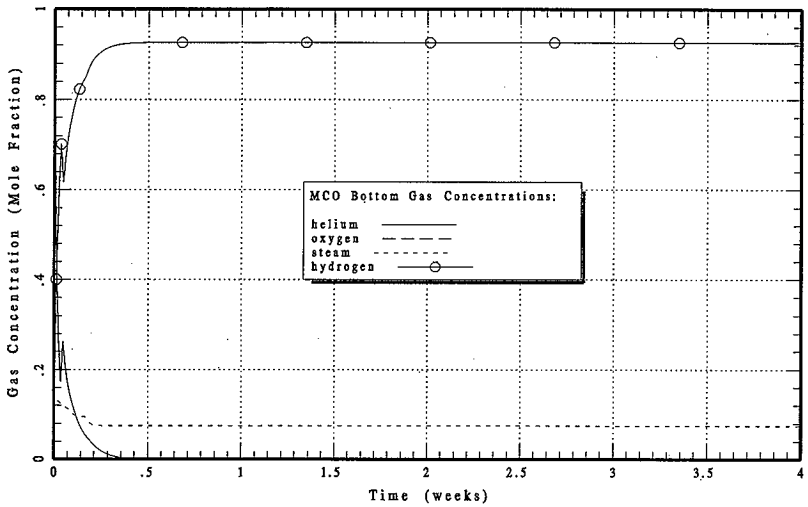
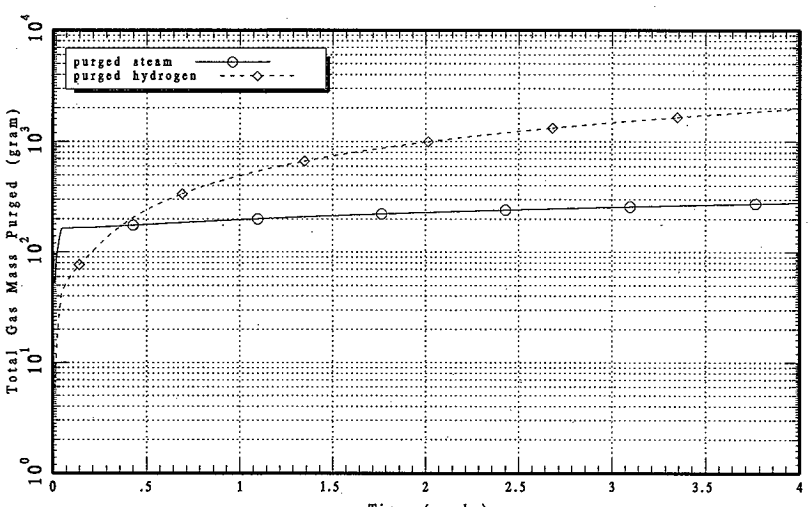
DSLOFOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



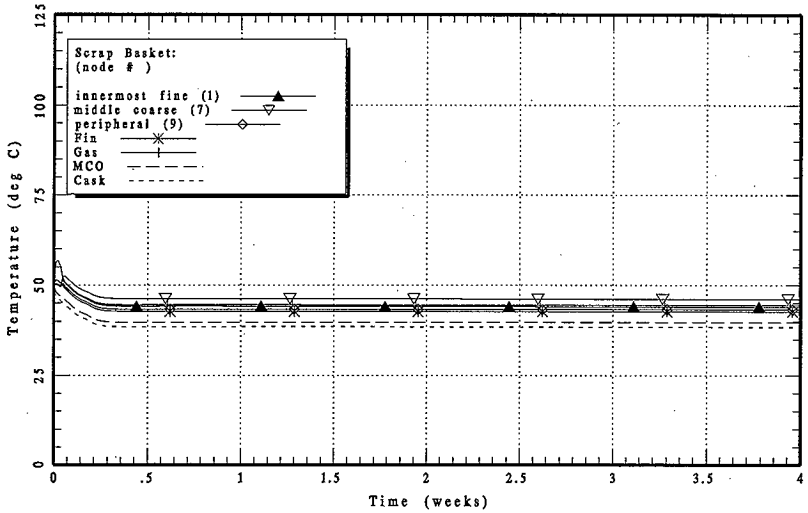


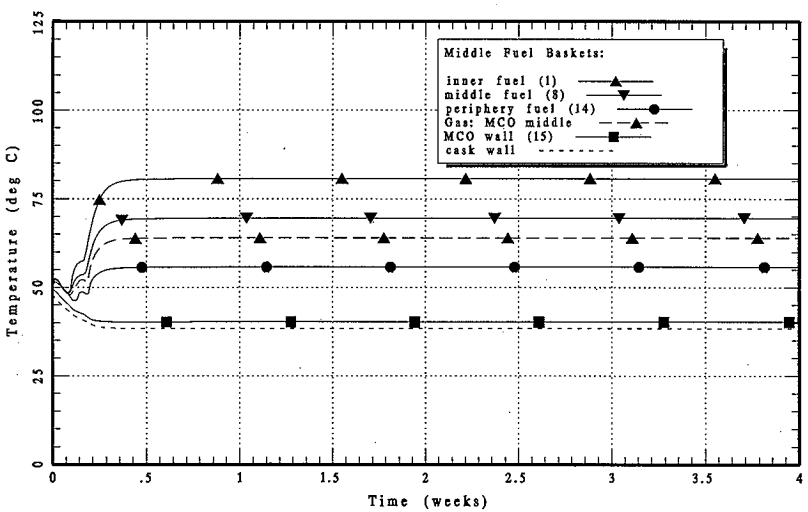
DSLOFOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



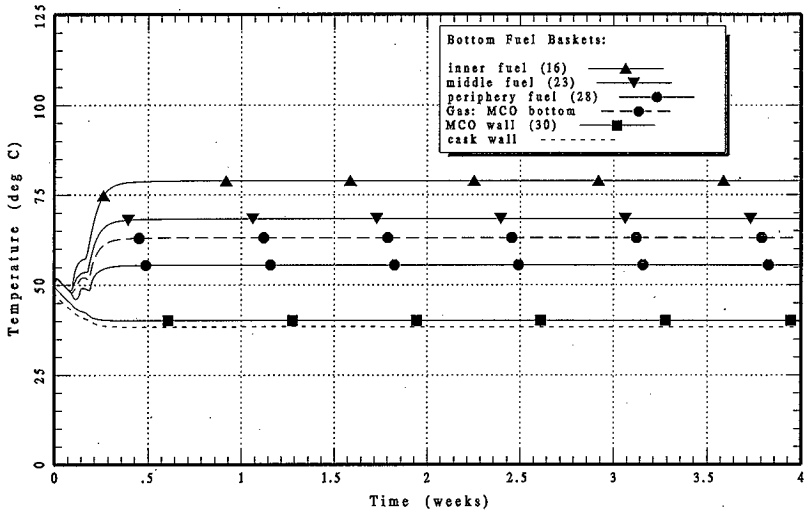


DSLOFOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus





DSLOFOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Flow in Annulus



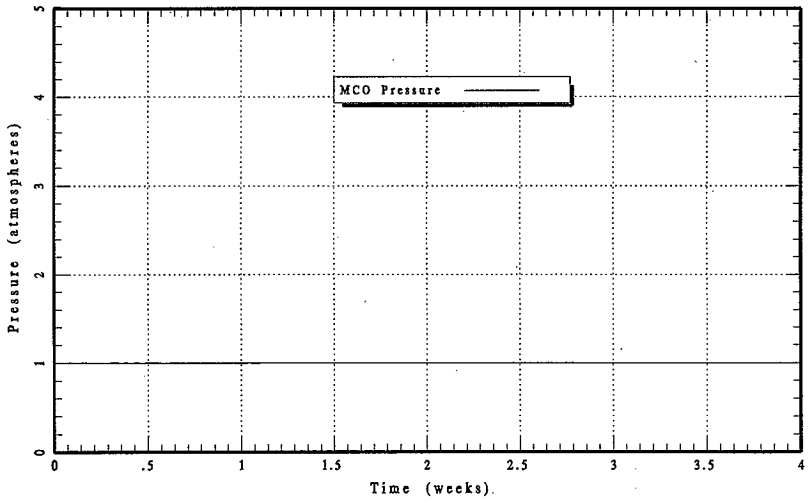


Figure A-20 DSLOC: High-Pressure Thermal Runaway with Loss of Coolant (LOC)

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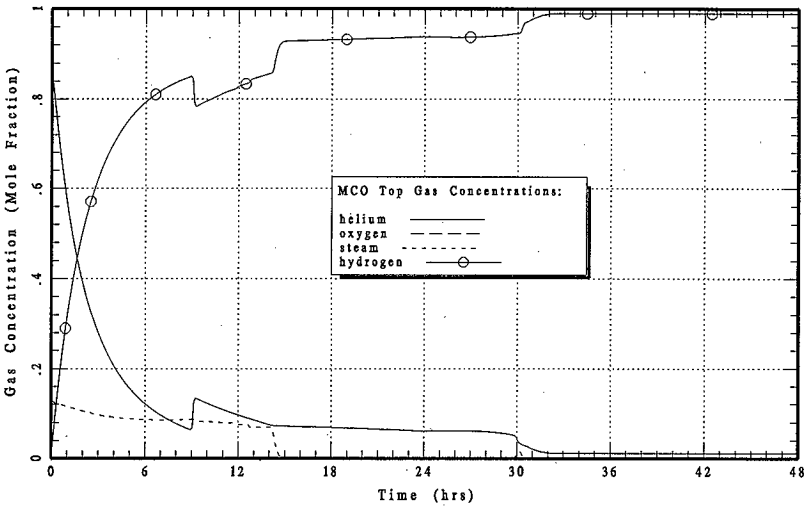
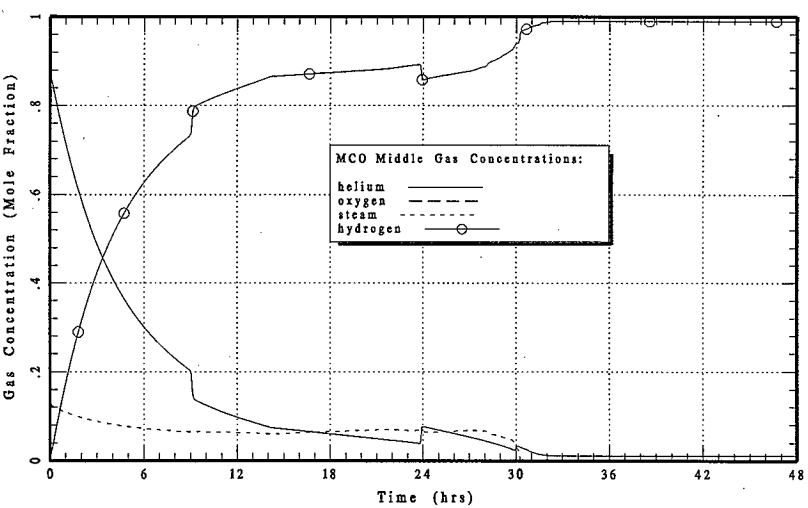
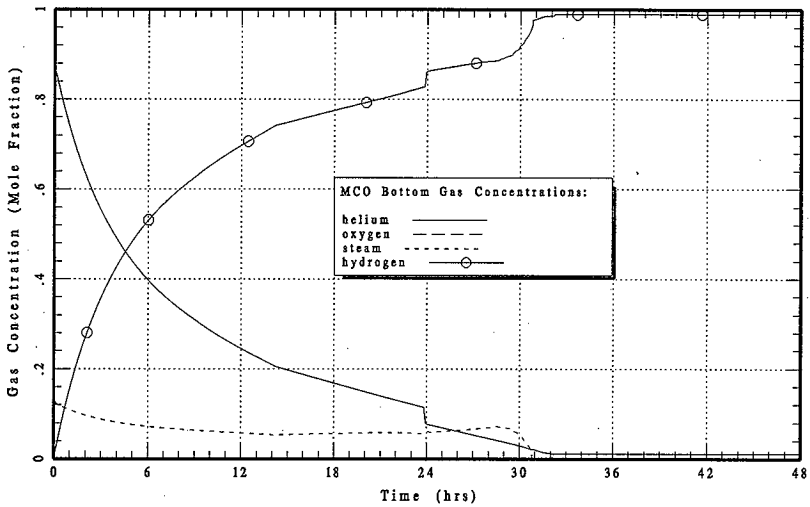
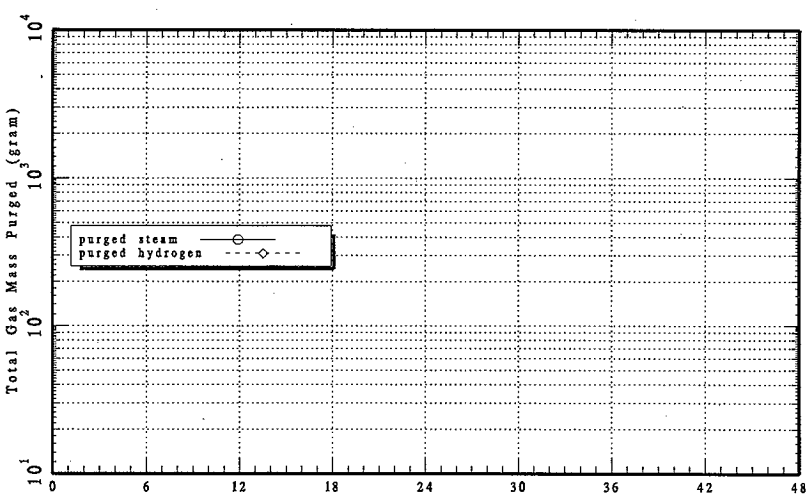
DSLOC: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Coolant



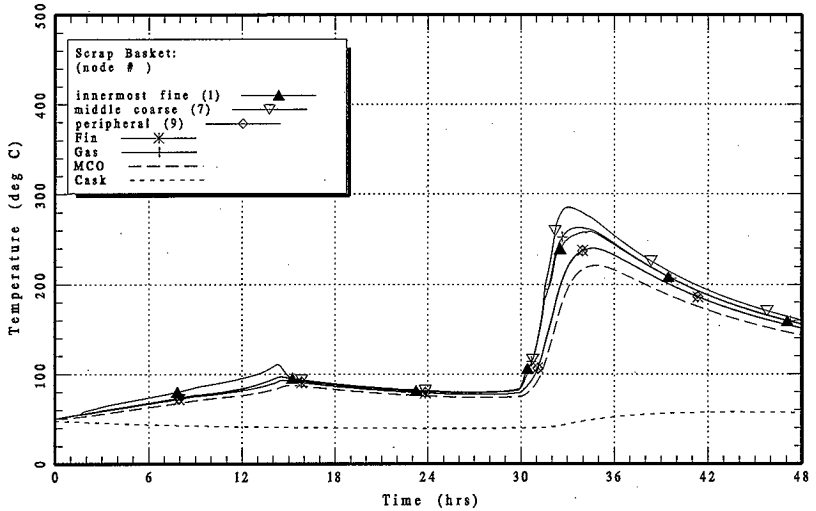


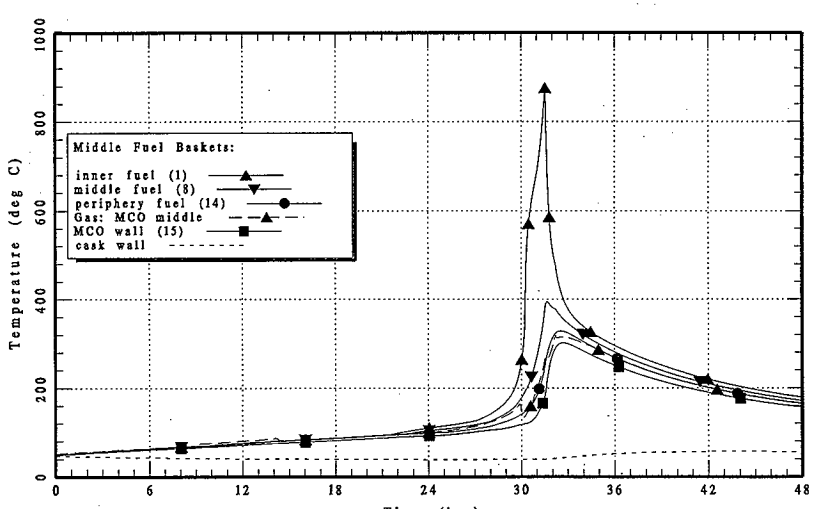
DSLOC: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Coolant

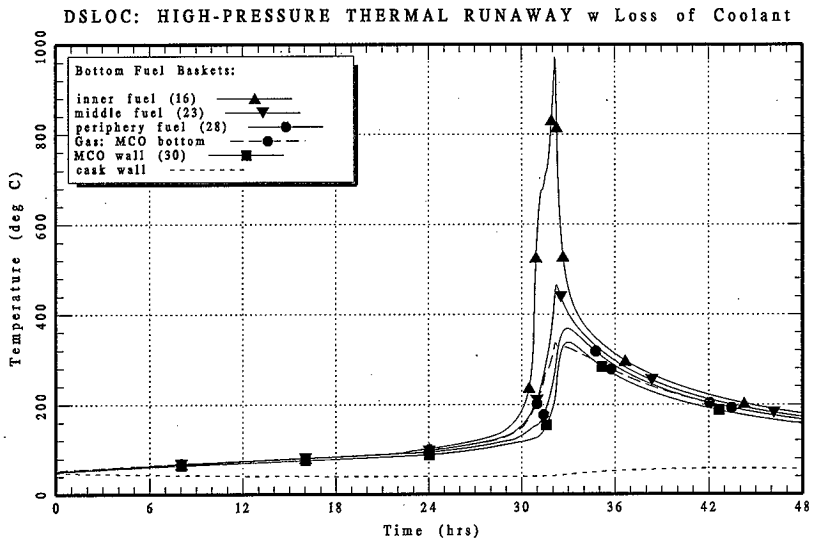




DSLOC: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Coolant






DSLOC: HIGH-PRESSURE THERMAL RUNAWAY w Loss of Coolant
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (deg C)
0
200
400
600
800
1000
0
6
12
18
24
30
36
42
48
Time (hrs)

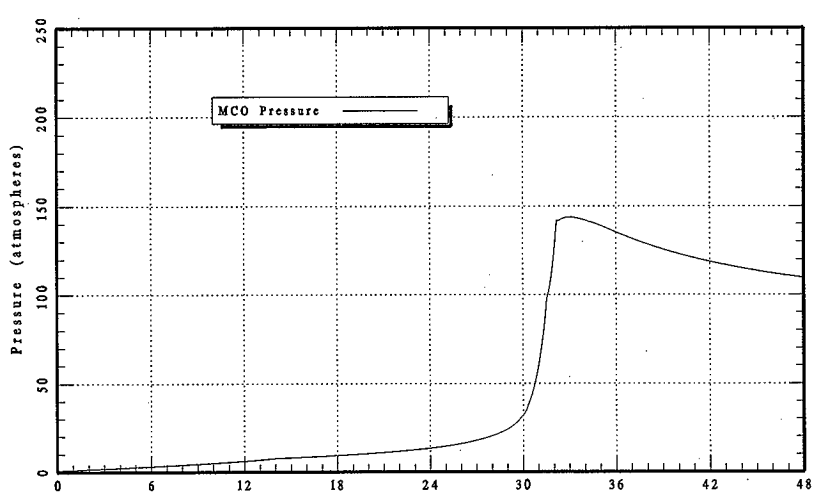

MCO Pressure
Pressure (atmospheres)
0
50
100
150
200
250
0
6
12
18
24
30
36
42
48
Time (hrs)

Figure A-21 DLOC75KG: High-Pressure Thermal Runaway with 75 Kg Water and Loss of Coolant (LOC)

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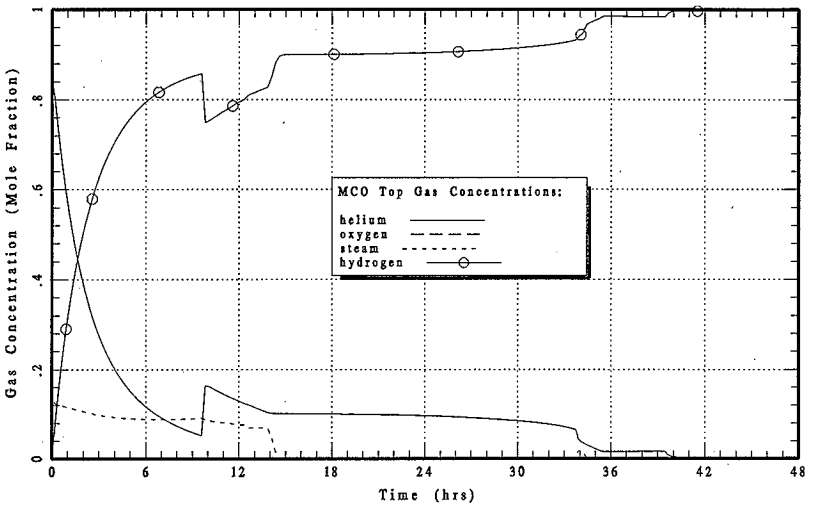
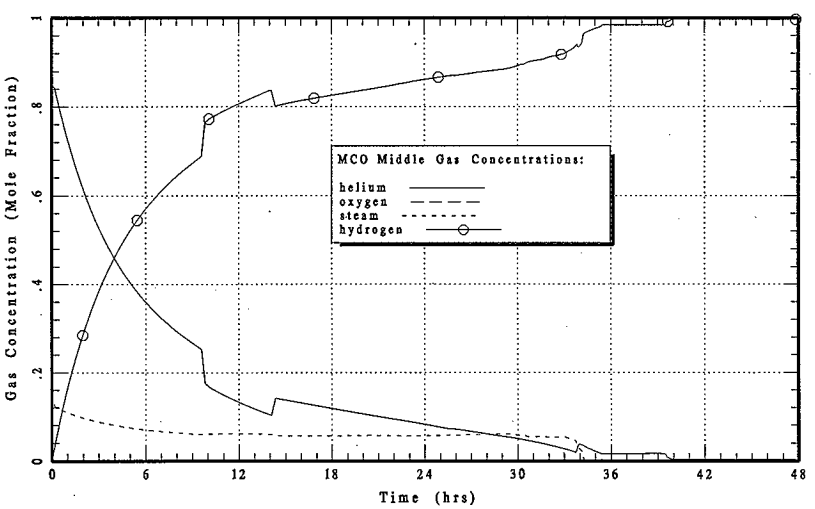
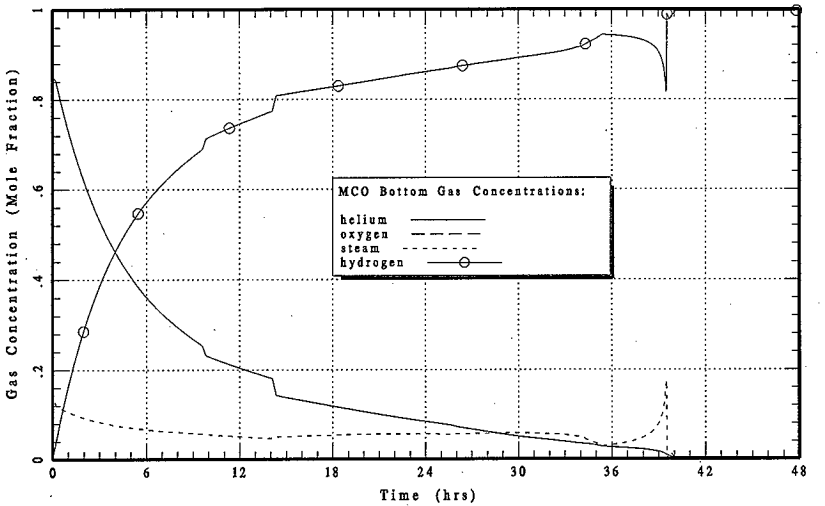
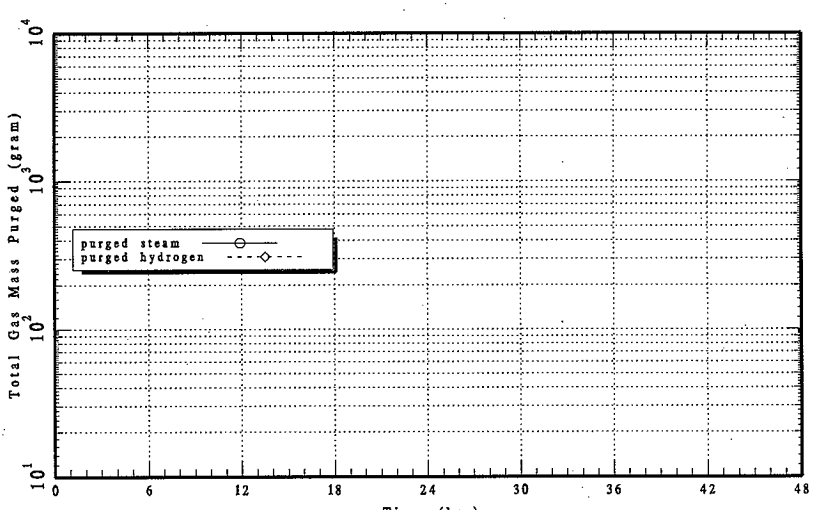
DLOC75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Coolant



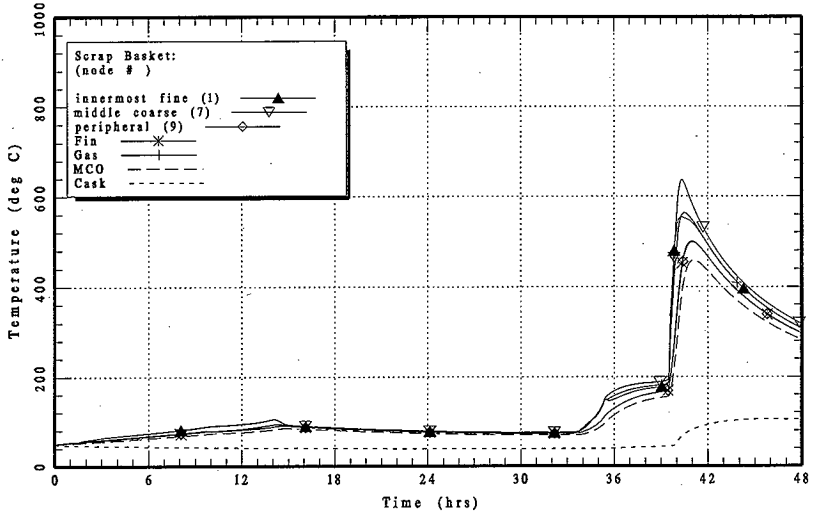


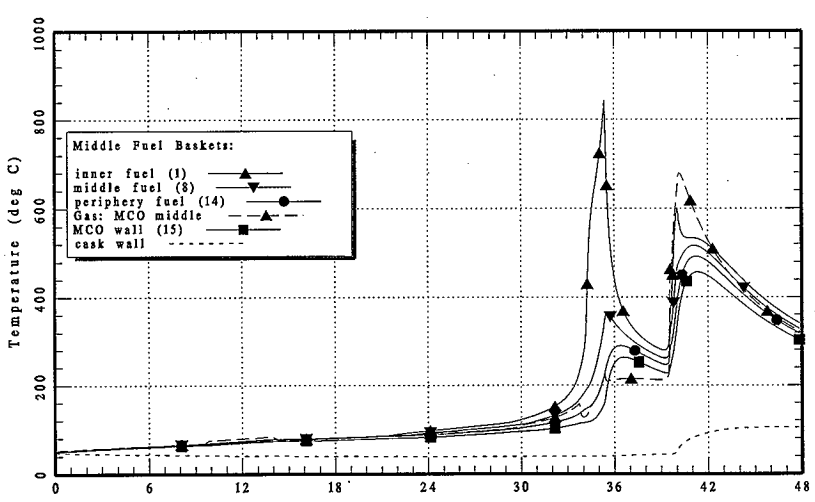
DLOC75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Coolant



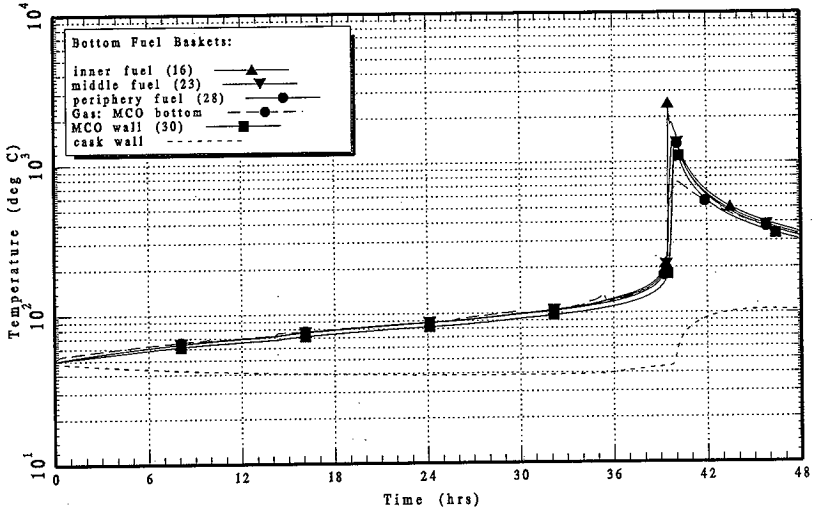


DLOC75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Coolant





DLOC75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & Loss of Coolant



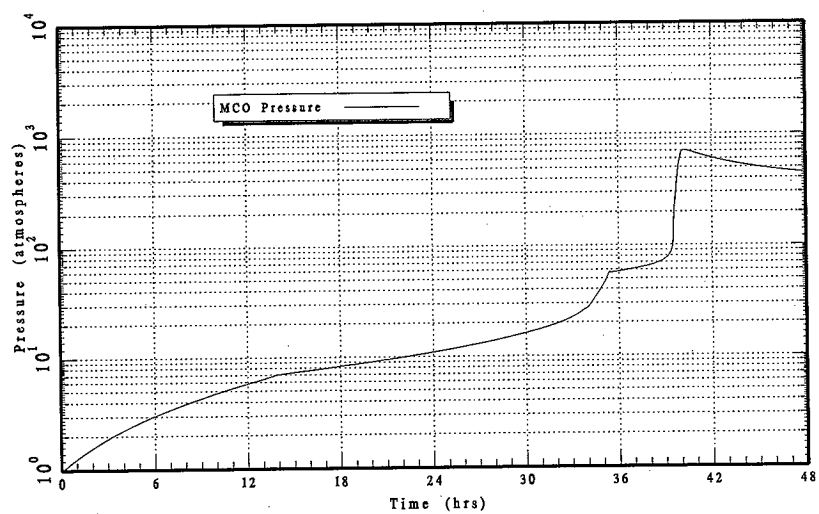


Figure A-22 DSLOCNOM: High-Pressure Thermal Runaway with Nominal and Bounding Parameters and Loss of Coolant (LOC)

The long-dashed curves are from case 22, DSLOCNOM, which includes a loss of coolant condition for a Multi-Canister Overpack (MCO) with nominal parameter values. The solid and short-dashed curves are from case 22 except that the MCO has bounding parameter values.

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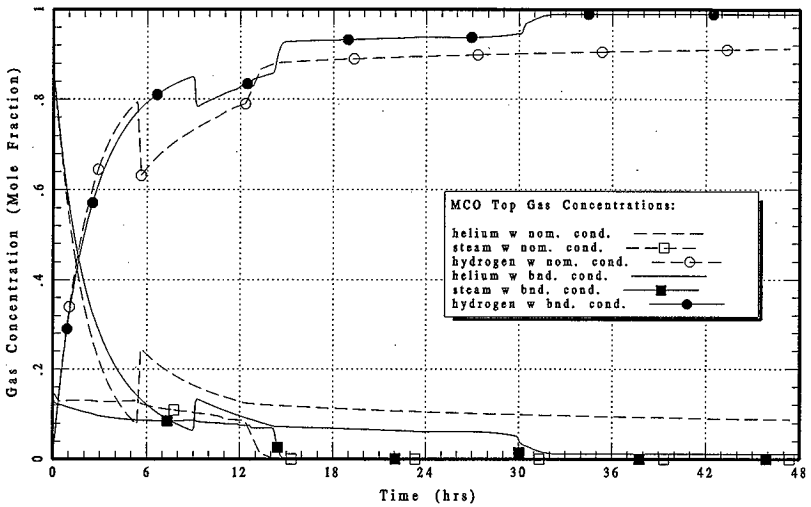
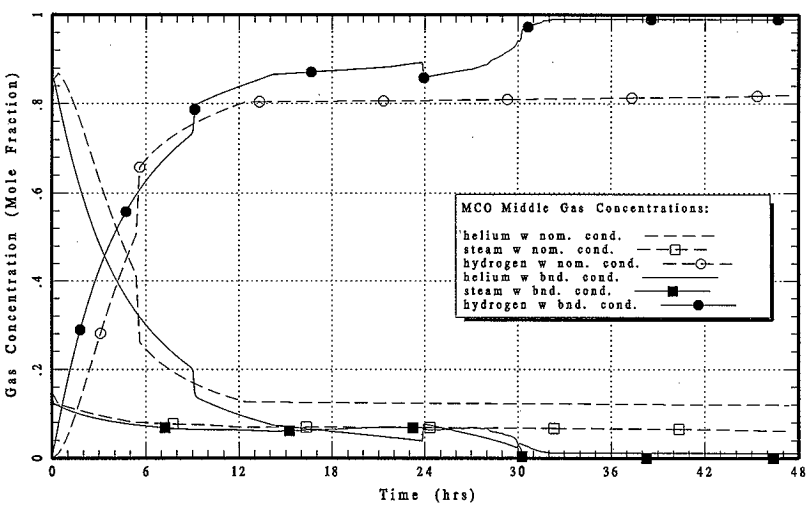
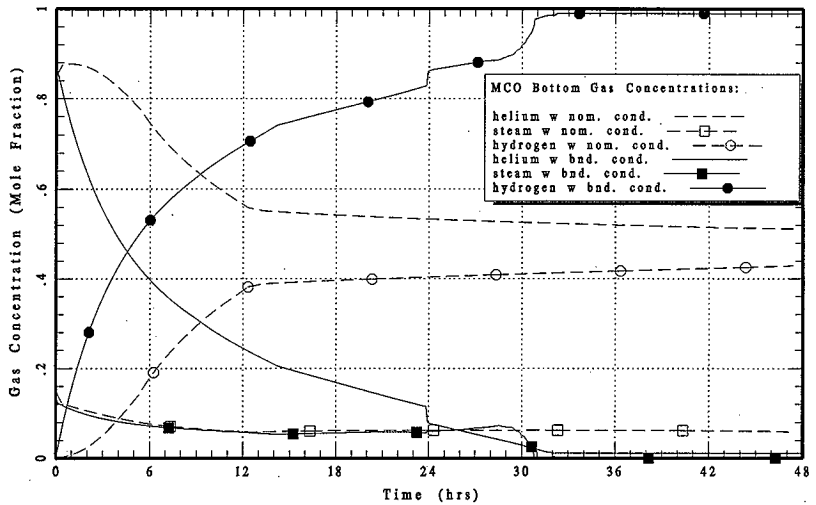
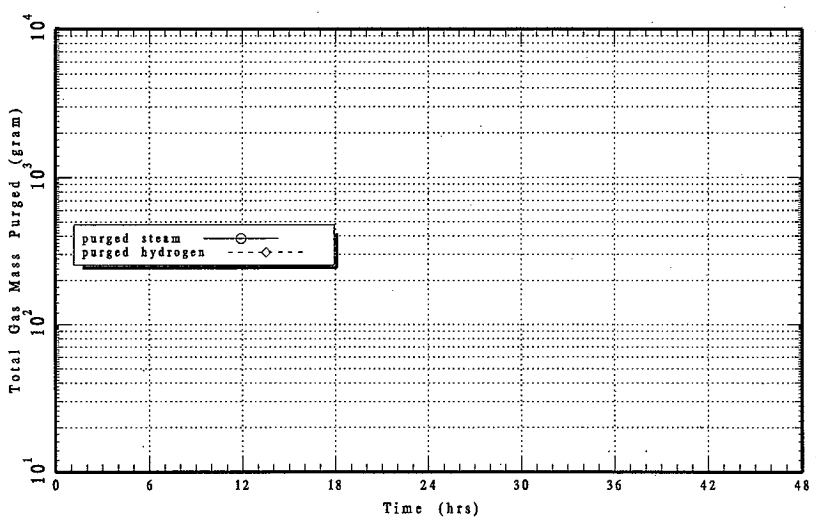
DSLOCNOM: HI-PRES THERM RUNAWAY w Nom & Bnd Param. & Loss of Coolant



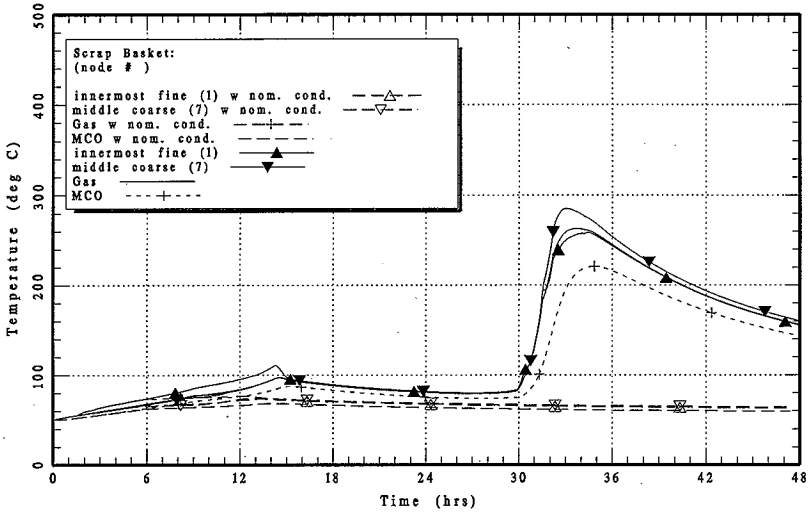


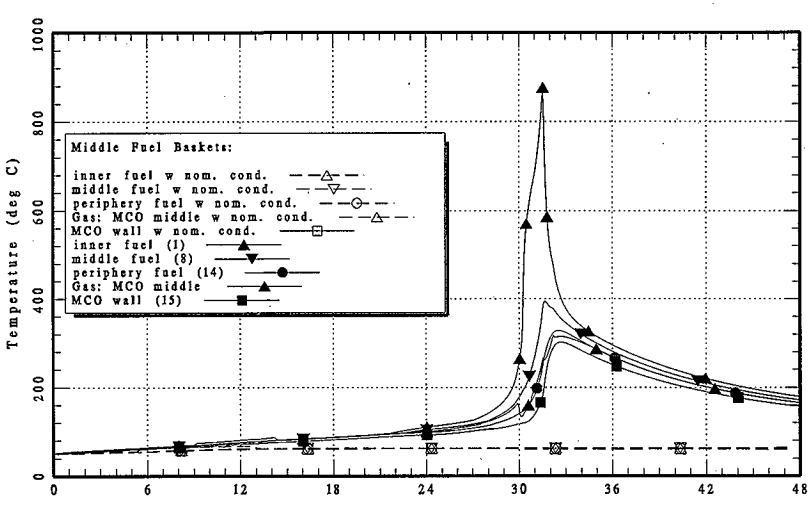
DSLOCNOM: HI-PRES THERM RUNAWAY w Nom & Bnd Param. & Loss of Coolant



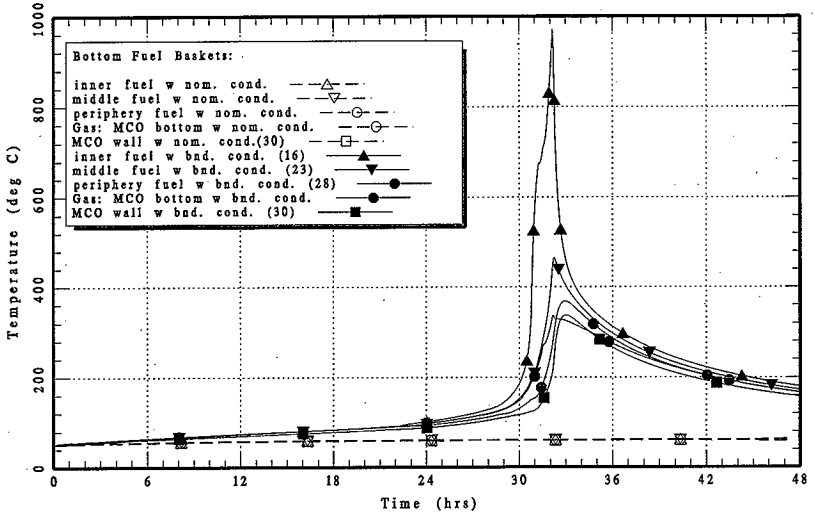


DSLOCNOM: HI-PRES THERM RUNAWAY w Nom & Bnd Param. & Loss of Coolant





DSLOCNOM: HI-PRES THERM RUNAWAY w Nom & Bnd Param. & Loss of Coolant



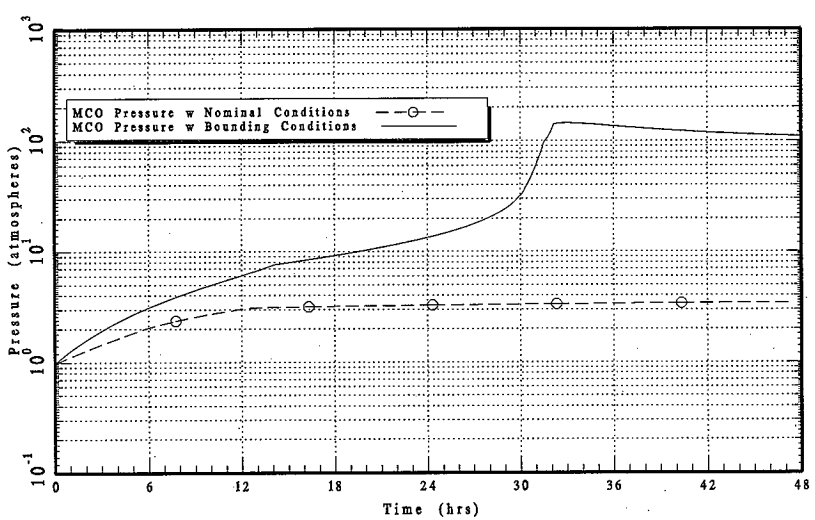


Figure A-23 DSLOCREC: High-Pressure Thermal Runaway with Loss of Coolant (LOC) and Recovery at 21 Hours

The long-dashed curves are from case 23, DSLOCREC, which includes a recovery from the loss of coolant condition by restoring 25 °C flowing annulus water at 21 hours. The solid and short-dashed curves are from case 20, DSLOC, which includes a bounding MCO with a loss of coolant condition and provides the initial conditions for case 23 at 21 hours.

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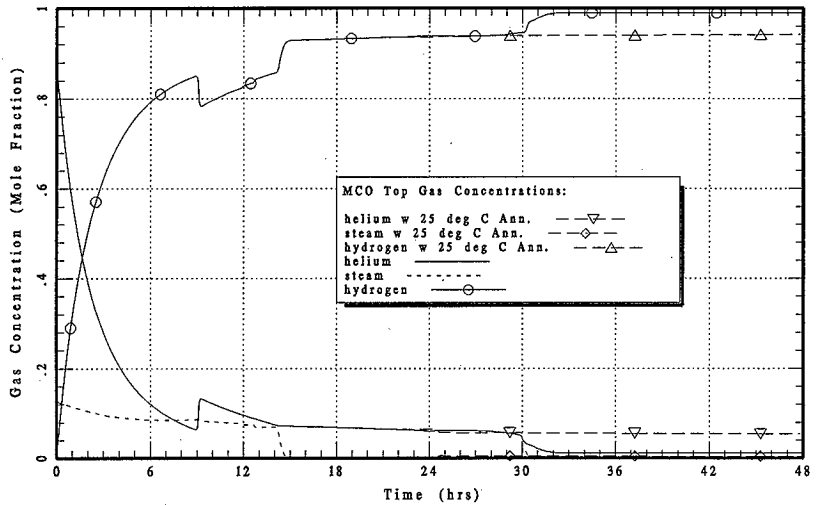
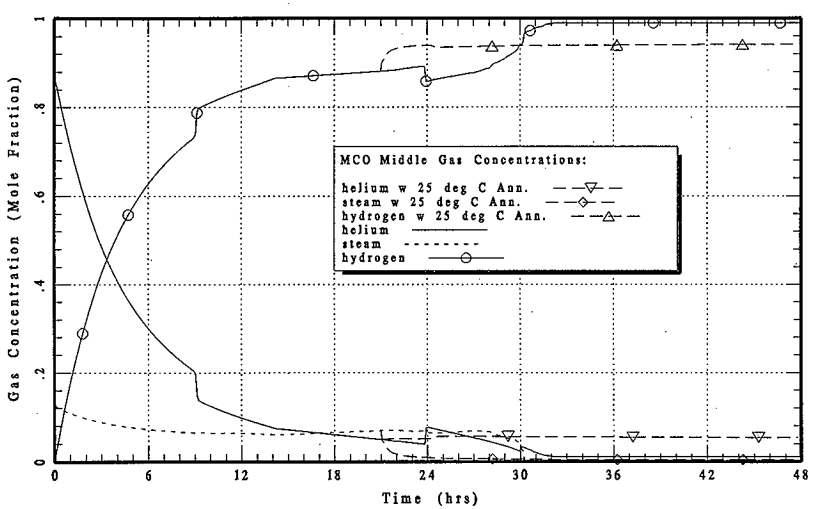
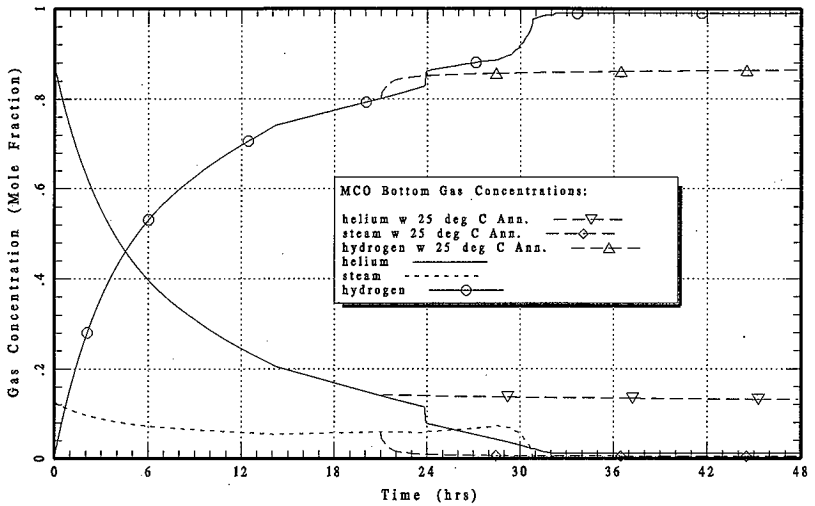
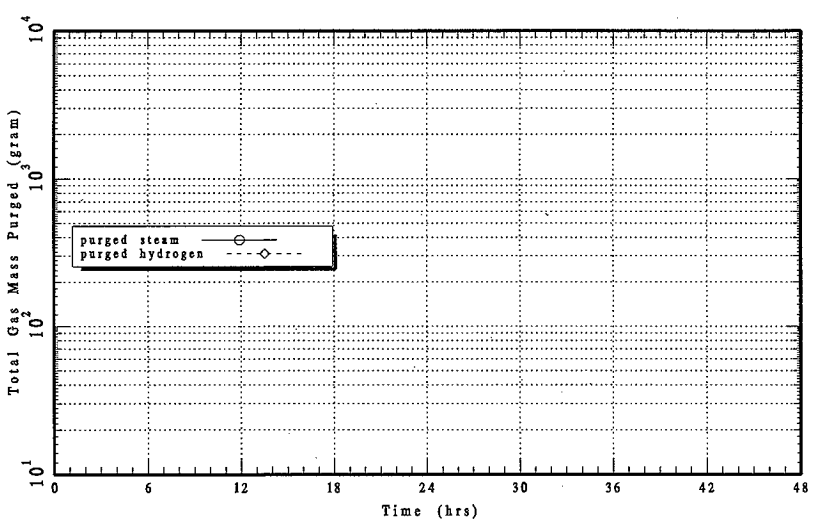
DSLOCREC: HI-PRES THERM RUNAWAY w LOC & Flowing Ann. Recovery @ 21 hrs



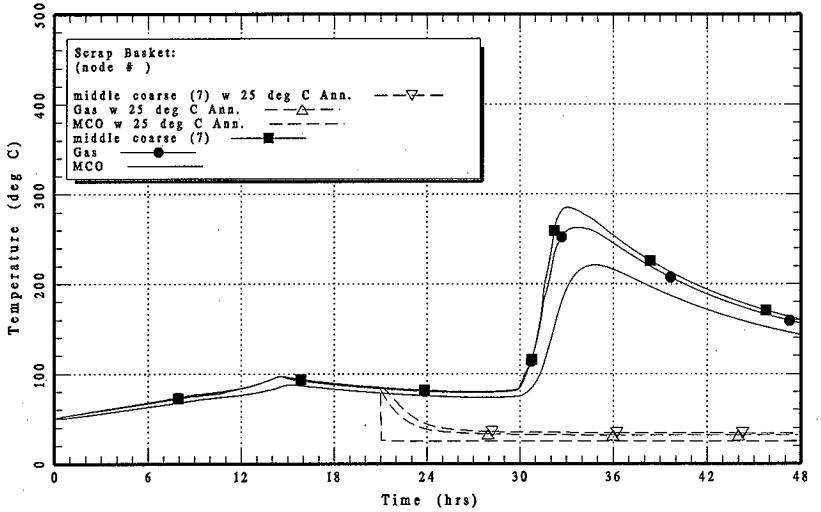


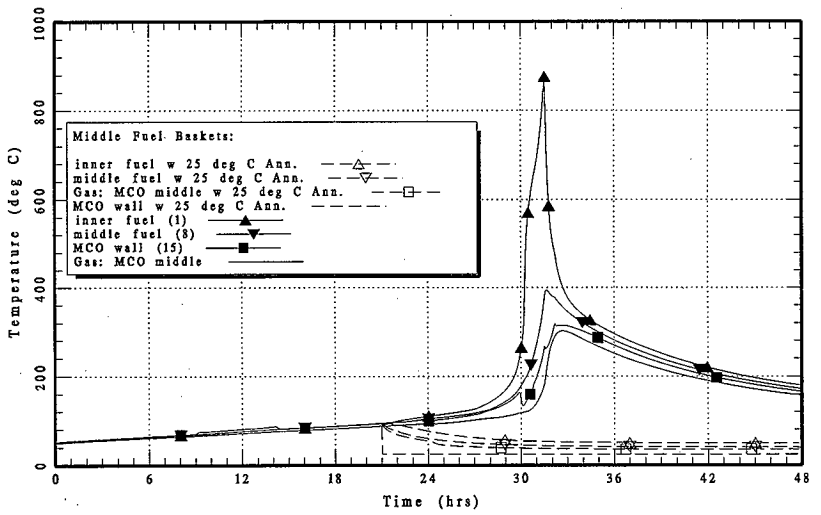
DSLOCREC: HI-PRES THERM RUNAWAY w LOC & Flowing Ann. Recovery @ 21 hrs



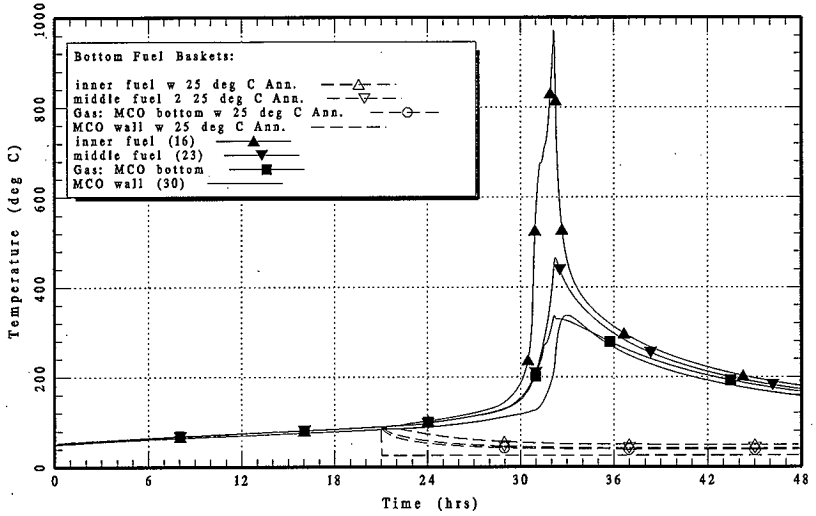


DSLOCREC: HI-PRES THERM RUNAWAY w LOC & Flowing Ann. Recovery @ 21 hrs





DSLOCREC: HI-PRES THERM RUNAWAY w LOC & Flowing Ann. Recovery @ 21 hrs



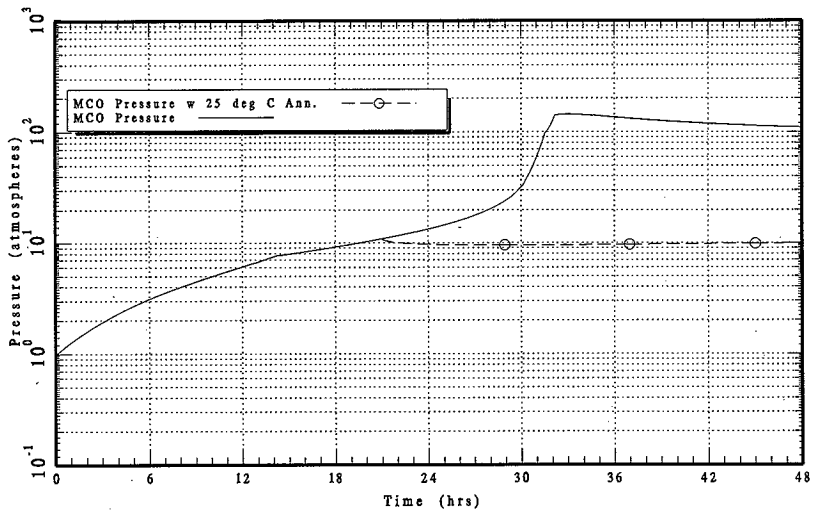


Figure A-24 DSLOCRE2: High-Pressure Thermal Runaway with Loss of Coolant (LOC) and Stationary Annulus Recovery at 21 Hours

The long-dashed curves are from case 24, DSLOCRE2, which includes a recovery from the loss of coolant condition by restoring 25 °C stationary annulus water at 21 hours. This case is the same is case 23, DSLOCREC, except that the restored annulus water is stationary instead of flowing. The solid and short-dashed curves are from case 20, DSLOC, which includes a bounding MCO with a loss of coolant condition and provides the initial conditions for case 24 at 21 hours.

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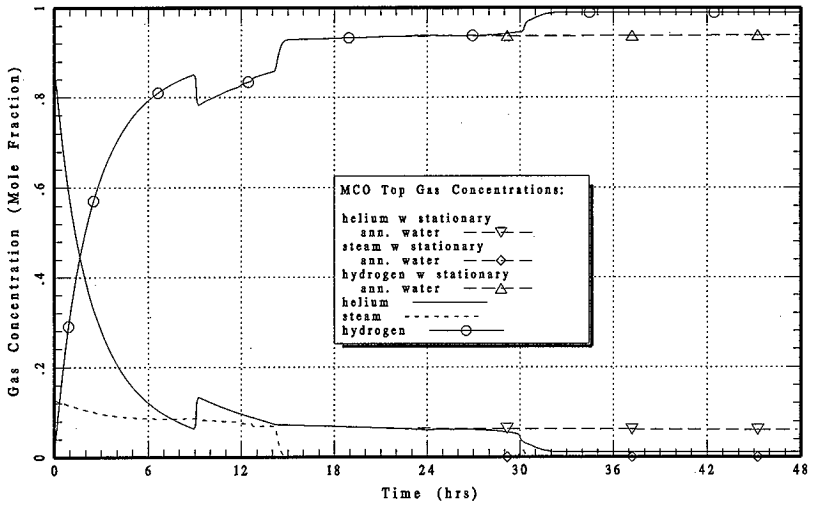
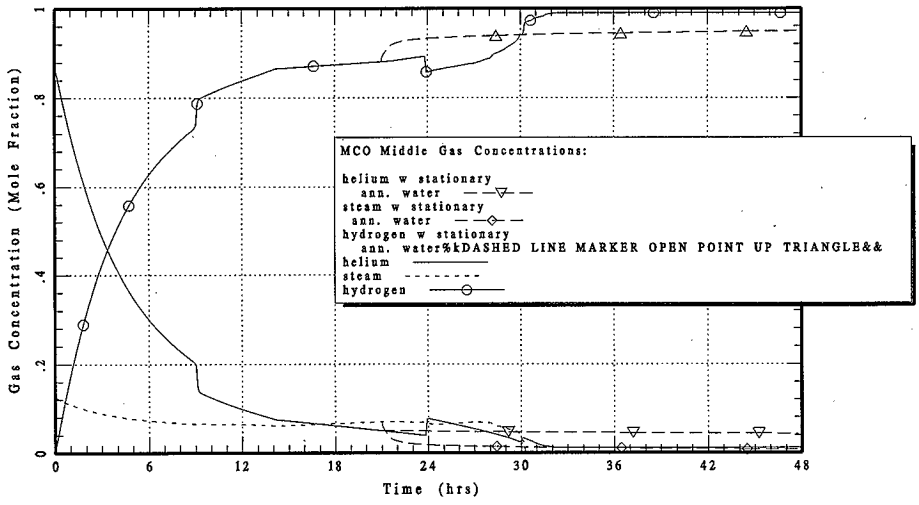
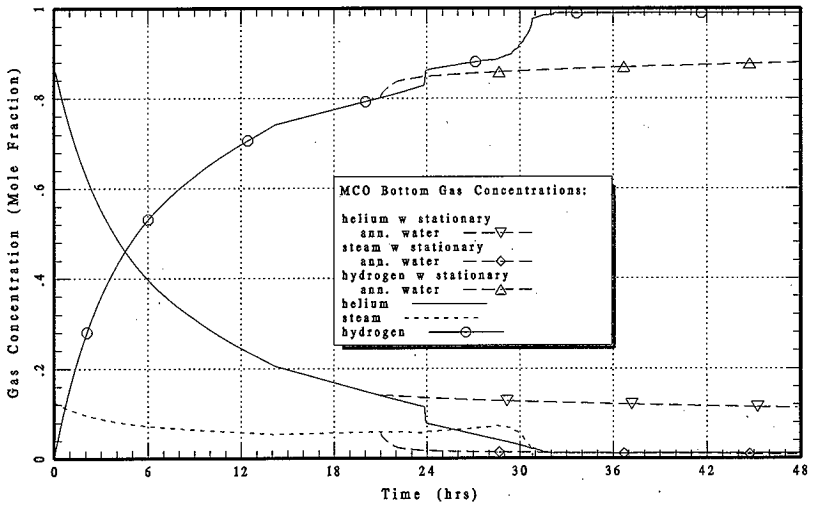
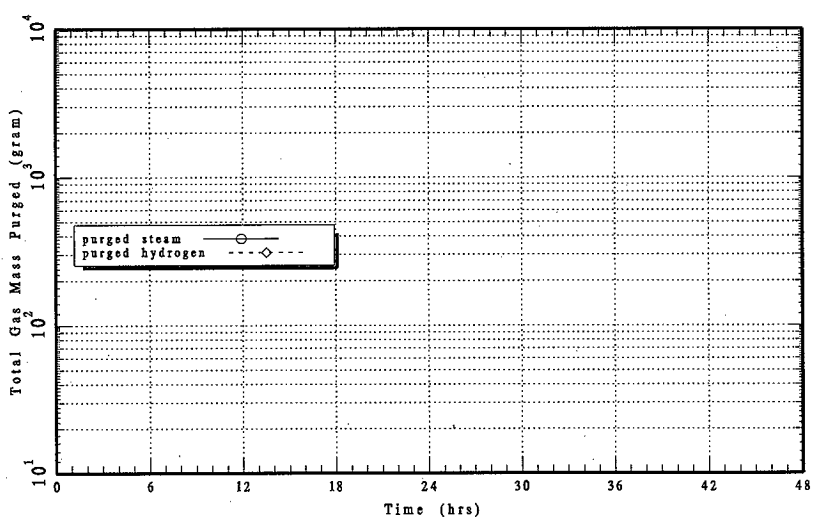
DSLOCRE2: HI-PRES THERM RUNAWAY w LOC & Stationary Ann. Recover. @ 21 hrs



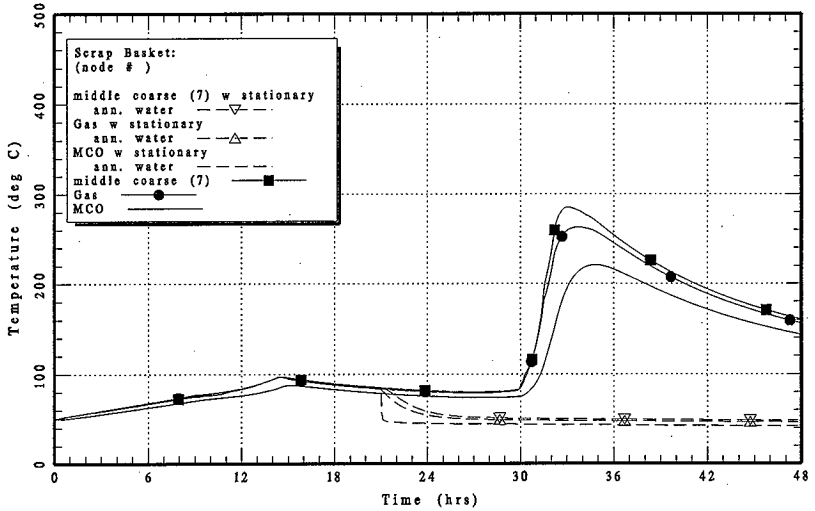


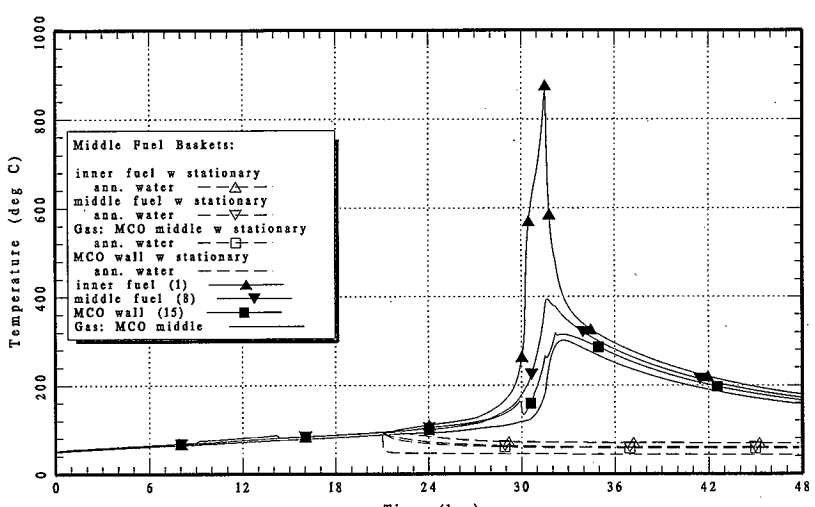
DSLOCRE2: HI-PRES THERM RUNAWAY w LOC & Stationary Ann. Recover. @ 21 hrs



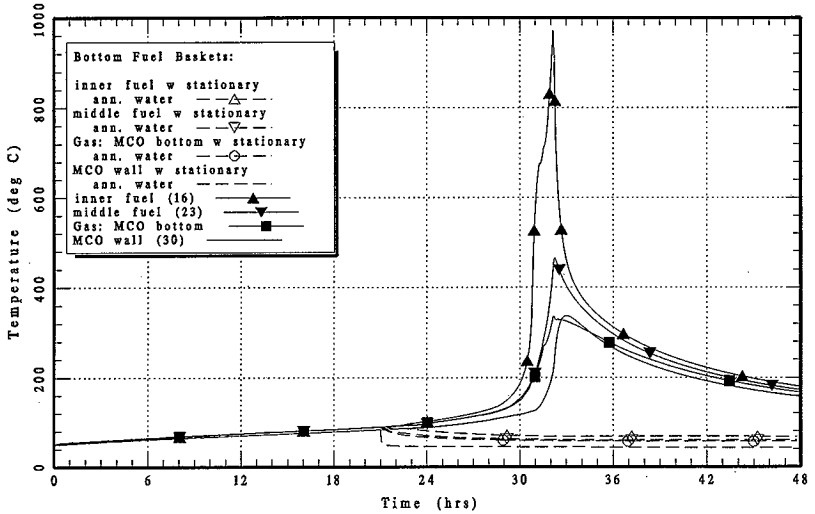


DSLOCRE2: HI-PRES THERM RUNAWAY w LOC & Stationary Ann. Recover. @ 21 hrs





DSLOCRE2: HI-PRES THERM RUNAWAY w LOC & Stationary Ann. Recover. @ 21 hrs



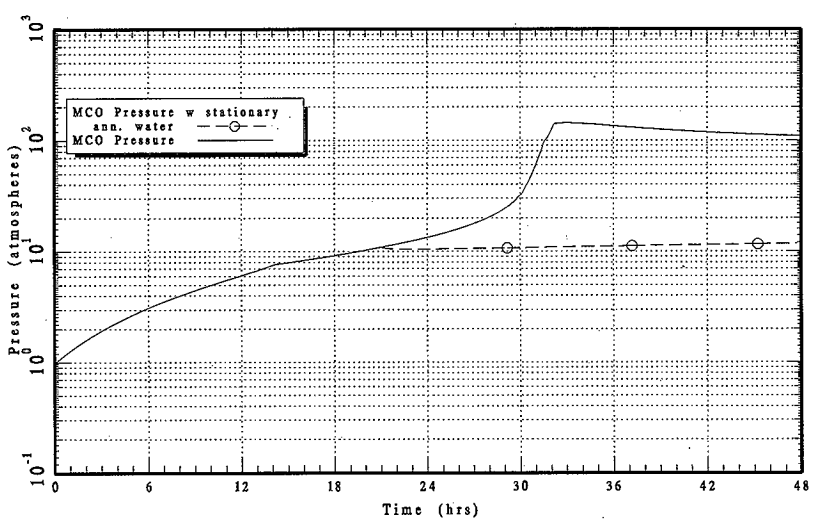


Figure A-25 DSLOCOV: Low-Pressure Thermal Runaway with Loss of Coolant (LOC) - Annulus

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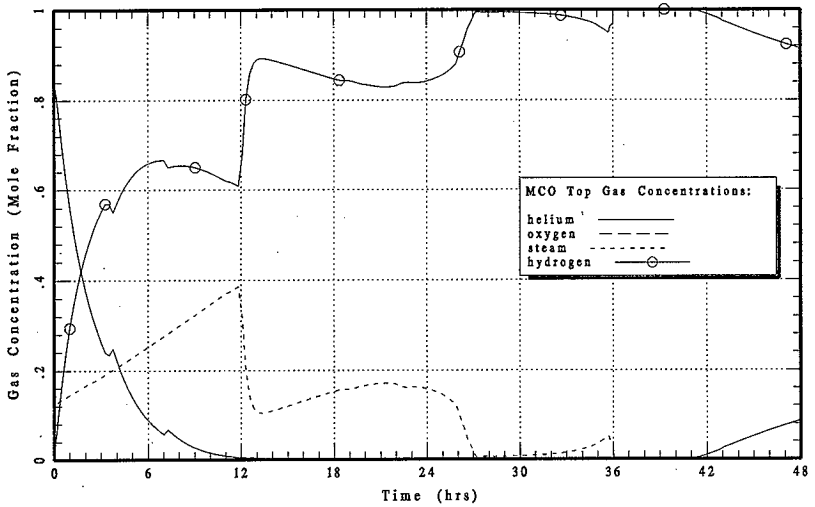
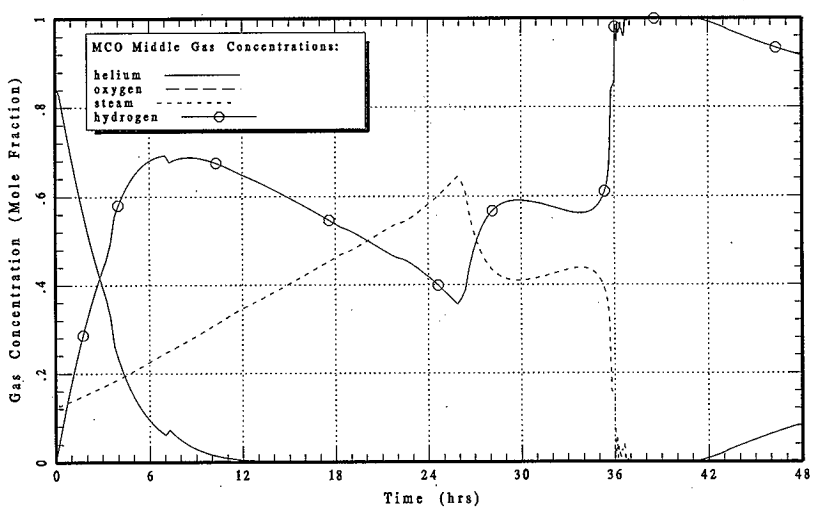
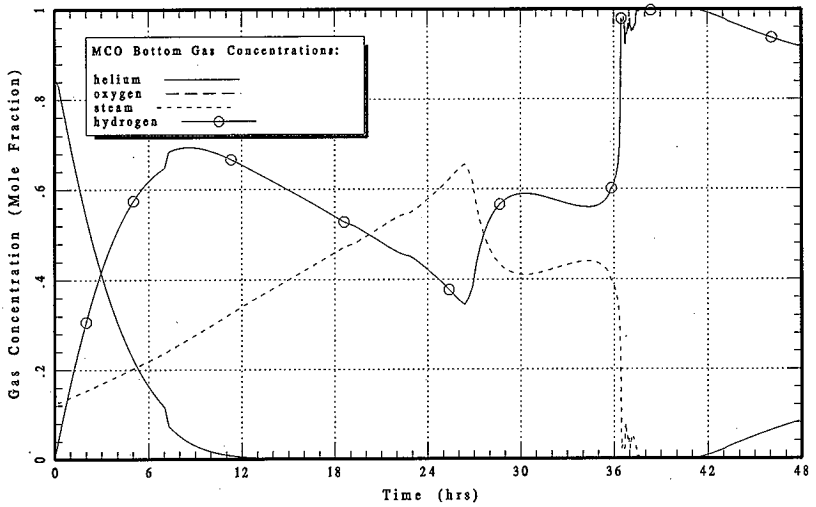
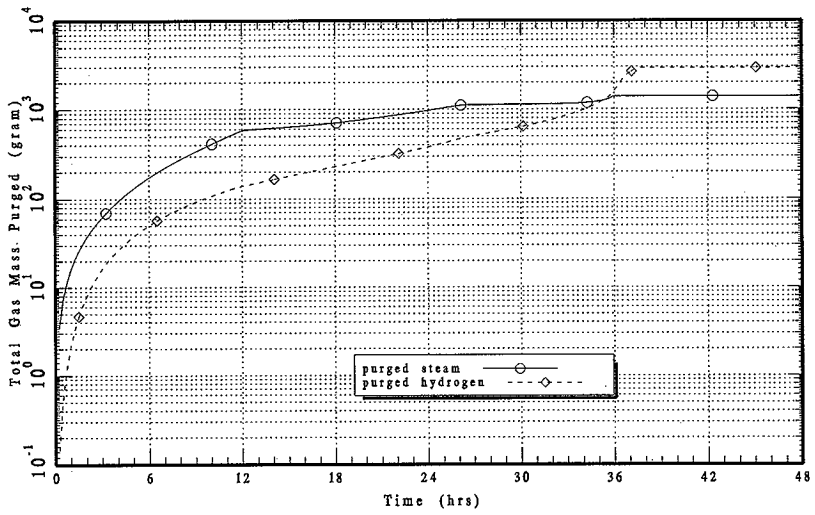
DSLOCOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Coolant - Annulus



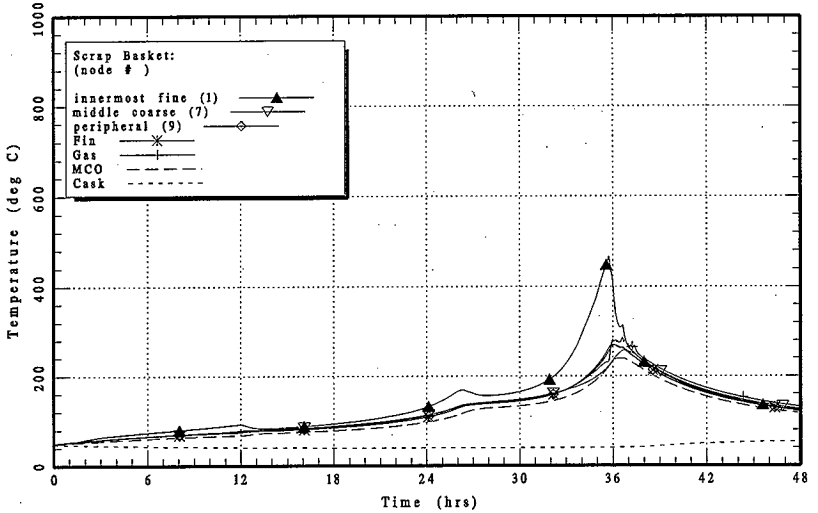


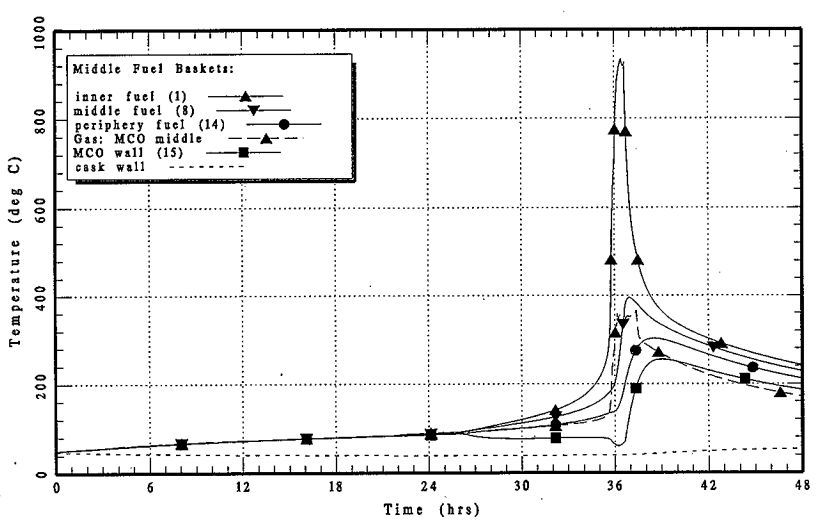
DSLOCOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Coolant - Annulus



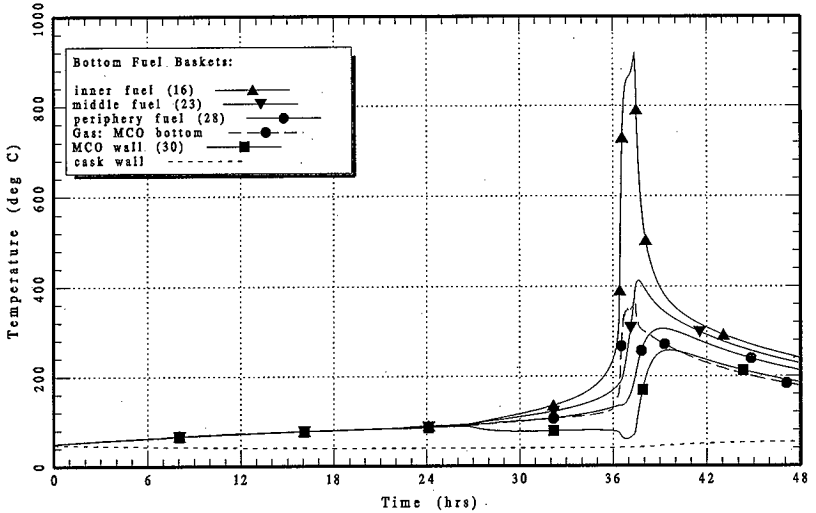


DSLOCOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Coolant - Annulus





DSLOCOV: LOW-PRESSURE THERMAL RUNAWAY w Loss of Coolant - Annulus



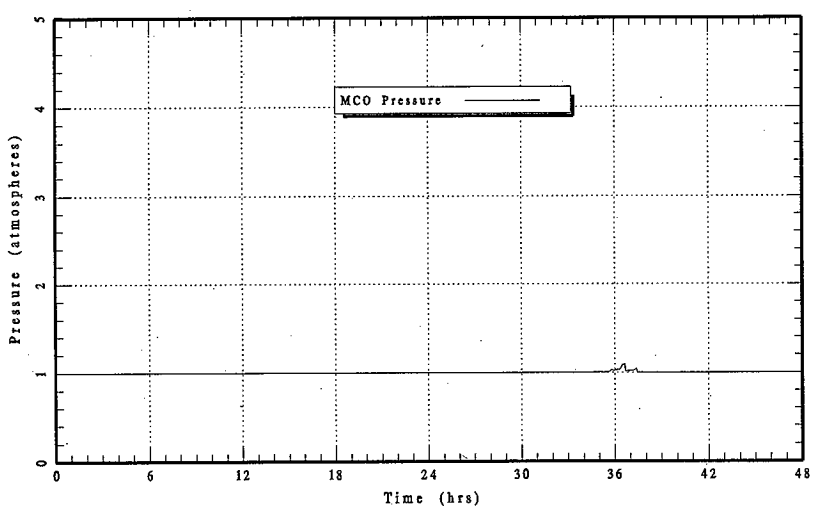


Figure A-26 DS46DEG: High-Pressure Thermal Runaway with 46 °C Annulus

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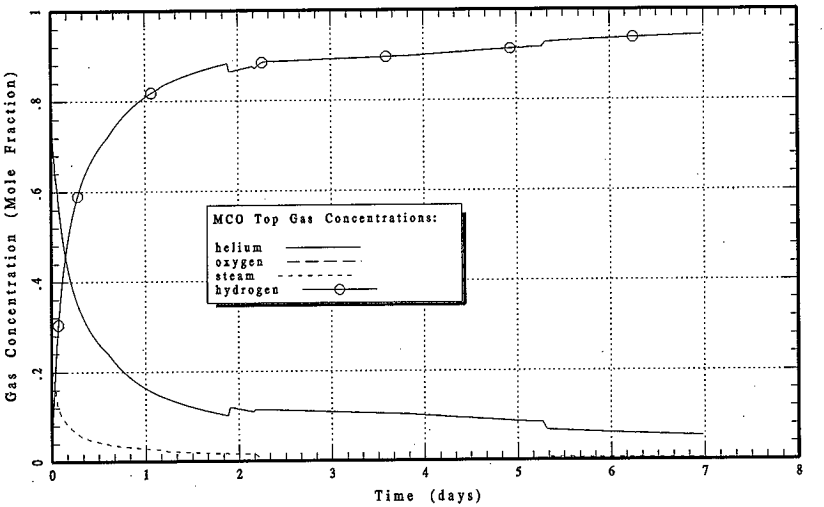
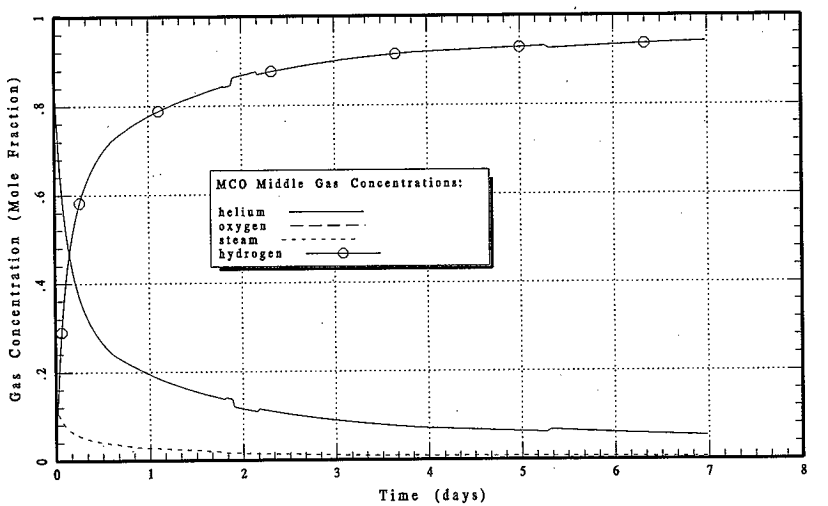
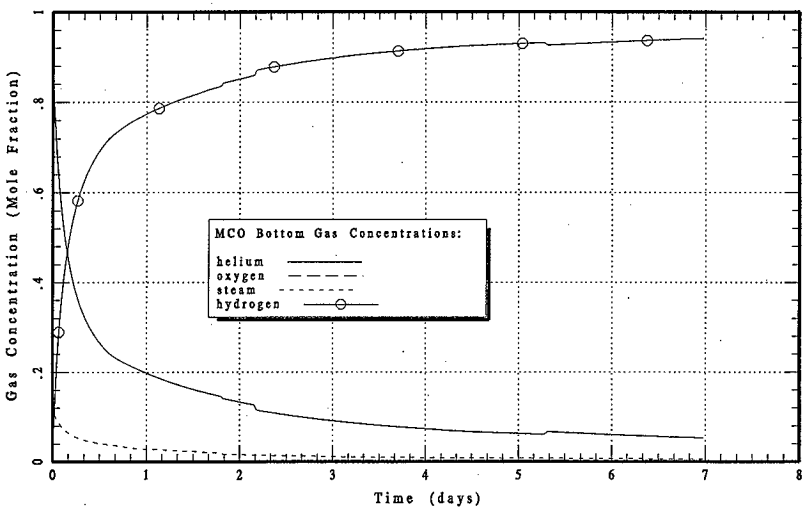
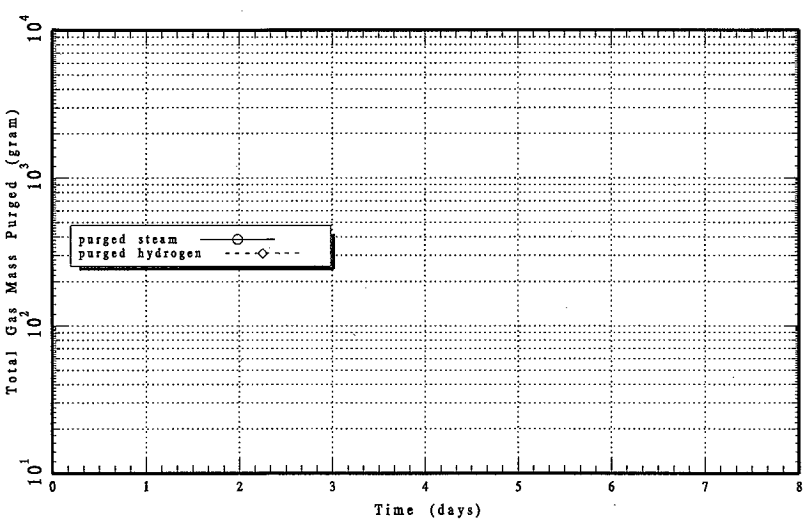
DS46DEG: HIGH-PRESSURE THERMAL RUNAWAY w 46 Deg C Annulus



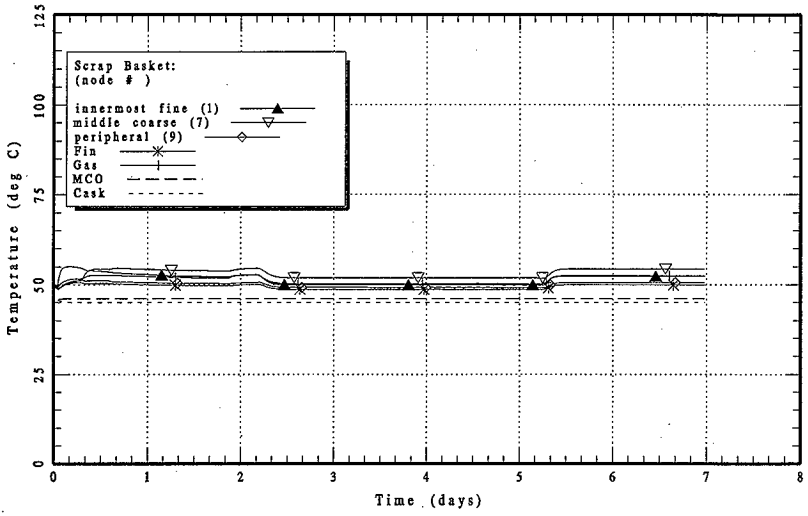


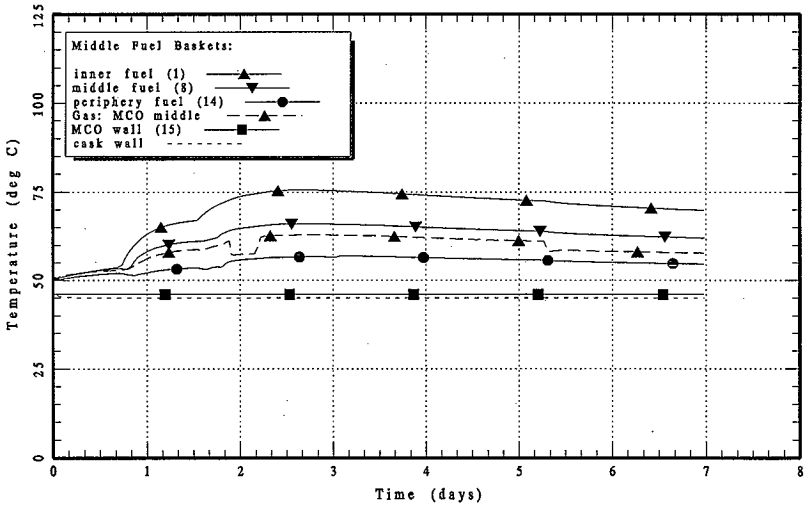
DS46DEG: HIGH-PRESSURE THERMAL RUNAWAY w 46 Deg C Annulus



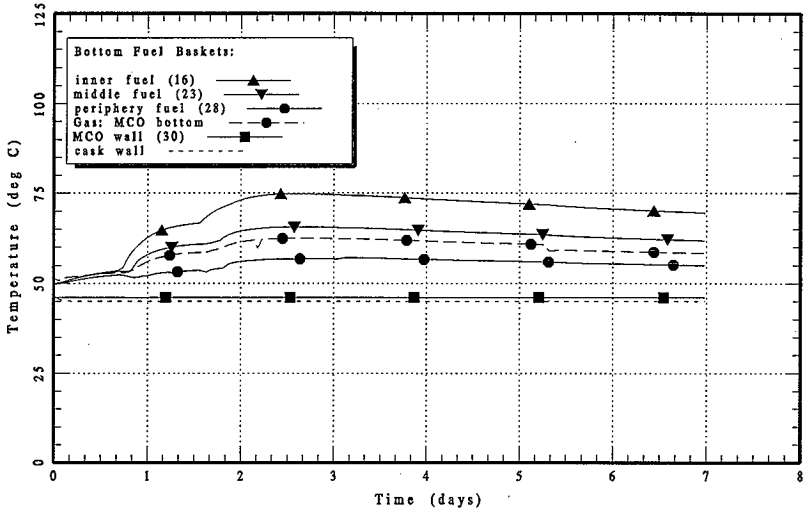


DS46DEG: HIGH-PRESSURE THERMAL RUNAWAY w 46 Deg C Annulus





DS46DEG: HIGH-PRESSURE THERMAL RUNAWAY w 46 Deg C Annulus



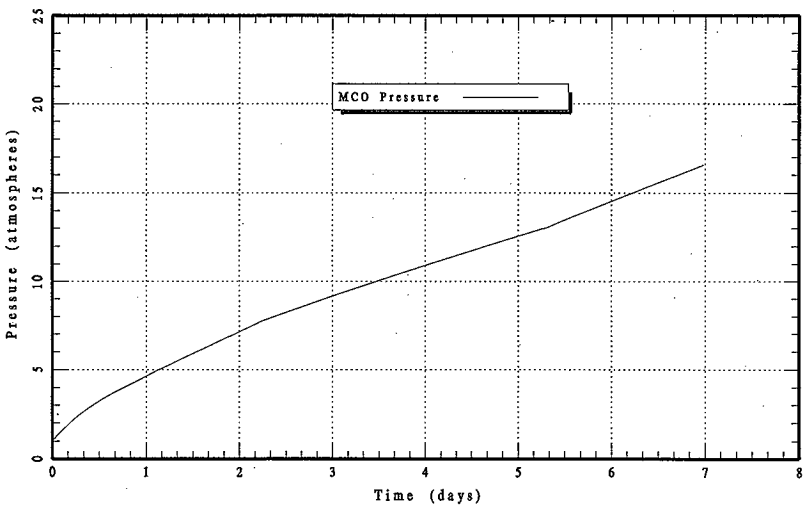


Figure A-27 DS55DEG: High-Pressure Thermal Runaway with 55 °C Annulus

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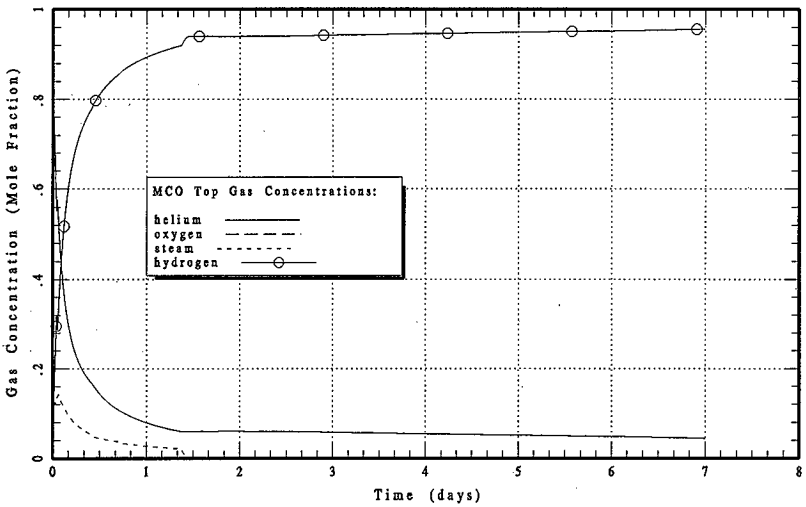
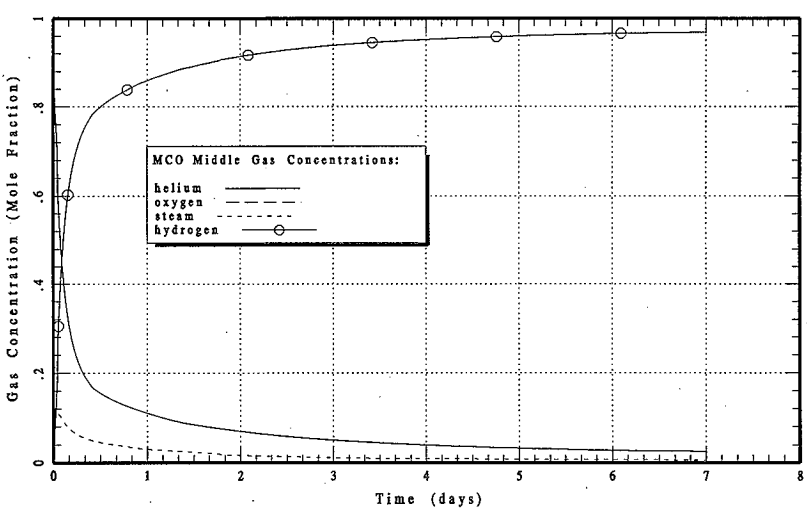
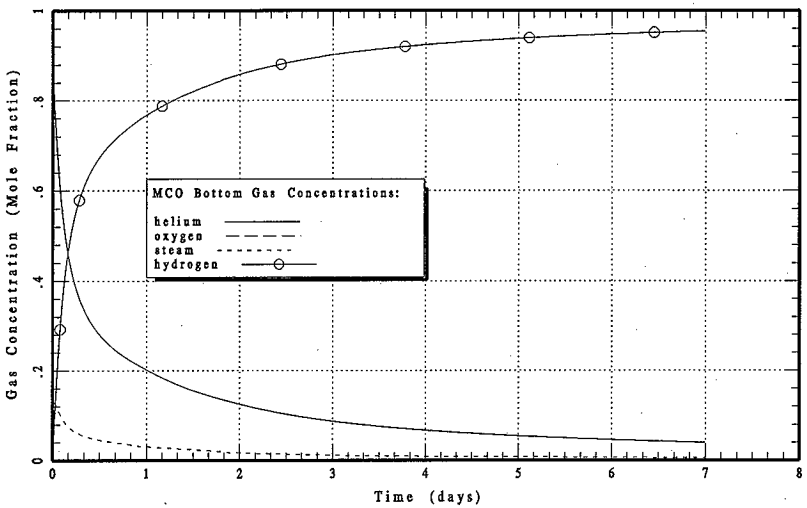
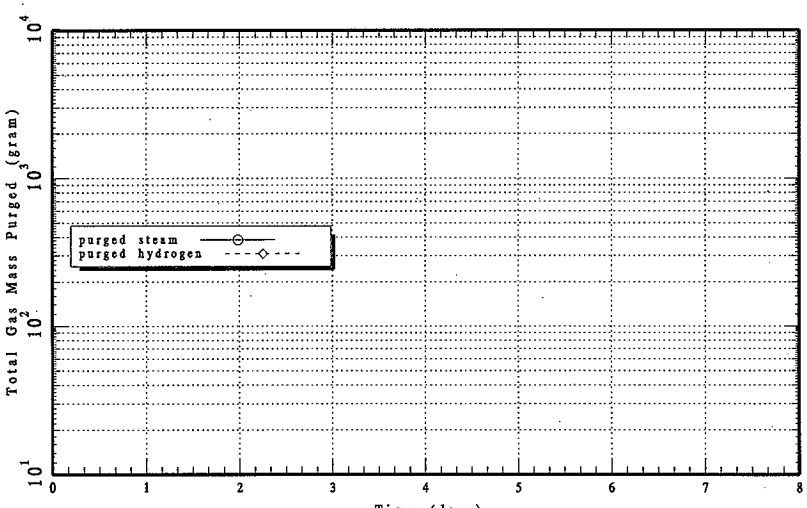
DS55DEG: HIGH-PRESSURE THERMAL RUNAWAY w 55 Deg C Annulus



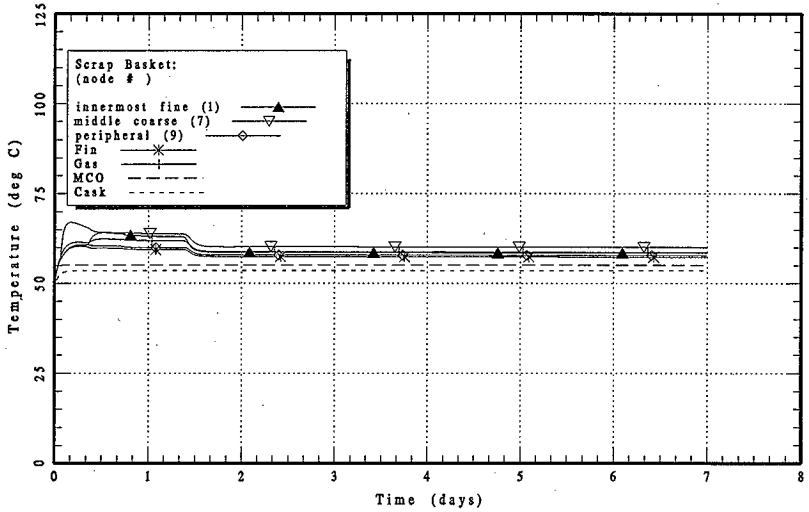


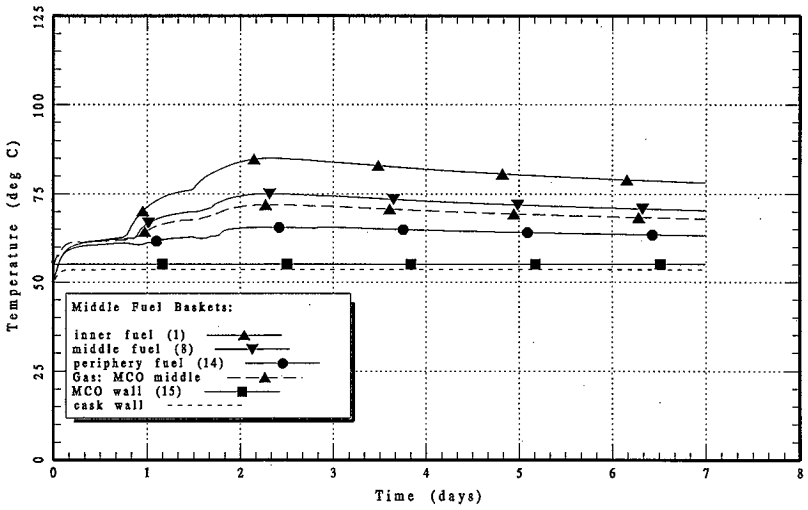
DS55DEG: HIGH-PRESSURE THERMAL RUNAWAY w 55 Deg C Annulus



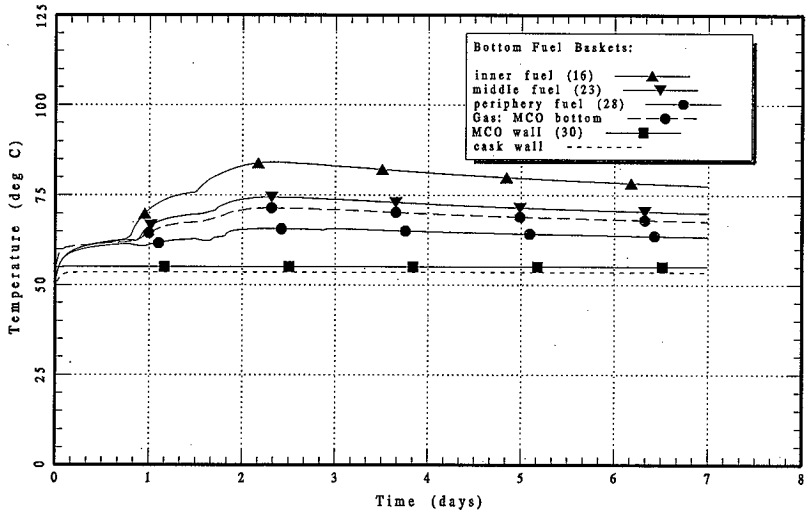


DS55DEG: HIGH-PRESSURE THERMAL RUNAWAY w 55 Deg C Annulus





DS55DEG: HIGH-PRESSURE THERMAL RUNAWAY w 55 Deg C Annulus



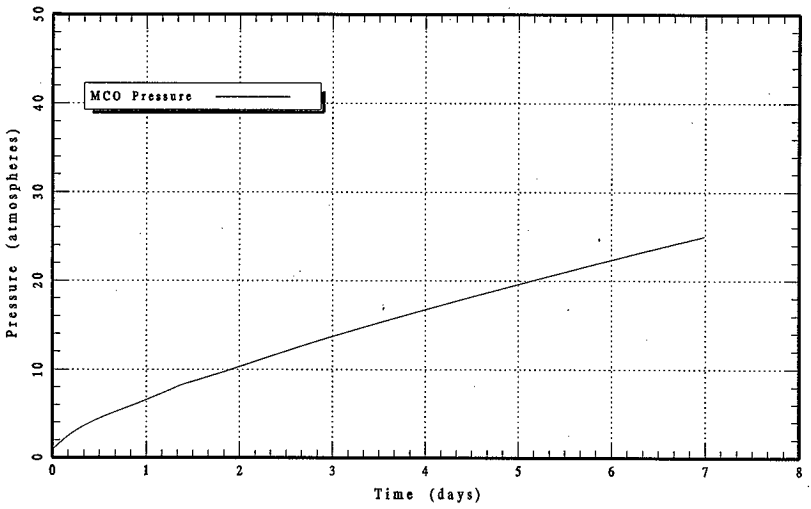


Figure A-28 DS75DEG: High-Pressure Thermal Runaway w 75 °C Annulus

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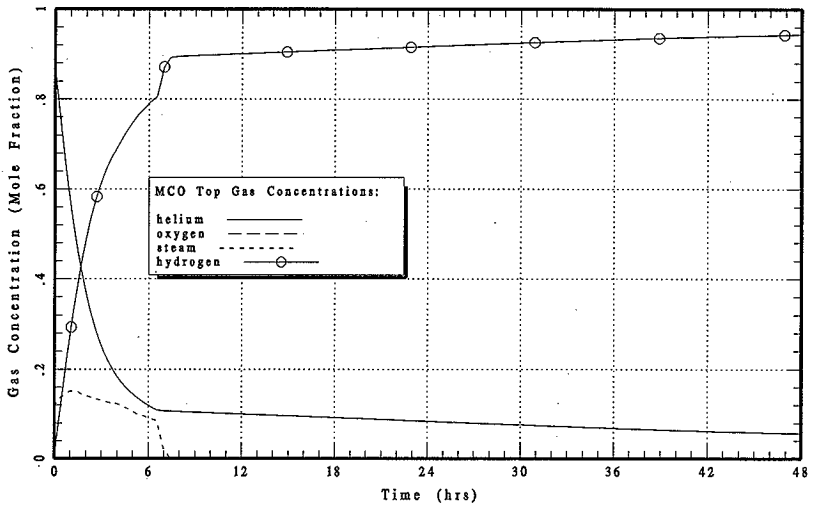
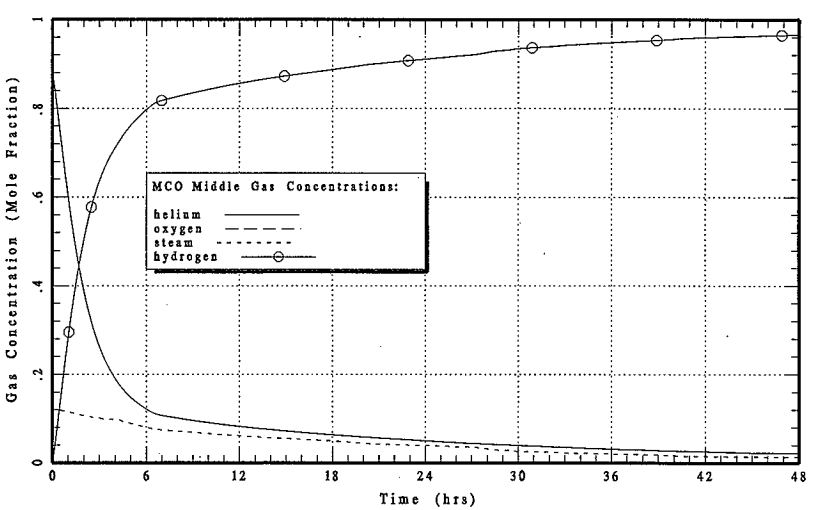
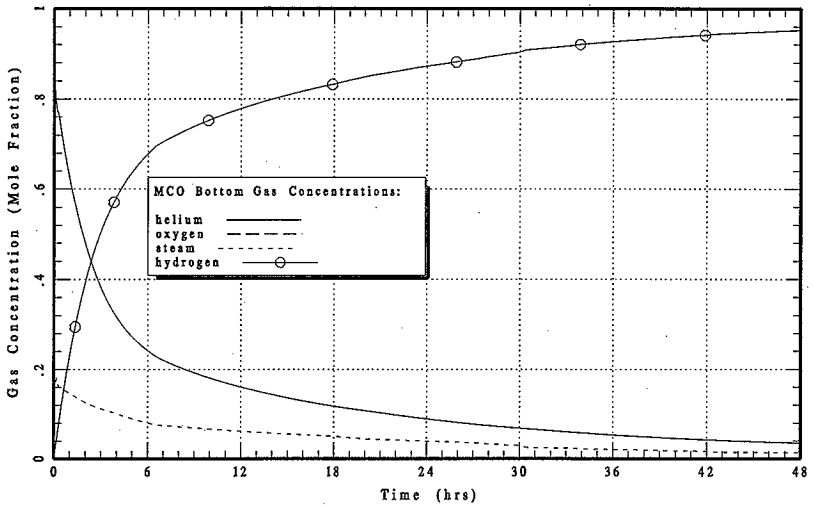
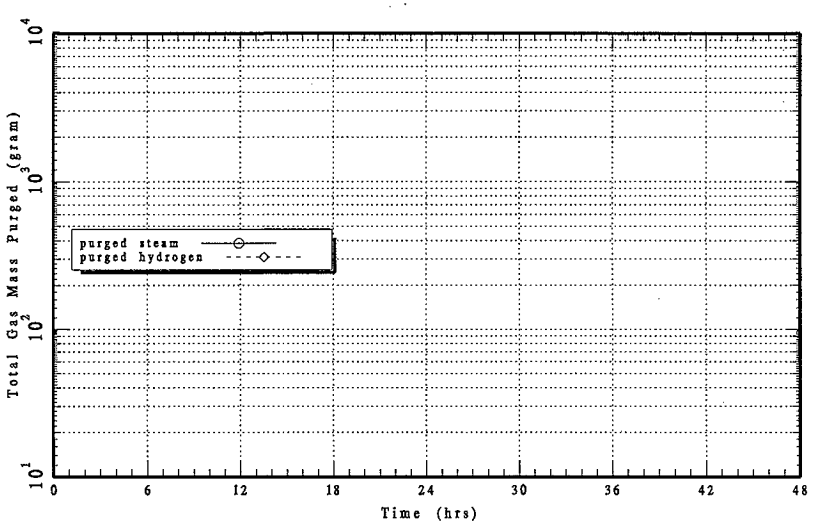
DS75DEG: HIGH-PRESSURE THERMAL RUNAWAY w 75 Deg C Annulus



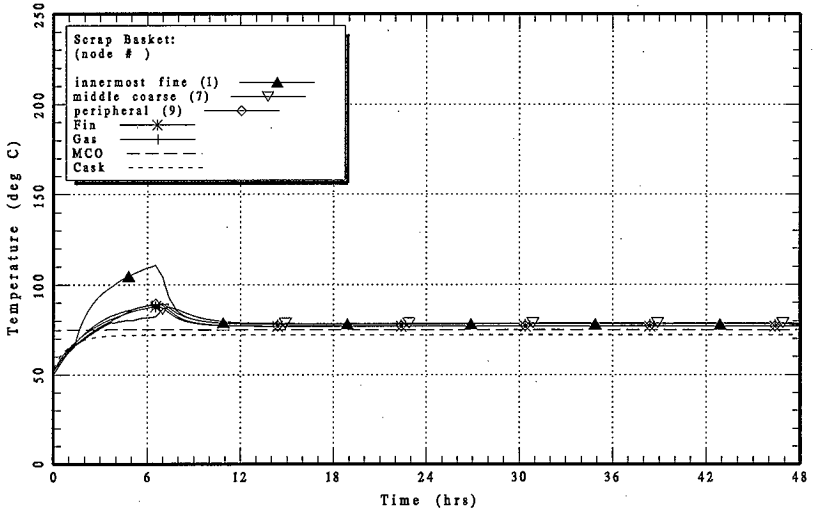


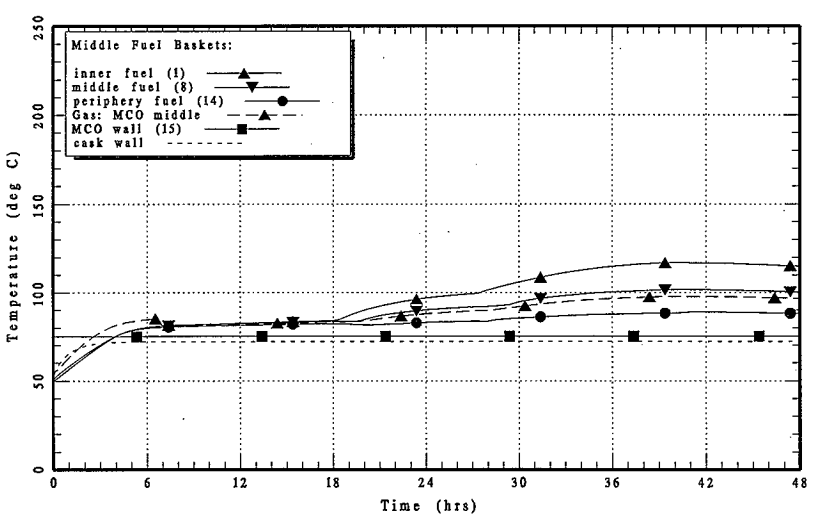
DS75DEG: HIGH-PRESSURE THERMAL RUNAWAY w 75 Deg C Annulus



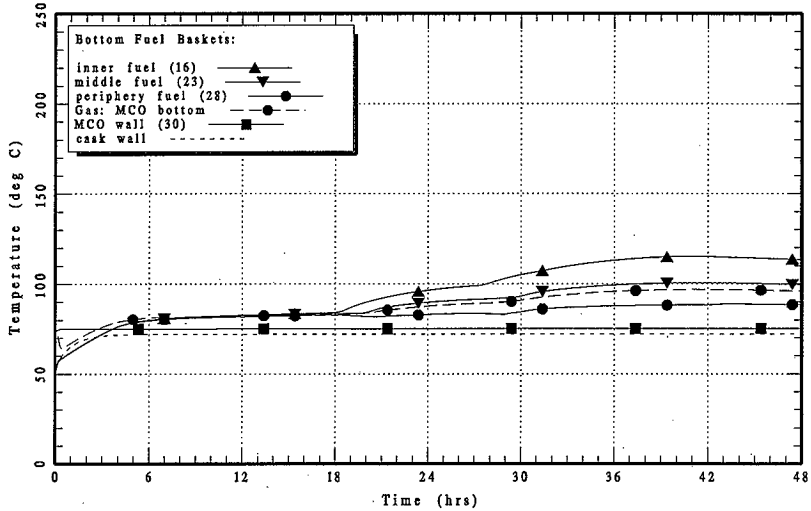


DS75DEG: HIGH-PRESSURE THERMAL RUNAWAY w 75 Deg C Annulus





DS75DEG: HIGH-PRESSURE THERMAL RUNAWAY w 75 Deg C Annulus



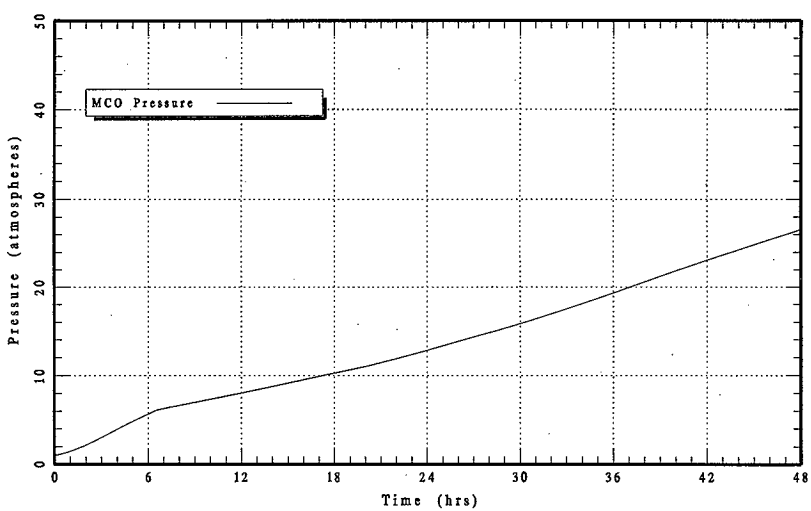


Figure A-29 DSHOT: High-Pressure Thermal Runaway with 85 °C Annulus

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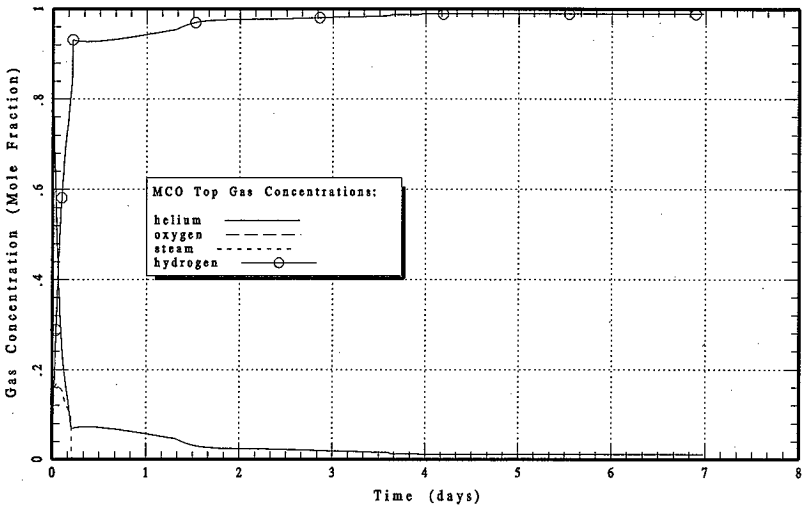
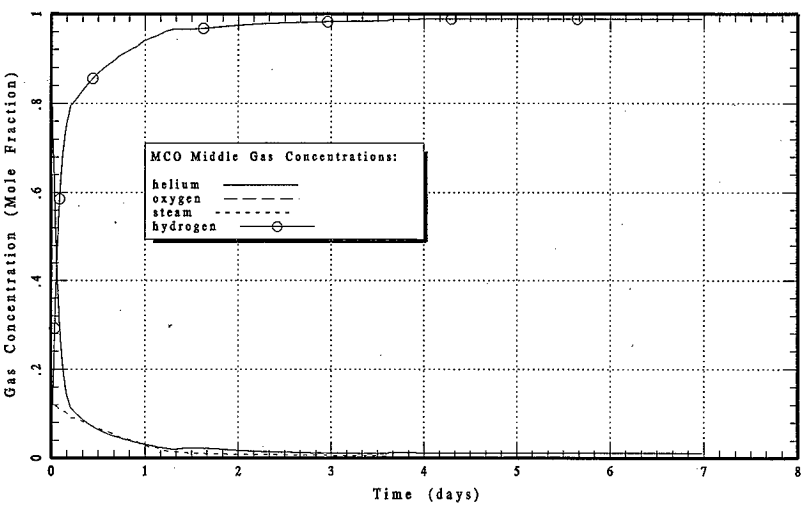
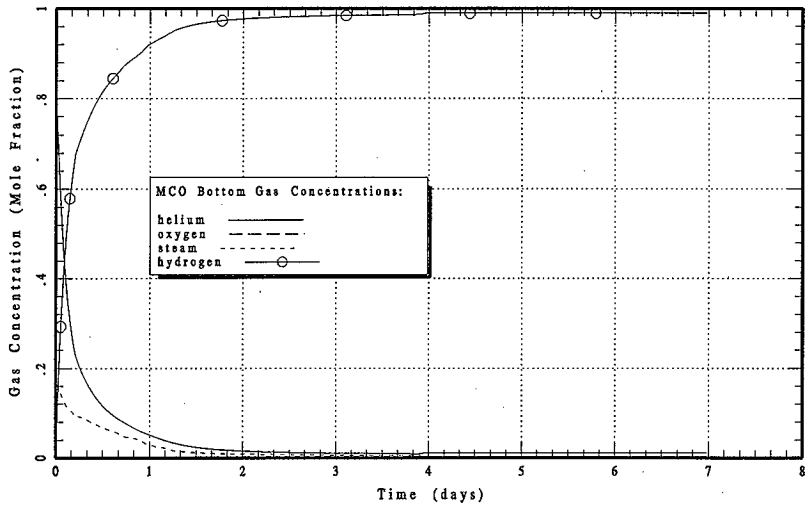
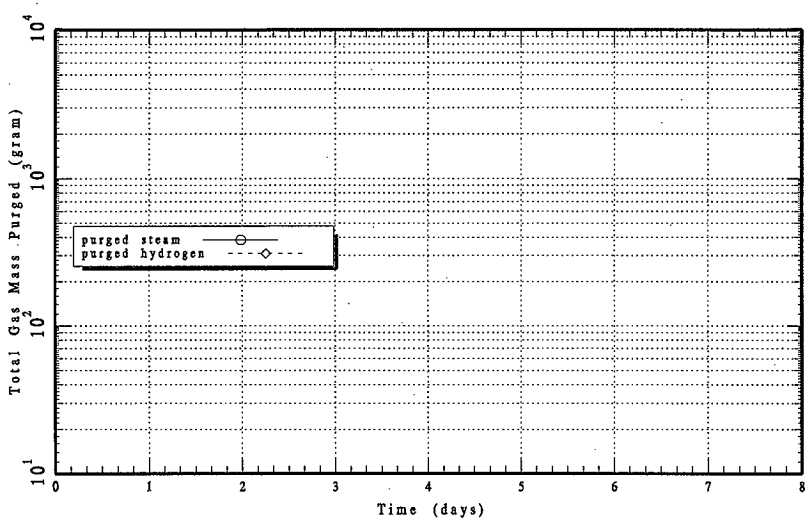
DSHOT: HIGH-PRESSURE THERMAL RUNAWAY w 85 Deg C Annulus



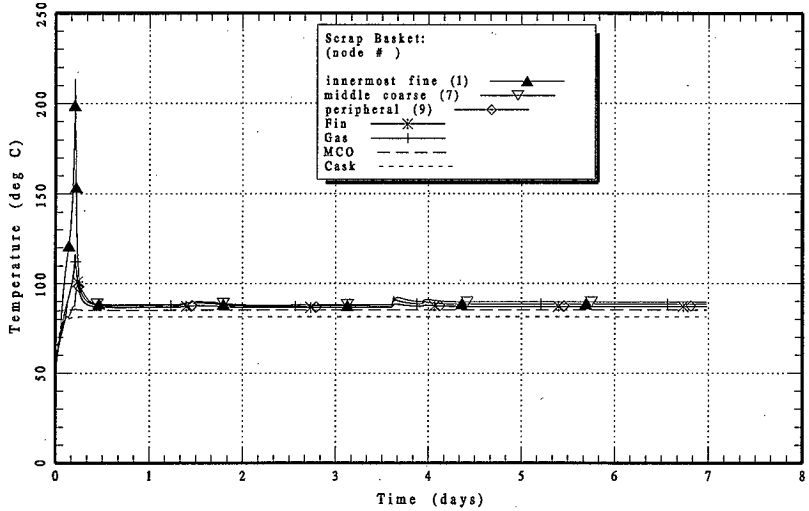


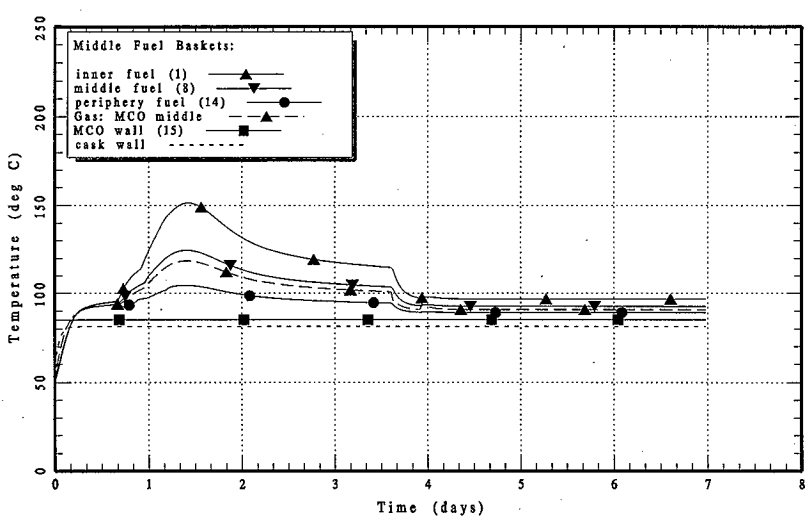
DSHOT: HIGH-PRESSURE THERMAL RUNAWAY w 85 Deg C Annulus



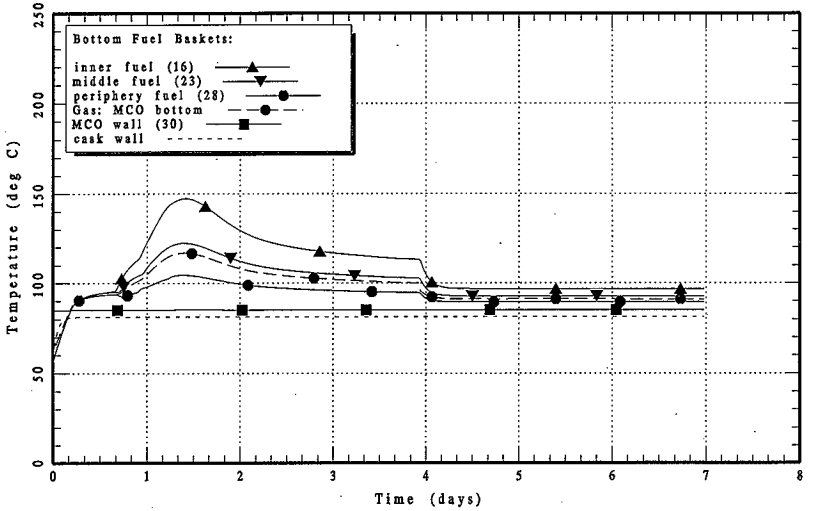


DSHOT: HIGH-PRESSURE THERMAL RUNAWAY w 85 Deg C Annulus





DSHOT: HIGH-PRESSURE THERMAL RUNAWAY w 85 Deg C Annulus



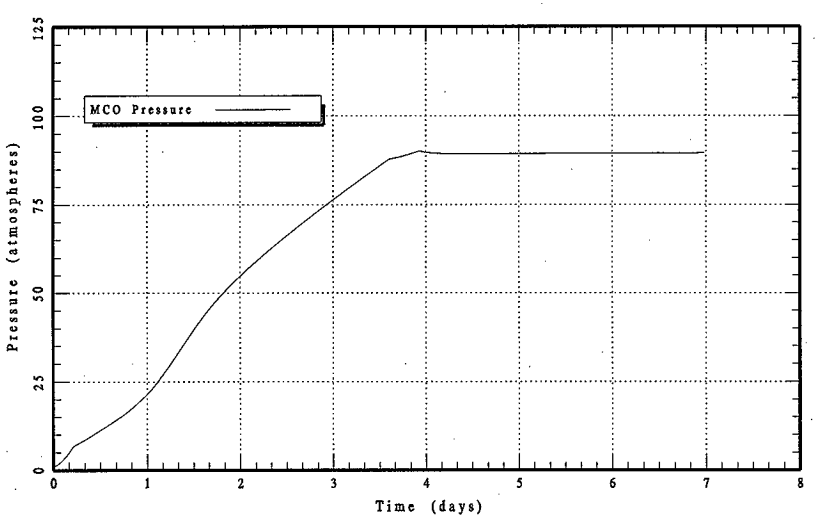


Figure A-30 DHOT75KG: High-Pressure Thermal Runaway with 75 Kg Water and 85 °C Annulus

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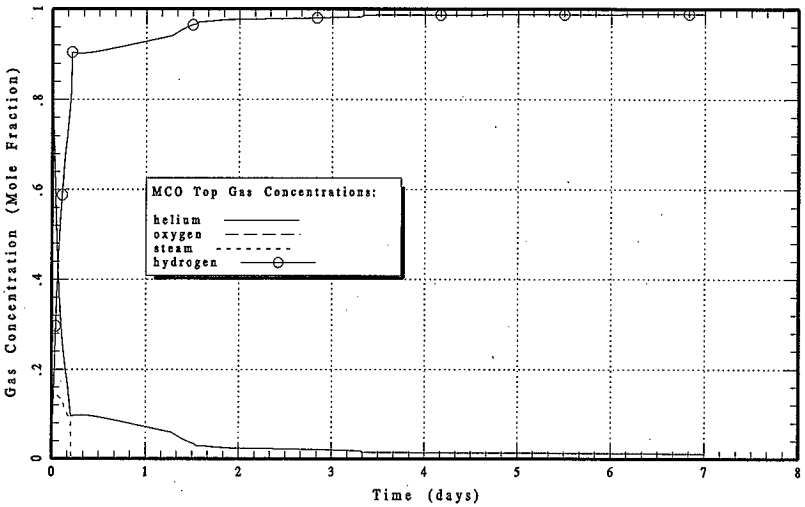
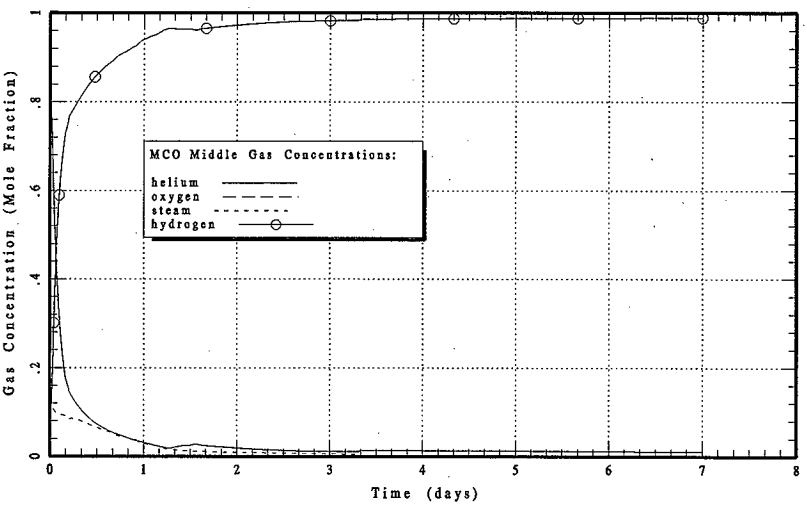
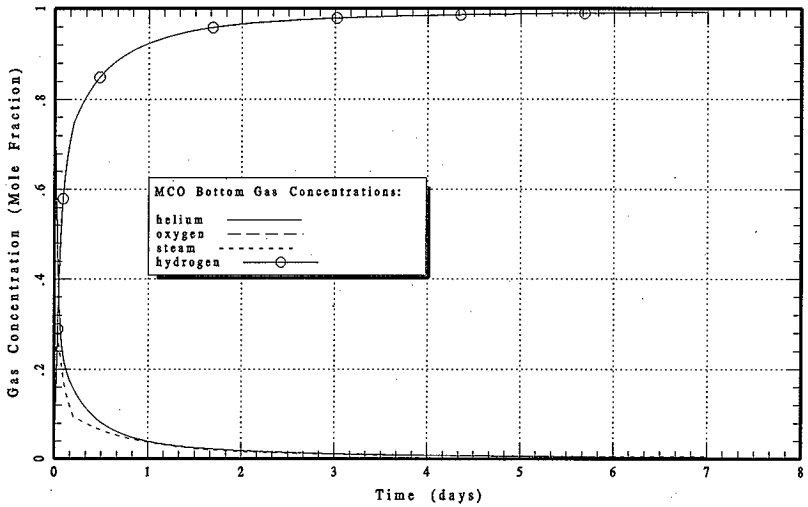
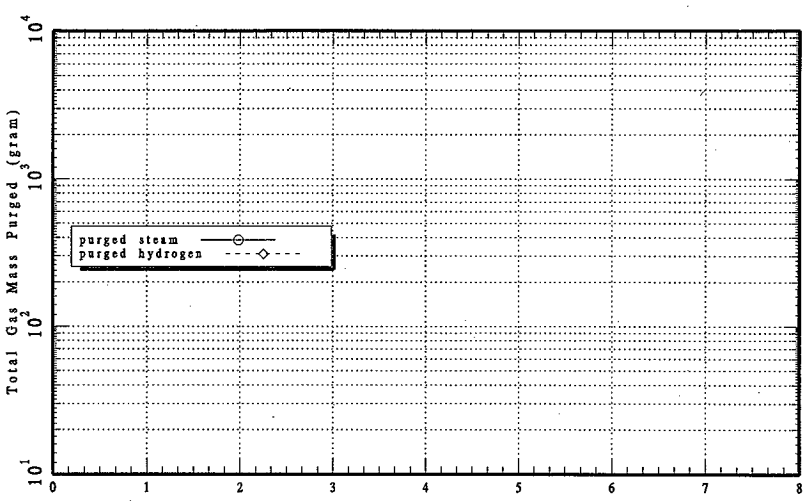
DHOT75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 85 Deg C Annulus



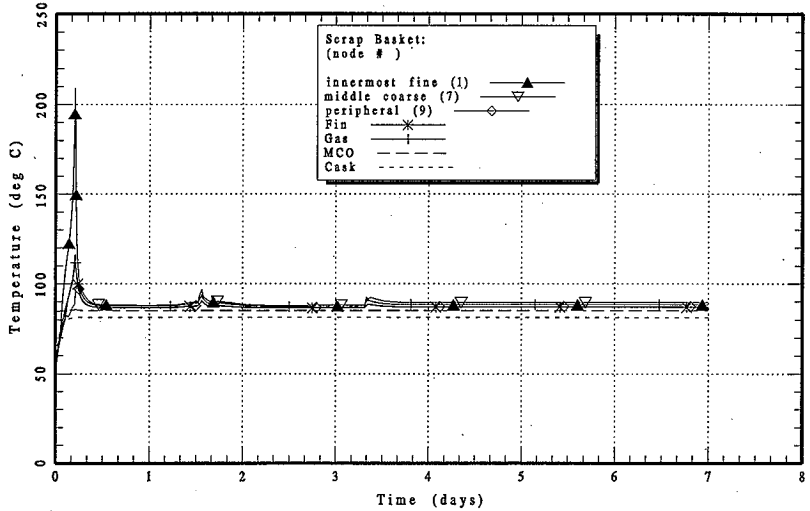


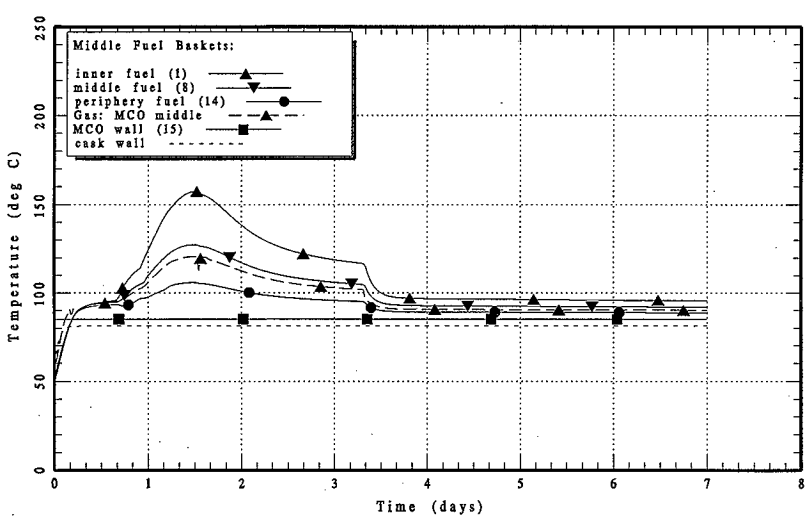
DHOT75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 85 Deg C Annulus



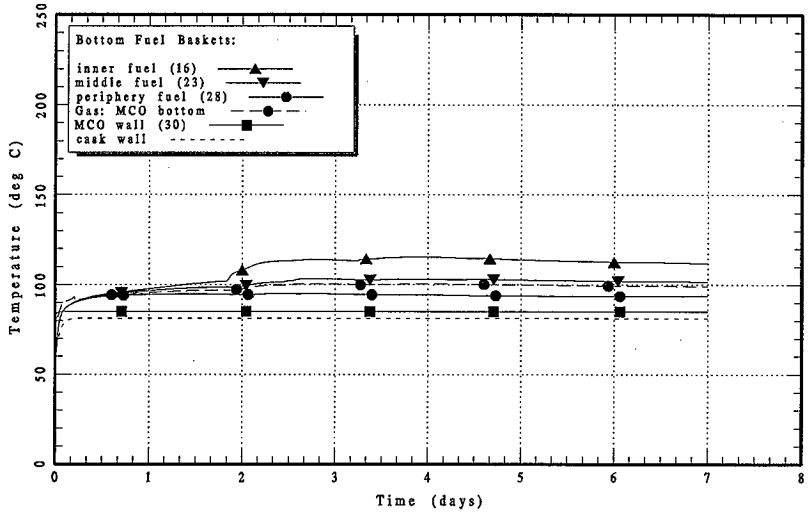


DHOT75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 85 Deg C Annulus





DHOT75KG: HI-PRES THERM RUNAWAY w 75 Kg Water & 85 Deg C Annulus



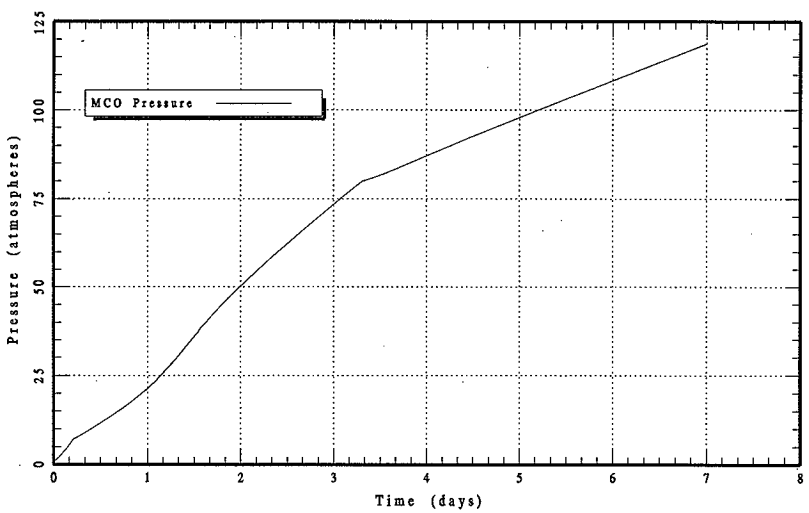


Figure A-31 DSHOTOV: Low-Pressure Thermal Runaway with 85 °C Annulus

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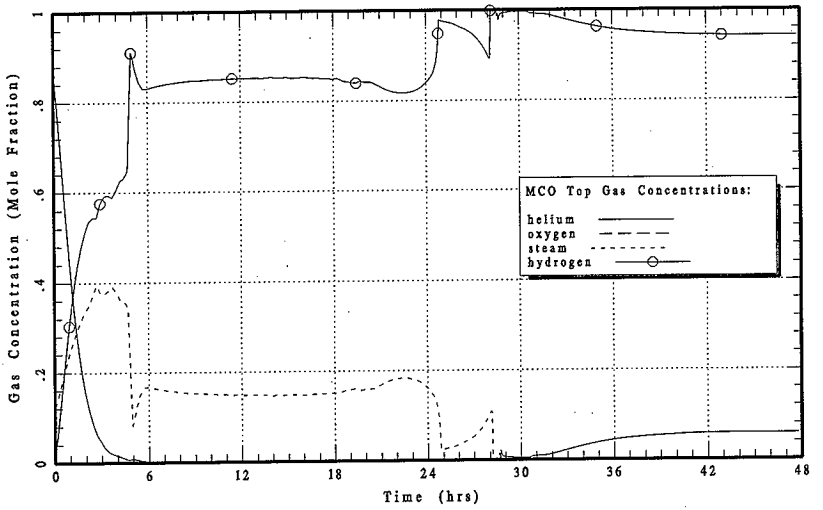
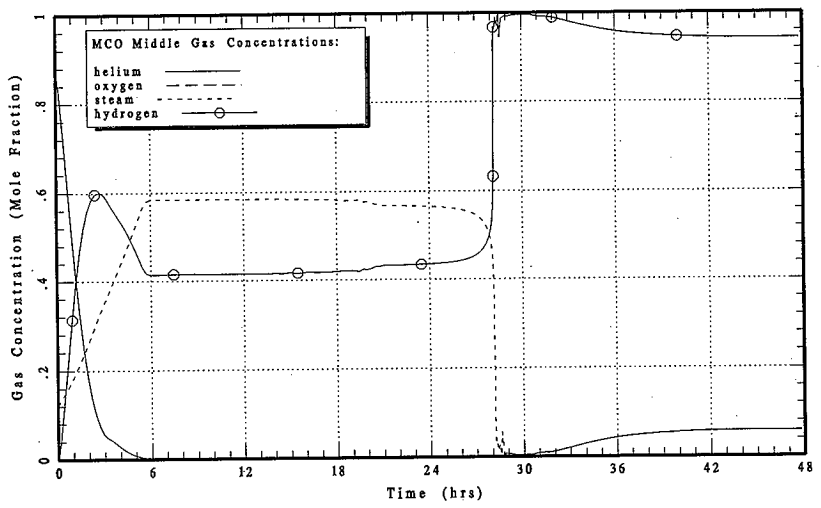
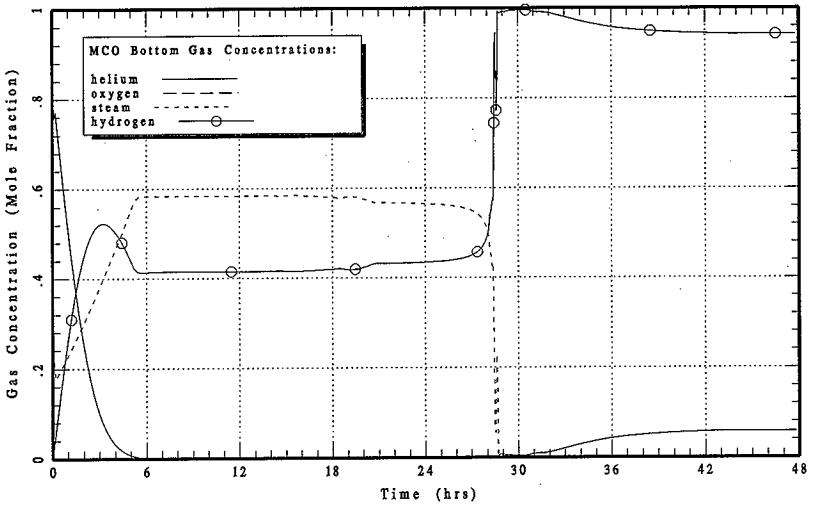
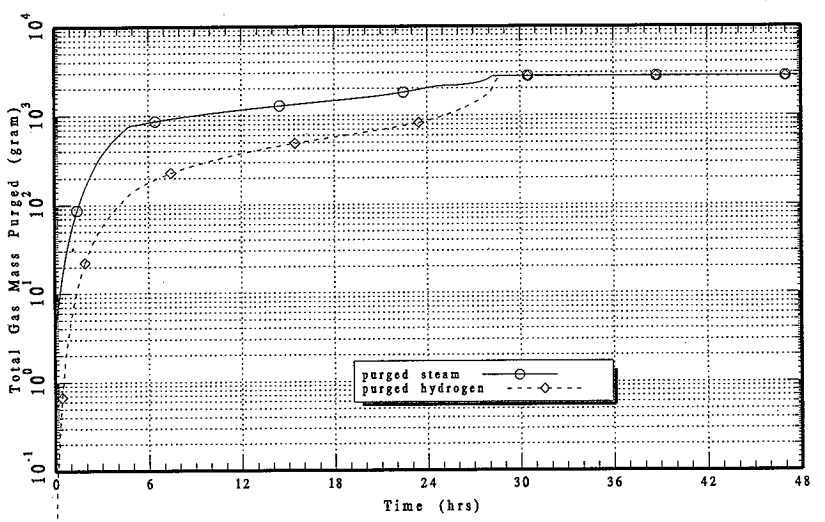
DSHOTOV: LOW-PRESSURE THERMAL RUNAWAY w 85 Deg Annulus

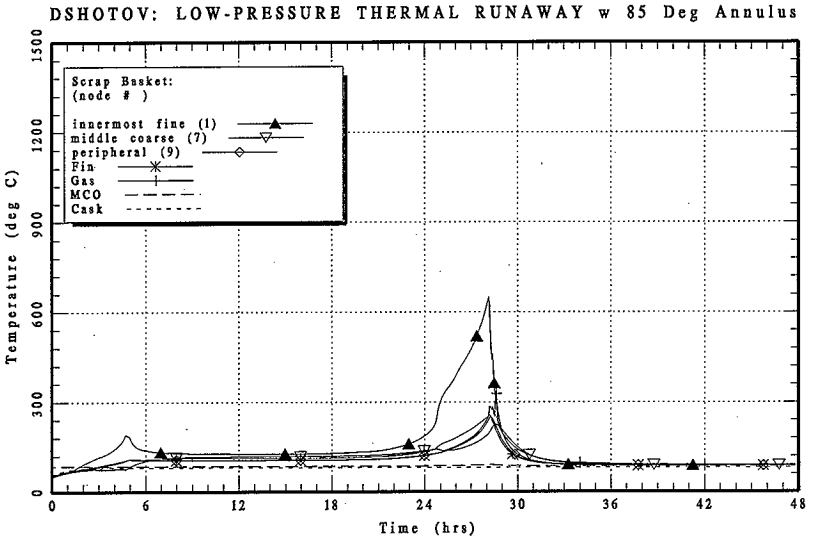


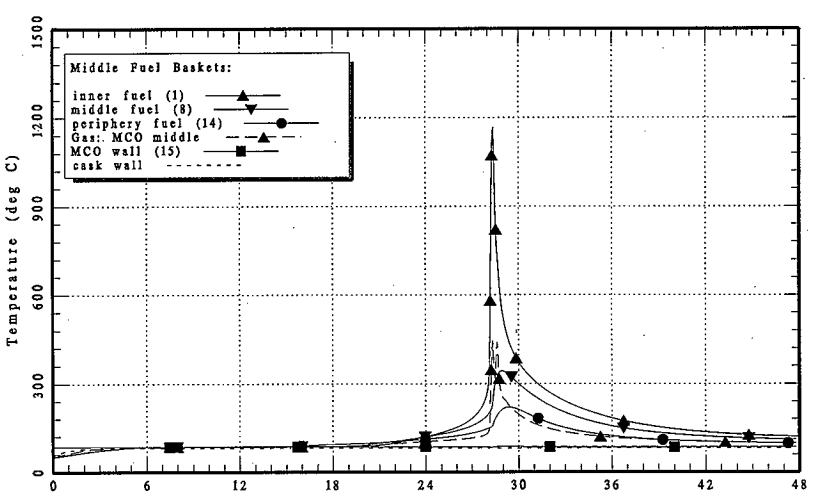


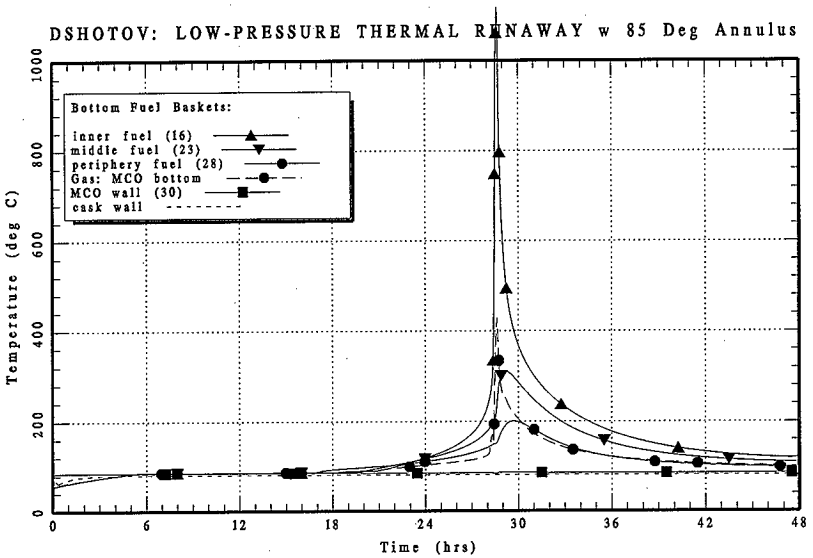
DSHOTOV: LOW-PRESSURE THERMAL RUNAWAY w 85 Deg Annulus






DSHOTOV: LOW-PRESSURE THERMAL RUNAWAY w 85 Deg Annulus
Scrap Basket:
(node #)
innermost fine (1)
middle coarse (7)
peripheral (9)
Fin
Gas
MCO
Cask
Temperature (deg C)
Time (hrs)
0
300
600
900
1200
1500
0
6
12
18
24
30
36
42
48


Middle Fuel Baskets:
inner fuel (1)
middle fuel (8)
periphery fuel (14)
Gas: MCO middle
MCO wall (15)
cask wall
Temperature (deg C)
Time (hrs)
0
300
600
900
1200
1500
0
6
12
18
24
30
36
42
48


DSHOTOV: LOW-PRESSURE THERMAL RUNAWAY w 85 Deg Annulus
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (deg C)
0
200
400
600
800
1000
0
6
12
18
24
30
36
42
48
Time (hrs)

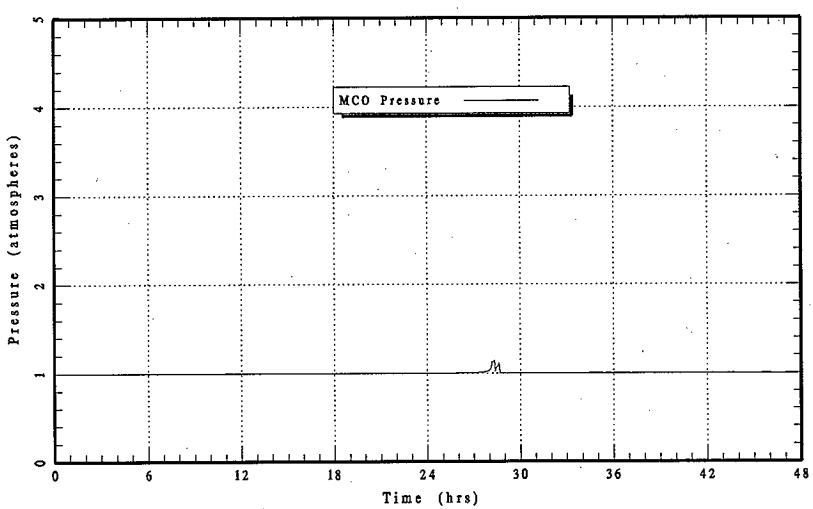

MCO Pressure
Pressure (atmospheres)
0
1
2
3
4
5
0
6
12
18
24
30
36
42
48
Time (hrs)

Figure A-32 VACAIRI: Indefinite Vacuum with Air Ingress and 50 °C Annulus

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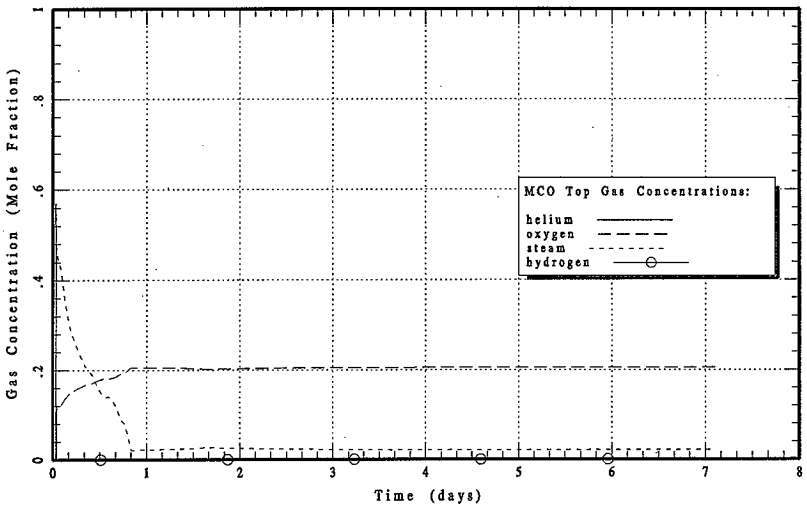
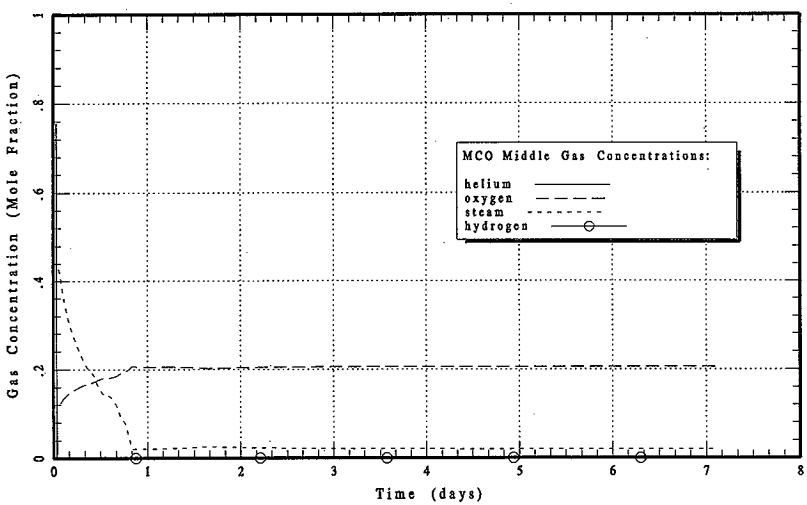
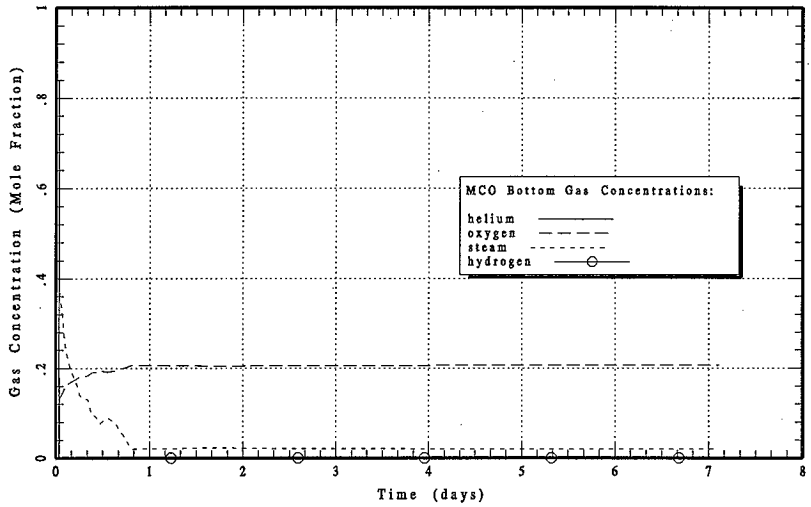
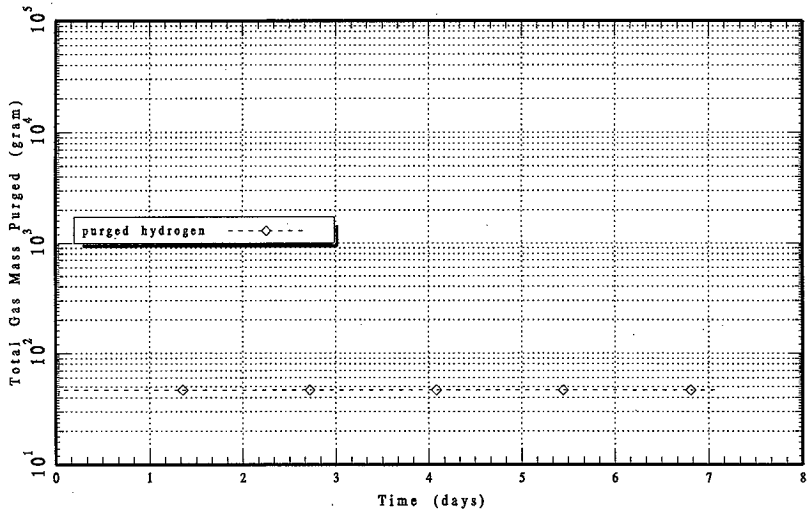
VACAIRI: INDEFINITE VACUUM w Air Ingress & 50 Deg C Annulus



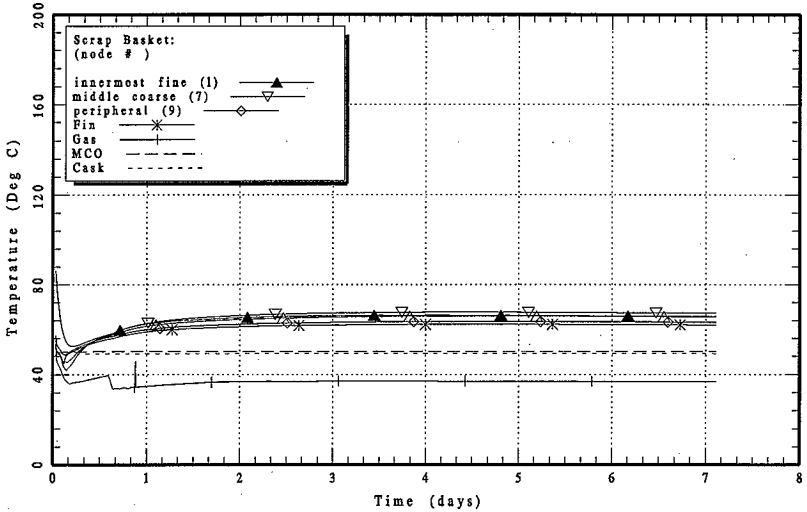


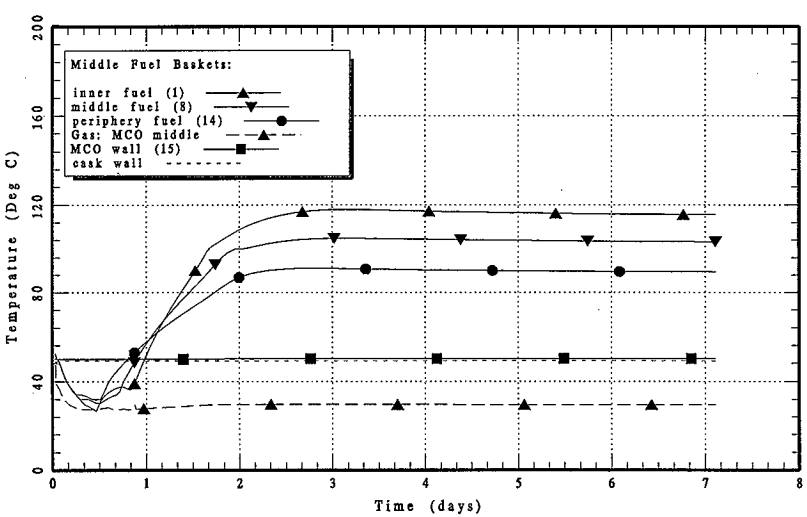
VACAIRI: INDEFINITE VACUUM w Air Ingress & 50 Deg C Annulus



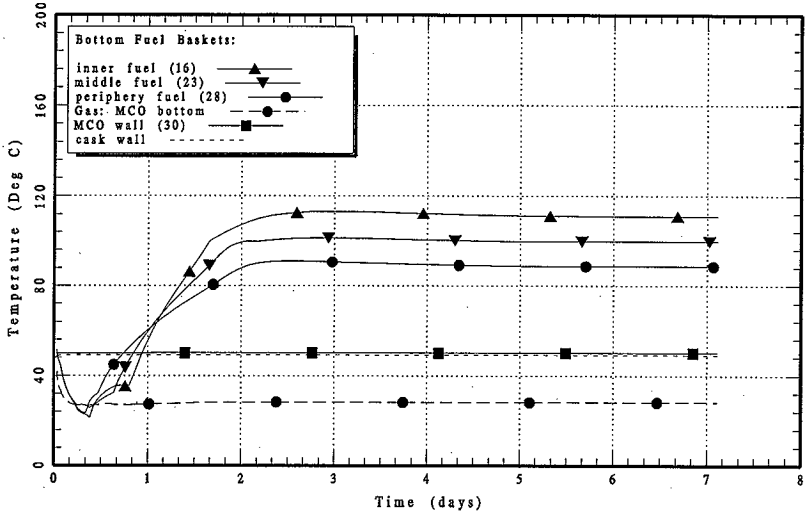


VACAIRI: INDEFINITE VACUUM w Air Ingress & 50 Deg C Annulus





VACAIRI: INDEFINITE VACUUM w Air Ingress & 50 Deg C Annulus



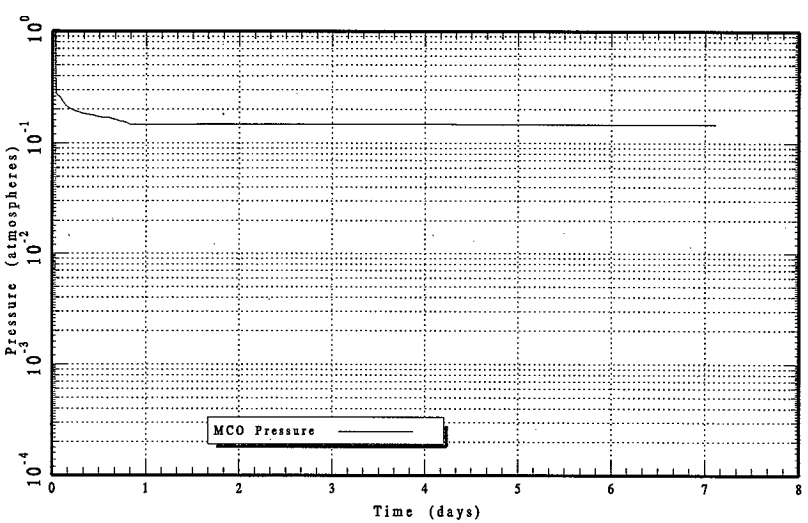


Figure A-33 VAIRIHOT: Indefinite Vacuum with Air Ingress and 85 °C Annulus

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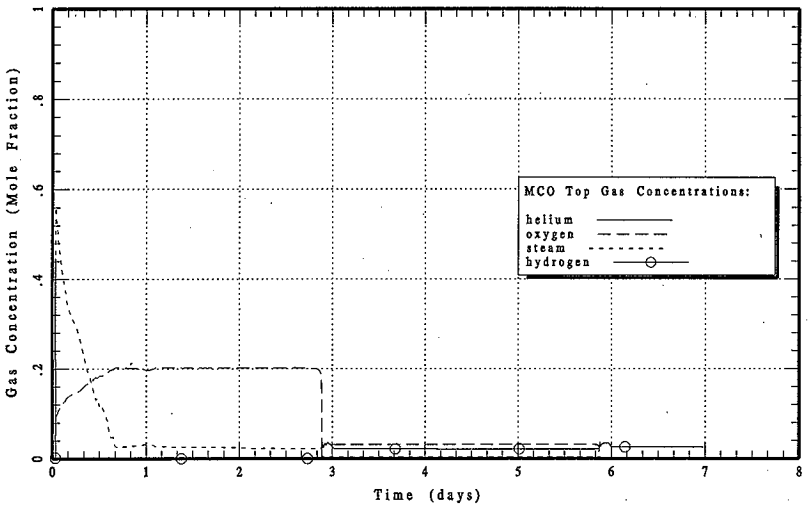
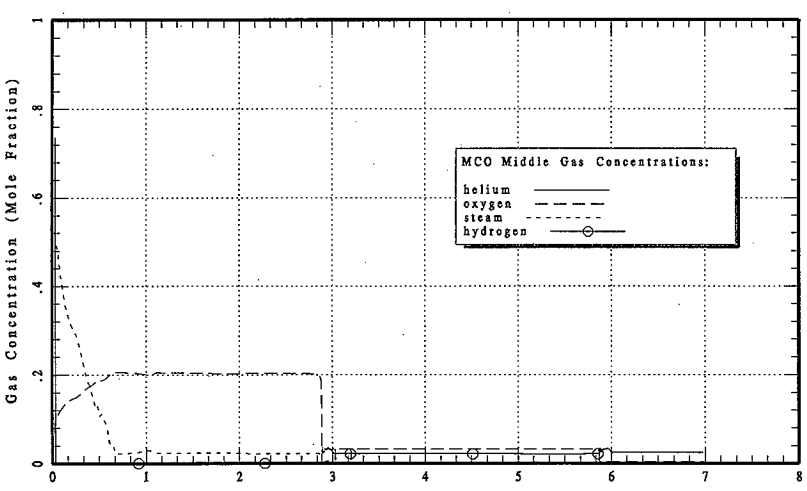
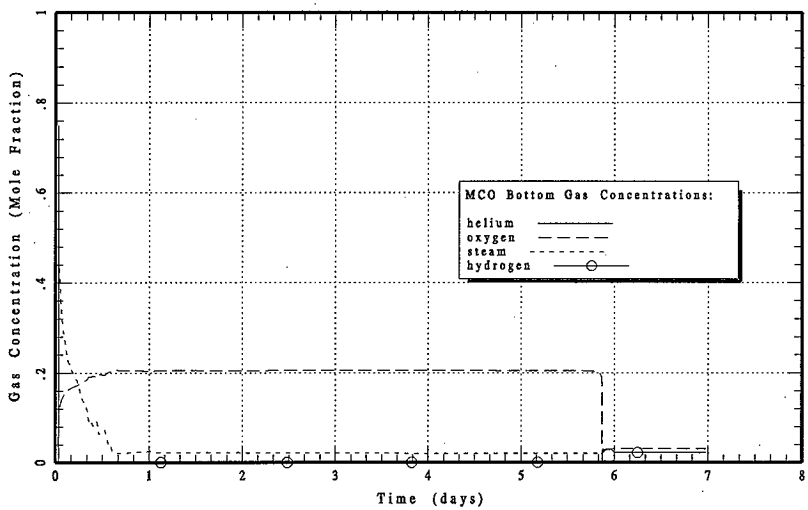
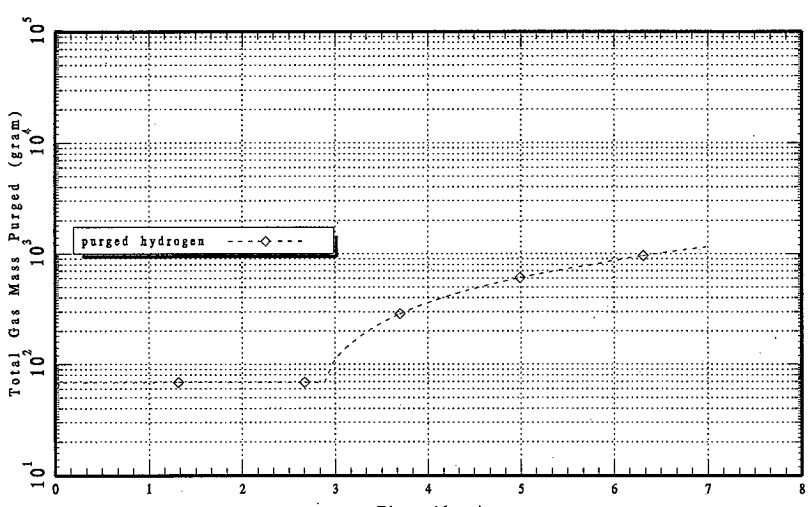
VAIRIHOT: INDEFINITE VACUUM w Air Ingress & 85 Deg C Annulus



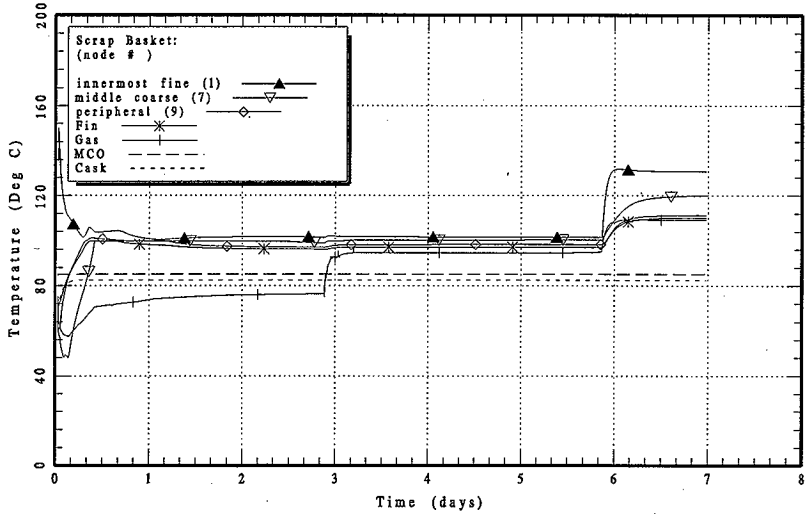


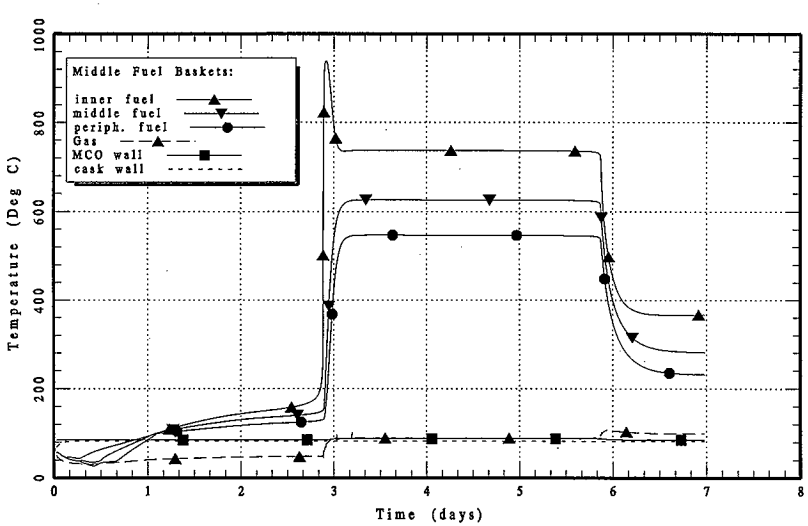
VAIRIHOT: INDEFINITE VACUUM w Air Ingress & 85 Deg C Annulus



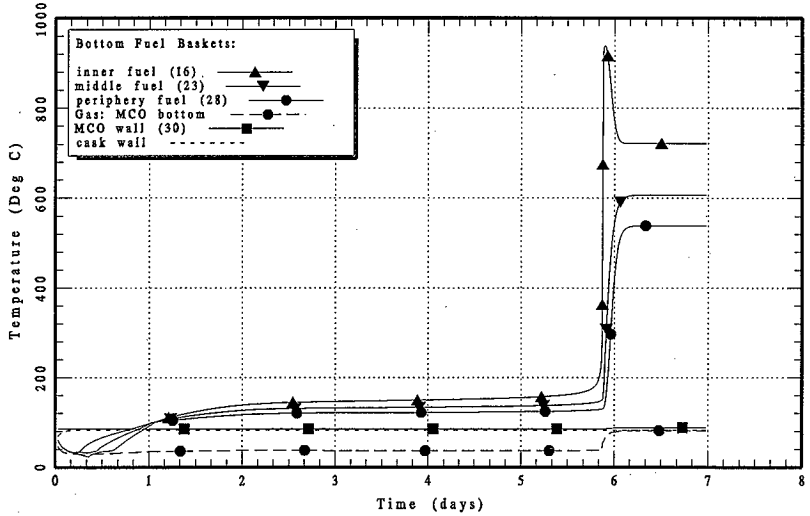


VAIRIHOT: INDEFINITE VACUUM w Air Ingress & 85 Deg C Annulus





VAIRIHOT: INDEFINITE VACUUM w Air Ingress & 85 Deg C Annulus



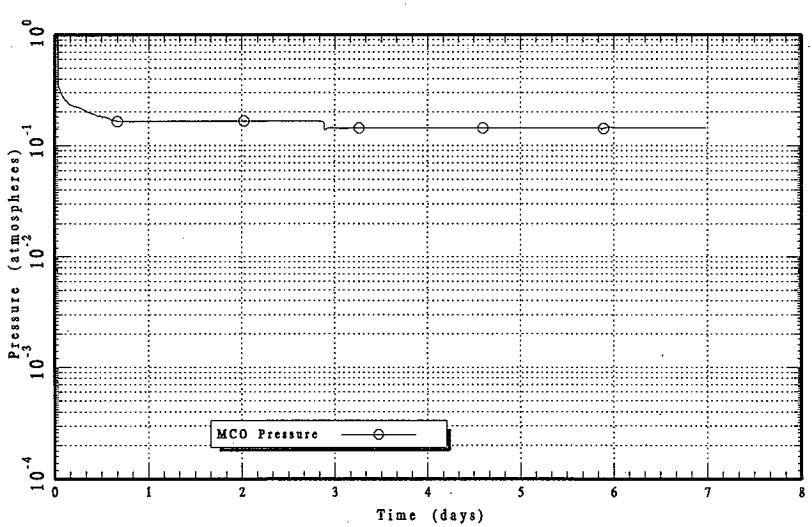


Figure A-34 VAIRILOC: Indefinite Vacuum with Air Ingress and Loss of Coolant (LOC)

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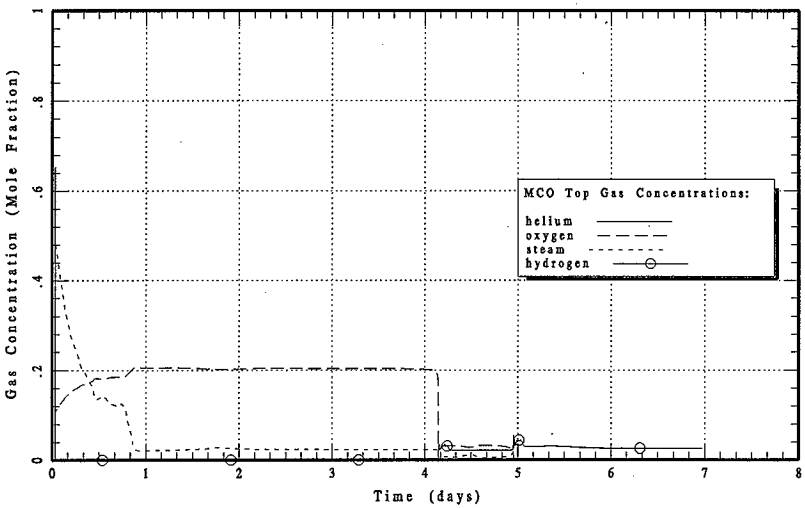
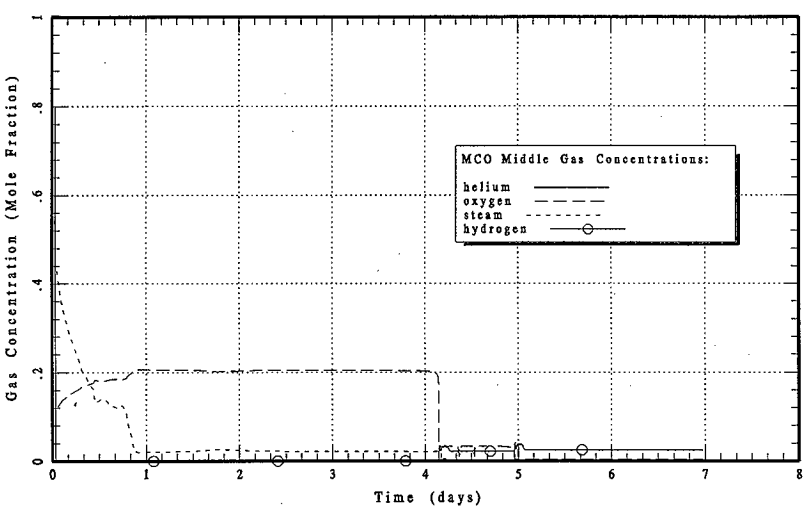
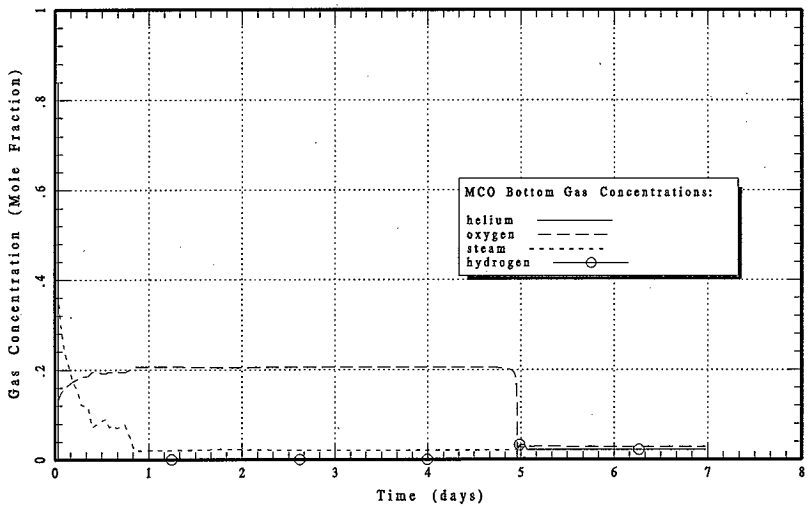
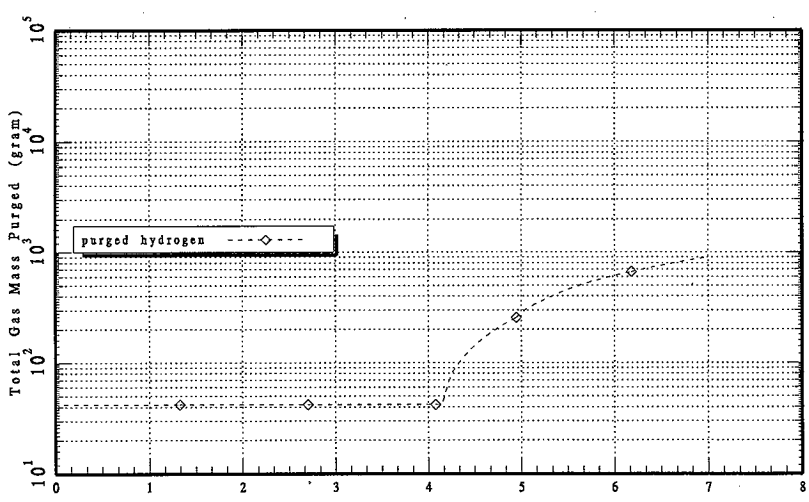
VAIRILOC: INDEFINITE VACUUM w Air Ingress & Loss of Coolant



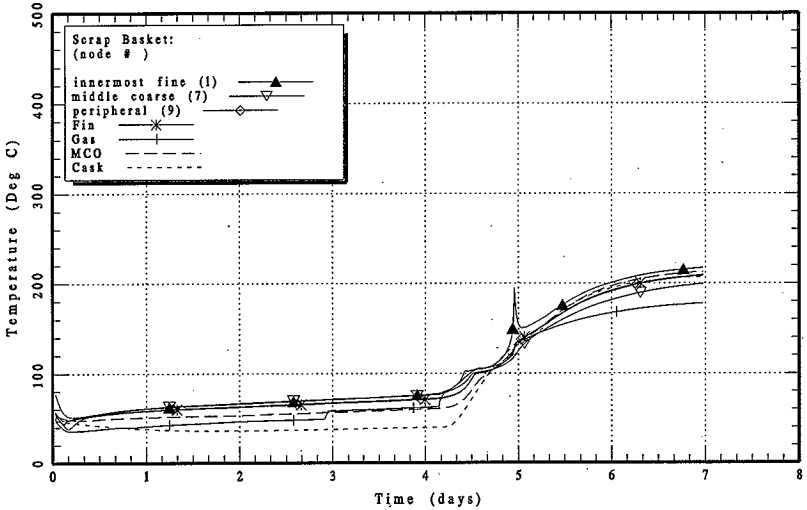


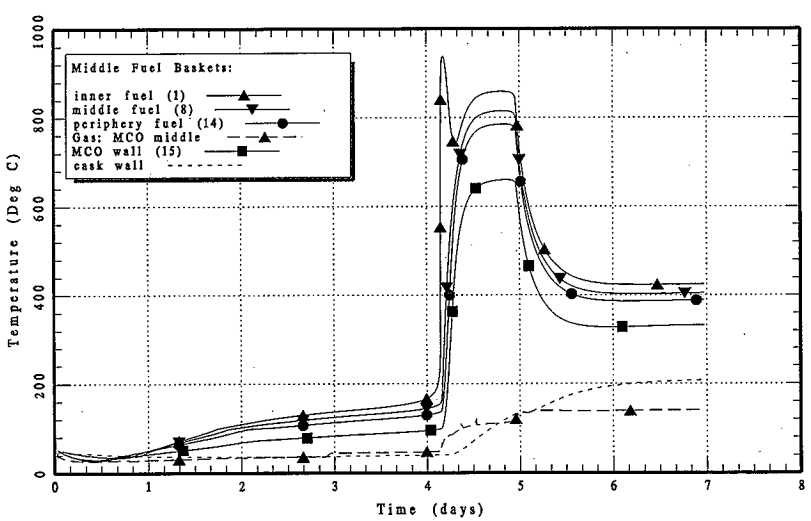
VAIRILOC: INDEFINITE VACUUM w Air Ingress & Loss of Coolant

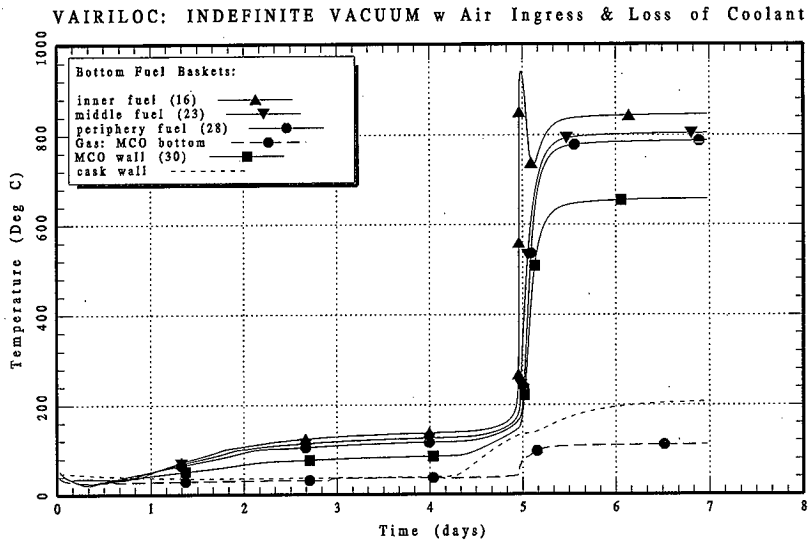




VAIRILOC: INDEFINITE VACUUM w Air Ingress & Loss of Coolant






VAIRILOC: INDEFINITE VACUUM w Air Ingress & Loss of Coolant
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (Deg C)
Time (days)

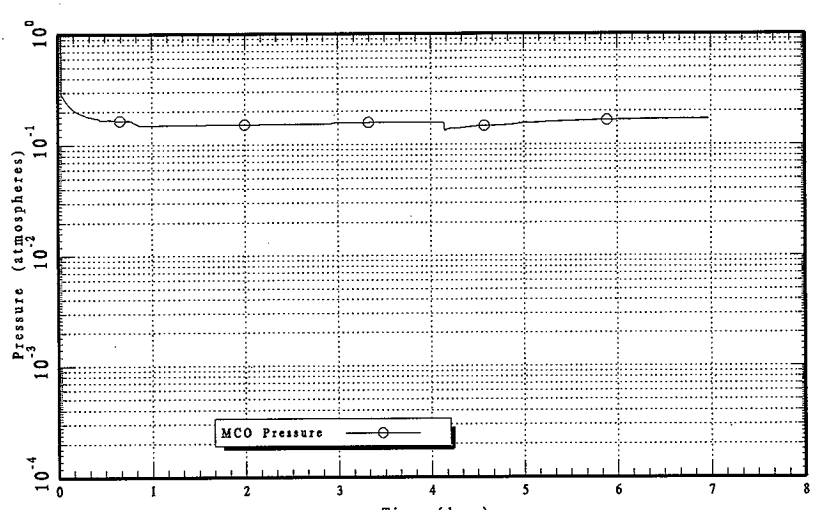

Pressure (atmospheres)
MCO Pressure
Time (days)

Figure A-35 PURAIRI: Indefinite Purge with Air Ingress and 50 °C Annulus

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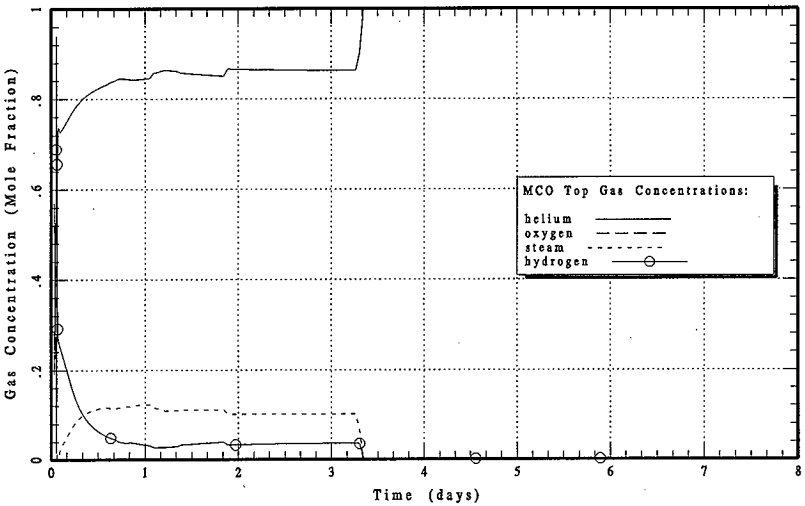
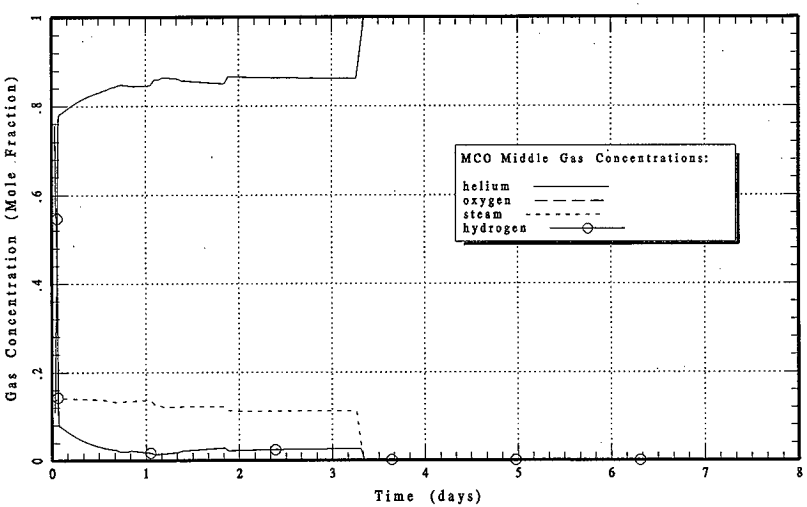
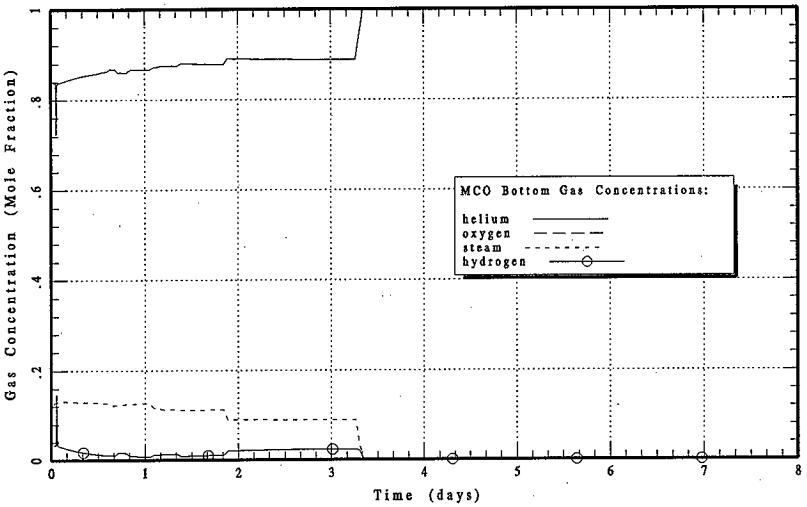
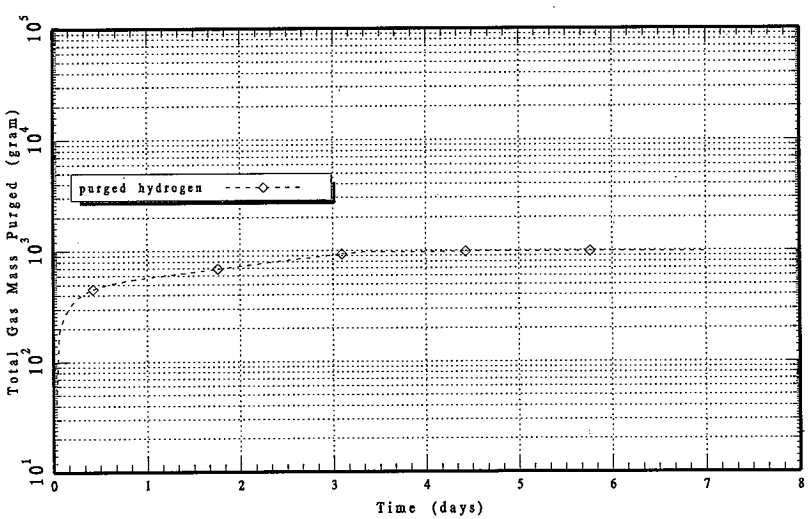
PURAIRI: INDEFINITE PURGE w Air Ingress & 50 Deg C Annulus

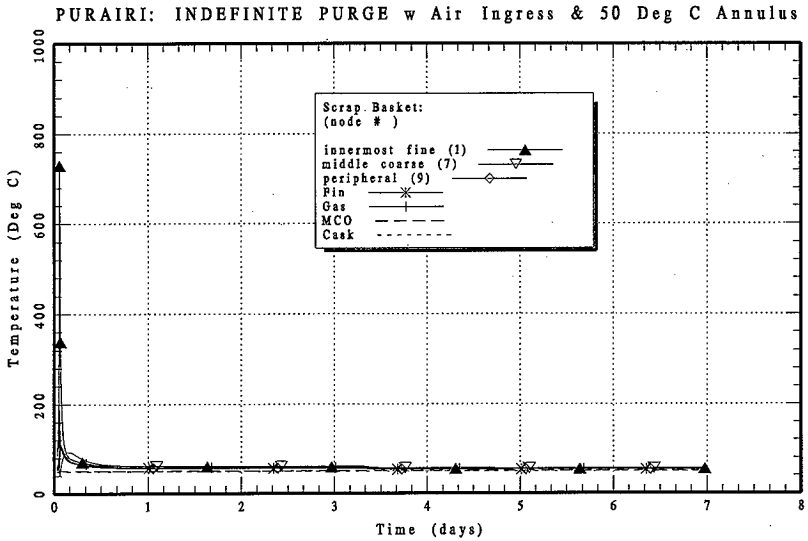


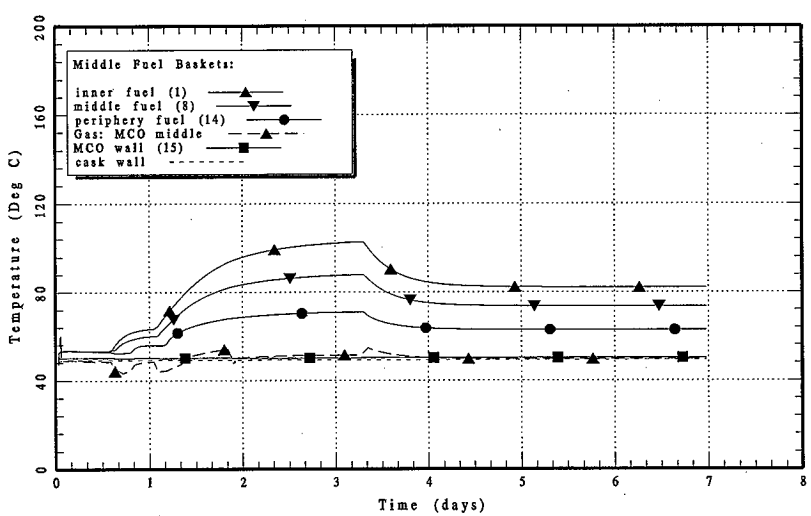


PURAIRI: INDEFINITE PURGE w Air Ingress & 50 Deg C Annulus






PURAIRI: INDEFINITE PURGE w Air Ingress & 50 Deg C Annulus
Scrap Basket:
(node #)
innermost fine (1)
middle coarse (7)
peripheral (9)
Fin
Gas
MCO
Cask
Temperature (Deg C)
Time (days)


Middle Fuel Baskets:
inner fuel (1)
middle fuel (8)
periphery fuel (14)
Gas: MCO middle
MCO wall (15)
cask wall
Temperature (Deg C)
Time (days)

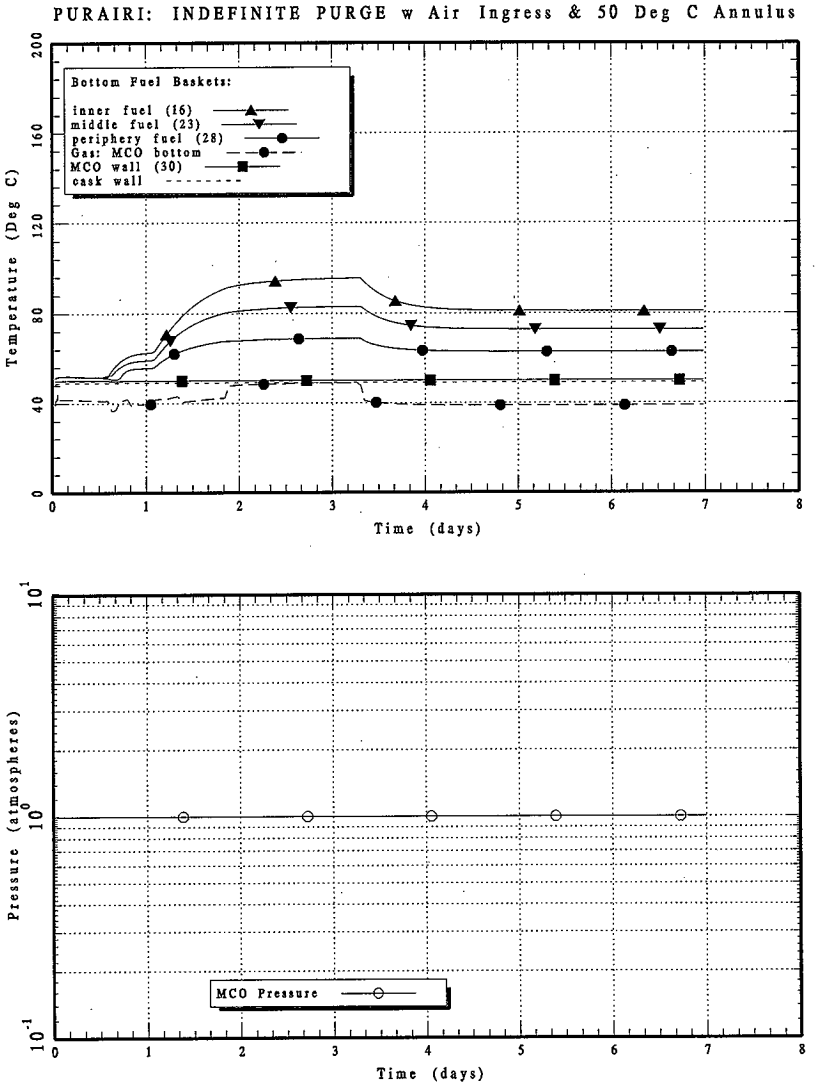

PURAIRI: INDEFINITE PURGE w Air Ingress & 50 Deg C Annulus
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (Deg C)
Time (days)
Pressure (atmospheres)
MCO Pressure
Time (days)

Figure A-36 PAIRIHOT: Helium Purge with Air Ingress and 85 °C Annulus

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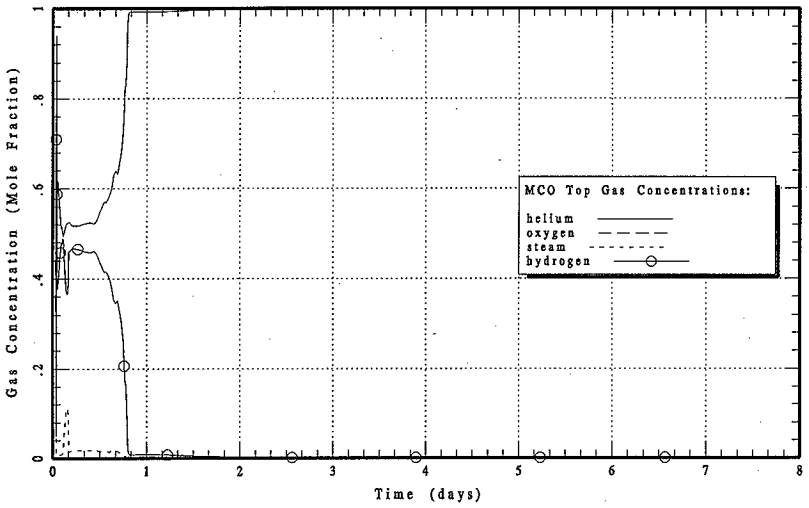
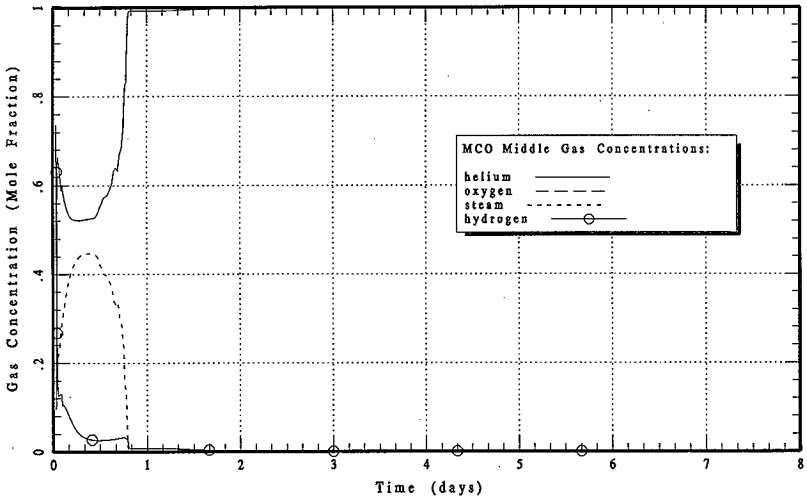
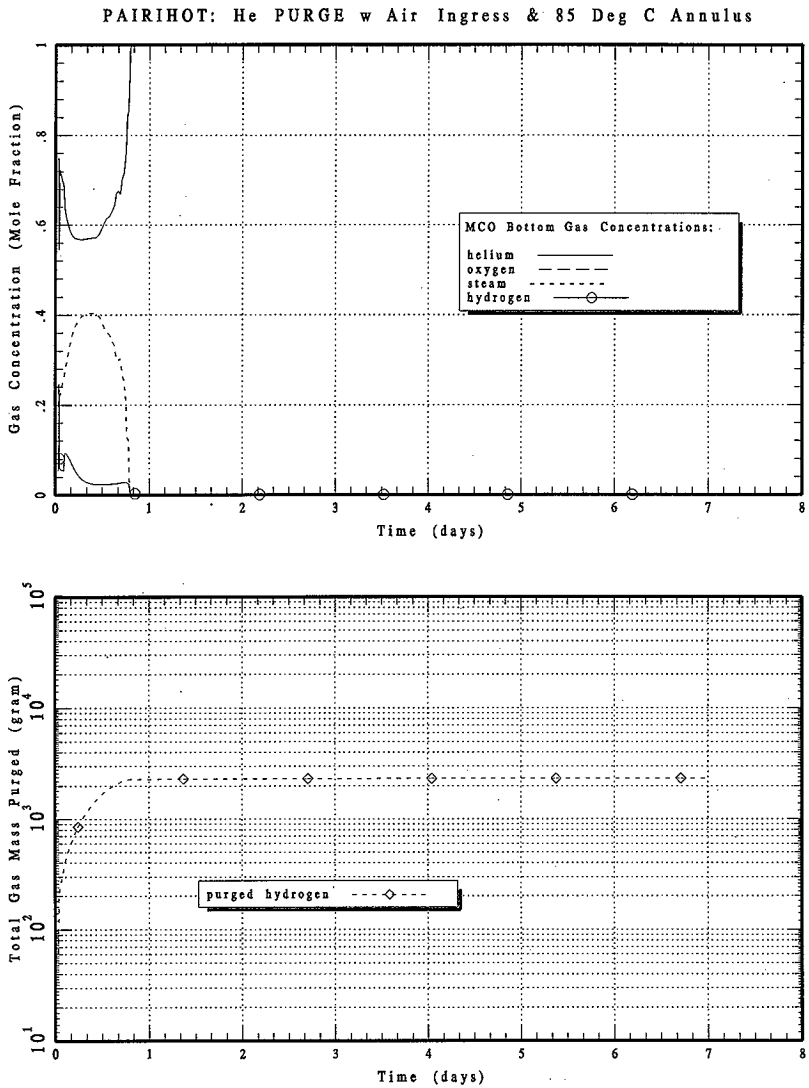
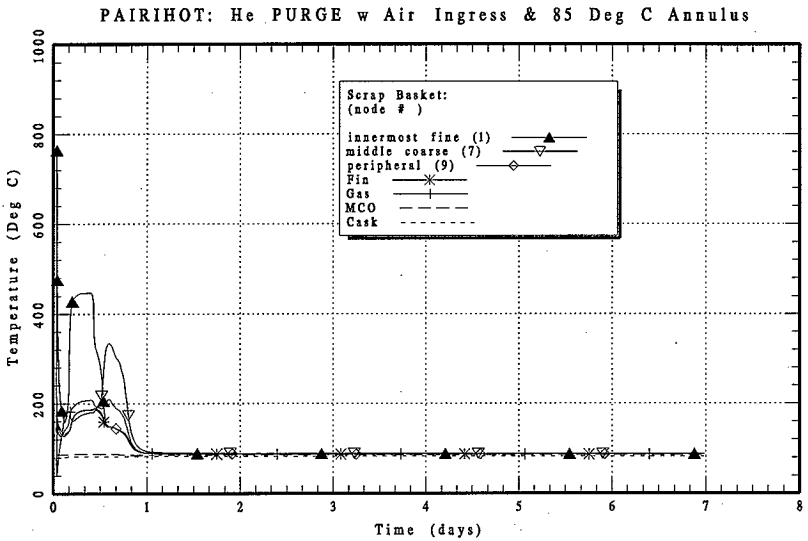
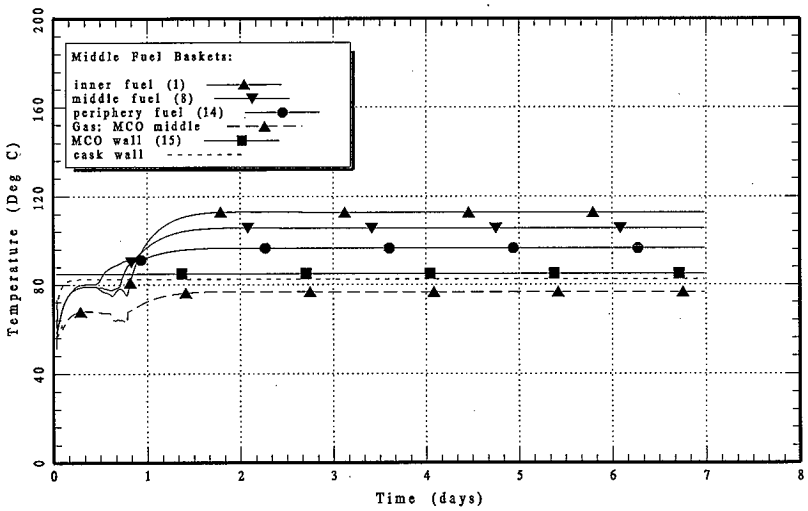
PAIRIHOT: He PURGE w Air Ingress & 85 Deg C Annulus






PAIRIHOT: He PURGE w Air Ingress & 85 Deg C Annulus
Gas Concentration (Mole Fraction)
Time (days)
MCO Bottom Gas Concentrations:
helium
oxygen
steam
hydrogen
Total Gas Mass Purged (gram)
purged hydrogen


PAIRIHOT: He PURGE w Air Ingress & 85 Deg C Annulus
Scrap Basket:
(node #)
innermost fine (1)
middle coarse (7)
peripheral (9)
Fin
Gas
MCO
Cask
Temperature (Deg C)
Time (days)


Middle Fuel Baskets:
inner fuel (1)
middle fuel (8)
periphery fuel (14)
Gas: MCO middle
MCO wall (15)
cask wall
Temperature (Deg C)
Time (days)

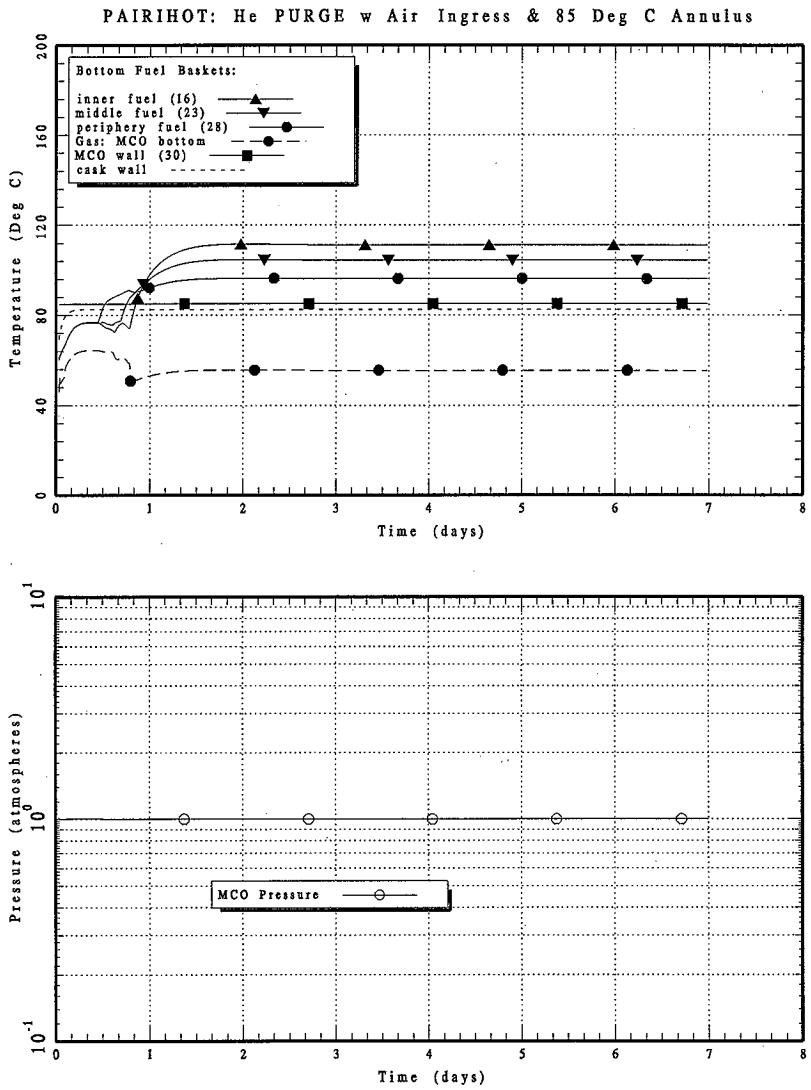

PAIRIHOT: He PURGE w Air Ingress & 85 Deg C Annulus
Bottom Fuel Baskets:
inner fuel (16)
middle fuel (23)
periphery fuel (28)
Gas: MCO bottom
MCO wall (30)
cask wall
Temperature (Deg C)
Time (days)
MCO Pressure
Pressure (atmospheres)
Time (days)

Figure A-37 VACAIRI2: Vacuum with No Hydrides, Air Ingress and 50 °C Annulus

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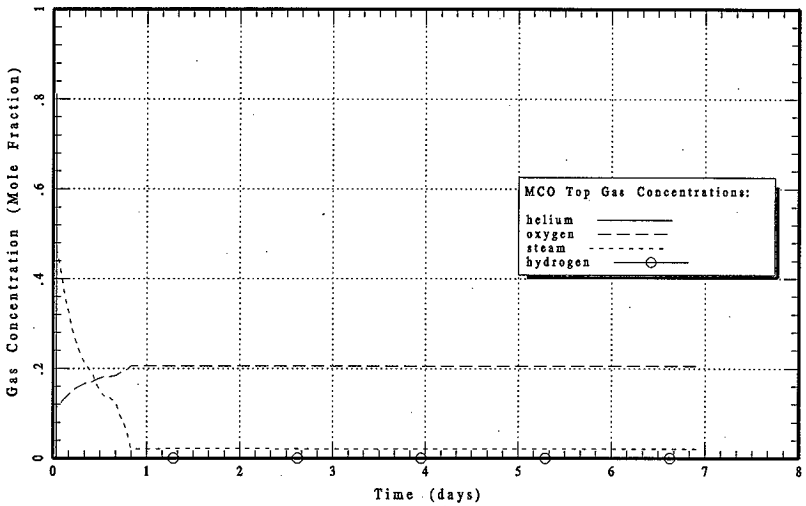
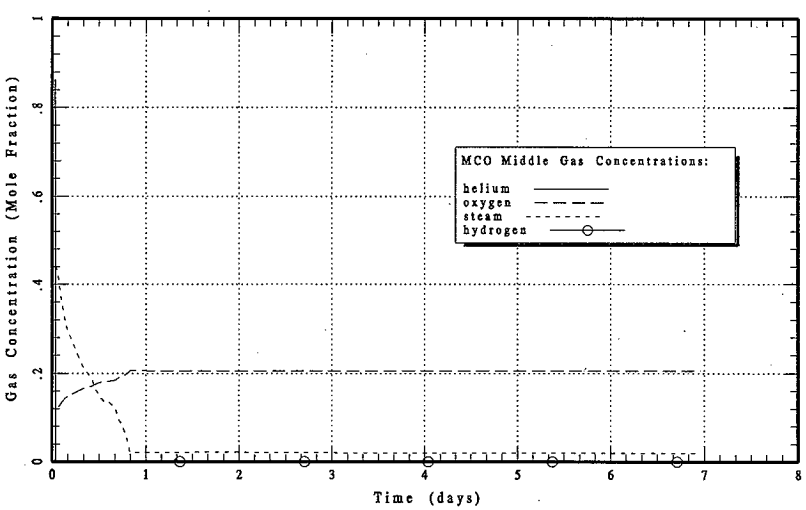
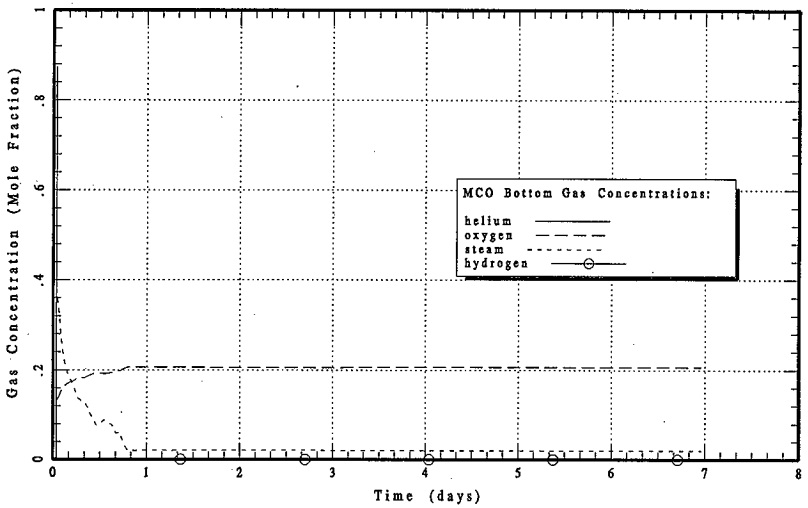
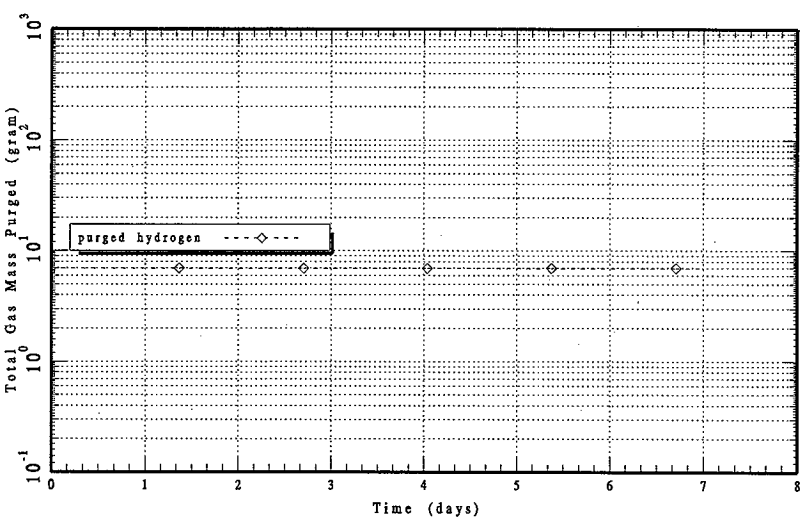
VACAIRI2: VACUUM w No Hydrides, Air Ingress & 50 Deg C Annulus



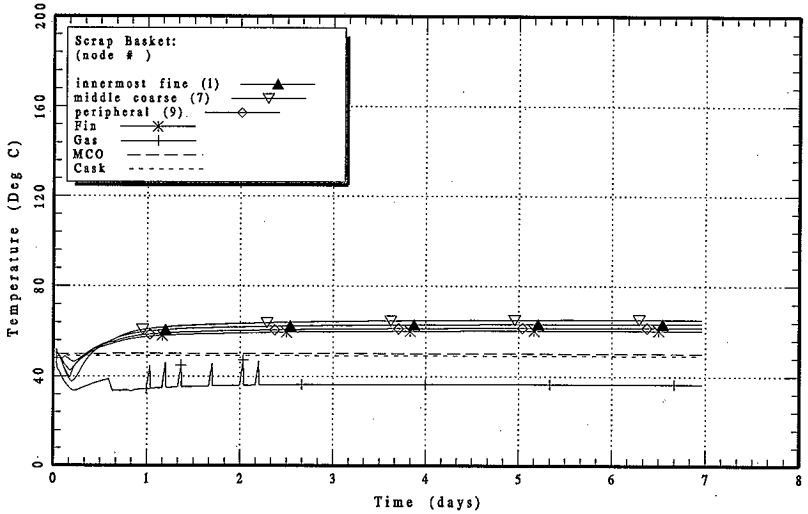


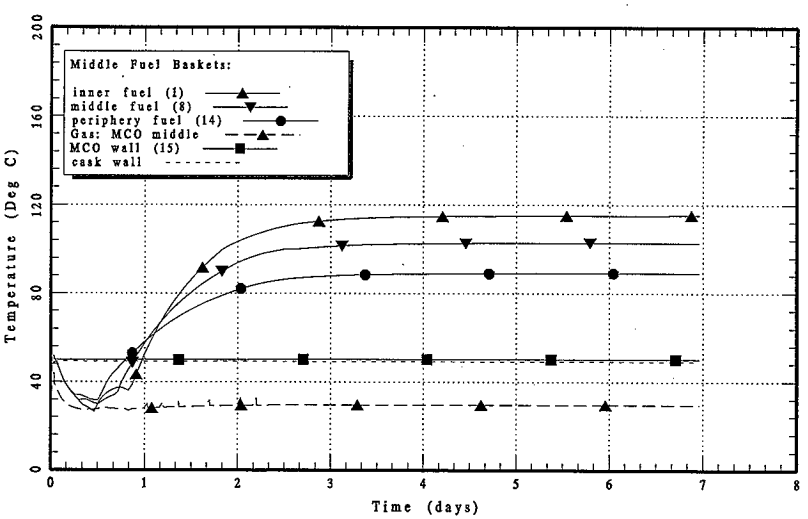
VACAIRI2: VACUUM w No Hydrides, Air Ingress & 50 Deg C Annulus



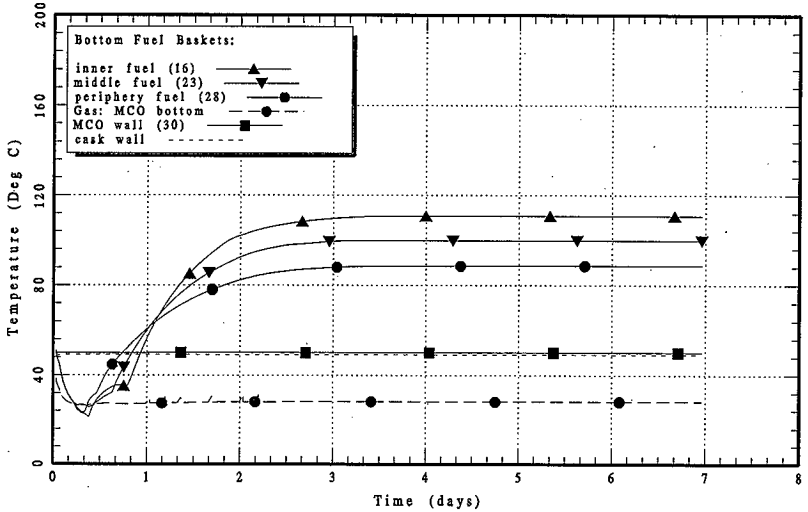


VACAIRI2: VACUUM w No Hydrides, Air Ingress & 50 Deg C Annulus





VACAIRI2: VACUUM w No Hydrides, Air Ingress & 50 Deg C Annulus



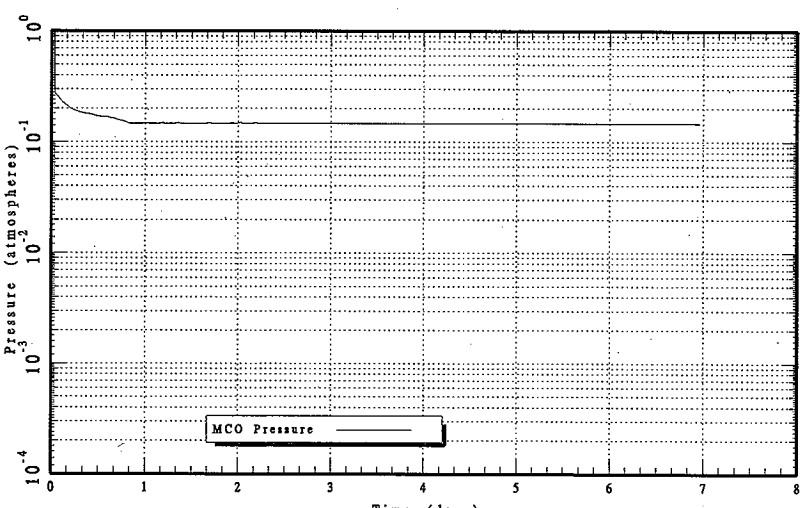


Figure A-38 DSLOCSA4: High-Pressure Thermal Runaway with 35.5 Kg Water and Loss of Coolant (LOC)

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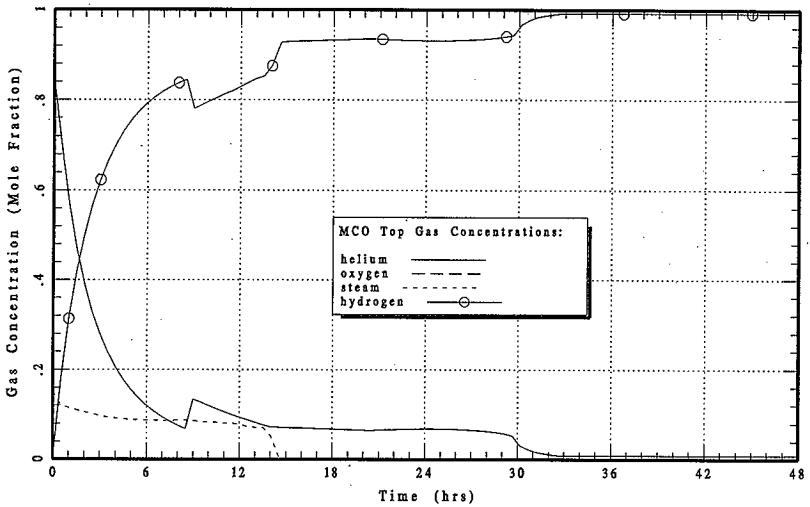
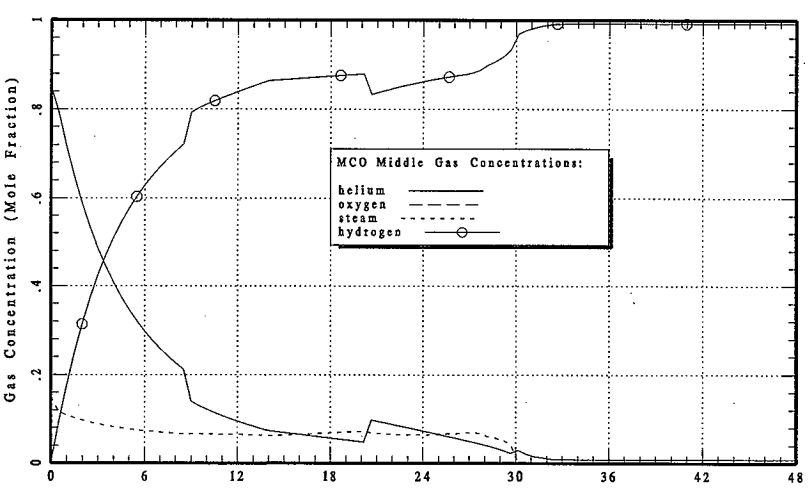
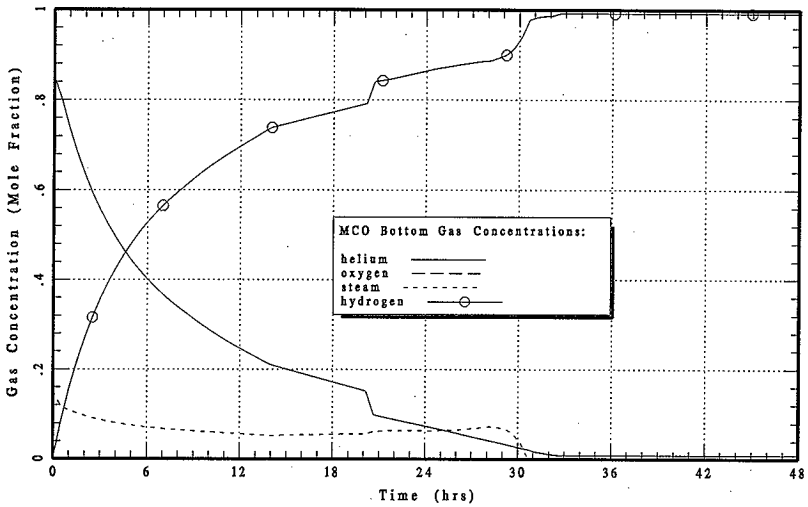
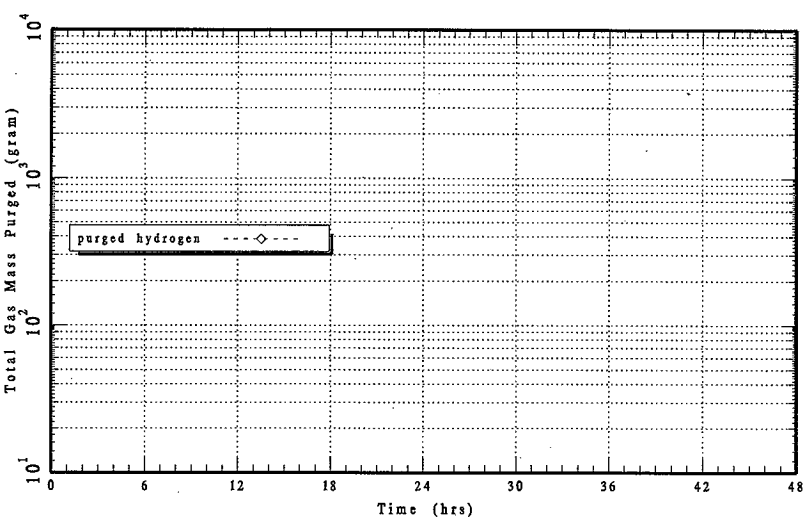
DSLOCSA4: HI-PRES THERM RUNAWAY w 35.5 Kg Water & Loss of Coolant



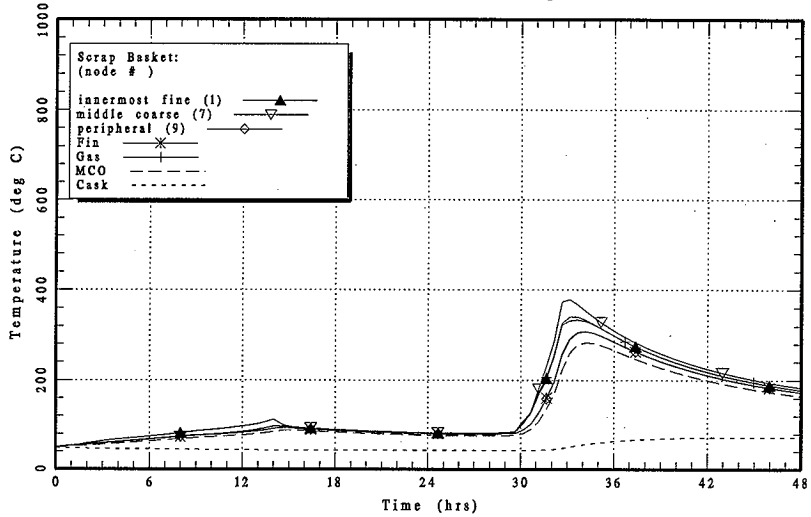


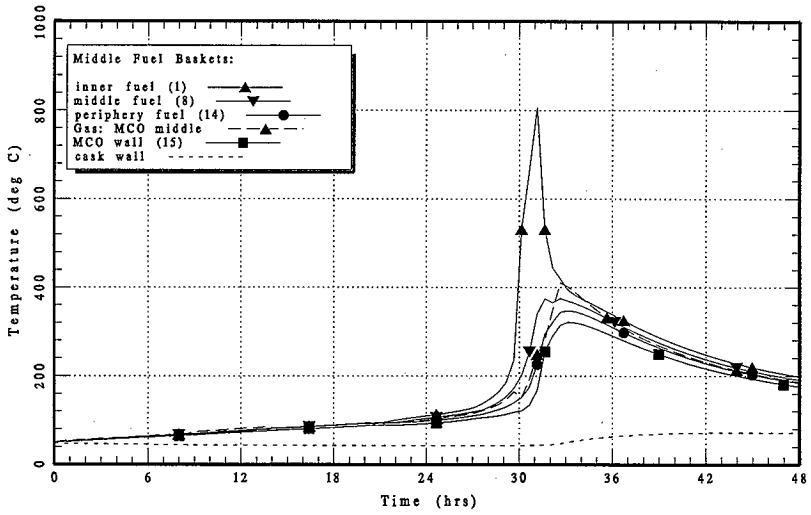
DSLOCSA4: HI-PRES THERM RUNAWAY w 35.5 Kg Water & Loss of Coolant



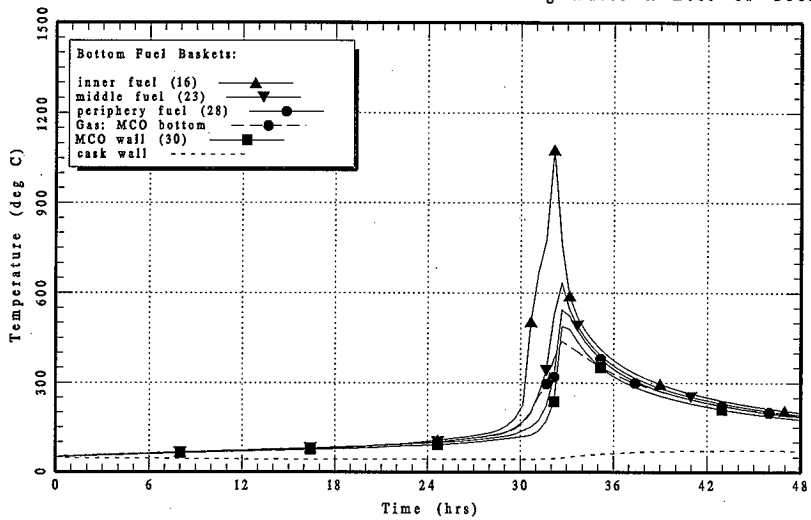


DSLOCSA4: HI-PRES THERM RUNAWAY w 35.5 Kg Water & Loss of Coolant





DSLOCSA4: HI-PRES THERM RUNAWAY w 35.5 Kg Water & Loss of Coolant



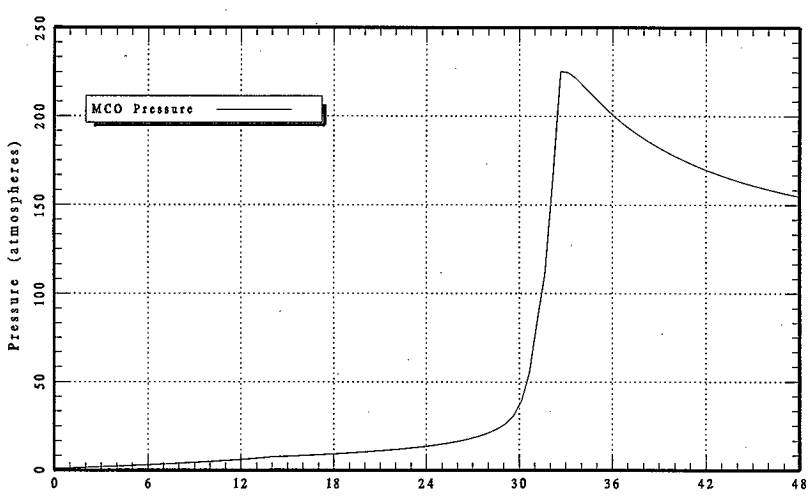


Figure A-39 BLOW4N: High-Pressure Thermal Runaway Blowdown with Air Ingress

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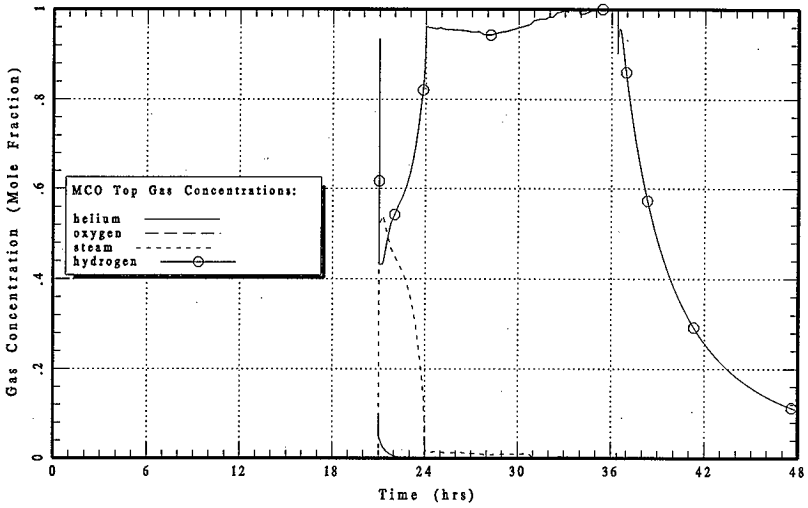
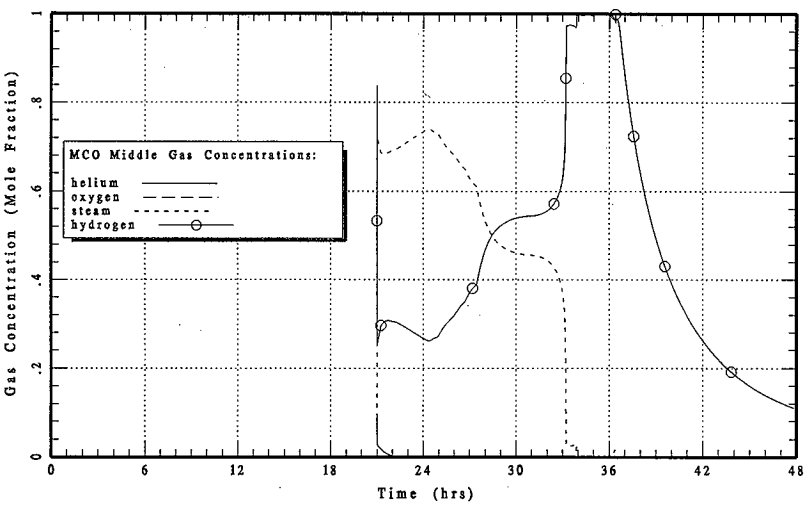
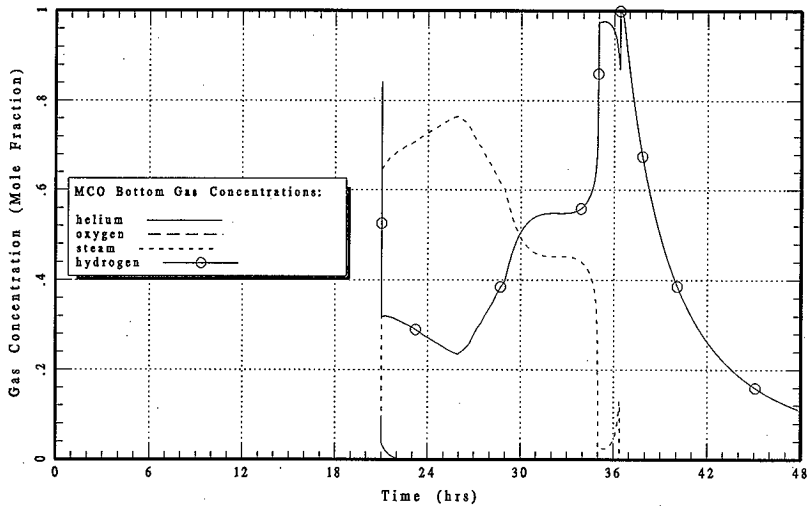
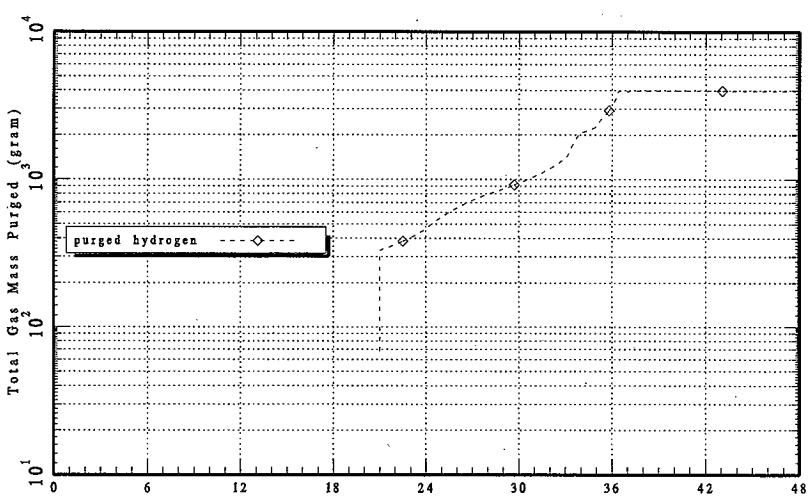
BLOW4N: HIGH-PRESSURE THERMAL RUNAWAY BLOWDOWN w Air Ingress



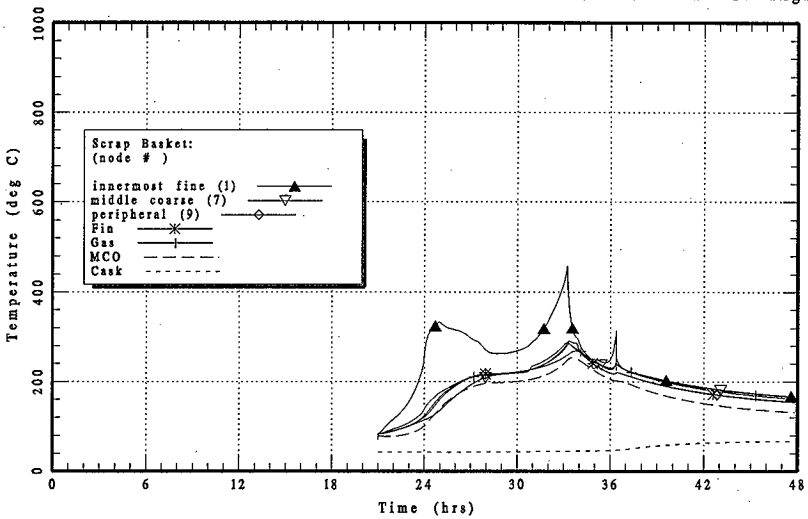


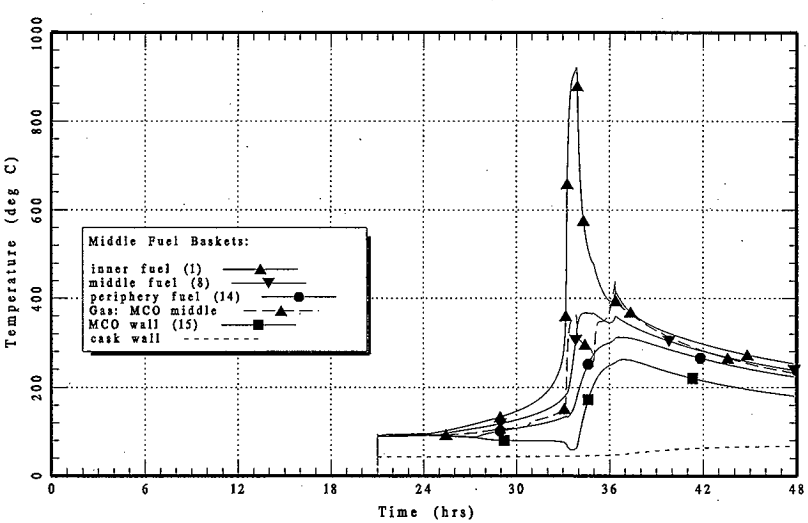
BLOW4N: HIGH-PRESSURE THERMAL RUNAWAY BLOWDOWN w Air Ingress



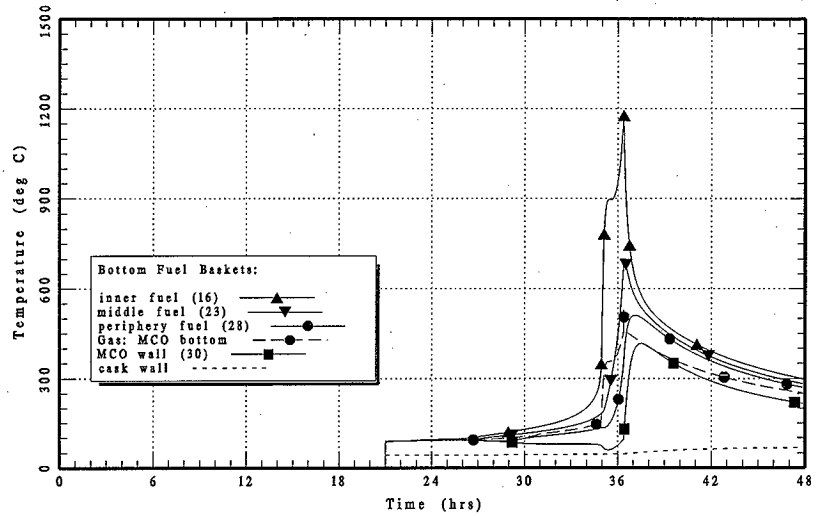


BLOW4N: HIGH-PRESSURE THERMAL RUNAWAY BLOWDOWN w Air Ingress





BLOW4N: HIGH-PRESSURE THERMAL RUNAWAY BLOWDOWN w Air Ingress



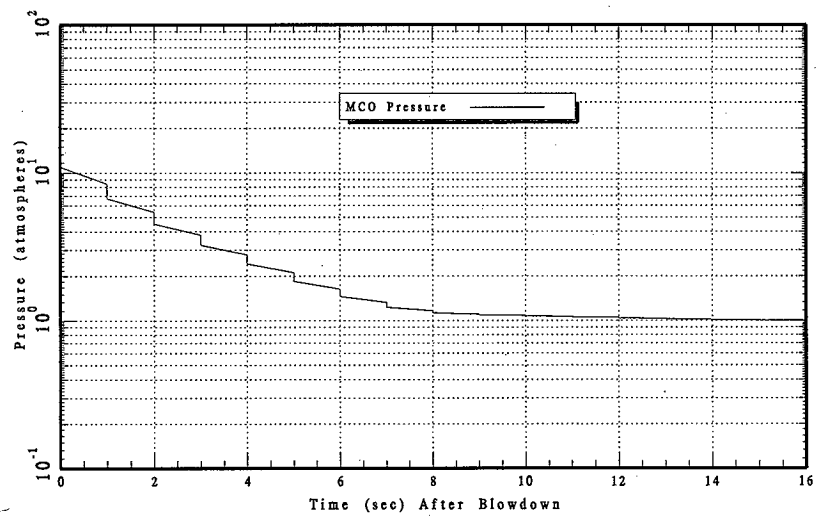


Figure A-40 DSSA4REC: High-Pressure Thermal Runaway with Loss of Coolant (LOC), 35.5 Kg, and Recovery at 21 hrs

The long-dashed curves are from case 40, DSSA4REC, which includes a recovery from the loss of coolant condition by restoring 25 °C stationary annulus water. The solid and short-dashed curves are from case 38, DSLOCSA4, which includes a bounding MCO with a loss of coolant condition and provides the initial conditions for case 40 at 21 hours.

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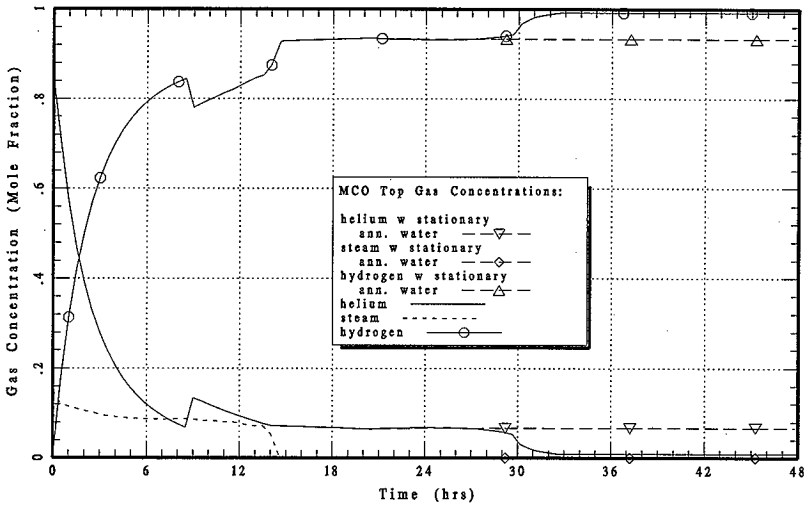
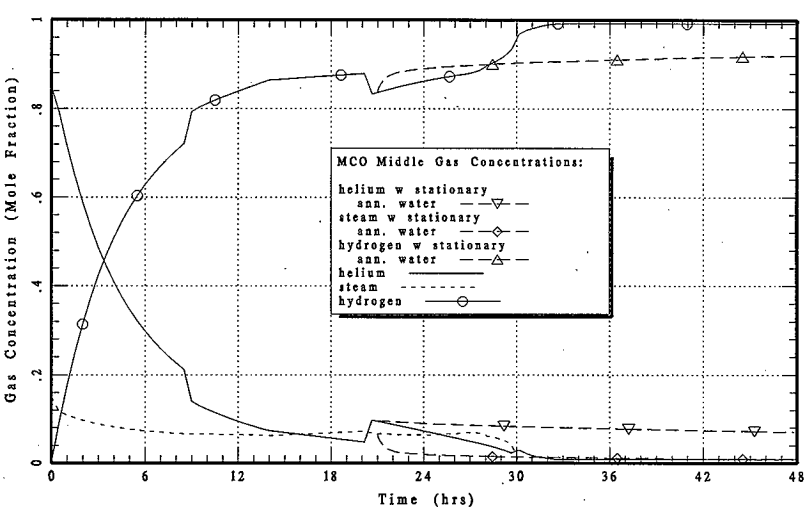
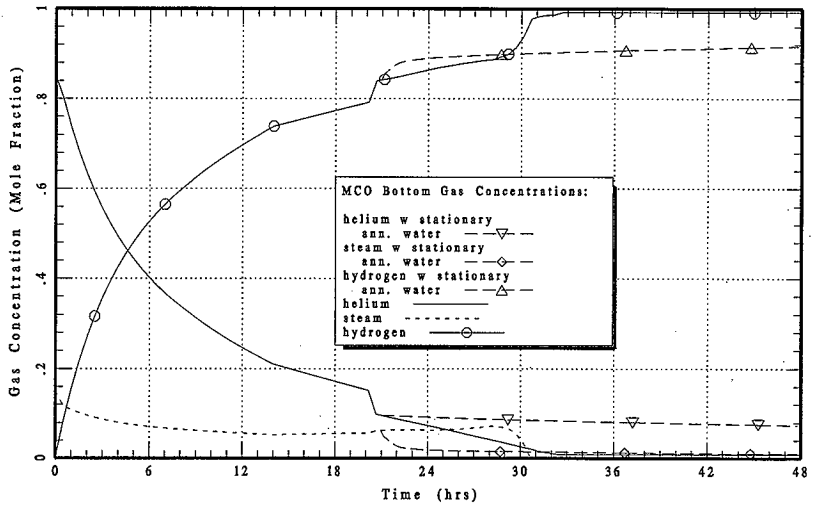
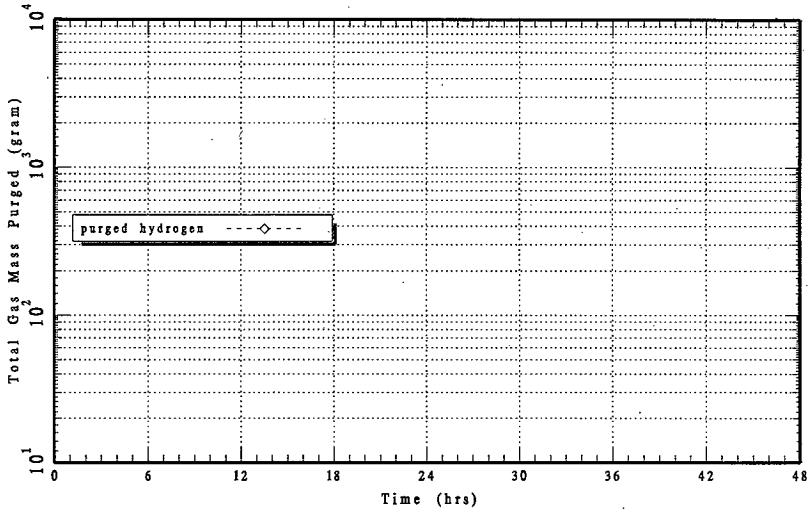
DSSA4REC: HI-PRES THERM RUNAWAY w LOC, 35.5 kg & Ann. Recovery @ 21 hrs



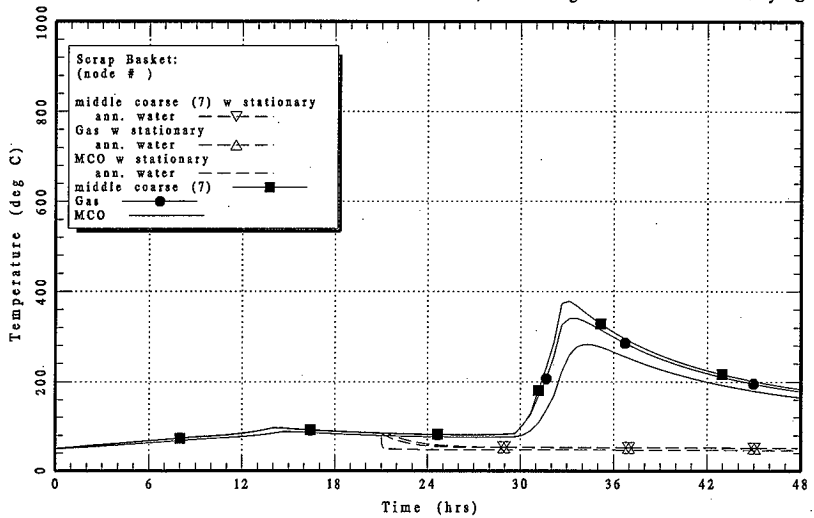


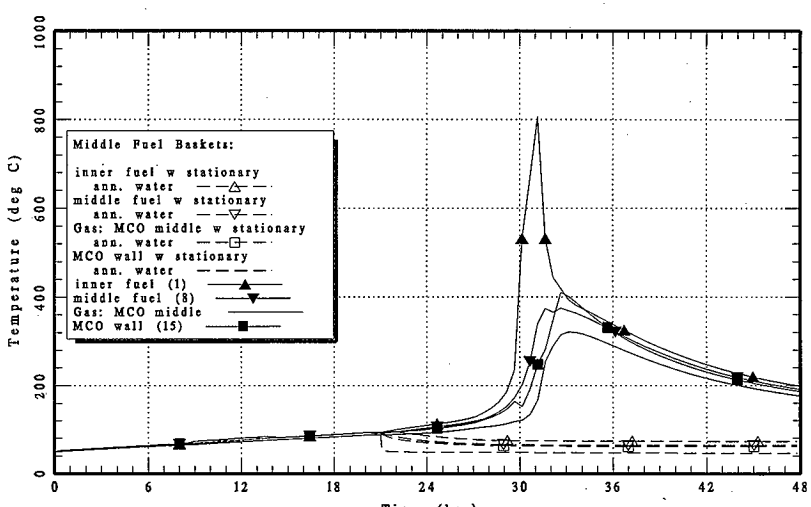
DSSA4REC: HI-PRES THERM RUNAWAY w LOC, 35.5 kg & Ann. Recovery @ 21 hrs



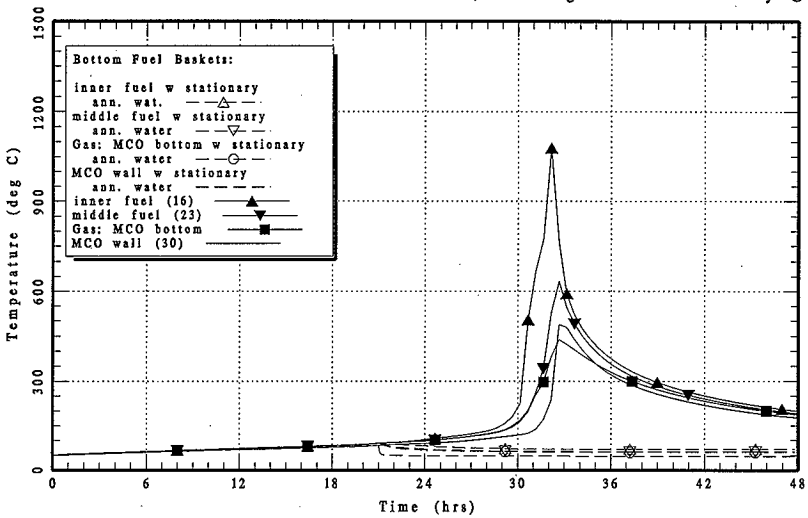


DSSA4REC: HI-PRES THERM RUNAWAY w LOC, 35.5 kg & Ann. Recovery @ 21 hrs





DSSA4REC: HI-PRES THERM RUNAWAY w LOC, 35.5 kg & Ann. Recovery @ 21 hrs



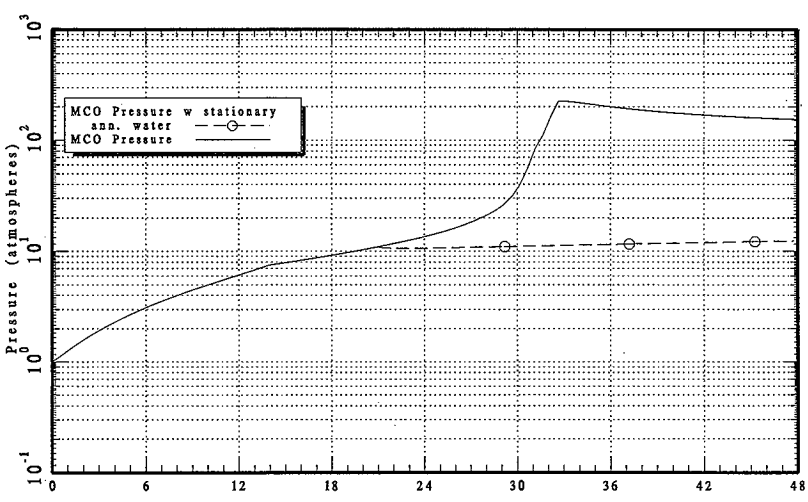


Figure A-41 BLOWREOV: Blowdown with Stationary Annulus Recovery From Loss of Coolant (LOC) at 1 Hour After Blowdown

The long-dashed curves are from case 41, BLOWREOV, which includes a recovery from the loss of coolant condition by restoring 25 °C stationary annulus water at 22 hours, which is 1 hour after the blowdown. The blowdown of a bounding MCO is simulated by case 39, BLOW4N. The solid and short-dashed curves are from case 39 which provides the initial conditions for case 41 at 22 hours.

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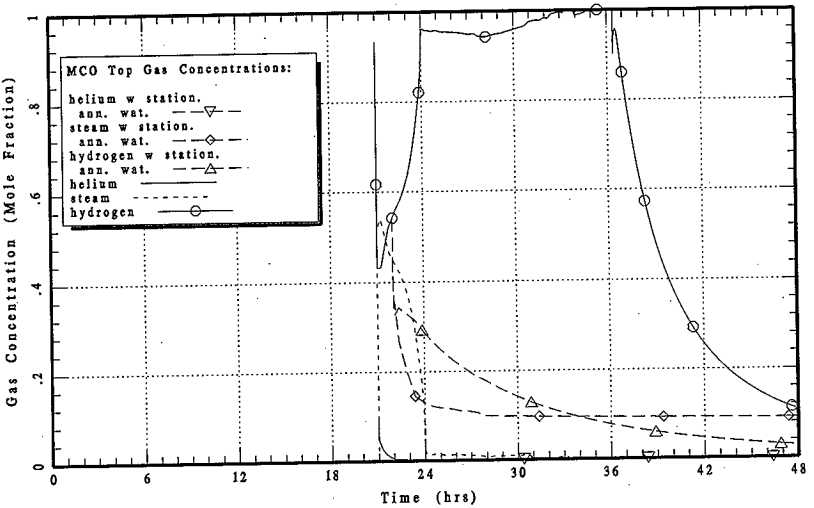
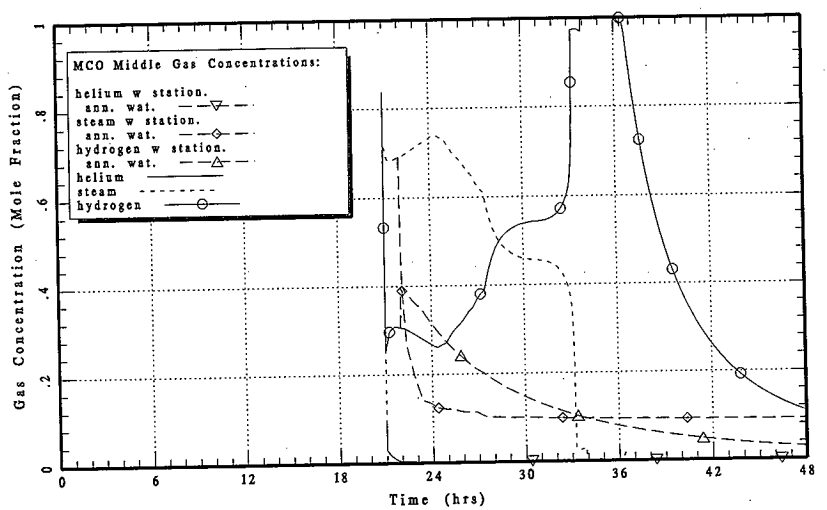
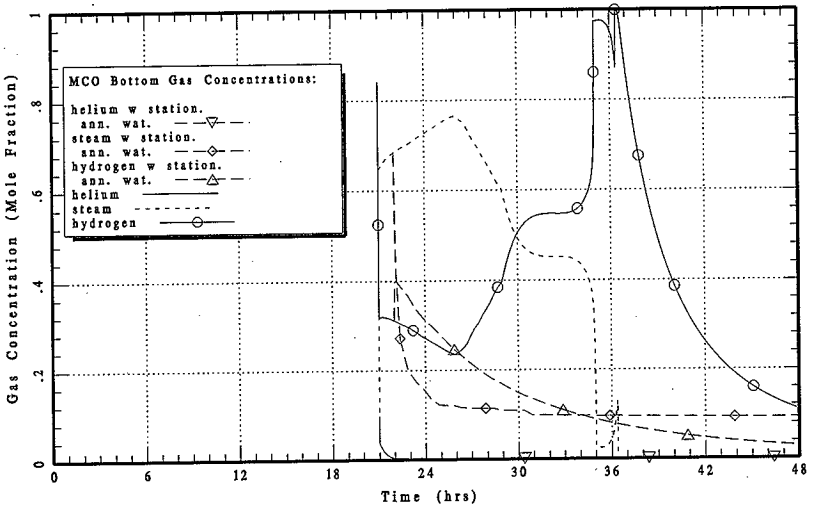
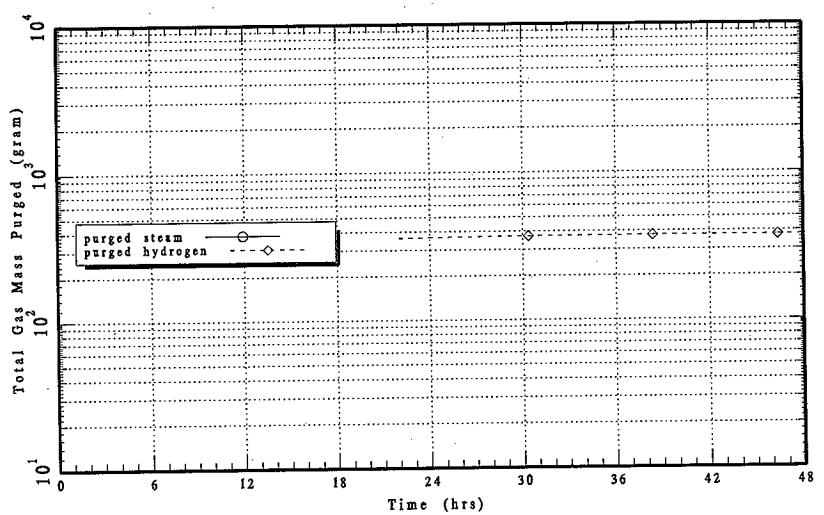
BLOWREOV: BLOWDOWN w Station. Ann. Recovery from LOC @ 1 hr aft. blowdown



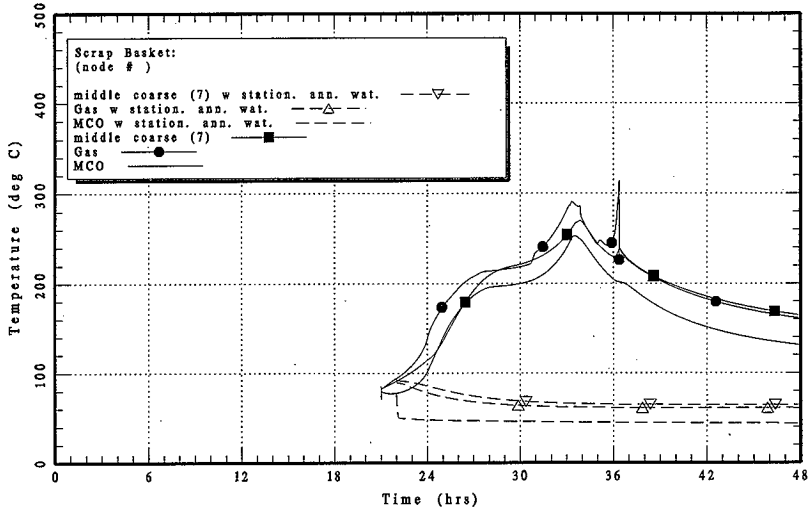


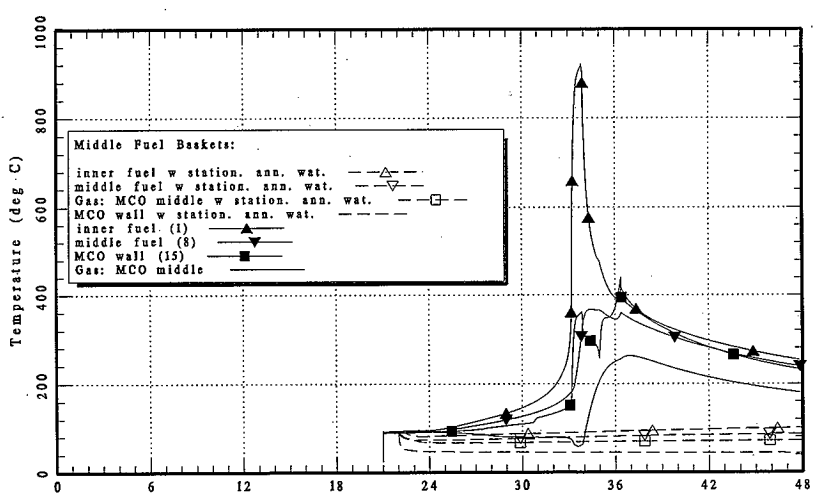
BLOWREOV: BLOWDOWN w Station. Ann. Recovery from LOC @ 1 hr aft. blowdown



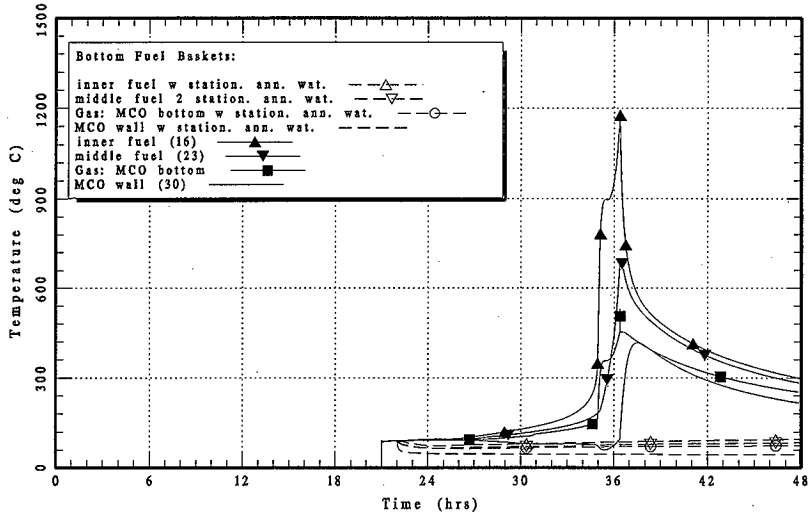


BLOWREOV: BLOWDOWN w Station. Ann. Recovery from LOC @ 1 hr aft. blowdown





BLOWREOV: BLOWDOWN w Station. Ann. Recovery from LOC @ 1 hr aft. blowdown



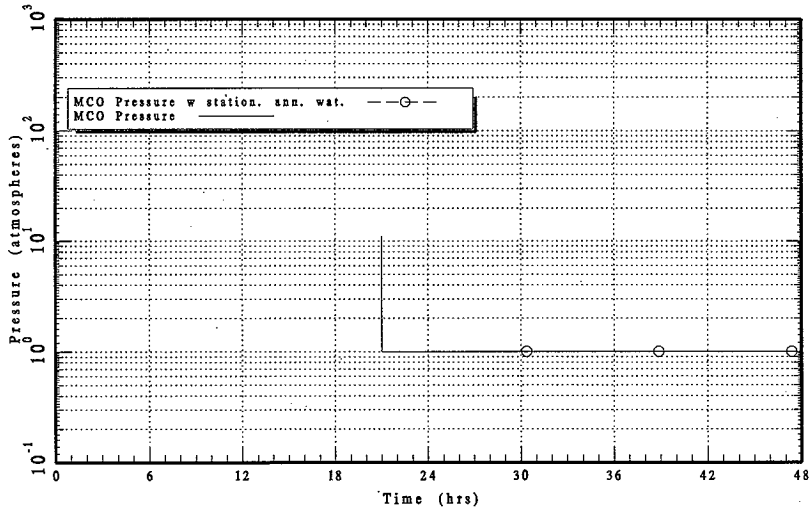


Figure A-42 DSLOCOV2: Low-Pressure Thermal Runaway with 35.5 Kg Water, Loss of Coolant (LOC), and Open Vent

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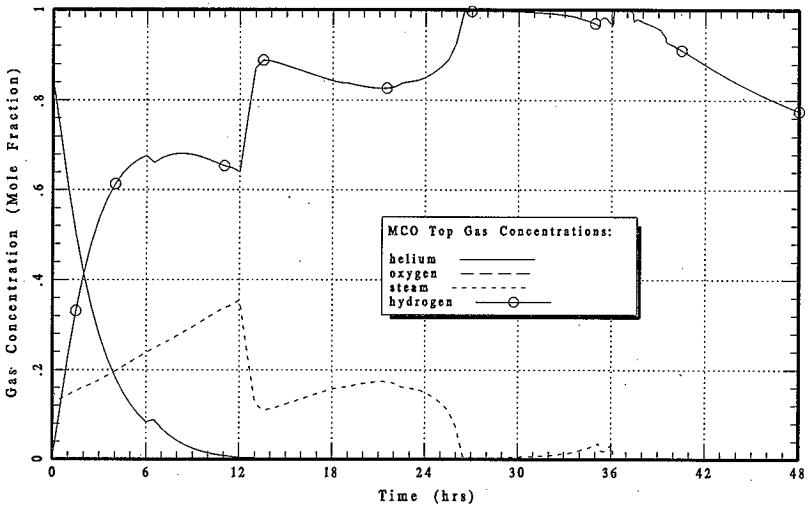
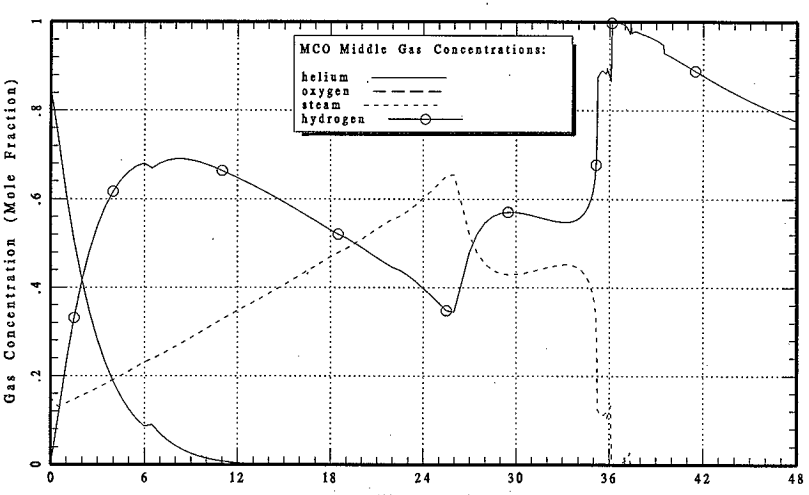
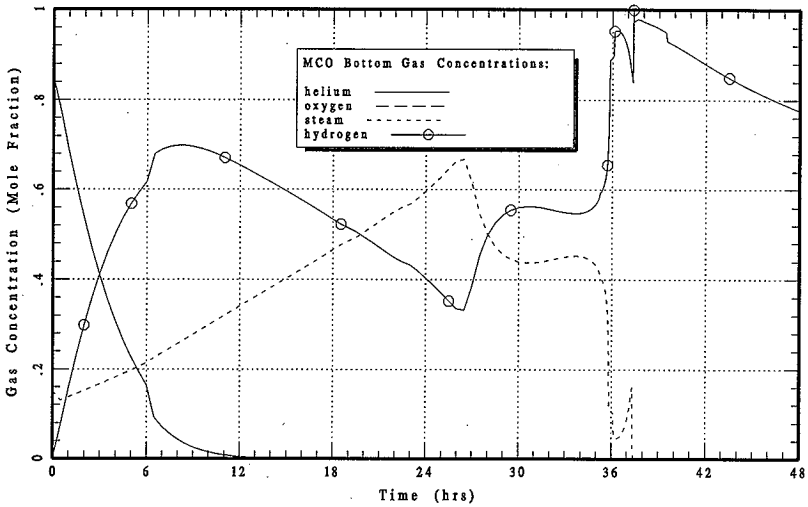
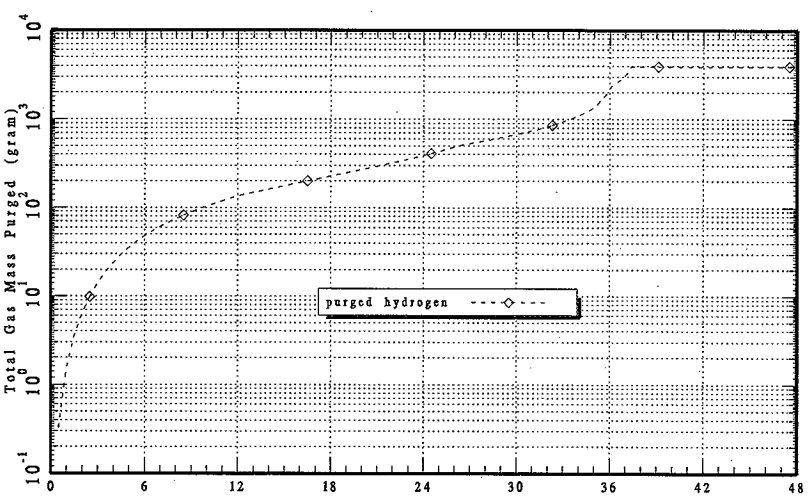
DSLOCOV2: LO-PRES THERM RUNAWAY w 35.5 Kg Water, Loss of Cool., Open Vent



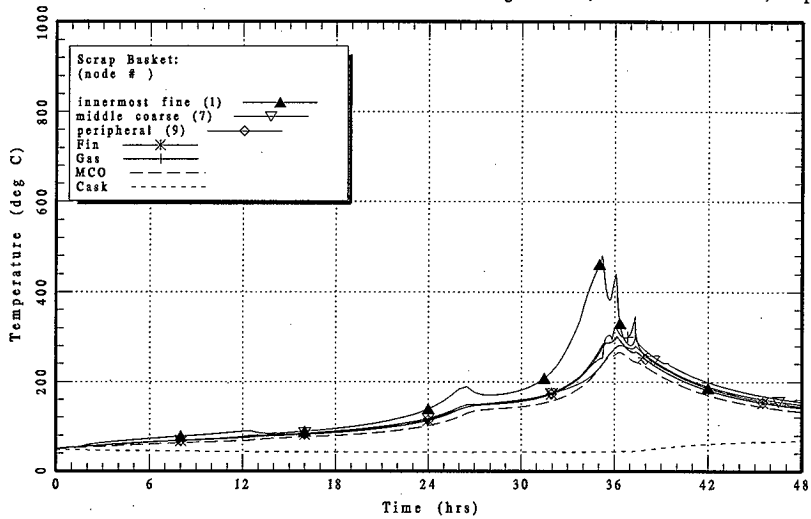


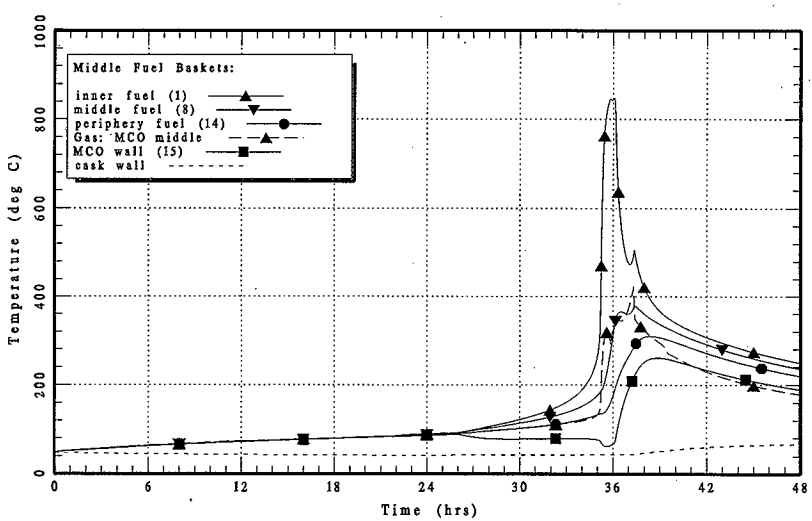
DSLOCOV2: LO-PRES THERM RUNAWAY w 35.5 Kg Water, Loss of Cool., Open Vent



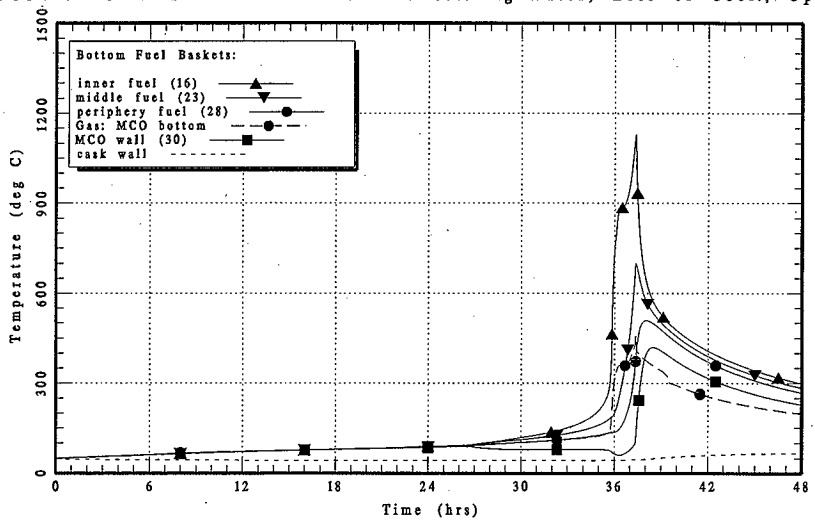


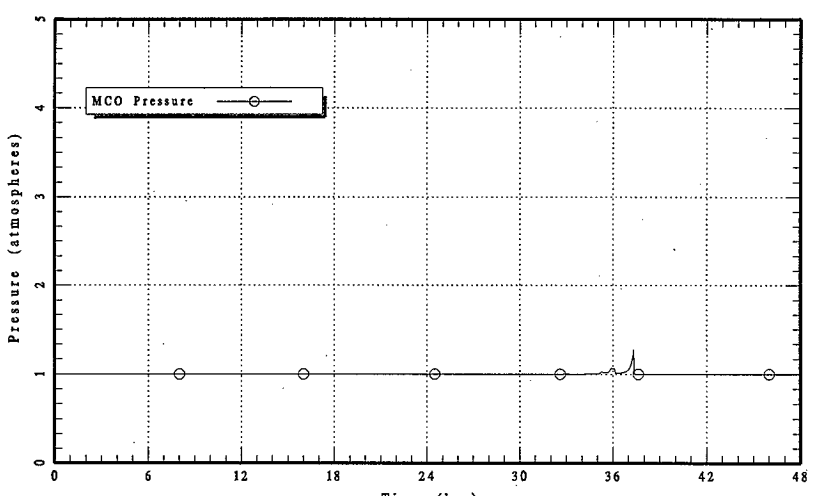
DSLOCOV2: LO-PRES THERM RUNAWAY w 35.5 Kg Water, Loss of Cool., Open Vent





DSLOCOV2: LO-PRES THERM RUNAWAY w 35.5 Kg Water, Loss of Cool., Open Vent





APPENDIX B

INPUT FILE AND INPUT DIFFERENCES

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APPENDIX B

INPUT FILE AND INPUT DIFFERENCES

The input file for the HANSF code, version 1.2 (Plys et al, 1998) for the VACUUM case (case 1) is listed below. Then input files for cases 2 through 18 are compared to the VACUUM input so that only the differences show up (ignoring format or comment differences). After the DSTOP input (case 18) differences are listed, the next files are compared with DSTOP because these cases (group IV) are closer to DSTOP than to VACUUM. The air ingress cases (group V) are compared to VACUUM input and the last five cases (group VI) are compared to DSTOP because they are more similiar to it than to the VACUUM input.

CASE 1, VACUUM, INPUT FILE

```
**********************************************************************
*  VACUUM- Vac @ 30 scfm; NO He Flow; Nom. Hydrides; Normal Cond.
*  UNLESS OTHERWISE NOTED, MKS UNITS
*
*  - 1 TIER OF SCRAP BASKET
*  - 4 TIERS OF FUEL BASKETS (MODELED AS TWO FUEL BASKETS)
*
*  IMPROVED VERSION PER
*
*  - VACUUM FLOW RATE IS 30 CFM INSTEAD OF 40 CFM
*  - SWITCH OVER TIME IS 8 HRS, SO GENERATE THE RESTART FILE EVERY 2
*    HRS.
*  - RUN TO TWO DAYS USING 0.2 SEC TIME STEP
*  - AMBIENT TEMPERATURE (CASK EXTERIOR) IS 80 F (26.7 C) INSTEAD OF
*    86 F(30 C)
*  - NEW HYDRATE MODEL IS USED
*  - REACTION OF NITROGEN WITH URANIUM IS ADDED
*  - CASK/MCO GAP IS 0.61 INCH (0.0155 M) INSTEAD OF 1 INCH (0.0254 M)
*  - FUEL SURFACE AREA PER FUEL BASKET IS 1.75 M^2
*  - BOTH SIDES OF THE CASK AND OUTER SURFACE OF MCO WALL TEMPERATURES
*    ARE FIXED USING NEW 'IMPOSED HEAT SINK SURFACE TEMPERATURE'
*    FACILITY (DO AWAY WITH ARTIFICIALLY INCREASED EMISSIVITY) FOR
*    WATER FILLED ANNULUS
*  - THE CASK HAS INNER DIAMETER OF 25.19" AND OUTER DIAMETER OF 39.81"
*    I.E. 7.31" (0.1857 M) THICK
*  - LOOK-UP TABLE CONTROL IMPLEMENTED
*  - 'WATER' GAS IN THE MCO/CASK GAP
*  - RADIATION HEAT TRANSFER FROM FUEL/SCRAP TO LID/FLOOR.
**********************************************************************
*
*-------------------------------------------------
CONTROL    ! Major keyword group
*-------------------------------------------------
*
*
 TITLE     ! Keyword; next line is title, title can be any length* -
 VACUUM- Vac @ 30 scfm; NO He Flow; Nom. Hydrides; Normal Cond.
END TITLE  ! Anything after END is a comment
*
```

```
*
 TIMING   ! Keyword
  TSTART       2703.01      ! START TIME=2700 sec, >0 FOR RESTART RUN
                            ! RESTART FILE IS READ FROM HANSF.RER
  TLAST      604800.     ! 168 hr = END TIME
  DTMIN
   0.0 0.05       ! MIN TIMESTEP (Seconds)
  DTMAX
   0.0    2.0        ! MAX TIMESTEP (Seconds)
   54000.   3.0        ! MAX TIMESTEP (Seconds)
  DTPRIN
  0.0  7200.     ! PRINT INTERVAL (Seconds)
  PLTMIN
  0.0    3600.     ! MIN PLOT INTERVAL (Seconds)
  PLTMAX
  0.0    3600.     ! MAX INTERVAL WITHOUT PLOT (Seconds)
  DTRST
  0.0    3600.     ! RESTART INTERVAL (Seconds)
  FTPCH    0.005       ! FRACTIONAL CHANGE IN T AND P
  FAECH    0.005       ! FRACTIONAL CHANGE IN Aerosol Mass
  FPPLCH   0.03        ! FRACTIONAL CHANGE FOR PLOTTING
END TIMING ! TIMING is a comment.
*
*
 PLOT    ! Keyword for plotting section
* Plotting syntax:
*
* PRESSURE n rlist - Pressure, Pa
* GAS-T  n rlist  - Gas Temperature, K
* HS-TI  n hlist  - Heat Sink Temperature - Inner Surface, K
* HS-TO  n hlist  - Heat Sink Temperature - Outer Surface, K
* HS-TA  n hlist  - Heat Sink Temperature - Average, K
* AEROSOL n rlist - Aerosol Mass (Total), kg
* GAS-W  n jlist  - Mass Flowrate, kg/s
* GAS-WX n jlist  - CounterCurrent Mass Flowrate, kg/s
* GAS-X   GASNAME n rlist  - Gas Mole Fraction
* GAS-RH  GASNAME n rlist  - Gas Relative Humidity
* GAS-MASS GASNAME n rlist - Gas Mass (Species), kg
* AER-MASS GASNAME n rlist - Aerosol Mass (Species), kg
* MASS    GASNAME n rlist - Total Mass (Species), kg
* LIQ-MASS - GASNAME n rlist - Deposited Mass (Species), kg
*
* Pressure, Gas Temperature, and total aerosol mass require a region
* list
*
* Heat Sink Temperatures need a heat sink number list
*
* Flowrates need a junction number list
*
* Gas concentration, relative humidity, individual species gas mass,
* individual species aerosol mass, total (gas+aerosol) individual
* species mass, and individual species deposited liquid mass require
* a region and gas name
*
 PRESSURE   1  1              ! Pressure in MCO
 GAS-T      5  1  2  3  4  5  ! Temps in regions 1,2,3,4 & 5
 HS-TI     11 31 32 33 34 35 36 37 38 39 40 41 !Scrap basket
 HS-TA      3  42 43 44          ! Cask, bottom, and lid
 HS-TA     10  1  2  3  4  5  6  7  8  9  10 !Mid. fuel
 HS-TA      5  11 12 13 14 15
```

```
 HS-TA     10  16  17  18  19  20  21  22  23  24  25 !Bot. fuel
 HS-TA      5  26  27  28  29  30
 GAS-X NITROGEN  3  1  2  3 ! N2 concentration in MCO
 GAS-X OXYGEN    3  1  2  3 ! O2 concentration in MCO
 GAS-X STEAM     3  1  2  3 ! H2O concentration in MCO
 GAS-X HYDROGEN  3  1  2  3 ! H2 concentration in MCO
 GAS-X HELIUM    3  1  2  3 ! He concentration in MCO
 GAS-W           3  1  2  3 ! Uni-directional mass flowrate
 GAS-WX          3  1  2  3 ! Counter-current mass flowrate
 GAS-MASS HYDROGEN   1  5 ! Mass of hydrogen in region 5
 GAS-MASS STEAM      1  5 ! Mass of steam in region 5
END PLOT ! PLOT is a comment
*
*
ACTIVE MODELS ! Keyword; MODELS is a comment; 1 = on, 0 = off
 IJUNC  1   ! Junction flow model
 ICCFLW 1   ! Counter-current flow model
 IHSINK 1   ! Heat sinks
 ICNDS  0   ! Condensation
 IASED  0   ! Aerosol Sedimentation
 IALEAK 0   ! Aerosol Leakage
 IFOG   0   ! Fog formation
 ISRC   1   ! User-defined sources
 IMCO   1   ! MCO models
 ISENS  0   ! Sensitivity runs
END ACTIVE MODELS ! ACTIVE MODELS  is a comment
*
*
C-------------------------------------------------
C    SOURCE GROUP:  GROUPS REPEATED FOR INPUT # OF REGIONS
C      END OF GROUP DESIGNATED BY 'REGION' OR 'END' KEYWORDS
C    ENTER: TIME, TEMP, FLOWRATES, POWER
C    SYNTAX EXAMPLE:
*SOURCES 1              ! -- KEYWORD AND # SOURCE GROUPS
* REGION  3  GASES 1        !-- REGION #, # GASES
*   HELIUM             !-- GAS NAMES MUST BE ON NEXT LINE
*  0    26.7   1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
*  1.0E9 26.7   1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
* END REGION              !-- ENDS A REGION SOURCE
*END SOURCES
*                    !-- FOR AEROSOL, SPECIFY -IVE REGION
*  REGION -1 GASES 1
*   NA2O
*   0.  300.0   4.44E-1  0.E0
*   10. 300.0   4.44E-1  0.E0
*   900. 300.0  4.44E-1  0.E0
*   901. 300.0  0.E0     0.E0
*   1.E5 300.0  0.E0     0.E0
*   END REGION              !-- ENDS A REGION SOURCE
* END SOURCE                !-- ENDS ALL SOURCE INPUT
*
*
END CONTROL    ! End of CONTROL keyword group
*
*
*-------------------------------------------------
VOLUMES   5     ! total number of control volumes
*-------------------------------------------------
* total MCO gas volume is 0.55 m^3, 0.55/3=0.183 per each node
* No more than 5 columns (regions) at a time
```

```
* Units:
* VOLUME m^3, SED_AREA m^2, ELEVATION m, TEMP_GAS K, PRESSURE Pa
*
*          MCO top   MCO middle  MCO bottom   gap    environment
 REGIONS      1         2         3         4         5
  VOLUME     0.153     0.186     0.199     0.115     1.E9
  SED_AREA   0.172     0.172     0.172     0.0       0.0
  ELEVATION  2.65      1.33      0.0       0.0       0.0
  TEMP_GAS   50.0      50.0      50.0      50.0      26.7
  PRESSURE   1.017E5   1.017E5   1.017E5   1.013E5   1.013E5
 END REGIONS  ! REGIONS is a comment
*
* If there are more than five regions, continue here
*
* REGIONS      6         7
*  VOLUME     0.183     1.E9
*  SED_AREA   0.27      0.0
*  ELEVATION  0.0       0.0
*  TEMP_GAS   323.15    26.85
*  PRESSURE   1.047E5   1.047E5
* END REGIONS  ! REGIONS is a comment
*
* Gas composition of each region; specify mole fraction of each gas
* No more than five columns at a time
*
 GASES        1         2         3         4         5
  HYDROGEN    0.05      0.05      0.05      0.0       0.0
  HELIUM      0.85      0.85      0.85      0.0       1.0
  STEAM       0.10      0.10      0.10      0.0       0.0
  OXYGEN      0.0       0.0       0.0       0.0       0.0
  NITROGEN    0.0       0.0       0.0       0.0       0.0
  WATER       0.0       0.0       0.0       1.0       0.0
 END GASES         ! GASES is a comment
*
* If there are more than five regions, continue here.
*
* GASES        6         7
*  HELIUM      0.89      0.0
*  STEAM       0.11      0.0158
*  OXYGEN      0.0       0.2067
*  NITROGEN    0.0       0.7775
*  WATER       0.0       0.0
* END GASES         ! GASES is a comment
*
* Aerosol concentration of each region (kg/m^3)
* No more than five columns at a time
*
* AEROSOLS     1         2         3         4         5
*  STEAM       0.0001    0.0       0.0       0.0       0.0
* END AEROSOLS ! AEROSOLS is a comment
*
* No more than five columns at a time, so continue with 6 & 7
*
* AEROSOLS     6         7
*  STEAM       0.0       0.0
* END AEROSOLS  ! AEROSOLS is a comment
*
* OPTIONAL TEMPERATURE AND PRESSURE CONTROL
* CONTROL MCO HEATUP GASES AND MCO INLET GAS TEMPERATURE
* IMPOSE TEMPERATURE LOOK-UP TABLE
```

```
* SYNTAX:
*  OFFSET_TIMETG
*  EXTRAPOLATION_TIMETG
*  TIMETG  IREG TIME1, TIME2...TIMELAST
*  TGFIX  IREG TEMP1, TEMP2... TEMPLAST   TEMPS ARE IN K!!!
*  LINEAR INTERPOLATION BETWEEN VALUES
*
*  SIMILAR SYNTAX FOR PRESSURE:
*  OFFSET_TIMETG
*  EXTRAPOLATION_TIMEPG
*  TIMEP  IREG  TIME1, TIME2...
*  PRFIX  IREG  PRES1, PRES2...PRESSURES ARE IN PA!!!
*
*  OFFSET_TIMETG=  OFFSET TIME; ENTER LOOKUP TABLE WITH
*            TIME+OFFSET_TIMETG
*  EXTRAPOLATION_TIMETG= LAST TO USE LAST VALUE IN THE TABLE,
*              = EXTRAP TO EXTRAPOLATE FROM LAST TWO POINTS,
*              = PERIOD TO WRAP AROUND.
*  OFFSET_TIMETG       50.
*  EXTRAPOLATION_TIMETG    LAST
*  TIMETG 1  0.0   100.    200.
*  TGFIX  1  293.15  373.15  473.15
*
*  CONTROL MCO BOUNDARY P,
*  OFFSET_TIMEPG       30.
*  EXTRAPOLATION_TIMEPG    EXTRAP
*  TIMEP 1  0.0   100.    200.
*  PRFIX  1  1.E5  1.2E5   1.4E5
*
END VOLUMES ! VOLUMES is a comment
*
C SOURCES 1              ! -- KEYWORD AND # SOURCE GROUPS
C REGION  1  GASES 1        !-- REGION #, # GASES
C   HELIUM           !-- GAS NAMES MUST BE ON NEXT LINE
C  0    323.15  2.2027E-3   0.E0
C  36000 323.15  2.2027E-3   0.E0
C  END REGION              !-- ENDS A REGION SOURCE
C END SOURCE
*
* Major keyword----------------------------------------------
HEAT_SINKS    44      ! Total number of heat sinks
*----------------------------------------------------------
* decay power based on 740 W per MCO.(776 W/5 FBs)
* No more than 5 columns at a time,
* Repeat the following structure,
* SINKS
* .
* .
* .
* END
*
* Syntax:
* IGEOM  1 for plane, 0 or 2 for cylinder
* RHO    Density (kg/m^3)
* KHS    Thermal Conductivity (W/m/K)
* CPHS   Specific Heat (J/kg/K)
* QV     Volumetric Heat Generation (W/m^3)
* XRI    Inner Radius (m)
* XRO    Outer Radius (m); for plane wall, thickness = XRO-XRI
* AHS    One-sided heat sink area (m^2)
```

```
* TIINIT  Initial inside surface temperature (C)
* TOINIT  Initial outside surface temperature (C)
* IMSLAB  Number of slabs; 3 is minimum
* IREGI   Region index for inner surface or 0 (insulated)
*         or -1 for constant temperature
* TIHS    Region surface temperature when IREGI = -1  (C)
* IREGO   Region index for outer surface or 0 (insulated)
*         or -1 for constant temperature
* TOHS    Region surface temperature when IREGO = -1  (C)
* XLHS    Characteristic length for natural convection (m)
* EHSI    Emissivity of inner surface
* EHSO    Emissivity of outer surface
*
* Fuel Basket #1 heat sinks 1 through 15
*
SINKS     1        2        3        4        5
*
IGEOM     0        0        0        0        0
RHO     18573.3  18573.3  18573.3  18573.3  18573.3
KHS       24.2     24.2     24.2     24.2     24.2
CPHS     122.67   122.67   122.67   122.67   122.67
QV      1955.20  1955.20  1955.20  1955.20  1955.20
XRI     0.00610  0.02160  0.00610  0.02160  0.00610
XRO     0.01625  0.03075  0.01625  0.03075  0.01625
AHS       0.557    1.310    0.557    1.310    0.557
TIINIT    50.00    50.00    50.00    50.00    50.00
TOINIT    50.00    50.00    50.00    50.00    50.00
IMSLAB        3        3        3        3        3
IREGI         2        2        2        2        2
TIHS        0.0      0.0      0.0      0.0      0.0
IREGO         2        2        2        2        2
TOHS        0.0      0.0      0.0      0.0      0.0
XLHS      0.661    0.663    0.661    0.663    0.661
EHSI       0.43     0.43     0.43     0.43     0.43
EHSO       0.43     0.43     0.43     0.43     0.43
END
*
SINKS     6        7        8        9        10
*
IGEOM     0        0        0        0        0
RHO     18573.3  18573.3  18573.3  18573.3  18573.3
KHS       24.2     24.2     24.2     24.2     24.2
CPHS     122.67   122.67   122.67   122.67   122.67
QV      1955.20  1955.20  1955.20  1955.20  1955.20
XRI     0.02160  0.00610  0.02160  0.00610  0.02160
XRO     0.03075  0.01625  0.03075  0.01625  0.03075
AHS       1.310    1.114    2.620    0.557    1.310
TIINIT    50.00    50.00    50.00    50.00    50.00
TOINIT    50.00    50.00    50.00    50.00    50.00
IMSLAB        3        3        3        3        3
IREGI         2        2        2        2        2
TIHS        0.0      0.0      0.0      0.0      0.0
IREGO         2        2        2        2        2
TOHS        0.0      0.0      0.0      0.0      0.0
XLHS      0.663    0.661    0.663    0.661    0.663
EHSI       0.43     0.43     0.43     0.43     0.43
EHSO       0.43     0.43     0.43     0.43     0.43
END
*                                  MCO WALL
SINKS     11       12       13       14       15
```

```
*
IGEOM      0       0       0       0       1
RHO    18573.3  18573.3  18573.3  18573.3  8000.
KHS      24.2     24.2     24.2     24.2    16.0
CPHS    122.67   122.67   122.67   122.67   500.0
QV     1955.20  1955.20  1955.20  1955.20    0.00
XRI    0.00610  0.02160  0.00610  0.02160   0.0
XRO    0.01625  0.03075  0.01625  0.03075  0.0127
AHS      0.557    1.310    1.114    2.620     2.2
TIINIT   50.00    50.00    50.00    50.00    50.00
TOINIT   50.00    50.00    50.00    50.00    50.00
IMSLAB       3        3        3        3        3
IREGI        2        2        2        2        2
TIHS       0.0      0.0      0.0      0.0      0.0
IREGO        2        2        2        2        4
TOHS       0.0      0.0      0.0      0.0      0.0
XLHS     0.661    0.663    0.661    0.663    3.950
EHSI      0.43     0.43     0.43     0.43      0.3
EHSO      0.43     0.43     0.43     0.43      0.3
END
*
* Fuel Basket #2 heat sinks 16 through 30
*
SINKS       16       17       18       19       20
*
IGEOM       0        0        0        0        0
RHO    18573.3  18573.3  18573.3  18573.3  18573.3
KHS      24.2     24.2     24.2     24.2     24.2
CPHS    122.67   122.67   122.67   122.67   122.67
QV     1955.20  1955.20  1955.20  1955.20  1955.20
XRI    0.00610  0.02160  0.00610  0.02160  0.00610
XRO    0.01625  0.03075  0.01625  0.03075  0.01625
AHS      0.557    1.310    0.557    1.310    0.557
TIINIT   50.00    50.00    50.00    50.00    50.00
TOINIT   50.00    50.00    50.00    50.00    50.00
IMSLAB       3        3        3        3        3
IREGI        3        3        3        3        3
TIHS       0.0      0.0      0.0      0.0      0.0
IREGO        3        3        3        3        3
TOHS       0.0      0.0      0.0      0.0      0.0
XLHS     0.661    0.663    0.661    0.663    0.661
EHSI      0.43     0.43     0.43     0.43     0.43
EHSO      0.43     0.43     0.43     0.43     0.43
END
*
SINKS       21       22       23       24       25
*
IGEOM       0        0        0        0        0
RHO    18573.3  18573.3  18573.3  18573.3  18573.3
KHS      24.2     24.2     24.2     24.2     24.2
CPHS    122.67   122.67   122.67   122.67   122.67
QV     1955.20  1955.20  1955.20  1955.20  1955.20
XRI    0.02160  0.00610  0.02160  0.00610  0.02160
XRO    0.03075  0.01625  0.03075  0.01625  0.03075
AHS      1.310    1.114    2.620    0.557    1.310
TIINIT   50.00    50.00    50.00    50.00    50.00
TOINIT   50.00    50.00    50.00    50.00    50.00
IMSLAB       3        3        3        3        3
IREGI        3        3        3        3        3
TIHS       0.0      0.0      0.0      0.0      0.0
```

```
IREGO     3       3       3       3       3
TOHS      0.0     0.0     0.0     0.0     0.0
XLHS      0.663   0.661   0.663   0.661   0.663
EHSI      0.43    0.43    0.43    0.43    0.43
EHSO      0.43    0.43    0.43    0.43    0.43
END
*                                 MCO WALL
SINKS     26      27      28      29      30
*
IGEOM     0       0       0       0       1
RHO       18573.3 18573.3 18573.3 18573.3 8000.
KHS       24.2    24.2    24.2    24.2    16.0
CPHS      122.67  122.67  122.67  122.67  500.0
QV        1955.20 1955.20 1955.20 1955.20 0.0
XRI       0.00610 0.02160 0.00610 0.02160 0.0
XRO       0.01625 0.03075 0.01625 0.03075 0.0127
AHS       0.557   1.310   1.114   2.620   2.2
TIINIT    50.00   50.00   50.00   50.00   50.00
TOINIT    50.00   50.00   50.00   50.00   50.00
IMSLAB    3       3       3       3       3
IREGI     3       3       3       3       3
TIHS      0.0     0.0     0.0     0.0     0.0
IREGO     3       3       3       3       4
TOHS      0.0     0.0     0.0     0.0     0
XLHS      0.661   0.663   0.661   0.663   3.950
EHSI      0.43    0.43    0.43    0.43    0.3
EHSO      0.43    0.43    0.43    0.43    0.3
END
*
* scrap basket heat sinks 31 through 41
*
*         R1-1    R2-2    R2-3    R3-4    R4-5
SINKS     31      32      33      34      35
*
IGEOM     0       0       0       0       0
RHO       19000.  19000.  19000.  19000.  19000.
KHS       26.9    26.9    26.9    26.9    26.9
CPHS      122.67  122.67  122.67  122.67  122.67
QV        2326.53 2326.53 2326.53 2326.53 2326.53
XRI       0.034930 0.055  0.075   0.09654 0.13
XRO       0.055   0.0750  0.09336 0.13    0.16
AHS       0.191   0.276   0.358   0.481   0.616
TIINIT    50.00   50.00   50.00   50.00   50.0
TOINIT    50.00   50.00   50.00   50.00   50.0
IMSLAB    5       5       5       5       5
IREGI     1       1       1       1       1
TIHS      0.0     0.0     0.0     0.0     0.0
IREGO     1       1       1       1       1
TOHS      0.0     0.0     0.0     0.0     0.0
XLHS      0.676   0.676   0.676   0.676   0.676
EHSI      0.7     0.7     0.7     0.7     0.7
EHSO      0.7     0.7     0.7     0.7     0.7
END
*         R5-6    R6-7    R7-8    R8-9    FIN
SINKS     36      37      38      39      40
*
IGEOM     0       0       0       0       1
RHO       19000.  19000.  19000.  19000.  8954.0
KHS       26.9    26.9    26.9    26.9    398.0
CPHS      122.67  122.67  122.67  122.67  384.0
```

```
QV      2326.53   2326.53   2326.53   2326.53    0.0
XRI      0.16    0.190      0.220     0.250      0.0
XRO      0.19    0.220      0.250    0.28416   0.00318
AHS     0.743    0.871      0.998     1.134     3.1187
TIINIT  50.00    50.00      50.00     50.00     50.00
TOINIT   50.00    50.00      50.00     50.00     50.00
IMSLAB    10       10         10        10        3
IREGI      1        1          1         1        1
TIHS     0.0      0.0        0.0       0.0      0.0
IREGO      1        1          1         1        1
TOHS     0.0      0.0        0.0       0.0      0.0
XLHS    0.676    0.676      0.676     0.676     0.676
EHSI     0.7      0.7        0.7       0.7      0.7
EHSO     0.7      0.7        0.7       0.7      0.7
END
*          MCO WALL
*
SINKS       41
*
IGEOM        1
RHO       8000.0
KHS        16.0
CPHS       500.0
QV          0.0
XRI         0.0
XRO        0.0127
AHS         1.32
TIINIT     50.00
TOINIT      50.00
IMSLAB       3
IREGI        1
TIHS        0.0
IREGO        4
TOHS        0.0
XLHS        3.95
EHSI        0.3
EHSO        0.3
END
*
*         CASK WALL   MCO BOT    MCO LID
SINKS       42        43        44
*
IGEOM        0         1         1
RHO       8000.     8000.     8000.
KHS        16.0      16.0      16.0
CPHS       500.0     500.0     500.0
QV          0.0       0.0       0.0
XRI        0.3199    0.0       0.0
XRO         0.5056    0.063     0.30
AHS        10.24      0.29      0.29
TIINIT     50.00     50.40     25.80
TOINIT      46.00     50.35     25.75
IMSLAB      10        10        20
IREGI        4         3         1
TIHS        0.0       0.0       0.0
IREGO        5         4         5
TOHS        0.0       0.0       0.0
XLHS        3.950      0.3       0.3
EHSI       0.25      0.25      1.00
EHSO        0.25      0.25      0.25
```

```
END
*
* USER CAN CONTROL HEAT SINK BOUNDARY TEMPERATURE
* SYNTAX:
*       OFFSET_TIMEHS
*       EXTRAPOLATION_TIMEHS
*       TIMTHS IHS ISD TIME1, TIME2...
*       THSFIX IHS ISD TEMP1, TEMP2..
* IHS = HEAT SINK NO.; ISD = SIDE NO. (1 OR 2) FOR IHS
* CONTROL HEAT SINK BOUNDARY T
 OFFSET_TIMEHS        0.
EXTRAPOLATION_TIMEHS    EXTRAP
TIMTHS 15 2 0.0    1.E6
THSFIX 15 2 50.0   50.0
TIMTHS 30 2 0.0    1.E6
THSFIX 30 2 50.0   50.0
TIMTHS 41 2 0.0    1.E6
THSFIX 41 2 50.0   50.0
TIMTHS 42 1 0.0    1.E6
THSFIX 42 1 50.0   50.0
TIMTHS 43 2 0.0    1.E6
THSFIX 43 2 50.0   50.0
*
*
END HEAT_SINKS ! HEAT_SINKS is a comment
*-----------------------------------------------------------------
JUNCTIONS  3  ! 3 Junctions
*-----------------------------------------------------------------
* 1) MCO bottom to MCO middle, 3->2
* 2) MCO middle to MCO top, 2->1
* 3) MCO top to Outlet volume, 1->5 (deactivated)
*
* Syntax:
* IJTYP  Junction Type: 1 = Normal, 2 = HEPA, 3 = Cover
* IR1    Upstream Region
* IR2    Downstream Region
* AJN    Area (m^2)
* ABYP   Bypass area for HEPA junction (m^2)
* PHEPA  HEPA Filter Failure Pressure (Pa)
* ACOV   Cover Area (m^2)
* MCOV   Cover Weight (kg)
* Z1JN   Elevation wrt floor of IR1 opening (m)
* Z2JN   "      "  "  "  IR2  "   "
* CJN    Loss coefficient multiplies 0.5*rho*v^2
* IHORIZ Orientation: 1 = horizontal, 0 = vertical
* XWJN   Characteristic width, m
* XHJN   Characteristic height, m
* XLJN   Characteristic length, m
* DFJN   Decontamination Factor
* N90    No. of 90 bends
*
  PATHS     1          2          3
*
    IJTYP   1          1          1
    IR1     3          2          1
    IR2     2          1          5
    IHORIZ  1          1          1
    XWJN    0.61       0.61       2.54E-2
    XHJN    0.61       0.61       2.54E-2
    XLJN    0.01       0.01       10.025
```

```
    AJN    0.10        0.013        0.
    Z1JN   1.2         1.2          1.2
    Z2JN   0.0         0.0          4.0
    CJN    1.0         1.0          4.0
    DFJN   1.0         1.0          1.0
    N90    0           0            3
  END PATHS  ! PATHS is a comment.
*
END JUNCTIONS  ! JUNCTIONS is a comment.
*-----------------------------------------------------------------
MCO    ! MCO Major Keyword
*-----------------------------------------------------------------
 GENERAL       ! Keyword for general inputs
 IOXDTN 1      ! =1, do oxidation of fuel/scrap
          ! =0, disable oxidation of fuel/scrap
 IHYD   0      ! =1, do hydriding/dehydriding calculation
          ! =0, disable hydriding/dehydriding calculation
 IDIVRT 1      ! =1, divert heat transfer to gas
          ! =0, do not divert heat transfer to gas
 IEVAP  1      ! =1, do evaporation/condensation of water
          ! =0, do not do evaporation/condensation
 ILAW   1      ! oxidation rate law, 0 - McGillivrary/Ritchie
          !              1 - Pearce
 IDEENT 0      ! =1,de-entrainment of aerosol due to scrap basket
          ! =0, disable de-entrainment calculation
 IENTR  0      ! =1, do entrainment of sludge particle calculation
          ! =0, disable entrainment calculation
 IHYDRA 1      ! =1, do decomposition of fuel oxide hydrate
          ! =0, disable hydrate decomposition calculation
 INITRI 0      ! =1, do nitriding calculation
          ! =0, disable nitriding calculation
 IRADIO 0      ! =1, do radiolysis calculation
          ! =0, disable radiolysis calculation
 XDHYD  2.E-5  ! average diameter of hydride particle (m)
 IHSCSK 42     ! define the cask heat sink
 IRGAP  4      ! define the gap node (between MCO wall and the cask)
          ! radiative/convective h.t. between the MCO wall and
          !the cask is computed and some of the heat is diverted
          ! to gas for stability
 XGPCSK 0.0152 ! gap distance between the MCO wall and the cask
 FHTLID 1.0    ! =0, turn off the raditive heat transfer between the
          !    fuel/scrap and the lid/floor
          ! =1, fully account for the radiative heat transfer
 RHOSL  5000.  ! sludge particle density (kg/m^3)
 SASL   1000.  ! sludge specific area (m^2/m^3)
 XDSL   1.E-6  ! sludge particle diameter (m)
*
* Hydrate Model: two-step decomposition,
*   input curves for ln P and ln K
*   first step for x > XHYD2, second step for x < XHYD2
*
* 10 % weight fraction of sludge being water is equivalent to 90 %
* of sludge being hydrated with 2 moles of
* water per mole of uranium oxide
*
 FHYSL  0.5    ! fraction of sludge that is hydrated
 XHYSL  2.0    ! stoichiometry number of hydrate: no. of moles of
          ! water per mole of uranium oxide (UO3.H2O)
 XHYD2  1.0    ! H2O/U ratio (stoich. number) to switch
          ! from first to second correlation
```

```
 XHYD3  0.5  ! H20/U ratio (stoich. number) to switch
          ! from second to third correlation
 AHYEQ1 15.912  ! 'A' IN LN P = A + B/T  FOR X > XHYD2
 BHYEQ1 -6131.E0  ! 'B' IN LN P = A + B/T  FOR X > XHYD2
 AHYEQ2 18.382  ! 'A' IN LN P = A + B/T  FOR X < XHYD2
 BHYEQ2 -7766.E0  ! 'B' IN LN P = A + B/T  FOR X < XHYD2
 AHYEQ3 18.408  ! 'A' IN LN P = A + B/T  FOR X < XHYD3
 BHYEQ3 -8488.E0  ! 'B' IN LN P = A + B/T  FOR X < XHYD3
*
 ADEHY1 2.793E0  ! 'A' IN LN K = A + B/T  FOR X > XHYD2
 BDEHY1 -5111.E0  ! 'B' IN LN K = A + B/T  FOR X > XHYD2
 ADEHY2 6.348E0  ! 'A' IN LN K = A + B/T  FOR X < XHYD2
 BDEHY2 -7241.E0  ! 'B' IN LN K = A + B/T  FOR X < XHYD2
 ADEHY3 4.632E0  ! 'A' IN LN K = A + B/T  FOR X < XHYD3
 BDEHY3 -7548.E0  ! 'B' IN LN K = A + B/T  FOR X < XHYD3
*
 DHHY1  2.86E6  !  Decomposition enthalpy J/kg H2O: 1st step
 DHHY2  3.70E6  !  Decomposition enthalpy J/kg H2O: 2nd step
 DHHY3  3.70E6  !  Decomposition enthalpy J/kg H2O: 3rd step
 FPROHY  1.0     ! hydride production rate law multiplier
 FCONHY  1.0     ! hydride consumption rate law multiplier
 FNITRI  1.0     ! nitriding rate law multiplier
*
* PUMP, FEED, AND CONDENSER MODELS
* Syntax:
* PUMP IRIPUM IROPUM ICONPM ITFEED WVPUMP  WVFEED  TGFEED TCONPM
* Definitions:
* IRIPUM - Pump inlet region
* IROPUM - Pump outlet region
* ICONPM - Node to which the condensed steam is dumped for book-keeping
* ITFEED - If non-zero, overides TGFEED with the desingated region
*        temperature.  Used to specified time-varying feed temperature
* WVPUMP - Pump volumetric flowrate (m^3/s)
* WVFEED - Feed volumetric flowrate (m^3/s)
* TGFEED - Feed temperature  (K)
* TCONPM - Condenser cooling coil temperature  (K)
*
* 30 FT^3/MIN * 1 MIN/60 SEC * 0.02832 M^3/1 FT^3 = 0.01416 M^3/SEC
*  4 ft3/min = 0.0022027 m3/s
* 1.6 ft3/min * 1min/60 sec * 0.02832 m3/ft3 *299.85/273.15 = 0.000829 m3/s
* PUMP IRIPUM IROPUM ICONPM ITFEED WVPUMP  WVFEED  TGFEED TCONPM
  PUMP 1     5     0    0   1.416E-2 0.     0.0    0.0
*
* Radiolysis parameters
*
 FRAD   1.0     ! multiplier for radiolysis
 FALPHA  0.197    ! alpha fractional heat load
 FBETA  0.486    ! beta fractional heat load
 FGAMMA  0.317    ! gamma fractional heat load
 QPHOTO  2.4E-6   ! heat deposition rate in MCO free water per gram
          ! per MTU of fuel loading
END GENERAL       ! GENERAL is a comment
*
SOLAR_RAD
*
* pointers to heat sinks representing the cask wall and the top
* solar radiation impinges on these
*
IHCASK  42
IHTOP   44
```

```
*
* look-up table for solar radiation throughout a day (sec .vs. W/m^2)
*
 OFFSET_TIMDAY       21600. ! offset by six hours
 EXTRAPOLATION_TIMDAY  PERIOD ! repeat the diurnal cycle
 TIMDAY     0.0  3600.0  7200.0 10800.0 14400.0 18000.0 21600.0
      25200.0 28800.0 32400.0 36000.0 39600.0 43200.0 46800.0
      50400.0 54000.0 57600.0 61200.0 64800.0 68400.0 72000.0
      75600.0 79200.0 82800.0 86400.0
 RADSUN    0.0   0.0   0.0   0.0   0.0   0.0   0.0
        0.0   0.0   0.0   0.0   0.0   0.0   0.0
        0.0   0.0   0.0   0.0   0.0   0.0   0.0
        0.0   0.0   0.0   0.0
END SOLAR_RAD
*
*
PLOT    ! Keyword for MCO specific plotting section
* Plotting syntax:
*
* PUMPH2        - Hydrogen flow rate into the vacuum pump
* CORRODH2      - Hydogen generation rate by fuel/scrap corrosion
* HS-H2O n hlist  - Water mass on heat sink surfaces, kg
* HS-HYH2O n hlist- Water mass in sluge on heat sink surfaces, kg
* GAS-WH2 n jlist - Hydrogen flow rate through junctions, kg/s
*
* Water mass and sludge water mass require a heat sink list
*
* Hydrogen flow rate requires a junction list
*
 PUMPH2     ! hydrogen pumping flow rate
 CORRODH2   ! hydrogen generation rate by corrosion
 HS-H2O   2 1 14  ! mass of water on h.s. 1 & 14
 HS-HYH2O 2 1 14  ! mass of slude water on h.s. 1& 14
 GAS-WH2  3 1 2 3 ! hydrogen flow rate thru junctions 1, 2, & 3
END PLOT  ! PLOT is a comment
FUEL_BSKT 2  ! Total number of fuel baskets
*
* 1st Fuel Basket
*
IHSFL  1 2 3 4 5 6 7 8 9 10 11 12 13 14
* define the heat sinks comprising the first fuel basket (must be
* in pairs, for inner and outer elements)
*
IFLINS 0     ! define the adjacent center insert heat sink,
*            0 for no insert
IFLMCO 15    ! define the adjacent MCO wall heat sink
IFLLID 0     ! define the lid or floor heat sink to which the fuel
          ! radiate to
AFLFL  0.10  ! flow area in the basket
*
* fraction of geometric area exposed for oxidation
*     = area available for oxidation/total heat sink area
*
* 7.0 m^2 / (2*33.6 m^2) = 0.10417
FAOXFL  0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
      0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
FOX    10  0.0  ! multiplier for FAOXFL
*
*
*Bounding Hydride: 28% of exposed surface with mulitplier of 370
```

```
* XFLOX0*FXHD0 = 0.28 * 370 * 2.E-5/6
*          = 3.45E-4
* Bounding hydride-FAI has mulitiplier of 300 * .28
*          = 2.8E-4
* Nominal Hydride: 3.7% of exposed surface with Mult of 370
*          = 0.037 * 370 *2.0E-5 / 6
*          = 4.56E-5
* Nominal Hydride-FAI has mult of 300 * 0.037
*          = 3.7E-5
*
  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
! initial oxide/Hydride thickness on the exposed surface (m)
  FXHYD0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
       1.0 1.0 1.0 1.0 1.0 1.0 1.0
! fraction of oxide which is hydride
* initial amount (kg) of water per geometric surface area (m^2) of fuel
* 24 kg / (2*33.6 m^2) = 0.3571
* 480 kg/(2*33.53 m2) = 20*0.3571
* 8.6/2/17.0 = 0.256 kg/m^2 (per side)
 FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
      0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
 FWFLI0 0.00   ! on the outer surface of the insert
 FWFLM0 0.00   ! on the inner surface of the MCO wall
 FAWFL  0.1    ! wetted fraction of fuel surface
 FAWFLM 1.0    ! wetted fraction of MCO wall
 MSLFL  5.9    ! mass of sludge particles (kg) in the fuel basket
          ! 11.8 kg per fuel basket x 2 basket = 23.6 kg
*
* view factor matrix between the insert,
* outer surface of outer fuel elements,
* and the MCO wall.  Therefore, the dimension of the square matrix is
* 1+number of fuel rods+1. If there is no insert, number of fuel rods+1.
*
 FVIEW 0.473 0.320 0.181 0.028 0.000 0.000 0.000 0.000
      0.320 0.028 0.306 0.306 0.028 0.014 0.000 0.000
      0.181 0.306 0.000 0.334 0.153 0.000 0.028 0.000
      0.014 0.153 0.167 0.167 0.153 0.153 0.167 0.028
      0.000 0.028 0.153 0.306 0.000 0.028 0.306 0.181
      0.000 0.014 0.000 0.306 0.028 0.000 0.306 0.348
      0.000 0.000 0.014 0.167 0.153 0.153 0.049 0.466
      0.000 0.000 0.000 0.0354 0.1146 0.2202 0.5898 0.040
*
*
* gap distance for micro-convection calculation
*
 XGAP  0.000 0.021 0.021 0.073 0.000 0.000 0.000 0.000
      0.021 0.000 0.021 0.021 0.073 0.073 0.000 0.000
      0.021 0.021 0.000 0.021 0.021 0.000 0.073 0.000
      0.073 0.021 0.021 0.000 0.021 0.021 0.021 0.083
      0.000 0.073 0.021 0.021 0.000 0.073 0.021 0.058
      0.000 0.073 0.000 0.021 0.073 0.000 0.021 0.026
      0.000 0.000 0.073 0.021 0.021 0.021 0.000 0.016
      0.000 0.000 0.000 0.083 0.058 0.026 0.016 0.000
  END IHSFL for first fuel basket
*
* 2nd Fuel Basket
*
* heat sink pairs for second fuel basket
*
```

```
IHSFL  16 17 18 19 20 21 22 23 24 25 26 27 28 29
IFLINS 0    ! define the adjacent center insert heat sink,
        ! 0 for no insert
IFLMCO 30   ! define the adjacent MCO wall heat sink
IFLLID 43   ! define the lid or floor heat sink to which the fuel
        ! radiate to
AFLFL  0.10 ! flow area in the basket,
*
* fraction of geometric area exposed for oxidation
* 7.0 m^2 / (2*33.6 m^2) = 0.10417
FAOXFL 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
     0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
FOX    10  0.0  ! multiplier for FAOXFL
*
*
*Bounding Hydride: 28% of exposed surface with mulitplier of 370
* XFLOX0*FXHD0 = 0.28 * 370 * 2.E-5/6
*          = 3.45E-4
* Bounding hydride-FAI has mulitiplier of 300 * .28
*          = 2.8E-4
* Nominal Hydride: 3.7% of exposed surface with Mult of 370
*          = 0.037 * 370 *2.0E-5 / 6
*          = 4.56E-5
* Nominal Hydride-FAI has mult of 300 * 0.037
*          = 3.7E-5
*
  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
! initial oxide/Hydride thickness on the exposed surface (m)
  FXHYD0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
       1.0 1.0 1.0 1.0 1.0 1.0 1.0
! fraction of oxide which is hydride
* initial amount (kg) of water per geometric surface area (m^2) of fuel
*
FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
     0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
FWFLI0 0.0   ! on the outer surface of the insert
* 1 kg / 2.2 m^2 = 0.4545
FWFLM0 0.4545 ! on the inner surface of the MCO wall
FAWFL  0.1   ! wetted fraction of fuel surface
FAWFLM 1.0   ! wetted fraction of MCO wall
MSLFL  5.9   ! mass of sludge particles (kg) in the fuel basket
        ! 11.8 kg per fuel basket x 2 basket = 23.6 kg
*
* view factor matrix between the insert,
* outer surface of outer fuel elements,
* and the MCO wall. Therefore, the dimension of the square matrix is
* 1+number of fuel rods+1. If there is no insert, number of fuel rods+1.
*
FVIEW 0.473 0.320 0.181 0.028 0.000 0.000 0.000 0.000
     0.320 0.028 0.306 0.306 0.028 0.014 0.000 0.000
     0.181 0.306 0.000 0.334 0.153 0.000 0.028 0.000
     0.014 0.153 0.167 0.167 0.153 0.153 0.167 0.028
     0.000 0.028 0.153 0.306 0.000 0.028 0.306 0.181
     0.000 0.014 0.000 0.306 0.028 0.000 0.306 0.348
     0.000 0.000 0.014 0.167 0.153 0.153 0.049 0.466
     0.000 0.000 0.000 0.0354 0.1146 0.2202 0.5898 0.040
*
*
* gap distance for micro-convection calculation
```

```
*
 XGAP  0.000 0.021 0.021 0.073 0.000 0.000 0.000 0.000
     0.021 0.000 0.021 0.021 0.073 0.073 0.000 0.000
     0.021 0.021 0.000 0.021 0.021 0.000 0.073 0.000
     0.073 0.021 0.021 0.000 0.021 0.021 0.021 0.083
     0.000 0.073 0.021 0.021 0.000 0.073 0.021 0.058
     0.000 0.073 0.000 0.021 0.073 0.000 0.021 0.026
     0.000 0.000 0.073 0.021 0.021 0.021 0.000 0.016
     0.000 0.000 0.000 0.083 0.058 0.026 0.016 0.000
 END IHSFL for 2nd fuel basket
 END FUEL_BSKT
*
 SCRAP_BSKT 1   ! Total number of scrap baskets
*
 IHSSC   31 32 33 ! ring 1, theta
       37  36 35 34   ! ring 6 & 5, radial
       38  39    ! ring 11 & 12, radial
*
  ISCINS 0    ! define the adjacent center insert heat sink,
           ! 0 for no insert
  ISCFIN 40    ! define copper fin heat sink
  ISCMCO 41    ! define the adjacent MCO wall heat sink
  ISCLID 44    ! define the lid or floor heat sink to which the scrap
           ! radiate to
* porosity of the scrap for each heat sink in the order read in
* (31, 32, 33, 34, ..)
  FPOROS 0.40 0.40 0.40 0.72293 0.72293 0.72293 0.72293 0.72293 0.72293 0.72293
* characteristic size for each scrap heat sink in the order read in (m)
  XDSCRP 0.00635 0.00635 0.00635 0.00635 0.00635
       0.0254  0.0254  0.0254  0.0254
  XRSCBK  0.2842 ! radius of scrap basket (m)
  XHSCBK  0.676  ! height of scrap basket (m)
*
* exposed surface area available for oxidation
* per unit volume of scrap (1/m) for
* each scrap basket heat sink in the order read in
* Example:
*   6 m^2 bounding oxidation area: 6/0.1676 = 35.8 m^2
*  3.0 m^2 fine oxidation area: 3/0.01592= 188.44 m^2/m^3
* 3 m^2 coarse oxidation area: 3.0/0.1517 = 19.776 m^2/m^3
*
  AVOXSC  188.44 188.44 188.44 19.776 19.776 19.776  19.776 19.776 19.776 19.776
  FOXSC   10  0.0    ! multiplier for AVOXSC
*
*Bounding Hydride: 28% of exposed surface with mulitplier of 370
* XFLOX0*FXHD0 = 0.28 * 370 * 2.E-5/6
*           = 3.45E-4
* Bounding hydride-FAI has mulitiplier of 300 * .28
*           = 2.8E-4
* Nominal Hydride: 3.7% of exposed surface with Mult of 370
*           = 0.037 * 370 *2.0E-5 / 6
*           = 4.56E-5
* Nominal Hydride-FAI has mult of 300 * 0.037
*           = 3.7E-5
*
  XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
! initial oxide/Hydride thickness on the exposed surface (m)
  FSCHYD  1.0  1.0  1.0  1.0  1.0  1.0  1.0
       1.0  1.0  1.0  1.0  1.0  1.0  1.0
```

```
! fraction of oxide which is hydride
* 1.5 kg of water total for scrap basket; 1.5/0.16782 = 8.949 kg/m^3
* 148.18 kg of water total for scrap basket; 148.18/0.17491m3 = 847.18
  MVWSC0  8.949  ! 1.5 kg initial amount (kg) of water per unit bulk volume
          ! (m^3) of scrap
  FWSCI0  0.0    ! on the outer surface of the insert
          ! (per unit area, m^2)
  FWSCM0  0.0    ! on the inner surface of the MCO wall
          ! (per unit area, m^2)
  FAWSC   0.1    ! wetted fraction of surface area
  FAWSCM  1.0    ! wetted fraction of MCO wall
  XSCINS  0.00   ! gap distance between the insert and scrap basket
          ! 1/4" gap for scrap basket and mco wall
  XSCMCO  0.00635 ! gap distance between scrap basket and MCO wall
  MSLSC   8.94   ! mass of sludge particles (kg) in the scrap basket
 END IHSSC for 1st scrap basket
 END SCRAP_BSKT
*
END MCO
```

CASE 0, NORMAL (initial run PURGENH0), INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> PURGENH0.DAT
-------------------------------
> SOURCES 1                ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1       !-- REGION #, # GASES
>    HELIUM                 !-- GAS NAMES MUST BE ON NEXT LINE
>  0.   26.7   0.0 0.0   ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>  1512. 26.7   1.23E-4 0.0   ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>  1.0E9 26.7   1.23E-4 0.0   ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION               !-- ENDS A REGION SOURCE
> END SOURCES
<       AJN     0.10        0.013        0.
---
>       AJN     0.10        0.013        3.1875E-5
<    PUMP  1     5     0     0   1.416E-2  0.     0.0    0.0
---
< MSLFL  5.9  ! mass of sludge particles (kg) in the fuel basket
<             ! 11.8 kg per fuel basket x 2 basket = 23.6 kg
---
> MSLFL  5.55  ! mass of sludge particles (kg) in the fuel volume
>             ! 5.6 kg per fuel volume x 2 vols = 11.2 kg
< MSLFL  5.9  ! mass of sludge particles (kg) in the fuel basket
---
> MSLFL  5.55  ! mass of sludge particles (kg) in the fuel basket
<  MSLSC  8.94  ! mass of sludge particles (kg) in the scrap basket
---
>  MSLSC  1.90  ! mass of sludge particles (kg) in the scrap basket
```

CASE 2, VAC75KG, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> VAC75KG.DAT
-------------------------------
< FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
<        0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
---
> * 24 kg / (2*33.6 m^2) = 0.3571
> * 51.5 kg / (33.6 m^2) = 1.5327
> FWFL0  1.5327  1.5327  1.5327  1.5327  1.5327  1.5327  1.5327
>        1.5327  1.5327  1.5327  1.5327  1.5327  1.5327  1.5327
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 3, VACPUR, INPUT DIFFERENCES

```
< VACUUM.DAT
> VACPUR.DAT
---
> SOURCES 1                ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1       !-- REGION #, # GASES
>    HELIUM                 !-- GAS NAMES MUST BE ON NEXT LINE
>  0    26.7   1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>  1.0E9 26.7   1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
```

```
>  END REGION              !-- ENDS A REGION SOURCE
> END SOURCES
```

CASE 4, PURGE, INPUT DIFFERENCES

```
< VACUUM.DAT
> PURGE.DAT
---------------
> SOURCES 1               ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1       !-- REGION #, # GASES
>     HELIUM            !-- GAS NAMES MUST BE ON NEXT LINE
>   0.0   26.7   1.23E-4 0.0   ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>   1.0E9 26.7   1.23E-4 0.0   ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION              !-- ENDS A REGION SOURCE
> END SOURCES
<       AJN     0.10        0.013        0.
---
>       AJN     0.10        0.013        3.1875E-5
<    PUMP  1     5     0    0   1.416E-2  0.      0.0    0.0
```

CASE 5, VACHOT, INPUT DIFFERENCES

```
< VACUUM.DAT
> VACHOT.DAT
< THSFIX 15 2 50.0   50.0
---
> THSFIX 15 2 85.0   85.0
< THSFIX 30 2 50.0   50.0
---
> THSFIX 30 2 85.0   85.0
< THSFIX 41 2 50.0   50.0
---
> THSFIX 41 2 85.0   85.0
< THSFIX 42 1 50.0   50.0
---
> THSFIX 42 1 85.0   85.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 85.0   85.0
```

CASE 6, VPURHOT, INPUT DIFFERENCES

```
< VACUUM.DAT
> VPURHOT.DAT
---
> SOURCES 1               ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1       !-- REGION #, # GASES
>     HELIUM            !-- GAS NAMES MUST BE ON NEXT LINE
>   0    26.7   1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>   1.0E9 26.7   1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION              !-- ENDS A REGION SOURCE
> END SOURCES
<  TEMP_GAS    50.0      50.0      50.0      50.0      26.7
---
```

```
>  TEMP_GAS    50.0      50.0     50.0      85.0     26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 85.0   85.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 85.0   85.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 85.0   85.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 85.0   85.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 85.0   85.0
```

CASE 7, PURHOT, INPUT DIFFERENCES

```
< VACUUM.DAT
> PURHOT.DAT
---
>  SOURCES 1                ! -- KEYWORD AND # SOURCE GROUPS
>   REGION  3  GASES 1        !-- REGION #, # GASES
>     HELIUM              !-- GAS NAMES MUST BE ON NEXT LINE
>    0.0   26.7   1.23E-4 0.0   ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>    1.0E9 26.7   1.23E-4 0.0   ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>   END REGION               !-- ENDS A REGION SOURCE
>  END SOURCES
<  TEMP_GAS    50.0      50.0     50.0      50.0     26.7
---
>  TEMP_GAS    50.0      50.0     50.0      85.0     26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 85.0   85.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 85.0   85.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 85.0   85.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 85.0   85.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 85.0   85.0
<       AJN     0.10        0.013        0.
---
>       AJN     0.10        0.013        3.1875E-5
<    PUMP 1     5     0    0   1.416E-2 0.     0.0    0.0
```

CASE 8, VACLOF, INPUT DIFFERENCES

```
< VACUUM.DAT
> VACLOF.DAT
```

```
< OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0   50.0
---
> * OFFSET_TIMEHS       0.
> *EXTRAPOLATION_TIMEHS    EXTRAP
> *TIMTHS 15 2 0.0    1.E6
> *THSFIX 15 2 50.0   50.0
> *TIMTHS 30 2 0.0    1.E6
> *THSFIX 30 2 50.0   50.0
> *TIMTHS 41 2 0.0    1.E6
> *THSFIX 41 2 50.0   50.0
> *TIMTHS 42 1 0.0    1.E6
> *THSFIX 42 1 50.0   50.0
> *TIMTHS 43 2 0.0    1.E6
> *THSFIX 43 2 50.0   50.0
```

CASE 9, VLOFHOT, INPUT DIFFERENCES

```
< VACUUM.DAT
> VLOFHOT.DAT
<  TEMP_GAS    50.0      50.0     50.0      50.0     26.7
---
>  TEMP_GAS    50.0      50.0     50.0      85.0     26.7
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS       0.
> CEXTRAPOLATION_TIMEHS    EXTRAP
> CTIMTHS 15 2 0.0    1.E6
> CTHSFIX 15 2 85.0   85.0
> CTIMTHS 30 2 0.0    1.E6
> CTHSFIX 30 2 85.0   85.0
> CTIMTHS 41 2 0.0    1.E6
> CTHSFIX 41 2 85.0   85.0
> CTIMTHS 42 1 0.0    1.E6
> CTHSFIX 42 1 85.0   85.0
> CTIMTHS 43 2 0.0    1.E6
```

```
> CTHSFIX 43 2 85.0   85.0
```

CASE 10, VACLOC, INPUT DIFFERENCES

```
< VACUUM.DAT
> VACLOC.DAT
<  TEMP_GAS   50.0      50.0    50.0      50.0    26.7
---
>  TEMP_GAS   50.0      50.0    50.0      26.7    26.7
<  OXYGEN     0.0      0.0     0.0       0.0      0.0
<  NITROGEN   0.0      0.0     0.0       0.0      0.0
<  WATER      0.0      0.0     0.0       1.0      0.0
---
>  OXYGEN     0.0      0.0     0.0       0.21     0.0
>  NITROGEN   0.0      0.0     0.0       0.79     0.0
>  WATER      0.0      0.0     0.0       0.0      0.0
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS   EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0   50.0
---
> * OFFSET_TIMEHS       0.
> *EXTRAPOLATION_TIMEHS   EXTRAP
> *TIMTHS 15 2 0.0   1.E6
> *THSFIX 15 2 50.0   50.0
> *TIMTHS 30 2 0.0   1.E6
> *THSFIX 30 2 50.0   50.0
> *TIMTHS 41 2 0.0   1.E6
> *THSFIX 41 2 50.0   50.0
> *TIMTHS 42 1 0.0   1.E6
> *THSFIX 42 1 50.0   50.0
> *TIMTHS 43 2 0.0   1.E6
> *THSFIX 43 2 50.0   50.0
```

CASE 11, VPURLOC, INPUT DIFFERENCES

```
< VACUUM.DAT
> VPURLOC.DAT
---
>  SOURCES 1              ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1     !-- REGION #, # GASES
>     HELIUM              !-- GAS NAMES MUST BE ON NEXT LINE
>  0    26.7   1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>   1.0E9 26.7   1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION             !-- ENDS A REGION SOURCE
> END SOURCES
<  OXYGEN     0.0      0.0     0.0       0.0      0.0
<  NITROGEN   0.0      0.0     0.0       0.0      0.0
```

```
< WATER      0.0     0.0     0.0      1.0      0.0
---
> OXYGEN     0.0     0.0     0.0     0.210     0.0
> NITROGEN   0.0     0.0     0.0     0.790     0.0
> WATER      0.0     0.0     0.0      0.0      0.0
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0  50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0  50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0  50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0  50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0  50.0
---
> C OFFSET_TIMEHS       0.
> CEXTRAPOLATION_TIMEHS    EXTRAP
> CTIMTHS 15 2 0.0    1.E6
> CTHSFIX 15 2 50.0   50.0
> CTIMTHS 30 2 0.0    1.E6
> CTHSFIX 30 2 50.0   50.0
> CTIMTHS 41 2 0.0    1.E6
> CTHSFIX 41 2 50.0   50.0
> CTIMTHS 42 1 0.0    1.E6
> CTHSFIX 42 1 50.0   50.0
> CTIMTHS 43 2 0.0    1.E6
> CTHSFIX 43 2 50.0   50.0
```

CASE 12, PURLOF, INPUT DIFFERENCES

```
< VACUUM.DAT
> PURLOF.DAT
---
> SOURCES 1              ! -- KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1        !-- REGION #, # GASES
>    HELIUM             !-- GAS NAMES MUST BE ON NEXT LINE
>  0.0  26.7  1.23E-4 0.0  ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>  1.0E9 26.7  1.23E-4 0.0  ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION             !-- ENDS A REGION SOURCE
> END SOURCES
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0  50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0  50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0  50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0  50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0  50.0
---
> * OFFSET_TIMEHS       0.
> *EXTRAPOLATION_TIMEHS    EXTRAP
```

```
> *TIMTHS 15 2 0.0   1.E6
> *THSFIX 15 2 85.0   85.0
> *TIMTHS 30 2 0.0   1.E6
> *THSFIX 30 2 85.0   85.0
> *TIMTHS 41 2 0.0   1.E6
> *THSFIX 41 2 85.0   85.0
> *TIMTHS 42 1 0.0   1.E6
> *THSFIX 42 1 85.0   85.0
> *TIMTHS 43 2 0.0   1.E6
> *THSFIX 43 2 85.0   85.0
<      AJN    0.10        0.013        0.
---
>      AJN    0.10        0.013        3.1875E-5
<   PUMP 1     5     0    0   1.416E-2 0.     0.0    0.0
```

CASE 13, PURLOC, INPUT DIFFERENCES

```
< VACUUM.DAT
> PURLOC.DAT
---
> SOURCES 1                ! – KEYWORD AND # SOURCE GROUPS
>  REGION  3  GASES 1        !-- REGION #, # GASES
>     HELIUM             !-- GAS NAMES MUST BE ON NEXT LINE
>   0.0  26.7   1.23E-4 0.0   ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
>   1.0E9 26.7   1.23E-4 0.0   ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
>  END REGION               !-- ENDS A REGION SOURCE
> END SOURCES
<  TEMP_GAS    50.0       50.0      50.0       50.0      26.7
---
>  TEMP_GAS    50.0       50.0      50.0       26.7      26.7
<  OXYGEN      0.0        0.0       0.0        0.0       0.0
<  NITROGEN    0.0        0.0       0.0        0.0       0.0
<  WATER       0.0        0.0       0.0        1.0       0.0
---
>  OXYGEN      0.0        0.0       0.0        0.21      0.0
>  NITROGEN    0.0        0.0       0.0        0.79      0.0
>  WATER       0.0        0.0       0.0        0.0       0.0
< OFFSET_TIMEHS        0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0   50.0
---
> * OFFSET_TIMEHS        0.
> *EXTRAPOLATION_TIMEHS    EXTRAP
> *TIMTHS 15 2 0.0   1.E6
> *THSFIX 15 2 85.0   85.0
> *TIMTHS 30 2 0.0   1.E6
> *THSFIX 30 2 85.0   85.0
> *TIMTHS 41 2 0.0   1.E6
> *THSFIX 41 2 85.0   85.0
```

```
> *TIMTHS 42 1 0.0    1.E6
> *THSFIX 42 1 85.0   85.0
> *TIMTHS 43 2 0.0    1.E6
> *THSFIX 43 2 85.0   85.0
<      AJN    0.10        0.013       0.
---
>      AJN    0.10        0.013       3.1875E-5
<   PUMP 1     5     0    0   1.416E-2 0.     0.0    0.0
```

CASE 14, DSTOP, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> DSTOP.DAT
---
> * SOURCES 2              ! -- KEYWORD AND # SOURCE GROUPS
> *  REGION  1  GASES 2        !-- REGION #, # GASES
> *  STEAM HYDROGEN           !-- GAS NAMES MUST BE ON NEXT LINE
> *   0  300   1.E-3  1.E-3  0.E0
> *   10 300   1.E-3  1.E-3  0.E0
> *  END REGION              !-- ENDS A REGION SOURCE
<  PRESSURE    1.017E5  1.017E5   1.017E5   1.013E5   1.013E5
---
>  PRESSURE    1.013E5  1.013E5   1.013E5   1.013E5   1.013E5
<   PUMP 1     5     0    0   1.416E-2 0.     0.0    0.0
```

CASE 15, DS75KG, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DS75KG.DAT
-------------------------
< FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
<        0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
---
> FWFL0  1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
>        1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 16, DSTOPOV, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSTOPOV.DAT
<      AJN    0.10        0.013       0.000
---
>      AJN    0.10        0.013       3.1875E-5
```

CASE 17, DSLOF, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOF.DAT
<  OFFSET_TIMEHS       0.
```

```
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0    50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0    50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0    50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0    50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0    50.0
---
> C  OFFSET_TIMEHS        0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0    50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0    50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0    50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0    50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0    50.0
```

CASE 18, DLOF75KG, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DLOF75KG.DAT
<  OFFSET_TIMEHS        0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0    50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0    50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0    50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0    50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0    50.0
---
> C  OFFSET_TIMEHS        0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0    50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0    50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0    50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0    50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0    50.0
< FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
<        0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
---
> FWFL0  1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
```

```
>      1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 19, DSLOFOV, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOFOV.DAT
<   OFFSET_TIMEHS       0.
<  EXTRAPOLATION_TIMEHS    EXTRAP
<  TIMTHS 15 2 0.0   1.E6
<  THSFIX 15 2 50.0   50.0
<  TIMTHS 30 2 0.0   1.E6
<  THSFIX 30 2 50.0   50.0
<  TIMTHS 41 2 0.0   1.E6
<  THSFIX 41 2 50.0   50.0
<  TIMTHS 42 1 0.0   1.E6
<  THSFIX 42 1 50.0   50.0
<  TIMTHS 43 2 0.0   1.E6
<  THSFIX 43 2 50.0   50.0
---
> C  OFFSET_TIMEHS       0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0   1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0   1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0   1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0   1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0   1.E6
> * THSFIX 42 2 50.0   50.0
<      AJN    0.10        0.013        0.000
---
>      AJN    0.10        0.013        3.1875E-5
```

CASE 20, DSLOC, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOC.DAT
<  OXYGEN     0.0     0.0     0.0      0.0      0.0
<  NITROGEN   0.0     0.0     0.0      0.0      0.0
<  WATER      0.0     0.0     0.0      1.0      0.0
---
>  OXYGEN     0.0     0.0     0.0      0.21     0.0
>  NITROGEN   0.0     0.0     0.0      0.79     0.0
>  WATER      0.0     0.0     0.0      0.0      0.0
<   OFFSET_TIMEHS       0.
<  EXTRAPOLATION_TIMEHS    EXTRAP
<  TIMTHS 15 2 0.0   1.E6
<  THSFIX 15 2 50.0   50.0
<  TIMTHS 30 2 0.0   1.E6
<  THSFIX 30 2 50.0   50.0
<  TIMTHS 41 2 0.0   1.E6
```

```
<  THSFIX 41 2 50.0   50.0
<  TIMTHS 42 1 0.0    1.E6
<  THSFIX 42 1 50.0   50.0
<  TIMTHS 43 2 0.0    1.E6
<  THSFIX 43 2 50.0   50.0
---
> C  OFFSET_TIMEHS        0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0   50.0
```

CASE 21, DLOC75KG, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DLOC75KG.DAT
<  OXYGEN     0.0     0.0     0.0      0.0      0.0
<  NITROGEN   0.0     0.0     0.0      0.0      0.0
<  WATER      0.0     0.0     0.0      1.0      0.0
---
>  OXYGEN     0.0     0.0     0.0      0.21     0.0
>  NITROGEN   0.0     0.0     0.0      0.79     0.0
>  WATER      0.0     0.0     0.0      0.0      0.0
<   OFFSET_TIMEHS        0.
<  EXTRAPOLATION_TIMEHS    EXTRAP
<  TIMTHS 15 2 0.0    1.E6
<  THSFIX 15 2 50.0   50.0
<  TIMTHS 30 2 0.0    1.E6
<  THSFIX 30 2 50.0   50.0
<  TIMTHS 41 2 0.0    1.E6
<  THSFIX 41 2 50.0   50.0
<  TIMTHS 42 1 0.0    1.E6
<  THSFIX 42 1 50.0   50.0
<  TIMTHS 43 2 0.0    1.E6
<  THSFIX 43 2 50.0   50.0
---
> C  OFFSET_TIMEHS        0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0   50.0
< FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
<        0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
---
```

```
> FWFL0  1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
>       1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 22, DSLOCNOM, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOCNOM.DAT
< OXYGEN     0.0     0.0     0.0      0.0      0.0
< NITROGEN   0.0     0.0     0.0      0.0      0.0
< WATER      0.0     0.0     0.0      1.0      0.0
---
> OXYGEN     0.0     0.0     0.0      0.21     0.0
> NITROGEN   0.0     0.0     0.0      0.79     0.0
> WATER      0.0     0.0     0.0      0.0      0.0
< * decay power based on 740 W per MCO.(776 W/5 FBs)
---
> * nominal decay power based on 384.7 W per MCO.(403 W/5 FBs)
< QV       1955.20   1955.20   1955.20   1955.20   1955.20
---
> QV       1015.37   1015.37   1015.37   1015.37   1015.37
< QV       1955.20   1955.20   1955.20   1955.20   1955.20
---
> QV       1015.37   1015.37   1015.37   1015.37   1015.37
< QV       1955.20   1955.20   1955.20   1955.20   0.00
---
> QV       1015.37   1015.37   1015.37   1015.37   0.00
< QV       1955.20   1955.20   1955.20   1955.20   1955.20
---
> QV       1015.37   1015.37   1015.37   1015.37   1015.37
< QV       1955.20   1955.20   1955.20   1955.20   1955.20
---
> QV       1015.37   1015.37   1015.37   1015.37   1015.37
< QV       1955.20   1955.20   1955.20   1955.20   0.0
---
> QV       1015.37   1015.37   1015.37   1015.37   0.0
<  OFFSET_TIMEHS      0.
< EXTRAPOLATION_TIMEHS   EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS      0.
> C EXTRAPOLATION_TIMEHS   EXTRAP
> C TIMTHS 15 2 0.0   1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0   1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0   1.E6
```

```
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0   50.0
< FAOXFL  0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
<         0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
< FOX    10  0.0  ! multiplier for FAOXFL
---
> FAOXFL  0.004464 0.004464 0.004464 0.004464 0.004464 0.004464 0.004464
>         0.004464 0.004464 0.004464 0.004464 0.004464 0.004464 0.004464
> FOX    3  0.0  ! multiplier for FAOXFL
< FAOXFL  0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
<         0.10417 0.10417 0.10417 0.10417 0.10417 0.10417 0.10417
< FOX    10  0.0  ! multiplier for FAOXFL
---
> FAOXFL  0.004464 0.004464 0.004464 0.004464 0.004464 0.004464 0.004464
>         0.004464 0.004464 0.004464 0.004464 0.004464 0.004464 0.004464
> FOX    3  0.0  ! multiplier for FAOXFL
```

CASE 23, DSLOCREC, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> DSLOCREC.DAT
<   TSTART       0.     ! START TIME=469 sec, >0 FOR RESTART RUN
---
>   TSTART       75603.01    ! START TIME= 21 hrs + 3.01 sec, >0 FOR RESTART RUN
< VOLUMES    5     ! total number of control volumes
---
> VOLUMES    6     ! total number of control volumes
---
>  REGIONS      6
>   VOLUME      0.115
>   SED_AREA    0.0
>   ELEVATION   0.0
>   TEMP_GAS    25.1
>   PRESSURE    1.013E5
>  END REGIONS  ! REGIONS is a comment
---
>  GASES        6
>   HELIUM      0.
>   STEAM       0.
>   OXYGEN      0.0
>   NITROGEN    0.0
>   WATER       1.0
>  END GASES        ! GASES is a comment
< IREGO        2       2       2       2       4
---
> IREGO        2       2       2       2       6
< IREGO        3       3       3       3       4
---
> IREGO        3       3       3       3       6
< IREGO        4
---
> IREGO        6
< IREGI        4       3       1
---
> IREGI        6       3       1
```

```
< IREGO      5      4      5
---
> IREGO      5      6      5
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 25.0   25.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 25.0   25.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 25.0   25.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 25.0   25.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 25.0   25.0
<  IRGAP  4    ! define the gap node (between MCO wall and the cask)
---
>  IRGAP  6    ! define the gap node (between MCO wall and the cask)
```

CASE 24, DSLOCRE2, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOCRE2.DAT
<  TSTART      0.     ! START TIME=0 sec, >0 FOR RESTART RUN
---
>  TSTART      75603.01   ! START TIME=21 hrs + 3.01 sec, >0 FOR RESTART RUN
<VOLUMES   5    ! total number of control volumes
---
>VOLUMES   6    ! total number of control volumes
---
>  REGIONS     6
>   VOLUME     0.115
>   SED_AREA   0.0
>   ELEVATION  0.0
>   TEMP_GAS   25.1
>   PRESSURE   1.013E5
>  END REGIONS  ! REGIONS is a comment
>  GASES       6
>   HELIUM     0.
>   STEAM      0.
>   OXYGEN     0.0
>   NITROGEN   0.0
>   WATER      1.0
>  END GASES       ! GASES is a comment
< IREGO      2      2      2      2      4
---
> IREGO      2      2      2      2      6
< IREGO      3      3      3      3      4
---
> IREGO      3      3      3      3      6
< IREGO      4
---
> IREGO      6
< IREGI      4      3      1
---
```

```
> IREGI      6      3      1
< IREGO      5      4      5
---
> IREGO      5      6      5
<  OFFSET_TIMEHS      0.
<  EXTRAPOLATION_TIMEHS   EXTRAP
<  TIMTHS 15 2 0.0   1.E6
<  THSFIX 15 2 50.0  50.0
<  TIMTHS 30 2 0.0   1.E6
<  THSFIX 30 2 50.0  50.0
<  TIMTHS 41 2 0.0   1.E6
<  THSFIX 41 2 50.0  50.0
<  TIMTHS 42 1 0.0   1.E6
<  THSFIX 42 1 50.0  50.0
<  TIMTHS 43 2 0.0   1.E6
<  THSFIX 43 2 50.0  50.0
---
> C  OFFSET_TIMEHS      0.
> C EXTRAPOLATION_TIMEHS   EXTRAP
> C TIMTHS 15 2 0.0   1.E6
> C THSFIX 15 2 25.0  25.0
> C TIMTHS 30 2 0.0   1.E6
> C THSFIX 30 2 25.0  25.0
> C TIMTHS 41 2 0.0   1.E6
> C THSFIX 41 2 25.0  25.0
> C TIMTHS 42 1 0.0   1.E6
> C THSFIX 42 1 25.0  25.0
> C TIMTHS 43 2 0.0   1.E6
> C THSFIX 43 2 25.0  25.0
<  IRGAP  4    ! define the gap node (between MCO wall and the cask)
---
>  IRGAP  6    ! define the gap node (between MCO wall and the cask)
```

CASE 25, DSLOCOV, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOCOV.DAT
<  OXYGEN     0.0     0.0     0.0      0.0      0.0
<  NITROGEN   0.0     0.0     0.0      0.0      0.0
<  WATER      0.0     0.0     0.0      1.0      0.0
---
>  OXYGEN     0.0     0.0     0.0      0.21     0.0
>  NITROGEN   0.0     0.0     0.0      0.79     0.0
>  WATER      0.0     0.0     0.0      0.0      0.0
<  OFFSET_TIMEHS      0.
<  EXTRAPOLATION_TIMEHS   EXTRAP
<  TIMTHS 15 2 0.0   1.E6
<  THSFIX 15 2 50.0  50.0
<  TIMTHS 30 2 0.0   1.E6
<  THSFIX 30 2 50.0  50.0
<  TIMTHS 41 2 0.0   1.E6
<  THSFIX 41 2 50.0  50.0
<  TIMTHS 42 1 0.0   1.E6
<  THSFIX 42 1 50.0  50.0
<  TIMTHS 43 2 0.0   1.E6
<  THSFIX 43 2 50.0  50.0
---
> C  OFFSET_TIMEHS      0.
```

```
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0    50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0    50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0    50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0    50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0    50.0
<      AJN    0.10        0.013        0.000
---
>      AJN    0.10        0.013        3.1875E-5
```

CASE 26, DS46DEG, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> DS46DEG.DAT
<  TEMP_GAS    50.0   50.0        50.0        50.0    26.7
---
>  TEMP_GAS    50.0   50.0        50.0        46.0    26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 46.0   46.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 46.0   46.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 46.0   46.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 46.0   46.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 46.0   46.0
```

CASE 27, DS55DEG, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> DS55DEG.DAT
<  TEMP_GAS    50.0   50.0        50.0        50.0    26.7
---
>  TEMP_GAS    50.0   50.0        50.0        55.0    26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 55.0   55.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 55.0   55.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 55.0   55.0
<  THSFIX 42 1 50.0   50.0
---
```

```
> THSFIX 42 1 55.0   55.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 55.0   55.0
```

CASE 28, DS75DEG, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DS75DEG.DAT
< TEMP_GAS    50.0   50.0       50.0       50.0    26.7
---
> TEMP_GAS    50.0   50.0       50.0       75.0    26.7
< THSFIX 15 2 50.0   50.0
---
> THSFIX 15 2 75.0   75.0
< THSFIX 30 2 50.0   50.0
---
> THSFIX 30 2 75.0   75.0
< THSFIX 41 2 50.0   50.0
---
> THSFIX 41 2 75.0   75.0
< THSFIX 42 1 50.0   50.0
---
> THSFIX 42 1 75.0   75.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 75.0   75.0
```

CASE 29, DSHOT, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSHOT.DAT
-------------------------------
< TEMP_GAS    50.0   50.0       50.0       50.0    26.7
---
> TEMP_GAS    50.0   50.0       50.0       85.0    26.7
< THSFIX 15 2 50.0   50.0
---
> THSFIX 15 2 85.0   85.0
< THSFIX 30 2 50.0   50.0
---
> THSFIX 30 2 85.0   85.0
< THSFIX 41 2 50.0   50.0
---
> THSFIX 41 2 85.0   85.0
< THSFIX 42 1 50.0   50.0
---
> THSFIX 42 1 85.0   85.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 85.0   85.0
```

CASE 30, DHOT75KG, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> DHOT75KG.DAT
-------------------------------
<  TEMP_GAS    50.0   50.0       50.0       50.0    26.7
---
>  TEMP_GAS    50.0   50.0       50.0       85.0    26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 85.0   85.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 85.0   85.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 85.0   85.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 85.0   85.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 85.0   85.0
< FWFL0  0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
<        0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571 0.3571
---
> FWFL0  1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
>        1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327 1.5327
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 31, DSHOTOV, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> DSHOTOV.DAT
<  TEMP_GAS    50.0   50.0       50.0       50.0    26.7
---
>  TEMP_GAS    50.0   50.0       50.0       85.0    26.7
<  THSFIX 15 2 50.0   50.0
---
>  THSFIX 15 2 85.0   85.0
<  THSFIX 30 2 50.0   50.0
---
>  THSFIX 30 2 85.0   85.0
<  THSFIX 41 2 50.0   50.0
---
>  THSFIX 41 2 85.0   85.0
<  THSFIX 42 1 50.0   50.0
---
>  THSFIX 42 1 85.0   85.0
<  THSFIX 43 2 50.0   50.0
---
>  THSFIX 43 2 85.0   85.0
<      AJN    0.10       0.013      0.000
---
>      AJN    0.10       0.013      3.1875E-5
```

CASE 32, VACAIRI, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> VACAIRI.DAT
-------------------------------
<  HELIUM     0.85    0.85    0.85     0.0      1.0
<  STEAM      0.10    0.10    0.10     0.0      0.0
<  OXYGEN      0.0     0.0     0.0     0.0      0.0
<  NITROGEN    0.0     0.0     0.0     0.0      0.0
---
>  HELIUM     0.85    0.85    0.85     0.0      0.0
>  STEAM      0.10    0.10    0.10     0.0     0.020
>  OXYGEN      0.0     0.0     0.0     0.0     0.206
>  NITROGEN    0.0     0.0     0.0     0.0     0.774
< JUNCTIONS  3  ! 3 Junctions
---
> JUNCTIONS  4 ! 4 junctions
<    PATHS     1         2         3
---
>    PATHS     1         2         3       4
<      IJTYP   1         1         1
<      IR1     3         2         1
<      IR2     2         1         5
<      IHORIZ  1         1         1
<      XWJN    0.61      0.61      2.54E-2
<      XHJN    0.61      0.61      2.54E-2
<      XLJN    0.01      0.01      10.025
<      AJN     0.10      0.013     0.
<      Z1JN    1.2       1.2       1.2
<      Z2JN    0.0       0.0       4.0
<      CJN     1.0       1.0       4.0
<      DFJN    1.0       1.0       1.0
<      N90     0         0         3
---
>      IJTYP   1         1         1       1
>      IR1     3         2         1       5
>      IR2     2         1         5       3
>      IHORIZ  1         1         1       1
>      XWJN    0.61      0.61      2.54E-2   1.e-4
>      XHJN    0.61      0.61      2.54E-2   1.e-4
>      XLJN    0.01      0.01      10.       1.e-2
>      AJN     0.10      0.013     0.00      1.e-5
>      Z1JN    1.2       1.2       1.2       0.00
>      Z2JN    0.0       0.0       4.0       0.0
>      CJN     1.0       1.0       4.0       1.0
>      DFJN    1.0       1.0       1.0       1.0
>      N90     0         0         2         0.0
< XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<        4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
> XFLOX0 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>        1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
< XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<        4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
> XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>        1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
< XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<        4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
```

```
---
>  XSCOX0 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
>         3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
```

CASE 33, VAIRIHOT, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> VAIRIHOT.DAT
-------------------------------
<  HELIUM      0.85    0.85    0.85      0.0      1.0
<  STEAM       0.10    0.10    0.10      0.0      0.0
<  OXYGEN      0.0     0.0     0.0       0.0      0.0
<  NITROGEN    0.0     0.0     0.0       0.0      0.0
---
>  HELIUM      0.85    0.85    0.85      0.0      0.0
>  STEAM       0.10    0.10    0.10      0.0      0.020
>  OXYGEN      0.0     0.0     0.0       0.0      0.206
>  NITROGEN    0.0     0.0     0.0       0.0      0.774
< THSFIX 15 2 50.0   50.0
---
> THSFIX 15 2 85.0   85.0
< THSFIX 30 2 50.0   50.0
---
> THSFIX 30 2 85.0   85.0
< THSFIX 41 2 50.0   50.0
---
> THSFIX 41 2 85.0   85.0
< THSFIX 42 1 50.0   50.0
---
> THSFIX 42 1 85.0   85.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 85.0   85.0
< JUNCTIONS  3  ! 3 Junctions
---
> JUNCTIONS  4 ! 4 junctions
<    PATHS     1         2         3
---
>    PATHS     1         2         3       4
<      IJTYP   1         1         1
<      IR1     3         2         1
<      IR2     2         1         5
<      IHORIZ  1         1         1
<      XWJN    0.61      0.61      2.54E-2
<      XHJN    0.61      0.61      2.54E-2
<      XLJN    0.01      0.01      10.025
<      AJN     0.10      0.013     0.
<      Z1JN    1.2       1.2       1.2
<      Z2JN    0.0       0.0       4.0
<      CJN     1.0       1.0       4.0
<      DFJN    1.0       1.0       1.0
<      N90     0         0         3
---
>      IJTYP   1         1         1       1
>      IR1     3         2         1       5
>      IR2     2         1         5       3
>      IHORIZ  1         1         1       1
>      XWJN    0.61      0.61      2.54E-2  1.e-4
```

```
>     XHJN   0.61      0.61      2.54E-2  1.e-4
>     XLJN   0.01      0.01      10.      1.e-2
>     AJN    0.10      0.013     0.00     1.e-5
>     Z1JN   1.2       1.2       1.2      0.00
>     Z2JN   0.0       0.0       4.0      0.0
>     CJN    1.0       1.0       4.0      1.0
>     DFJN   1.0       1.0       1.0      1.0
>     N90    0         0         2        0.0
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XSCOX0 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
>       3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
```

CASE 34, VAIRILOC, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> VAIRILOC.DAT
< HELIUM     0.85    0.85    0.85     0.0      1.0
< STEAM      0.10    0.10    0.10     0.0      0.0
< OXYGEN     0.0     0.0     0.0      0.0      0.0
< NITROGEN   0.0     0.0     0.0      0.0      0.0
< WATER      0.0     0.0     0.0      1.0      0.0
---
> HELIUM     0.85    0.85    0.85     0.0      0.0
> STEAM      0.10    0.10    0.10     0.0      0.020
> OXYGEN     0.0     0.0     0.0      0.21     0.206
> NITROGEN   0.0     0.0     0.0      0.79     0.774
> WATER      0.0     0.0     0.0      0.0      0.0
< OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS       0.
> CEXTRAPOLATION_TIMEHS    EXTRAP
> CTIMTHS 15 2 0.0    1.E6
> CTHSFIX 15 2 85.0   85.0
> CTIMTHS 30 2 0.0    1.E6
> CTHSFIX 30 2 85.0   85.0
```

```
> CTIMTHS 41 2 0.0    1.E6
> CTHSFIX 41 2 85.0   85.0
> CTIMTHS 42 1 0.0    1.E6
> CTHSFIX 42 1 85.0   85.0
> CTIMTHS 43 2 0.0    1.E6
> CTHSFIX 43 2 85.0   85.0
< JUNCTIONS  3  ! 3 Junctions
---
> JUNCTIONS  4 ! 4 junctions
<    PATHS     1          2          3
---
>    PATHS     1          2          3       4
<    IJTYP  1          1          1
<    IR1    3          2          1
<    IR2    2          1          5
<    IHORIZ  1          1          1
<    XWJN    0.61       0.61       2.54E-2
<    XHJN    0.61       0.61       2.54E-2
<    XLJN    0.01       0.01       10.025
<    AJN     0.10       0.013      0.
<    Z1JN    1.2        1.2        1.2
<    Z2JN    0.0        0.0        4.0
<    CJN     1.0        1.0        4.0
<    DFJN    1.0        1.0        1.0
<    N90     0          0          3
---
>    IJTYP  1          1          1       1
>    IR1    3          2          1       5
>    IR2    2          1          5       3
>    IHORIZ  1          1          1       1
>    XWJN    0.61       0.61       2.54E-2   1.e-4
>    XHJN    0.61       0.61       2.54E-2   1.e-4
>    XLJN    0.01       0.01       10.       1.e-2
>    AJN     0.10       0.013      0.00      1.e-5
>    Z1JN    1.2        1.2        1.2       0.00
>    Z2JN    0.0        0.0        4.0       0.0
>    CJN     1.0        1.0        4.0       1.0
>    DFJN    1.0        1.0        1.0       1.0
>    N90     0          0          2         0.0
< XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
> XFLOX0 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
< XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
> XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
< XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
> XSCOX0 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
>       3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
```

CASE 35, PURAIRI, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
```

```
> PURAIRI.DAT
---------------------------------
> SOURCES 1                ! -- KEYWORD AND # SOURCE GROUPS
> REGION 3 GASES 1         !-- REGION #, # GASES
>  HELIUM                  !-- GAS NAMES MUST BE ON NEXT LINE
> 0   26.7  1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
> 1.0E9 26.7  1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
> END REGION               !-- ENDS A REGION SOURCE
> END SOURCES
< HELIUM     0.85    0.85    0.85     0.0      1.0
< STEAM      0.10    0.10    0.10     0.0      0.0
< OXYGEN     0.0     0.0     0.0      0.0      0.0
< NITROGEN   0.0     0.0     0.0      0.0      0.0
---
> HELIUM     0.85    0.85    0.85     0.0      0.0
> STEAM      0.10    0.10    0.10     0.0      0.020
> OXYGEN     0.0     0.0     0.0      0.0      0.206
> NITROGEN   0.0     0.0     0.0      0.0      0.774
< JUNCTIONS  3 ! 3 Junctions
---
> JUNCTIONS  4 ! 4 junctions
<   PATHS     1         2         3
---
>   PATHS     1         2         3       4
<     IJTYP   1         1         1
<     IR1     3         2         1
<     IR2     2         1         5
<     IHORIZ  1         1         1
<     XWJN    0.61      0.61      2.54E-2
<     XHJN    0.61      0.61      2.54E-2
<     XLJN    0.01      0.01      10.025
<     AJN     0.10      0.013     0.
<     Z1JN    1.2       1.2       1.2
<     Z2JN    0.0       0.0       4.0
<     CJN     1.0       1.0       4.0
<     DFJN    1.0       1.0       1.0
<     N90     0         0         3
---
>     IJTYP   1         1         1       1
>     IR1     3         2         1       5
>     IR2     2         1         5       3
>     IHORIZ  1         1         1       1
>     XWJN    0.61      0.61      2.54E-2   1.e-4
>     XHJN    0.61      0.61      2.54E-2   1.e-4
>     XLJN    0.01      0.01      10.       1.e-2
>     AJN     0.10      0.013     3.187E-5      1.e-5
>     Z1JN    1.2       1.2       1.2       0.00
>     Z2JN    0.0       0.0       4.0       0.0
>     CJN     1.0       1.0       4.0       1.0
>     DFJN    1.0       1.0       1.0       1.0
>     N90     0         0         2         0.0
<   PUMP 1    5    0    0  1.416E-2 0.    0.0    0.0
---
<   XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<          4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>   XFLOX0 1.97E-4 1.97E-4 1.97E-4  1.97E-4 1.97E-4 1.97E-4 1.97E-4
>          1.97E-4 1.97E-4 1.97E-4  1.97E-4 1.97E-4 1.97E-4 1.97E-4
<   XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<          4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
```

```
---
>  XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>          1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<         4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XSCOX0 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
>         3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
```

CASE 36, PAIRIHOT, INPUT DIFFERENCES with VACUUM

```
< VACUUM.DAT
> PAIRIHOT.DAT
-------------------------------
> SOURCES 1                ! -- KEYWORD AND # SOURCE GROUPS
> REGION  3  GASES 1       !-- REGION #, # GASES
>   HELIUM                 !-- GAS NAMES MUST BE ON NEXT LINE
> 0    26.7   1.23E-4 0.0 ! 1.23E-4 kg/s = He sour @ 1.6 cfm @ 26.7 C
> 1.0E9 26.7   1.23E-4 0.0 ! He dens=0.163 kg/m3 @ 26.7 C, 1cfm=4.72E-4 m3/s
> END REGION               !-- ENDS A REGION SOURCE
> END SOURCES
<  HELIUM     0.85    0.85    0.85     0.0      1.0
<  STEAM      0.10    0.10    0.10     0.0      0.0
<  OXYGEN      0.0     0.0     0.0     0.0      0.0
<  NITROGEN    0.0     0.0     0.0     0.0      0.0
---
>  HELIUM     0.85    0.85    0.85     0.0      0.0
>  STEAM      0.10    0.10    0.10     0.0      0.020
>  OXYGEN      0.0     0.0     0.0     0.0      0.206
>  NITROGEN    0.0     0.0     0.0     0.0      0.774
< THSFIX 15 2 50.0   50.0
---
> THSFIX 15 2 85.0   85.0
< THSFIX 30 2 50.0   50.0
---
> THSFIX 30 2 85.0   85.0
< THSFIX 41 2 50.0   50.0
---
> THSFIX 41 2 85.0   85.0
< THSFIX 42 1 50.0   50.0
---
> THSFIX 42 1 85.0   85.0
< THSFIX 43 2 50.0   50.0
---
> THSFIX 43 2 85.0   85.0
< JUNCTIONS  3  ! 3 Junctions
---
> JUNCTIONS  4 ! 4 junctions
<    PATHS     1          2          3
---
>    PATHS     1          2          3       4
<      IJTYP   1          1          1
<      IR1     3          2          1
<      IR2     2          1          5
<      IHORIZ  1          1          1
<      XWJN    0.61       0.61       2.54E-2
<      XHJN    0.61       0.61       2.54E-2
<      XLJN    0.01       0.01       10.025
```

```
<    AJN    0.10      0.013       0.
<    Z1JN   1.2       1.2         1.2
<    Z2JN   0.0       0.0         4.0
<    CJN    1.0       1.0         4.0
<    DFJN   1.0       1.0         1.0
<    N90    0         0           3
---
>    IJTYP  1         1           1       1
>    IR1    3         2           1       5
>    IR2    2         1           5       3
>    IHORIZ 1         1           1       1
>    XWJN   0.61      0.61        2.54E-2 1.e-4
>    XHJN   0.61      0.61        2.54E-2 1.e-4
>    XLJN   0.01      0.01        10.     1.e-2
>    AJN    0.10      0.013       3.187E-5      1.e-5
>    Z1JN   1.2       1.2         1.2     0.00
>    Z2JN   0.0       0.0         4.0     0.0
>    CJN    1.0       1.0         4.0     1.0
>    DFJN   1.0       1.0         1.0     1.0
>    N90    0         0           2       0.0
<  PUMP 1    5    0    0  1.416E-2 0.    0.0   0.0
---
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  XSCOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XSCOX0 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
>       3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4 3.7E-4
```

CASE 37, VACAIRI2, INPUT DIFFERENCES with VACUUM

```
<VACUUM.DAT
>VACAIRI2.DAT
<  HELIUM     0.85    0.85    0.85     0.0      1.0
<  STEAM      0.10    0.10    0.10     0.0      0.0
<  OXYGEN     0.0     0.0     0.0      0.0      0.0
<  NITROGEN   0.0     0.0     0.0      0.0      0.0
---
>  HELIUM     0.85    0.85    0.85     0.0      0.0
>  STEAM      0.10    0.10    0.10     0.0      0.020
>  OXYGEN     0.0     0.0     0.0      0.0      0.206
>  NITROGEN   0.0     0.0     0.0      0.0      0.774
<JUNCTIONS  3 ! 3 Junctions
---
>JUNCTIONS  4 ! 4 junctions
<    PATHS     1         2         3
---
>    PATHS     1         2         3      4
<      IJTYP   1         1         1
```

```
<    IR1   3        2        1
<    IR2   2        1        5
<    IHORIZ 1       1        1
<    XWJN   0.61    0.61     2.54E-2
<    XHJN   0.61    0.61     2.54E-2
<    XLJN   0.01    0.01     10.025
<    AJN    0.10    0.013    0.
<    Z1JN   1.2     1.2      1.2
<    Z2JN   0.0     0.0      4.0
<    CJN    1.0     1.0      4.0
<    DFJN   1.0     1.0      1.0
<    N90    0       0        3
---
>    IJTYP  1       1        1      1
>    IR1    3       2        1      5
>    IR2    2       1        5      3
>    IHORIZ 1       1        1      1
>    XWJN   0.61    0.61     2.54E-2  1.e-4
>    XHJN   0.61    0.61     2.54E-2  1.e-4
>    XLJN   0.01    0.01     10.      1.e-2
>    AJN    0.10    0.013    0.00     1.e-5
>    Z1JN   1.2     1.2      1.2      0.00
>    Z2JN   0.0     0.0      4.0      0.0
>    CJN    1.0     1.0      4.0      1.0
>    DFJN   1.0     1.0      1.0      1.0
>    N90    0       0        2        0.0
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  FXHYD0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
<       1.0 1.0 1.0 1.0 1.0 1.0 1.0
---
>  FXHYD0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
>       0.0 0.0 0.0 0.0 0.0 0.0 0.0
<  XFLOX0 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
<       4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5 4.56E-5
---
>  XFLOX0  1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
>       1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4 1.97E-4
<  FXHYD0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
<       1.0 1.0 1.0 1.0 1.0 1.0 1.0
---
>  FXHYD0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
>       0.0 0.0 0.0 0.0 0.0 0.0 0.0
```

CASE 38, DSLOCSA4, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOCSA4.DAT
-------------------------
< HELIUM     0.85    0.85    0.85     0.0      1.0
< STEAM      0.15    0.15    0.15     0.0      0.0
< OXYGEN     0.0     0.0     0.0      0.0      0.0
< NITROGEN   0.0     0.0     0.0      0.0      0.0
< WATER      0.0     0.0     0.0      1.0      0.0
---
```

```
> HELIUM     0.85    0.85    0.85     0.0      0.0
> STEAM      0.15    0.15    0.15     0.0      0.02
> OXYGEN     0.0     0.0     0.0      0.21     0.205
> NITROGEN   0.0     0.0     0.0      0.79     0.775
> WATER      0.0     0.0     0.0      0.0      0.0
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS   EXTRAP
< TIMTHS 15 2 0.0   1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0   1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0   1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0   1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0   1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS       0.
> C EXTRAPOLATION_TIMEHS   EXTRAP
> C TIMTHS 15 2 0.0   1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0   1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0   1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0   1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0   1.E6
> * THSFIX 42 2 50.0   50.0
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0   4.545 ! on the inner surface of the MCO wall
```

CASE 39, BLOW4N, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>BLOW4N.DAT
-------------------------
<  TSTART      0.     ! START TIME=469 sec, >0 FOR RESTART RUN
---
>  TSTART    75600.0001   ! START TIME=21 hr + 0.0001 sec >0 FOR RESTART RUN
< HYDROGEN    0.00   0.00    0.00     0.0      0.0
< HELIUM      0.85   0.85    0.85     0.0      1.0
< STEAM       0.15   0.15    0.15     0.0      0.0
< OXYGEN      0.0    0.0     0.0      0.0      0.0
< NITROGEN    0.0    0.0     0.0      0.0      0.0
< WATER       0.0    0.0     0.0      1.0      0.0
---
> HYDROGEN    0.985   0.985   0.985    0.0      0.0
> HELIUM      0.015   0.015   0.015    0.0      0.0
> STEAM       0.00    0.00    0.00     0.0      0.02
> OXYGEN      0.0     0.0     0.0      0.21     0.205
> NITROGEN    0.0     0.0     0.0      0.79     0.775
> WATER       0.0     0.0     0.0      0.0      0.0
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS   EXTRAP
< TIMTHS 15 2 0.0   1.E6
```

```
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS        0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0   50.0
<       AJN    0.10        0.013        0.000
---
>       AJN    0.10        0.013        0.00051
< INITRI 0     ! =1, do nitriding calculation
---
> INITRI 1     ! =1, do nitriding calculation
---
> FWFLM0 4.545   ! on the inner surface of the MCO wall
< FWFLM0 0.4545 ! on the inner surface of the MCO wall
```

CASE 40, DSSA4REC, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSSA4REC.DAT
-------------------------------
<  TSTART       0.     ! START TIME=469 sec, >0 FOR RESTART RUN
---
>  TSTART       75604.01    ! START TIME=21 hrs + 4.01 sec, >0 FOR RESTART RUN
<VOLUMES   5     ! total number of control volumes
---
>VOLUMES   6     ! total number of control volumes
<* REGIONS      6       7
<*  VOLUME      0.183     1.E9
<*  SED_AREA    0.27      0.0
<*  ELEVATION   0.0       0.0
<*  TEMP_GAS    323.15    299.85
<*  PRESSURE    1.047E5   1.047E5
<* END REGIONS  ! REGIONS is a comment
---
>  REGIONS      6
>   VOLUME      0.115
>   SED_AREA    0.0
>   ELEVATION   0.0
>   TEMP_GAS    25.1
>   PRESSURE    1.013E5
>  END REGIONS  ! REGIONS is a comment
```

```
< HELIUM     0.85    0.85    0.85     0.0      1.0
< STEAM      0.15    0.15    0.15     0.0      0.0
< OXYGEN     0.0     0.0     0.0      0.0      0.0
< NITROGEN   0.0     0.0     0.0      0.0      0.0
< WATER      0.0     0.0     0.0      1.0      0.0
---
> HELIUM     0.85    0.85    0.85     0.0      0.0
> STEAM      0.15    0.15    0.15     0.0      0.02
> OXYGEN     0.0     0.0     0.0      0.21     0.2050
> NITROGEN   0.0     0.0     0.0      0.79     0.77500
> WATER      0.0     0.0     0.0      0.0      0.0
---
> GASES      6
>  HELIUM    0.
>  STEAM     0.
>  OXYGEN    0.0
>  NITROGEN  0.0
>  WATER     1.0
>  END GASES      ! GASES is a comment
< IREGO      2       2       2       2       4
---
> IREGO      2       2       2       2       6
< IREGO      3       3       3       3       4
---
> IREGO      3       3       3       3       6
< IREGO      4
---
> IREGO      6
< IREGI      4       3       1
---
> IREGI      6       3       1
< IREGO      5       4       5
---
> IREGO      5       6       5
<  OFFSET_TIMEHS      0.
<  EXTRAPOLATION_TIMEHS    EXTRAP
<  TIMTHS 15 2 0.0   1.E6
<  THSFIX 15 2 50.0  50.0
<  TIMTHS 30 2 0.0   1.E6
<  THSFIX 30 2 50.0  50.0
<  TIMTHS 41 2 0.0   1.E6
<  THSFIX 41 2 50.0  50.0
<  TIMTHS 42 1 0.0   1.E6
<  THSFIX 42 1 50.0  50.0
<  TIMTHS 43 2 0.0   1.E6
<  THSFIX 43 2 50.0  50.0
---
> C  OFFSET_TIMEHS      0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0   1.E6
> C THSFIX 15 2 25.0  25.0
> C TIMTHS 30 2 0.0   1.E6
> C THSFIX 30 2 25.0  25.0
> C TIMTHS 41 2 0.0   1.E6
> C THSFIX 41 2 25.0  25.0
> C TIMTHS 42 1 0.0   1.E6
> C THSFIX 42 1 25.0  25.0
> C TIMTHS 43 2 0.0   1.E6
> C THSFIX 43 2 25.0  25.0
<  IRGAP  4    ! define the gap node (between MCO wall and the cask)
```

```
---
>  IRGAP  6     ! define the gap node (between MCO wall and the cask)
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 41, BLOWREOV, INPUT DIFFERENCES with DSTOP

```
< DSTOP.DAT
> BLOWREOV.DAT
-------------------------------
<  TSTART       0.     ! START TIME=469 sec, >0 FOR RESTART RUN
---
>  TSTART       79203.01    ! START TIME=22hr + 3.01 sec, >0 FOR RESTART RUN
< VOLUMES   5     ! total number of control volumes
---
> VOLUMES   6     ! total number of control volumes
>  REGIONS      6
>   VOLUME      0.115
>   SED_AREA    0.0
>   ELEVATION   0.0
>   TEMP_GAS    25.1
>   PRESSURE    1.013E5
>  END REGIONS  ! REGIONS is a comment
---
>  GASES        6
>   HELIUM      0.
>   STEAM       0.
>   OXYGEN      0.0
>   NITROGEN    0.0
>   WATER       1.0
>  END GASES        ! GASES is a comment
< IREGO       2       2       2       2       4
---
> IREGO       2       2       2       2       6
< IREGO       3       3       3       3       4
---
> IREGO       3       3       3       3       6
< IREGO       4
---
> IREGO       6
< IREGI       4       3       1
---
> IREGI       6       3       1
< IREGO       5       4       5
---
> IREGO       5       6       5
<   OFFSET_TIMEHS       0.
<  EXTRAPOLATION_TIMEHS    EXTRAP
<  TIMTHS 15 2 0.0    1.E6
<  THSFIX 15 2 50.0   50.0
<  TIMTHS 30 2 0.0    1.E6
<  THSFIX 30 2 50.0   50.0
<  TIMTHS 41 2 0.0    1.E6
<  THSFIX 41 2 50.0   50.0
<  TIMTHS 42 1 0.0    1.E6
<  THSFIX 42 1 50.0   50.0
<  TIMTHS 43 2 0.0    1.E6
```

```
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS       0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
> C THSFIX 15 2 25.0   25.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 25.0   25.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 25.0   25.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 25.0   25.0
> C TIMTHS 43 2 0.0    1.E6
> C THSFIX 43 2 25.0   25.0
<      AJN    0.10        0.013        0.000
---
>      AJN    0.10        0.013        5.1E-4
<  IRGAP  4     ! define the gap node (between MCO wall and the cask)
---
>  IRGAP  6     ! define the gap node (between MCO wall and the cask)
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0  4.545 ! on the inner surface of the MCO wall
```

CASE 42, DSLOCOV2, INPUT DIFFERENCES with DSTOP

```
<DSTOP.DAT
>DSLOCOV2.DAT
-------------------------------
< HELIUM     0.85    0.85    0.85     0.0      1.0
< STEAM      0.15    0.15    0.15     0.0      0.0
< OXYGEN      0.0     0.0     0.0      0.0      0.0
< NITROGEN    0.0     0.0     0.0      0.0      0.0
< WATER      0.0     0.0     0.0      1.0      0.0
---
> HELIUM     0.85    0.85    0.85     0.0      0.0
> STEAM      0.15    0.15    0.15     0.0      0.02
> OXYGEN      0.0     0.0     0.0      0.21     0.205
> NITROGEN    0.0     0.0     0.0      0.79     0.775
> WATER      0.0     0.0     0.0      0.0      0.0
< IGEOM       0       0       0        0        0
---
<  OFFSET_TIMEHS       0.
< EXTRAPOLATION_TIMEHS    EXTRAP
< TIMTHS 15 2 0.0    1.E6
< THSFIX 15 2 50.0   50.0
< TIMTHS 30 2 0.0    1.E6
< THSFIX 30 2 50.0   50.0
< TIMTHS 41 2 0.0    1.E6
< THSFIX 41 2 50.0   50.0
< TIMTHS 42 1 0.0    1.E6
< THSFIX 42 1 50.0   50.0
< TIMTHS 43 2 0.0    1.E6
< THSFIX 43 2 50.0   50.0
---
> C OFFSET_TIMEHS       0.
> C EXTRAPOLATION_TIMEHS    EXTRAP
> C TIMTHS 15 2 0.0    1.E6
```

```
> C THSFIX 15 2 50.0   50.0
> C TIMTHS 30 2 0.0    1.E6
> C THSFIX 30 2 50.0   50.0
> C TIMTHS 41 2 0.0    1.E6
> C THSFIX 41 2 50.0   50.0
> C TIMTHS 42 1 0.0    1.E6
> C THSFIX 42 1 50.0   50.0
> * TIMTHS 42 2 0.0    1.E6
> * THSFIX 42 2 50.0   50.0
<       AJN     0.10        0.013        0.000
---
>       AJN     0.10        0.10         3.1875E-5
< FWFLM0  0.4545 ! on the inner surface of the MCO wall
---
> FWFLM0   4.545 ! on the inner surface of the MCO wall
```

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APPENDIX C

KEY INPUT PARAMETERS

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APPENDIX C

KEY INPUT PARAMETERS

Key input parameters used in the analysis for the bounding and nominal MCO with one Mark IV scrap basket and four Mark IV fuel baskets are shown in Table C-1. Notes are provided following the table.

Table C-1. Key Input Parameters for Bounding and Nominal Multi-Canister Overpack. (3 sheets)

Parameter	Value	Reference
HEAT GENERATION PARAMETERS: power, reaction area, reaction rate		
Bounding decay power (776 W for five fuel baskets)	740.8 W per MCO	Reilly 1998 Note 1
Nominal decay power (403 W for five fuel baskets)	384.7 W per MCO	Reilly 1998 Note 2
Scrap fuel reaction surface area	6 m^2 - bounding 1.7 m^2 - nominal	Reilly 1998
Fuel reaction area	7 m^2 - bounding 0.3 m^2 - nominal	Reilly 1998
Reaction rate multiplier	10 - bounding 3 - nominal	Reilly 1998
Nominal effective rate multiplier for hydrides (nominal hydride mass)	13.7 - fuel basket 13.7 - scrap basket (2.4 kg per MCO)	Plys and Duncan 1998 Note 3
Bounding effective rate multiplier for hydrides (bounding hydride mass)	59.2 - fuel basket 111 - scrap basket (14.6 kg per MCO)	Plys and Duncan 1998 Note 4
RADIATION HEAT TRANSFER PARAMETERS: emissivity, view factors		
Scrap fuel emissivity	0.7	Reilly 1998
Cladding emissivity	0.43	Scott 1965 Note 5
Inner shield plug emissivity	1.0	Plys et al. 1998 Note 6
MCO wall emissivity	0.3	Reilly 1998
Cask, MCO bottom, and outer shield plug emissivity	0.25	Plys et al. 1998 Note 7

Table C-1. Key Input Parameters for Bounding and Nominal Multi-Canister Overpack. (3 sheets)

Parameter	Value	Reference
View factors between fuel rods and MCO wall	8 x 8 matrix	Plys et al. 1998 Note 8
CONDUCTION HEAT TRANSFER PARAMETERS mass, conductivity, specific heat, temperature		
Effective fuel–cladding mass density	18,573.3 kg/m^3	Note 9
Uranium (scrap) mass density at 100 °C	19,000 kg/m^3	Holden 1958 Note 10
Stainless steel mass density at 100 °C	8,000 kg/m^3	ORNL 1987 Note 11
Maximum fuel mass load (Mark IV fuel)	980 kg - scrap basket 1,268 kg - fuel basket 6,052 kg per MCO	Reilly 1998
Effective fuel/clad thermal conductivity	24.2 W/m/K	Note 12
Stainless steel thermal conductivity	16.0 W/m/K	ORNL 1987
Effective fuel–cladding and uranium specific heat	122.67 J/kg/K	Note 13
Stainless steel specific heat	500.0 J/kg/K	ORNL 1987
Free residual water after draining (1.5 kg per scrap basket, 6.0 kg per fuel basket, 1.0 kg per bottom)	26.5 kg per MCO	Duncan and Ball 1997
Water in uranium hydrates, $UO_3 \cdot 2H_2O$	1.16 kg (0.72 kg)*	Note 14
Helium purge and process bay temperature	26.7 °C (80 °F)	Irwin et al. 1998
Normal annulus water temperature	50 °C	Irwin et al. 1998
CONVECTION HEAT AND MASS TRANSFER PARAMETERS gas volume, flow area, flow rate		
Scrap basket gas volume	0.153 m^3	Note 15
Upper fuel (2 fuel baskets) volume	0.186 m^3	Note 16
Lower fuel (2 fuel baskets) volume	0.199 m^3	Note 17
Fine scrap porosity	0.40	Note 18
Course scrap porosity	0.7392	Note 19
Flow area in scrap basket bottom	0.013 m^2	Note 20

Table C-1. Key Input Parameters for Bounding and Nominal Multi-Canister Overpack. (3 sheets)

Parameter	Value	Reference
Vacuum pumping rate	0.01416 m^3/s (30 scfm)	Irwin et al. 1998
Base helium mass purge rate	1.23 E-04 kg/s (1.6 scfm)	Irwin et al. 1998

* The hydrate water mass for case 0 (NORMAL) is 0.72 kg.

MCO = multi-canister overpack.

Note 1 Bounding decay heat rate — The bounding decay power (i.e., decay heat rate) is given as 776 W per MCO with five Mark IV fuel baskets (155.2 W per fuel basket or 620.8 W for four fuel baskets), so the specific heat rate is 0.1224 W/kgU for Mark IV fuel (Duncan 1998). The scrap basket for Mark IV fuel has a maximum fuel loading of 980 kg (Kessler and Peck 1998), so the scrap basket has a maximum decay power of about 120 W (980 kgU × 0.1224 W/kgU). Hence, the bounding decay power (i.e., decay heat rate) is 740.8 W per MCO (620.8 W + 120 W) with four Mark IV fuel baskets and one Mark IV scrap basket.

Note 2 Nominal decay power — The nominal decay power is given as 403 W per MCO (Duncan 1998) with five Mark IV fuel baskets (80.6 W per fuel basket or 322.4 W for four fuel baskets), the specific heat rate is 0.06357 W/kgU based on bounding Mark IV fuel mass loading. The bounding mass loadings of Mark IV fuel is used in order to be consistent with Note 1 and conservative in the sense of maximizing the nominal decay power per MCO. The decay power for the 980 kg scrap basket is 62.3 W (980 kgU × 0.06357 W/kgU). Hence, the bounding decay power is 384.7 per MCO (322.4 W + 62.3 W) with four Mark IV fuel baskets and one Mark IV scrap basket.

Note 3 Nominal effective rate multiplier for hydrides (UH_3) — Air (oxygen) reacts faster with uranium hydride (Plys et al. 1997) than with just uranium metal. The current hydride model (Plys and Duncan 1998) models the enhanced reaction rate by increasing the effective surface area of reaction through the use of a rate multiplier. In the current hydride model (Plys and Duncan 1998), the hydrides in the MCO are strongly coupled thermally to the uranium fuel. Hence, any increase in hydride temperature is dissipated in the larger uranium fuel mass, resulting in a temperature increase for the entire fuel element. This analysis uses hydride loadings from an earlier model (Plys et al. 1997) which were revised downward later, but kept higher here in order to increase the margin for safety purposes. Otherwise, this analysis keeps the hydride model the same as in Plys and Duncan (1998). Because of this margin of safety, the nominal values for hydride mass loadings are used in all simulated cases with the bounding MCO except for the air-ingress simulations,

which used bounding hydride mass loadings. The equivalent rate multiplier for hydrides is expressed as a product of the fraction of fuel surface containing hydrides and the enhanced reaction rate (relative to literature values). The nominal hydrides cover 3.7% of the exposed fuel (Plys and Duncan 1998), and the enhanced reaction rate used was 370 (Plys et al. 1997). This means that 3.7% of the exposed fuel has a rate multiplier of 370 due to hydrides. Hence, the nominal effective rate multiplier for hydrides is 13.7 (0.037 × 370). The nominal mass loading of UH_3 in the MCO is 2.4 kg (1.3 kg in fuel elements, 1.1 kg in scrap fuel).

Note 4 Bounding effective rate multiplier for hydrides (UH_3) — The bounding rate multiplier is calculated in the same way as the nominal value, shown in Note 3, with the probability of the high effective rate of 370 increasing to 16% (99.99 percentile value based on Markov chain model with average reaction time of 30 minutes in Plys and Duncan [1998], Appendix G) for the fuel elements and 30% for the scrap fuel. Hence, the bounding rate multiplier for hydrides is 111.0 for the scrap fuel (0.30 × 370), and 59.2 for the fuel elements (0.16 × 370). The bounding mass loading of UH_3 in the MCO is 14.6 kg (5.6 kg in fuel elements, 9.0 kg in scrap fuel).

Preliminary data from dry-oven experiments with five damaged N Reactor fuel elements suggest that the maximum hydride mass per outer fuel element is 37 g and the average hydride mass without the maximum one is about 4.8 g per outer fuel element.[1] There are approximately 256 fuel assemblies per MCO, so using the preliminary data and assuming no hydrides exist on the inner elements, results in an average hydride mass of about 1.2 kg per MCO (0.0048 kg x 256 assemblies) for damaged fuel. This calculated 1.2 kg of UH_3 per MCO is half of the 2.4 kg used in most of the cases in this report. Using the maximum hydride measured mass of 37 g to estimate a large upper bound results in about 9.5 kg of UH_3 per MCO rather than the 14.6 kg used in the air ingress cases. Therefore, the hydride mass loadings in this report include a large margin, as they are much higher than the mass loadings suggested by the preliminary data.

Note 5 Cladding emissivity — Cladding emissivity is used for the combined fuel–cladding composite heat element in the model because the cladding covers the fuel element on the outside, keeping the uranium fuel hidden. The emissivity of Zircaloy-2 ranges from 0.43 to 0.46 (Scott 1965) at high temperatures. The more conservative lower value of 0.43 was chosen, which will cause less heat to radiate from the fuel–cladding heat element. This emissivity value, which is reported for high temperatures, is assumed to be the same at lower temperatures.

Note 6 Inner shield plug emissivity — The bottom of the MCO shield plug was given a high emissivity value of 1.0 (Plys and Duncan 1998) in order to increase the radiative heat transfer rate between the scrap basket fuel and the shield plug.

---

[1]Personnel communication with S. C. Marschman, Pacific Northwest National Laboratory, on June 10, 1998.

The increased heat transfer was needed to compensate for the lack of thermal conduction in the axial direction.

Note 7 Cask, MCO bottom, and outer shield plug emissivity — The emissivity of the cask, MCO bottom plate, and the outer shield plug was decreased to 0.25 (from 0.30) in order to conservatively reduce the heat removal rate from the MCO (Plys and Duncan 1998).

Note 8 View factors between fuel rods and MCO wall — The view factors between the fuel rods in the fuel basket and the MCO wall, which are used in the radiative heat transfer model for an MCO fuel basket, are documented in the HANSF code document (Plys et al. 1998). However, the view factors used in this analysis differ slightly from those in the code document. The view factors for this analysis, and for the two-scrap basket report (Plys and Duncan 1998), are described in detail in Appendix D.

Note 9 Effective fuel–cladding mass density — Since the cladding volume is merged with the fuel volume in the HANSF code (Plys et al. 1998), an effective mass density is needed for the combined fuel and cladding. To simplify the derivation, the inner fuel element and cladding are assumed to have the same effective mass density as the outer fuel element and its cladding. The total volume for the fuel elements and cladding in the HANSF code is 0.31752 m^3 (Plys et al. 1998). Since the maximum fuel mass for 216 Mark IV elements (four fuel baskets) is 5,072 kg (23.48 kg per element [Reilly 1998]), the volume of the fuel is about 0.26695 m^3, which is calculated by dividing the volume by the fuel density, 19,000 kg/m^3 at 100 °C (Holden 1958). The cladding volume is found by subtracting the fuel volume from the total volume:

$$V_{cladding} = V_{total} - V_{fuel} = 0.31752\ m^3 - 0.26695\ m^3 = 0.05057\ m^3 .$$

Multiplying the density of the Zircaloy-2 cladding, 6,541 kg/m^3 (Weakley 1979), by the volume of cladding gives a cladding mass of 330.8 kg:

$$M_{cladding} = 6{,}541\ kg/m^3 \times 0.26695\ m^3 = 330.8\ kg .$$

For thermal calculations, it is essential that the effective mass (and density) and specific heat product be conserved and, therefore, equal to the sum of the fuel and cladding parts:

$$(M \times C_p)_{eff} = M_{fuel} \times C_{p\text{-}fuel} + M_{cladding} \times C_{p\text{-}cladding}$$

where $C_{p\text{-}fuel}$ = 122.67 J/kg/K (Duncan 1998) and $C_{p\text{-}cladding}$ = 306.1 J/kg/K (Scott 1965) .

For convenience, the effective specific heat is set equal to the specific heat of uranium and the effective mass calculated, which can be done since it's the product that must be conserved. Hence, the equation above becomes the following after dividing by the uranium specific heat:

$$M_{eff} = M_{fuel} + M_{cladding} \times C_{p\text{-}cladding}/C_{p\text{-}fuel}$$

$$= 5{,}072 \text{ kg} + 330.8 \text{ kg} \times (306.1 \text{ J/kg/K} \div 122.67 \text{ J/kg/K})$$

$$= 5{,}897.4 \text{ kg}.$$

Since the Zircaloy-2 cladding has a higher heat capacity than uranium, the effective mass (in regards to mass times heat capacity product) is larger than just the sum of the masses. Using the calculated effective combined mass of the fuel and cladding above, the effective density of the fuel–cladding composite is simply the effective mass divided by the total volume:

$$\rho_{eff} = M_{eff}/V_{total}$$

$$= 5{,}897.4 \text{ kg}/0.31752 \text{ m}^3$$

$$= 18{,}573.3 \text{ kg/m}^3.$$

The temperature dependence of densities, specific heats, and conductivities is ignored in the analysis because the HANSF code does not have the capability to handle temperature-dependent material properties (Plys et al. 1998). In order to be consistent, the material parameter values were chosen at around 100 °C and rounded off.

Note 10 Uranium mass density — The mass density of uranium is about 19,000 kg/m^3 at 100 °C. Since the HANSF code (Plys et al. 1998) does not include temperature-dependent material parameters, approximate values are used. The standard reference temperature of 100 °C was chosen because it's higher than normal operating temperatures but lower than most temperatures during off-normal conditions.

Note 11 Stainless steel mass density — The mass density of 304L stainless steel is about 8,000 kg/m^3 at 100 °C (ORNL 1987). See the discussion above in Note 10 about temperature-dependent material properties.

Note 12 Effective fuel–cladding thermal conductivity — Since the fuel elements and cladding are combined in the model, an effective thermal conductivity is needed to represent the combined materials. Although the cladding has a lower conductivity, the conductivity of both metals is high, so the calculation of an effective thermal conductivity is not important to the calculational results.

The effective thermal conductivity, K_{eff}, was estimated using the following equation, which is valid for conductors connected in series such as the fuel and cladding in the radial direction:

$$x_{total}/K_{eff} = x_{fuel}/K_{fuel} + x_{cladding}/K_{cladding}$$

where

K_{fuel} = thermal conductivity of spent fuel (26.9 W/m/K [Kaufman 1962])

$K_{cladding}$ = thermal conductivity of Zircaloy-2 cladding (13.4 W/m/K [Scott 1965])

x_{total} = total radial thickness of fuel element and cladding ($x_{fuel} + x_{cladding}$) .

Since the cladding mass is about 7% of the spent fuel mass (Duncan 1998) and the cladding density is about one-third of the fuel density, the cladding was estimated to have about 20% (~7% × 3) of the combined fuel–cladding volume for both inner and outer fuel elements on the average. The thickness is proportional to the volume, therefore the cladding thickness is estimated to be $0.2 \times x_{fuel}$, making the total thickness $1.2 \times x_{fuel}$. Substituting these values into the equation above, the value of K_{eff} is derived to be 24.2 W/m/K, which is close to fuel conductivity value.

Note 13 Effective fuel–cladding (and uranium) specific heat — As discussed in Note 9, which derived the effective mass density, the effective specific heat for the combined fuel and cladding elements was chosen to be equal to the uranium specific heat, 122.67 J/kg/K at 100 °C (Kaufman 1962). This choice was in conjunction with the effective mass density calculation since it is the product of mass density and specific heat that must be conserved (i.e., the specific heat of the cladding is included in the effective mass density [see Note 9]).

Note 14 The water in hydrates was increased to 1.16 kg for this report in order to provide extra margin over the hydrate water reported elsewhere (e.g., 0.65 kg [Reilly 1998]). However, for the "normal" suite of 13 runs, case 0, which simulates a complete drying cycle with tests, the hydrate water was reduced to 0.72 kg (Sloughter 1997) because the decomposing hydrates can affect the rebound pressure tests after vacuum drying.

Note 15 Scrap basket volume — Based on the latest design drawings (Smith 1998), the scrap basket has a free volume of 0.153 m^3 when it contains 980 kg of uranium metal. This volume includes the 0.0533-m (2.1-in) gap between the scrap basket and the bottom of the MCO assembly (below the shield plug) and 0.159 m^3 void space (manifold) in the MCO assembly (Pajunen and Klimper 1998) that is always open to the MCO on top. The scrap basket volume excludes the volume of the stainless steel parts, support post inner volumes, and insert inner volume. The total length of the inner MCO is 3.6 m (141.85 in.) which includes a 0.0533-m (2.1-in.) gap above the scrap basket and a 0.0381-m (1.5-in) gap between the bottom fuel basket and the top of MCO bottom plate. The inner radius of the MCO is 0.2921 m (11.5 in.).

Note 16 Upper fuel volume (two fuel baskets) — The two upper fuel baskets are combined into one control volume in the HANSF model (Plys et al. 1998). The free volume for the two fuel baskets, excluding the stainless steel volume and inner volume of support posts and insert, is 0.186 m^3 based on the design drawings (Smith 1998).

Note 17 Lower fuel volume (two fuel baskets) — The bottom two fuel baskets have a combined free volume of 0.199 m^3. This volume includes the 0.0381-m (1.5-in) gap below the bottom fuel basket and above the MCO bottom plate and excludes the stainless steel volume and inner volume of support posts and insert.

Note 18 Fine scrap porosity — The porosity of the fine scrap fuel (0.25 in. to 1 in. maximum dimension) in the scrap basket is the void or gas space fraction (void volume divided by total volume) in the total scrap volume when the scrap is completely dry. The porosity of porous media such as a course sand is about 0.35 to 0.45. The porosity of fine scrap was calculated to be in the same range (Plys and Malinovic 1997). A fine scrap porosity of 0.40 was chosen for this analysis.

Note 19 Course scrap porosity — The largest dimension of the course scrap will not be less than 1 in. or greater than 3 in. The total open volume of an empty scrap basket is 0.16762 m^3 (total inner volume minus the insert and copper fin volumes). The fine scrap volume is 0.01592 m^3, and the course scrap volume is 0.1517 m^3. The total solid scrap volume is calculated by dividing the total bounding scrap mass, 980 kg, by the fuel mass density, 19,000 kg/m^3, resulting in a total solid volume of 0.05158 m^3. The solid (fuel) volume in the fine portion is 0.6 (1-porosity) times the total fine scrap volume, 0.01592 m^3, resulting in 0.009552 m^3. Hence, the coarse scrap solid volume is 0.05158 m^3 minus the fine scrap solid volume, 0.009552 m^3, for a value of 0.042028 m^3. Dividing the coarse scrap solid volume by the total coarse scrap volume gives the solid fraction of $0.042028\ m^3 \div 0.1517\ m^3 = 0.27707$ for the coarse portion. Hence, the porosity of the coarse scrap is just 1.0 - 0.27707 for a coarse scrap porosity value of 0.72293.

Note 20 Flow area in scrap basket bottom — The flow area at the bottom of the scrap basket is the only flow area available for the scrap and the total gas release out of the top of the MCO during vacuum drying. Since copper shims have been added between the outer scrap basket and MCO wall, the upward flow has nowhere to go except through the bottom of the scrap basket. The scrap basket bottom has 108 open 0.5-in. diameter holes (Smith 1998) in it. Hence, the total flow area is calculated as follows:

$$A_{SB} = 108 \times 3.14159 \times (0.5 \times 0.0254/2)^2\ m^2$$

$$= 108 \times 1.2668 \times 10^{-4}\ m^2$$

$$= 0.0137\ m^2$$

which was truncated to 0.013 m^2 in order to constrict the gas flow through the scrap basket a little more to account for the wire screen covering part of the holes.

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APPENDIX D

DERIVATION OF VIEW FACTORS FOR RADIATIVE THERMAL MODEL

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Fauske & Associates, Inc.

DATE: June 8, 1998

TO: Melvin G. Piepho, FDNW
Martin G. Plys
Boro Malinovic

FROM: Sung Jin Lee

SUBJECT: Calculation of View Factors Between Fuel Rods in MCO

1.0 INTRODUCTION

In HANSF code, the radiation heat transfer between individual fuel elements inside the 30-degree sector of a fuel basket in MCO is considered. This 30-degree sector defines the computational unit cell, as shown in Figure 1. The view factor between the inner and outer elements of each fuel rod is obviously one, a trivial result. Therefore, an analysis was done to determine the view factors between the outer elements and the MCO wall.

2.0 METHODS

It should be noted that view factors for direct radiation from an in-sector donor to an out-of-sector receiver must be incorporated by effectively adding that view factor to the in-sector mirror-image of the actual receiver node. For example (refer to Figure 1), the view factor which accounts for "Shine" from heat sink 6 that passes between heat sinks 4 and 8 is simply added to the view factor for radiation from 6 to 8. This way, all direct radiation paths are accounted for.

A close examination of the fuel rods arrangement inside the MCO reveals that the complete view factor matrix can be derived from the view factors of three basic configurations:

1. View factor to a adjacent fuel rod, F_a.
2. View factor to a second tier fuel rod through the gap, F_b.
3. View factor to a second tier fuel rod partially blocked by an adjacent rod, F_c.

These, with the requirement that sum of view factors from a surface must be one, and the symmetry relationship, $A_{i-j}\ F_{i-j} = A_{j-i}\ F_{j-i}$, provide sufficient information to determine the complete view factor matrix.

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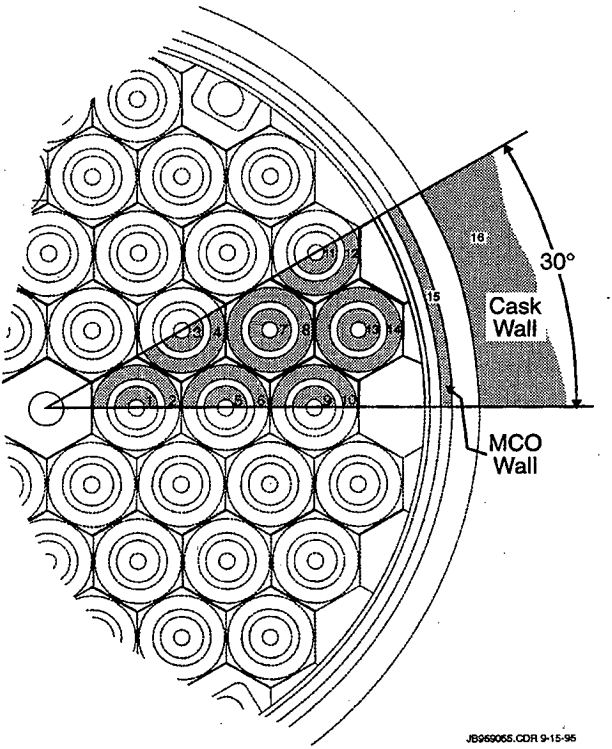
Figure 1: A 30-Degree Unit Sector of a Fuel Basket.



A computer program VIEWF was used to calculate the view factors for the above three basic configurations. This program computes the view factor matrix for a network of multiple planar or circular surfaces using the first principle view factor definition. The description of this program is included in Attachment 1. Six fuel rods and a 60 degree sector of the MCO wall were chosen as inputs to this code, as shown in Figure 2. They were chosen judiciously so that the result can provide the view factors for above three configurations (F_a, F_b, and F_c).

3.0 RESULTS

The input deck to VIEWF is shown in Table 1. The output from the program is shown in Table 2. Since seven surfaces are specified in the input deck (the MCO wall is the seventh surface), the output lists a 14-by-14 view factor matrix because each surface has inside and outside. Therefore,

A. view factor to an adjacent fuel rod = $F_a = 0.153$,
B. view factor to a second tier fuel rod through the gap = $F_b = 0.014$, and
C. view factor to a second tier fuel rod when the path is partially covered = $F_c = 0.049$.

Now, the derivation of the actual view factor between individual fuel rods and the MCO wall inside the 30-degree sector is shown in Table 3. These are documented in Table 3-3 of the HANSF 1.2 User's Manual [1], and are provided as inputs to the HANSF code.

4.0 REFERENCE

[1] FAI/98-40, Rev. 0, "Hanford Spent Nuclear Fuel Safety Analysis Model HANSF 1.2: User's Manual," May 1998.

Figure 2: Input Configuration to VIEWF Program.

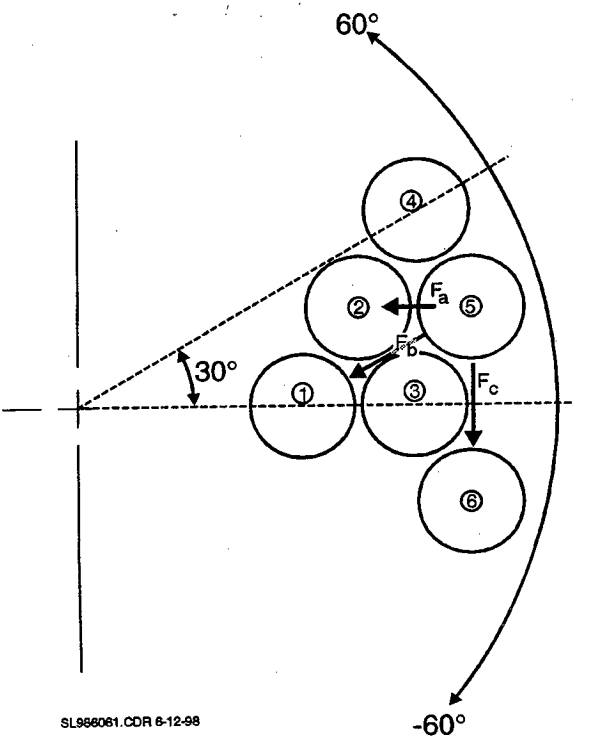


Table 1

Input Deck to VIEWF Program

```
C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                              MCO FUEL ELEMENTS
C
C  Six fuel rods and a 60 degree sector of the MCO wall were chosen
C  for this view factor calculation.  They were chosen judiciously so that
C  the result can provide view factors for following three configurations:
C
C  1.  view factor to a adjacent fuel rod
C  2.  view factor to a second tier fuel rod through the gap
C  3.  view factor to a second tier fuel rod when the path is partially
C      block by one adjacent rod.
C
C  The complete view factor matrix between outer elements and the MCO
C  wall inside the 30 degree sector of the MCO can be derived from the
C  above three view factors.
C
C  The radius of each fuel rod is 3.08 cm and the rods are packed with
C  the pitch of 2.75" (6.985 cm).  Therefore, the gap between the rods is
C  0.825 cm.
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - IN CLOCKWISE, ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - IN CLOCKWISE, ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - IN CLOCKWISE DIRECTION, X-COORDINATE OF THE STARTING POINT
C    YSTRT  - IN CLOCKWISE DIRECTION, Y-COORDINATE OF THE STARTING POINT
C    XEND   - IN CLOCKWISE DIRECTION, X-COORDINATE OF THE ENDING POINT
C    YEND   - IN CLOCKWISE DIRECTION, Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC   INHS      XORG        YORG       RADIUS     QSTRT      QEND
       1       1     0.13970     0.0        0.0308     0.0        6.2832
       1       1     0.174625    0.0604919  0.0308     0.0        6.2832
       1       1     0.20955     0.0        0.0308     0.0        6.2832
       1       1     0.20955     0.1209838  0.0308     0.0        6.2832
       1       1     0.244475    0.0604919  0.0308     0.0        6.2832
       1       1     0.244475   -0.0604919  0.0308     0.0        6.2832
       1       1     0.0         0.0        0.2920    -1.0472     1.0472
```

Table 2

Output of VIEWF Program

VIEW FACTORS

1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.153	0.000	0.153	0.000	0.000	0.000	0.014	0.000	0.048	0.138	0.000
0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.153	0.000	0.000	0.000	0.153	0.000	0.153	0.000	0.153	0.000	0.000	0.071	0.000
0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.153	0.000	0.153	0.000	0.000	0.000	0.014	0.000	0.153	0.000	0.153	0.228	0.000
0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.153	0.000	0.014	0.000	0.000	0.000	0.153	0.000	0.000	0.412	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
0.000	0.014	0.000	0.153	0.000	0.153	0.000	0.153	0.000	0.000	0.000	0.049	0.465	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
0.000	0.048	0.000	0.000	0.000	0.153	0.000	0.000	0.000	0.049	0.000	0.000	0.534	0.000
0.000	0.044	0.000	0.023	0.000	0.072	0.000	0.130	0.000	0.147	0.000	0.169	0.040	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3: Derivation of View Factors

	2	4	6	8	10	12	14	15	$\sum F_{i-j}$
2	$3F_a+2F_b-F_b$ = 0.473	$2F_a+F_b$ = 0.320	F_a+2F_b = 0.181	$2F_b$ = 0.028	0	0	0	0	1.002
4	F_{2-4} = 0.320	$2F_b$ = 0.028	$2F_a$ = 0.306	$2F_a$ = 0.306	$2F_b$ = 0.028	F_b = 0.014	0	0	1.002
6	F_{2-6} = 0.181	F_{4-6} = 0.306	0	$2F_a+2F_b$ = 0.334	F_a = 0.153	0	$2F_b$ = 0.028	0	1.002
8	F_{2-8} / 2 = 0.014	F_{4-8} / 2 = 0.153	F_{6-8} / 2 = 0.167	F_a+F_b = 0.167	F_a = 0.153	F_a = 0.153	F_a+F_b = 0.167	$2F_b$ = 0.028	1.002
10	F_{2-10} = 0	F_{4-10} = 0.028	F_{6-10} = 0.153	$2F_{8-10}$ = 0.306	0	$2F_b$ = 0.028	$2F_a$ = 0.306	F_a+2F_b = 0.181	1.002
12	F_{2-12} = 0	F_{4-12} = 0.014	F_{6-12} = 0	$2F_{8-12}$ = 0.306	F_{10-12} = 0.028	0	$2F_a$ = 0.306	$2F_a+3F_b$ = 0.348	1.002
14	F_{2-14} / 2 = 0	F_{4-14} / 2 = 0	F_{6-14} / 2 = 0.014	F_{8-14} = 0.167	F_{10-14} / 2 = 0.153	F_{12-14} / 2 = 0.153	F_c = 0.049	$3F_a+4F_b-F_c$ = 0.466	1.002
15	$\frac{A_2}{A_{15}} F_{2-15}$ =0	$\frac{A_4}{A_{15}} F_{4-15}$ =0	$\frac{A_6}{A_{15}} F_{6-15}$ =0	$\frac{A_8}{A_{15}} F_{8-15}$ =0.0354	$\frac{A_{10}}{A_{15}} F_{10-15}$ =0.1146	$\frac{A_{12}}{A_{15}} F_{12-15}$ =0.2202	$\frac{A_{14}}{A_{15}} F_{14-15}$ =0.5898	1 - F_{15-8} - F_{15-10} - F_{15-12} - F_{15-14} =0.04	1.000

F_a = 0.153

F_b = 0.014

F_c = 0.049

$A_2 = A_4 = A_6 = A_{10} = A_{12} = 2\pi\ (0.0308) / 2 = 0.09676$

$A_8 = A_{14} = 2\pi\ (0.0308) = 0.19352$

$A_{15} = (30 / 360)\ 2\pi\ (0.292) = 0.15289$

ATTACHMENT 1

Fauske & Associates, Inc.

DATE: August 22, 1995

TO: All FAI Engineers

FROM: Sung Jin Lee

SUBJECT: **Program VIEWF: View Factor Calculation Program**

1.0 INTRODUCTION

Fortran program VIEWF.FOR computes view factors for multiple surfaces. Currently, the program is written to handle two-dimensional configurations, but the algorithm as described herein is generalized to three-dimensional configurations. All surfaces must be either planar or sectors of a cylindrical shell. In two dimensions, these corresponds to either a line segment or the arc of a circle. The user may subdivide a sector into a number of equal size "sub-sectors". Each surface has an inside and an outside face. Therefore, the computed view factor matrix for a system of N surfaces would be of dimension 2N-by-2N.

2.0 HOW TO USE THE PROGRAM

Currently, the Fortran program and the executable code (VIEWF.EXE) reside in the directory:

2DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]

The user will be prompted to enter the input and the output file names. Each line in the input file contains a sequence of integers or real numbers (separated by one or more blanks) to describe one surface completely. Several such lines define a system of surfaces for which the view factors are to be computed. The format of an input line is:

ICIRC INHS XORG YORG RADIUS QSTRT QEND

or

ICIRC XSTRT YSTRT XEND YEND

where ICIRC = 1, for a sector
= 0, for a planar surface.

If ICIRC=1, the first format is used,

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where INHS = number of subdivisions in the sector,
XORG = X-coordinate of the origin of the sector,
YORG = Y-coordinate of the origin of the sector,
RADIUS = radius of the sector,
QSTRT = angle (in radians) of the starting point (counter-clockwise from X-axis), and
QEND = angle (in radians) of the ending point.

If ICIRC=0, the second format is used,

where XSTRT = X-coordinate of the starting point,
YSTRT = Y-coordinate of the starting point,
XEND = X-coordinate of the ending point, and
YEND = Y-coordinate of the ending point.

Also, comment lines can be added freely to the input file with "C" in the first column. Sample input files (Appendix B) contain sufficient comment lines to guide the user to prepare a new input file.

The program writes the computed view factors to the output file in matrix format where element f_{ij} designates the view factor F_{i-j}. Since there are two sides for each surface, the index-i is sequenced in the order of surface-1 inside, surface-1 outside, surface-2 inside, surface-2 outside, surface-3 inside, etc. For example, F_{5-8} designates the view factor of surface-3 inside seeing surface-4 outside.

To define inside and outside of a surface, it is instructive to draw a vector parallel to the surface as defined by the starting and the ending points of the surface. Then, rotate the vector 90 degrees clockwise to obtain the normal vector of the surface. The face in the same direction as the normal vector is herein defined as outside and the other as inside. Figure 1 illustrates how inside and outside are defined for surfaces.

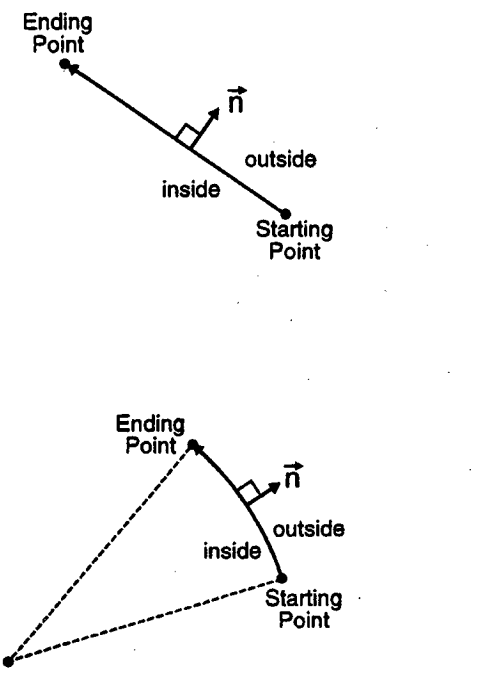
3.0 ALGORITHM

3.1 Step 1

Subdivide each surface into 10 nodes. For each surface node, determine its position coordinate (x_o, y_o, z_o) and define a normal vector $\vec{n} = (a, b, c)$, such that the magnitude of the normal vector represents the area of the surface. Then, the equation of the plane passing through a point $P_o\ (x_o, y_o, z_o)$ with the normal vector $\vec{n} = (a, b, c)$ is given by

$$a(x - x_o) + b(y - y_o) + c(z - z_o) = 0 \qquad (1)$$

Figure 1: Inside / Outside.



3.2 Step 2

For each surface node, determine the view factor to every other surface node as follows:

a. Determine the vector joining the two surfaces as shown in Figure 2.

$$\vec{v} = (\alpha, \beta, \gamma) = (x_{o_2} - x_{o_1},\ y_{o_2} - y_{o_1},\ z_{o_2} - z_{o_1}) \quad (2)$$

b. Equation of the line joining the two surfaces is represented by parametric equations:

$$x = x_{o_1} + t\alpha \quad (3a)$$

$$y = y_{o_1} + t\beta \quad (3b)$$

$$z = z_{o_1} + t\gamma \quad (3c)$$

c. Determine whether the line joining the two surfaces is intercepted by a third surface node as shown in Figure 3. Hence, for every possible third surface, do the following calculation. The line intersects the third plane at $t = t^*$ such that:

$$a_3 (x_{o_1} + t\alpha - x_{o_3}) + b_3 (y_{o_1} + t\beta - y_{o_3}) + c_3 (z_{o_1} + t\gamma - z_{o_3}) = 0 \quad (4)$$

or

$$t^* = \frac{-a_3 (x_{o_1} - x_{o_3}) - b_3 (y_{o_1} - y_{o_3}) - c_3 (z_{o_1} - z_{o_3})}{a_3\alpha + b_3\beta + c_3\gamma} \quad (5)$$

Note that if $a_3 \alpha + b_3 \beta + c_3 \gamma = 0$, there is no intersection. Therefore, it intersects at (x*, y*, z*) where

$$x^* = x_{o_1} + t^*\alpha \quad (6a)$$

$$y^* = y_{o_1} + t^*\beta \quad (6b)$$

$$z^* = z_{o_1} + t^*\gamma \quad (6c)$$

d. Check if the distance between the intersection point (x*, y*, z*) and the third surface coordinate $(x_{o_3}, y_{o_3}, z_{o_3})$ is less than the square root of the surface area. That is,

Figure 2: A Vector Joining Two Surfaces.

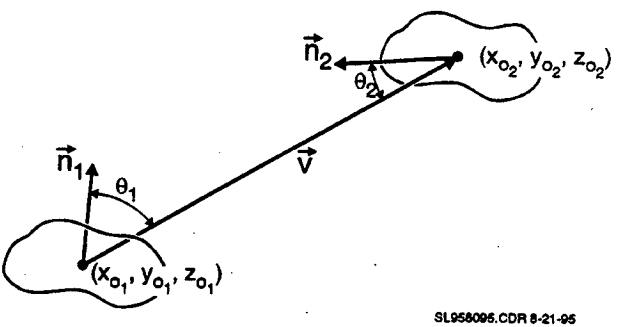
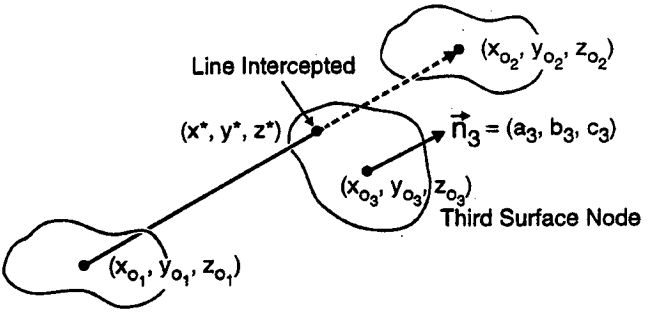


Figure 3: Line Joining Two Surfaces Intercepted by a Third Surface.



$$\sqrt{(x^* - x_{o_3})^2 + (y^* - y_{o_3})^2 + (z^* - z_{o_3})^2} \quad < \quad (a_3^2 + b_3^2 + c_3^2)^{1/4} \tag{7}$$

If the inequality of equation (7) is satisfied, the line is intercepted by the third surface and the two surfaces cannot see each other. Hence,

$$F_{12}^* = 0 \tag{8}$$

Otherwise, the subnode view factor can be computed as

$$F_{12}^* = \frac{\cos Q_1 \ \cos Q_2 \ |\vec{n}_2|}{\pi \ |\vec{v}|^2} \tag{9}$$

3.3 Step 3

Sum up subnode view factors to determine view factors between surfaces.

$$F_{ij} = \sum_{k \in i} \sum_{\ell \in j} F_{k\ell}^* \tag{10}$$

4.0 VALIDATION

The program was validated against analytical solutions for a variety of two-dimensional configurations. Seven configurations selected from page 459 of A Heat Transfer Textbook by John H. Lienhard were tested. The results are summarized in Figure 4. In general, the error was less than 3%. Only for two concentric circles, 6% error was observed. It should be noted that the resolution can be improved by using finer mesh. Currently 10 meshes are used for each surface. Since the number of meshes is hardwired in the program, the program needs to be changed to increase the number of meshes. The input files for all seven cases are included in the Appendix B.

SJL:vdl

Figure 4: View Factors for a Variety of Two-Dimensional Configurations.
(infinite in extent normal to the paper)

SL9586091.CDR 8-22-95

Configuration	Equation	Dimensions	Analytical Results	VIEWF Results
1.	$F_{1\text{-}2} = F_{2\text{-}1} = \sqrt{1 + \left(\frac{h}{w}\right)^2} - \left(\frac{h}{w}\right)$	h = 2 w = 2	$F_{1\text{-}2}$ = 0.414	$F_{1\text{-}2}$ = 0.415
2.	$F_{1\text{-}2} = F_{2\text{-}1} = 1 - \sin(\alpha/2)$	$\alpha = 90°$	$F_{1\text{-}2}$ = 0.293	$F_{1\text{-}2}$ = 0.302
3.	$F_{1\text{-}2} = \frac{1}{2}\left[1 + H - \sqrt{1+H^2}\right]$, $H = \left(\frac{h}{w}\right)$	h = 1 w = 2	$F_{1\text{-}2}$ = 0.191	$F_{1\text{-}2}$ = 0.194
4.	$F_{1\text{-}2} = (A_1 + A_2 - A_3)/2A_1$	$A_1 = \sqrt{6}$ $A_2 = 1$ $A_3 = 2$	$F_{1\text{-}2}$ = 0.276	$F_{1\text{-}2}$ = 0.278
5.	$F_{1\text{-}2} = \frac{r}{b-a}\left[\tan^{-1}\frac{b}{c} - \tan^{-1}\frac{a}{c}\right]$	a = 2 b = 4 c = 2 r = 1	$F_{1\text{-}2}$ = 0.161	$F_{1\text{-}2}$ = 0.160
6.	Let X = 1 + s/D, Then: $F_{1\text{-}2} = F_{2\text{-}1} = \frac{1}{\pi}\left[\sqrt{X^2-1} + \sin^{-1}\left(\frac{1}{X}\right) - X\right]$	s = 1 D = 2	$F_{1\text{-}2}$ = 0.111	$F_{1\text{-}2}$ = 0.108
7.	$F_{1\text{-}2} = 1$, $F_{2\text{-}1} = \frac{r_1}{r_2}$, and $F_{2\text{-}2} = 1 - F_{2\text{-}1} = 1 - \frac{r_1}{r_2}$	$r_1 = 1$ $r_2 = 2$	$F_{2\text{-}1}$ = 0.500	$F_{2\text{-}1}$ = 0.529

APPENDIX A

PROGRAM LISTING

File: 2DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF.FOR;40 Thu Aug 17 15:01:41 1995 Page 1

```
      IMPLICIT REAL (A-H,K-Z)
      DIMENSION XM(300),YM(300),AM(300),NXM(300),NYM(300),AHS(30),
     @   F(30,2,30,2),IHSIM(300)
      CHARACTER*30 INFILE,OUTFIL,NUL
      CHARACTER*132 A
      DATA PI/3.141593E0/,TINY/1.E-3/,AHS/30*0.E0/,F/3600*0.E0/
      NUL=' '
C FOR NOW, SUBDIVIDE EACH HEAT SINK INTO 10 MESHES
      INMESH=20
      IHS=0
      IM=0
      WRITE(*,*) 'What is the input file name ?'
      READ(*,50) INFILE
   50 FORMAT(A30)
      WRITE(*,*) 'What is the output file name ?'
      READ(*,50) OUTFIL
      OPEN(UNIT=5,FILE=INFILE,STATUS='OLD')
      IF (OUTFIL .NE. NUL) OPEN(UNIT=6,FILE=OUTFIL,STATUS='UNKNOWN')
C LOOP FOR READING LINES FROM INPUT FILE
  100 CONTINUE
      READ(5,110,END=1000) A
  110 FORMAT(A132)
      IF (A(1:1) .EQ. 'C') GOTO 100
      READ(A,*) ICIRC
      IF (ICIRC .EQ. 1) THEN
         READ(A,*) ICIRC,INHS,XORG,YORG,RADIUS,QSTRT,QEND
C COORDINATE OF THE STARTING POINT
         XSTRT=RADIUS*COS(QSTRT)+XORG
         YSTRT=RADIUS*SIN(QSTRT)+YORG
C TOTAL ARC ANGLE
         QARCT=QEND-QSTRT
         IF (QARCT .LT. 0.E0) QARCT=QARCT+2.E0*PI
      ELSE
         READ(A,*) ICIRC,INHS,XSTRT,YSTRT,XEND,YEND
C VECTOR JOINING THE TWO END POINTS
         L12X=XEND-XSTRT
         L12Y=YEND-YSTRT
C MAGNITUDE OF THE VECTOR
         MAGL12=SQRT(L12X*L12X+L12Y*L12Y)
C NORMALIZE THE VECTOR
         L12X=L12X/MAGL12
         L12Y=L12Y/MAGL12
      ENDIF
      X1=XSTRT
      Y1=YSTRT
      DO 200 I=1,INHS
         IHS=IHS+1
         DO 300 J=1,INMESH
            IM=IM+1
            IHSIM(IM)=IHS
            IF (ICIRC .EQ. 0) THEN
               X2=XSTRT+((I-1)*INMESH+J)*L12X*MAGL12/INHS/INMESH
               Y2=YSTRT+((I-1)*INMESH+J)*L12Y*MAGL12/INHS/INMESH
            ELSE
               Q=((I-1)*INMESH+J)*QARCT/INHS/INMESH
               X2=(XSTRT-XORG)*COS(Q)-(YSTRT-YORG)*SIN(Q)+XORG
               Y2=(XSTRT-XORG)*SIN(Q)+(YSTRT-YORG)*COS(Q)+YORG
            ENDIF
C  COORDINATE OF THE MESH
```

```
            XM(IM)=(X1+X2)/2.E0
            YM(IM)=(Y1+Y2)/2.E0
C  AREA OF THE MESH
            AM(IM)=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1))
C  UNIT NORMAL VECTOR OF THE MESH
            NXM(IM)=-(Y2-Y1)
            NYM(IM)=X2-X1
            MAGNM=SQRT(NXM(IM)*NXM(IM)+NYM(IM)*NYM(IM))
            NXM(IM)=NXM(IM)/MAGNM
            NYM(IM)=NYM(IM)/MAGNM
            X1=X2
            Y1=Y2
  300     CONTINUE
  200 CONTINUE
C READ THE NEXT INPUT LINE
      GOTO 100
C END OF INPUT LINE
 1000 CONTINUE
C
      IMX=IM
      IHSX=IHS
      DO 600 IMI=1,IMX
      IHSI=IHSIM(IMI)
      AHS(IHSI)=AHS(IHSI)+AM(IMI)
      DO 700 IMJ=1,IMX
         IHSJ=IHSIM(IMJ)
         IF (IMI .EQ. IMJ) GOTO 700
C  DETERMINE THE VECTOR JOINING THE TWO SURFACES
         VX=XM(IMJ)-XM(IMI)
         VY=YM(IMJ)-YM(IMI)
         MAGV=SQRT(VX*VX+VY*VY)
         VX=VX/MAGV
         VY=VY/MAGV
C  FOR EACH THIRD SURFACE, EVALUATE INTERCEPTION
         DO 800 IMK=1,IMX
            IHSK=IHSIM(IMK)
            IF (IMK .EQ. IMJ .OR. IMK .EQ. IMI) GOTO 800
            IF (ABS(NXM(IMK)*VX+NYM(IMK)*VY) .LT. TINY) GOTO 800
            T=(-NXM(IMK)*(XM(IMI)-XM(IMK))-NYM(IMK)*(YM(IMI)-YM(IMK)))/
     @        (NXM(IMK)*VX+NYM(IMK)*VY)
            IF (T .LT. 0.E0) GOTO 800
C  INTERSECTION POINT
            XPRIM=XM(IMI)+T*VX
            YPRIM=YM(IMI)+T*VY
            IF (XPRIM .GT. XM(IMI) .AND. XPRIM .GT. XM(IMJ)) GOTO 800
            IF (XPRIM .LT. XM(IMI) .AND. XPRIM .LT. XM(IMJ)) GOTO 800
            IF (YPRIM .GT. YM(IMI) .AND. YPRIM .GT. YM(IMJ)) GOTO 800
            IF (YPRIM .LT. YM(IMI) .AND. YPRIM .LT. YM(IMJ)) GOTO 800
C  DISTANCE BETWEEN THE INTERSECTION POINT AND THE SURFACE COORDINATE
            LXPXM=SQRT((XPRIM-XM(IMK))**2.E0+(YPRIM-YM(IMK))**2.E0)
C  CHECK IF DISTANCE BETWEEN THE INTERSECTION POINT AND THE THIRD SURFACE
C  COORDINATE IS LESS THAN SQUARE ROOT OF THE SURFACE AREA.
C  IF TRUE, THEN INTERCEPTED
            IF (LXPXM .LT. AM(IMK)/2.E0) GOTO 700
  800     CONTINUE
         VDOTMI=NXM(IMI)*VX+NYM(IMI)*VY
         VDOTMJ=NXM(IMJ)*VX+NYM(IMJ)*VY
         IF (VDOTMI .GE. 0.E0) THEN
C SIDE-1 OF FIRST SURFACE RADIATING TO
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF.FOR;40 Thu Aug 17 15:01:41 1995  Page 3

            IF (VDOTMJ .GE. 0.E0) THEN
C SIDE-2 OF SECOND SURFACE
               FM=VDOTMI*VDOTMJ*AM(IMI)*AM(IMJ)/2.E0/MAGV
               F(IHSI,1,IHSJ,2)=F(IHSI,1,IHSJ,2)+FM
            ELSE
C SIDE-1 OF SECOND SURFACE
               FM=-VDOTMI*VDOTMJ*AM(IMI)*AM(IMJ)/2.E0/MAGV
               F(IHSI,1,IHSJ,1)=F(IHSI,1,IHSJ,1)+FM
            ENDIF
         ELSE
C SIDE-2 OF FIRST SURFACE RADIATING TO
            IF (VDOTMJ .GE. 0.E0) THEN
C SIDE-2 OF SECOND SURFACE
               FM=-VDOTMI*VDOTMJ*AM(IMI)*AM(IMJ)/2.E0/MAGV
               F(IHSI,2,IHSJ,2)=F(IHSI,2,IHSJ,2)+FM
            ELSE
C SIDE-1 OF SECOND SURFACE
               FM=VDOTMI*VDOTMJ*AM(IMI)*AM(IMJ)/2.E0/MAGV
               F(IHSI,2,IHSJ,1)=F(IHSI,2,IHSJ,1)+FM
            ENDIF
         ENDIF
  700 CONTINUE
  600 CONTINUE
C
      DO 910 IHSI=1,IHSX
         DO 950 IHSJ=1,IHSX
            F(IHSI,1,IHSJ,1)=F(IHSI,1,IHSJ,1)/AHS(IHSI)
            F(IHSI,1,IHSJ,2)=F(IHSI,1,IHSJ,2)/AHS(IHSI)
            F(IHSI,2,IHSJ,1)=F(IHSI,2,IHSJ,1)/AHS(IHSI)
            F(IHSI,2,IHSJ,2)=F(IHSI,2,IHSJ,2)/AHS(IHSI)
  950    CONTINUE
  910 CONTINUE
C
      WRITE (6,1100)
 1100 FORMAT(1X,30X,'VIEW FACTORS'/
     @       1X,30X,'------------')
      WRITE (6,*)
      WRITE (6,*)
      DO 1200 IHS=1,IHSX
         WRITE(6,1210) ((F(IHS,1,JHS,I2),I2=1,2),JHS=1,IHSX)
 1210    FORMAT(1X,20(1X,F5.3))
         WRITE(6,1210) ((F(IHS,2,JHS,I2),I2=1,2),JHS=1,IHSX)
 1200 CONTINUE
      STOP
      END
```

APPENDIX B

INPUT FILES FOR TESTING

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST1.DAT;3 Thu Aug 17 15:01:50 1995  Pag
 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                                 TEST 1
C
C
C                                    :Y
C                                    :
C                                  1_____
C                                    :
C                                    :
C                                    :
C                 - - - - +- - - - - + - - - - - -+- - - X
C                        -1          :           1
C                                    :
C                                    :
C                                  -1_____
C                                    :
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS       XSTRT       YSTRT       XEND       YEND
       0        1         1.0         1.0        -1.0        1.0
       0        1        -1.0        -1.0         1.0       -1.0
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST2.DAT;4 Thu Aug 17 15:01:54 1995  Pag
 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                        TEST 2 - JOHN H. LIENHARD P459
C
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C     INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C     XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C     YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C     RADIUS - RADIUS OF THE CURVATURE
C     QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C     QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C     XSTRT  - X-COORDINATE OF THE STARTING POINT
C     YSTRT  - Y-COORDINATE OF THE STARTING POINT
C     XEND   - X-COORDINATE OF THE ENDING POINT
C     YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC   INHS       XSTRT       YSTRT       XEND       YEND
       0       1       0.7071      0.7071      0.0        0.0
       0       1       0.0         0.0         0.7071    -0.7071
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST3.DAT;3 Thu Aug 17 15:01:58 1995  Pag
 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                        TEST 3 - JOHN H. LIENHARD P459
C
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS       XSTRT       YSTRT       XEND       YEND
       0        1         0.0         0.0         2.0        0.0
       0        1         0.0         1.0         0.0        0.0
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST4.DAT;3 Thu Aug 17 15:02:02 1995  Pag
 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                        TEST 4 - JOHN H. LIENHARD P459
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS       XSTRT       YSTRT       XEND       YEND
       0        1         0.0         0.0        -2.0       -1.0
       0        1         0.0        -1.0         0.0        0.0
       0        1        -2.0        -1.0         0.0       -1.0
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST5.DAT;10 Thu Aug 17 15:02:18 1995  Pa
e 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                        TEST 5 - JOHN H. LIENHARD P459
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS      XSTRT      YSTRT      XEND      YEND
       0        1        -4.0       -2.0       -2.0      -2.0
C    ICIRC    INHS      XORG       YORG       RADIUS    QSTRT      QEND
       1        1        0.0        0.0        1.0       0.0        6.283
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST6.DAT;2 Thu Aug 17 15:02:22 1995  Page
 1

C
C              INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                          TEST 6 - JOHN H. LIENHARD P459
C
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS      XORG       YORG       RADIUS     QSTRT      QEND
       1        1       -1.5        0.0         1.0       0.0       6.283
       1        1        1.5        0.0         1.0       0.0       6.283
```

```
File: $2$DIA2:[MAAP4.LEE.PWR.HOT.MCO.VIEW]VIEWF_TEST7.DAT;2 Thu Aug 17 15:02:28 1995  Pag
 1

C
C            INPUT FILE FOR VIEWF.FOR - VIEW FACTOR CALCULATION PROGRAM
C
C                        TEST 6 - JOHN H. LIENHARD P459
C
C
C ICIRC  - =1, CURVED SURFACE
C          =0, PLANNAR SURFACE
C
C IF ICIRC=1, SUPPLY FOLLOWING PARAMETERS
C
C    INHS   - NUMBER OF HEAT SINKS TO REPRESENT THE SURFACE
C    XORG   - X-COORDINATE OF THE ORGIN OF THE CURVATURE
C    YORG   - Y-COORDINATE OF THE ORGIN OF THE CURVATURE
C    RADIUS - RADIUS OF THE CURVATURE
C    QSTRT  - ANGLE OF THE STARTING POINT (IN RADIANT)
C    QEND   - ANGLE OF THE ENDING POINT (IN RADIANT)
C
C IF ICIRC=0, SUPPLY FOLLOWING PARAMETERS
C    XSTRT  - X-COORDINATE OF THE STARTING POINT
C    YSTRT  - Y-COORDINATE OF THE STARTING POINT
C    XEND   - X-COORDINATE OF THE ENDING POINT
C    YEND   - Y-COORDINATE OF THE ENDING POINT
C
C    ICIRC    INHS       XORG       YORG       RADIUS     QSTRT      QEND
       1        1        0.0        0.0         1.0       0.0        6.283
       1        1        0.0        0.0         2.0       0.0        6.283
```

APPENDIX E

HANSF CODE QUALITY ASSURANCE

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APPENDIX E

HANSF CODE QUALITY ASSURANCE

This appendix describes the quality assurance that was performed on version 1.2 of the HANSF code (Plys et al. 1998) by personnel at the Hanford Site following the software practices described in HNF-PRO-437, *Software Practices — Software Application.*

The primary quality assurance for the HANSF code was performed by the developers at Fauske & Associates, Inc. (FAI).[1] FAI maintains configuration control on the source code, and performs the verification and validation of the HANSF code (Plys et al. 1998).

Personnel at the Hanford Site demonstrated that the final (earlier beta versions existed) executable version (1.2) supplied by FAI on July 2, 1998, produced the same results on the Hanford Site computer used for calculating the results for this report as it did on the FAI computers, which have been documented in detail (Plys et al. 1998). The Hanford Site computer was a 200 Mhz Pentium PC (AST, Bravo MS 5200M) with 32 MBytes of memory. This was accomplished by running the test case input files (25 in all) on the Hanford Site computer, and then comparing the Site-generated output files with the corresponding output files from FAI. The comparison of the output files was performed in detail by performing a "diff" operation on each pair of files being compared. The "diff" operation detects all differences between the two files being compared. The only differences detected for each of the 25 cases were the date and file names, which means all of the calculated variables were exactly the same to the number of significant digits printed in the output files (up to 7 digits for some variables) for all cases. Hence, the HANSF code (version 1.2) runs the same on the Hanford Site computer as it does on the FAI computers.

Most of the 25 test input files were originally created by FAI personnel to test 15 specific effects or physical processes. The code results for each separate effects test were compared to experimental data and/or analytical solutions and documented (Plys et al. 1998, Section 7). The separate effects tests included the following physical phenomena:

1. Region thermodynamics
2. Fog formation
3. Intercompartmental flow
4. Heat transfer by conduction
5. Aerosol transport and deposition
6. Countercurrent flow
7. Aerosol de-entrainment
8. Evaporation/condensation
9. Hydride formation and decomposition

---

[1]Fauske & Associates, Inc., 16W070 West 83rd Street, Burr Ridge, Illinois 60521, with phone number 630-323-8750.

10. Uranium oxidation
11. Entrainment
12. Hydrate decomposition
13. Fuel and scrap basket heat transfer
14. Nitride formation
15. Vacuum and recirculation pump.

For some of the physical processes, more than one test was performed. Altogether, 22 test input files were created for the HANSF code to test the 15 physical processes. Some of the processes, such as aerosol entrainment and de-entrainment, were not used by this analysis, but most of the others were.

In addition to the specific effects testing, three integral tests that illustrate use of the code for typical multi-canister overpack transients, which include several physical processes, were developed by FAI personnel (Plys et al. 1998). The three integral tests demonstrate reasonable performance consistent with expectation in the following areas:

1. Vacuum cycle simulation of cold vacuum drying process
2. Shipping simulation
3. Interim storage.

In summary, the HANSF code (version 1.2) runs the same at the Hanford Site as it was meant to run and demonstrated to run at FAI. Furthermore, the HANSF code has the capability to model the physical processes that are important to the Cold Vacuum Drying Facility.

REFERENCES

HNF-PRO-437, *Software Practices — Software Application*, Fluor Daniel Hanford, Incorporated, Richland, Washington.

Plys, M. G., S. J. Lee, B. Malinovic, and M. Epstein, 1998, *Hanford Spent Nuclear Fuel Safety Analysis Model HANSF 1.2: User's Manual*, FAI/98-40, Rev. 0, Fauske & Associates, Incorporated, Burr Ridge, Illinois.

APPENDIX F

PEER REVIEW CHECKLIST

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CHECKLIST FOR PEER REVIEW

Document Reviewed: HNF-SD-SNF-CN-023, Revision 1, *Thermal Analysis of Cold Vacuum Drying of Spent Nuclear Fuel*

Scope of Review: Entire document

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

[X] [ ] [ ] **Document approved.**

Boo Malmo — 7/15/98

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.

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