AUG 2 8 1996 Sta. 37 (20)

ENGINEERING DATA TRANSMITTAL

Page 1 of 1

1. EDT № 614687

2. To: (Receiving Organization) Distribution	3. From: (Originating Organization) Process Engineering Analysis	4. Related EDT No.: N/A
5. Proj./Prog./Dept./Div.: W74A50	6. Design Authority/ Design Agent/Cog. Engr.: J. J. Irwin/D. M. Ogden	7. Purchase Order No.: N/A
8. Originator Remarks: Approval/Release		9. Equip./Component No.: N/A
		10. System/Bldg./Facility: N/A
11. Receiver Remarks: 11A. Design Baseline Document? [] Yes [X] No		12. Major Assm. Dwg. No.: N/A
		13. Permit/Permit Application No.: N/A
		14. Required Response Date:

15. DATA TRANSMITTED

(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	(F) Approval Designator	(G) Reason for Transmittal	(H) Originator Disposition	(I) Receiver Disposition
1	WHC-SD-WM-ER-607		0	Spent Nuclear Fuel Vacuum Drying Thermal-Hydraulic Analysis and Dynamic Model Development Status Report	N/A	1	1	

16. KEY

Approval Designator (F)	Reason for Transmittal (G)	Disposition (H) & (I)
E, S, Q, D or N/A (see WHC-CM-3-5, Sec.12.7)	1. Approval 2. Release 3. Information 4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)	1. Approved 2. Approved w/comment 3. Disapproved w/comment 4. Reviewed no/comment 5. Reviewed w/comment 6. Receipt acknowledged

17. SIGNATURE/DISTRIBUTION
(See Approval Designator for required signatures)

(G) Reason	(H) Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN	(G) Reason	(H) Disp.	(J) Name	(K) Signature	(L) Date	(M) MSIN
1	1	Design Authority J. J. Irwin	J. J. Irwin		H0-34						
		Design Agent									
1	1	Cog.Eng. D. M. Ogden	D. M. Ogden		H0-34						
1	1	Cog. Mgr. D. M. Ogden			H0-34						
		QA									
		Safety									
		Env.									

18.	19.	20.	21. DOE APPROVAL (if required)
J. J. Irwin — J. J. Irwin 8/26/96 — Signature of EDT Originator / Date	Authorized Representative for Receiving Organization / Date	D. M. Ogden — D. M. Ogden 8/26/96 — Design Authority/ Cognizant Manager / Date	Ctrl. No. [] Approved [] Approved w/comments [] Disapproved w/comments

BD-7400-172-2 (05/96) GEF097

Spent Nuclear Fuel Vacuum Drying Thermal-Hydraulic Analysis and Dynamic Model Development Status Report

J. J. Irwin/D. M. Ogden
Westinghouse Hanford Company, Richland, WA 99352
U.S. Department of Energy Contract DE-AC06-87RL10930

EDT/ECN: 614687 UC: 2020
Org Code: 74A50 Charge Code: LH053
B&R Code: EW3135040 Total Pages: 87

Key Words: Spent nuclear fuel, vacuum, drying, modeling, pumps, piping, heat transfer, fluid flow experiments, transport properties, freezing

Abstract: This report summarizes preliminary thermal hydraulic scoping analysis and model development associated with the K Basin spent fuel MCO draining and vacuum drying system. The purpose of the draining and drying system is to remove all free water from the interior of the MCO, baskets, and fuel prior to backfilling with inert gas and transfer to the hot conditioning process. Dominant physical processes and parameters are delineated and related quantitatively. Minimum dynamic modeling capability required to simulate the process of transporting heat to the residual water on the fuel and transport of the steam produced from the system by vacuum pumping are defined.

Janis Bishop 8-28-96
Release Approval Date

Release Stamp

Approved for Public Release

SPENT NUCLEAR FUEL VACUUM DRYING

THERMAL HYDRAULIC ANALYSIS

AND DYNAMIC MODEL DEVELOPMENT

STATUS REPORT

By

B. C. Fryer

M. J. Thurgood

JOHN MARVIN, INC.

J. J. Irwin
D. M. Ogden

WESTINGHOUSE HANFORD COMPANY

For

WESTINGHOUSE HANFORD COMPANY

March 1995

TABLE OF CONTENTS

LIST OF FIGURES

1. SUMMARY

This report summarizes preliminary thermal hydraulic scopeing analysis and model development associated with the K-basis spent fuel MCO draining and vacuum drying system. The purpose of the draining and drying system is to remove all free water from the interior of the MCO, baskets, and fuel prior to backfilling with inert gas and transfer to the hot conditioning process. The method used involves forced drainage of water with pressurized purge gas, then drying by depressurization and heating. The design and operations criteria include:

1. removal of all free water in less than 1 day of operation,

2. prevention of freezing of any residual water during the depressurization and evaporation process,

3. prevention of heating local fuel areas to their or uranium/steam ignition temperature, and,

4. minimization of radioactive aerosol generation and transport out of the MCO.

During the vacuum drying process the dominant thermal hydraulic factors affecting the rate of water evaporation and the local water temperature are:

1. the vacuum pump's volumetric flow verses inlet pressure characteristics,

2. the flow resistance between the MCO and the pump inlet,

3. the quantity and distribution of water within the MCO, fuel, and basket system,

4. the available heat sources, and mechanisms and rates

of heat transport from the heat sources to the water,

5. the potential for thermally isolated water filled cavities within damaged and corrosion wasted fuel elements,

6. the potential for water filled cavities within damaged and corrosion wasted fuel elements which have restricted steam flow exit paths, and,

7. the propensity for aerosol generation and the mass flow pumping rates that can be achieved without aerosol generation and transport.

Preliminary results associated with the first 3 design and operations criteria, and the first 6 dominant factors affecting performance are presented and discussed in this report. Although these results are preliminary in nature, they should provide insight and guidance towards completion of the design and operating procedures for the system. Significant additional work remains to be done relatively to all 4 criteria items, and all 7 performance factors.

2. INTRODUCTION AND BACKGROUND

Engineered design of the K-basin spent fuel MCO draining and fuel vacuum drying system, and operating specifications, must result in draining and drying of the fuel in a short period of time, without allowing the fuel to overheat to ignition temperature, nor allowing any residual water to freeze. The vacuum drying process operating conditions depend upon the equilibrium achieved between the vacuum pumps capability to remove steam from the MCO, and the capability to transport heat to the water being evaporated. The residual water can be located at the bottom of the MCO or at the surface of the metal structures. Water can also be isolated within corroded fuel cavities and/or sludge. Heat transport to the water can be limited and the flow of steam evaporated from the liquid trapped in cavities can be restricted.

In addition, aerosol generation and transport from the MCO through various mechanisms must be precluded. Potential aerosol generation mechanisms include bulk boiling, entrainment of liquid or solid particles due to excessive gas velocities during initial evacuation when gas pressures and densities are high, and dynamic failure of the corroded uranium/clad structure due to excessive pressure differentials between trapped water and the MCO vacuum.

This status report summarizes the results of preliminary analysis and modeling conducted to date related to the draining and vacuum drying system for the K-basin spent fuel. Analysis and modeling todate, coupled with review and evaluation of vacuum technology/terminology, and review and evaluation of vacuum drying tests conducted during 1993-1994 at Montana State University (MSU) and at Idaho National Engineering Laboratory (INEL) indicates that vacuum drying of K-basin spent nuclear fuel can be conducted effectively and safely. However, care must be exercised in the engineering of the system and the procedures for conduct of draining and vacuum drying operations. Additional analysis and considerable model development remains to be conducted beyond this preliminary beginning. However, the background and basis has now been developed from which to proceed to a successful conclusion in terms of assisting the synthesis of the final system design and operating procedures, providing direction to proposed Westinghouse Hanford Company (WHC) experiments, and conducting safety evaluations.

Preliminary evaluation and analysis of the issues outlined immediately below are discussed in detail in the body of the report.

2.1. Example of Impact of Preliminary Analysis on Equipment Design

One example identified as a result of this preliminary study effects both the design of the bottom of the MCO and or cask, and the experiments that WHC is planning to conduct. The design of the MCO initially provided no direct bath heating between the bottom of the MCO and the cask, and the flow of water within the cask/MCO annulus was blocked at the bath water outlet by the overlay of the MCO bottom plate above the cask outlet port. Indirect heating of the bottom of the MCO would have occurred by conduction heat transfer from the annular bath through the bottom of the cask to the bottom of the MCO. However, the design is based upon a solid stainless steel forging for the cask. Since the conduction path was long, and the conductivity of stainless steel is relatively poor, heating of residual water in the bottom of the MCO may have been excessively limited. Direct bath heating at the MCO bottom is now included in the design.

One of two undesirable operating conditions may have resulted from the initial design. First, the potential for freezing residual water exists at this location unless MCO vacuum pressure is restricted to that corresponding to a few degrees above the triple point of water and all non condensible purge gas is removed from the MCO. Second, although MCO vacuum pressure control combined with removal of all residual purge gas within the MCO may preclude freezing, operation at lower residual water temperature conditions due to poor heat transport to the liquid, will inherently result in extended time periods to dry up all the water.

Changing the design to include forced circulation bath heating at the bottom of the MCO to maintain bottom MCO temperatures at bath temperature alleviates the potential of operating under these conditions. Additional analysis is required to examine the potential for freezing, or extending dryout time periods for water located on the surface of the fuel elements and baskets, or water trapped or untrapped within corroded fuel elements and/or sludge.

2.2. Evaluation of Prior Experiments, Need for Additional Experiments, Direction of Experiment Design & Evaluation of Data

WHC initially planned to conduct vacuum drying experiments at the University of Idaho (UI) in equipment previously used by Idaho National Engineering Laboratory (INEL) for spent fuel drying experiments. A review of this equipment and related experiments and deficiencies, coupled with the identification and availability of near prototypic equipment at Hanford, has resulted in a decision to conduct these experiments at Hanford. This decision will eliminate the deficiencies in the UI facility relative to non-prototypic equipment and the use of vacuum vessel band heaters, rather than water bath heating planned for the WHC vacuum drying system.

The MSU and INEL vacuum drying tests demonstrate the need for careful engineering of both the vacuum system design and the operating procedures to prevent freezing of residual water, sporadic boiling, and excessive periods of time required to dryout the MCO contents. Design of meaningful WHC experiments which can also be utilized for validating vacuum drying simulation models, also requires considerable engineering effort and experiments which are near prototypic.

2.3. Example of Awareness of Potential Operating Problem

The potential problem of freezing water when it is uniformly distributed over the bottom of the MCO during the vacuum drying process can be alleviated by using a bath at the bottom. However, if vacuum pressure control is not employed, puddling of the last small amount of liquid on the floor of the MCO could result in freezing of this water. If puddling occurs due to surface tension effects, in contrast to maintaining a uniform film across the MCO floor, the heat transfer area at the MCO metal/liquid interface will drop faster than the decrease in evaporative cooling being induced by the vacuum pump. When puddling occurs, liquid temperatures will drop rapidly, and freezing of the remaining puddled water could occur. This preliminary analysis and experiments conducted at INEL and MSU clearly indicate the potential for this to occur. Additional evaluation of the current design and operating conditions, including water bath temperature, is needed to insure this potential problem will not occur.

2.4. Fluid Flow and Thermal Transport Properties--Expected Range of Operation

A review of vacuum technology [Roth, 1983], [O'Hanlon, J.F., 1980], [Scott, R.B., 1959], [Bird, 1960], review of a prior WHC vacuum drying system evaluation report [Irwin, 1996.], and subsequent analysis based on the proposed vacuum system operating conditions indicates the following. The flow of water vapor through the MCO/basket/fuel/piping system will be in the viscous flow regime, both laminar and turbulent, not in the molecular flow regime prior to dryout. The water vapor can be treated as an ideal gas for engineering purposes. For transport phenomena calculations, conductivity and viscosity of the water vapor will be temperature dependent, but not dependent upon pressure in this operating regime.

Pressure drop losses in the vacuum system can be reduced to a small fraction of the vacuum chamber pressure through adequate sizing of pipes, fittings, etc. The current 25 ft long, 2 inch ID pipe size proposed for the vacuum line between the MCO and the pump inlet results in almost negligible loss in vacuum between the pump inlet and the MCO for the 65 ft^3/min capacity vacuum pump. A 1 inch line results in a significant loss. Some consideration could be given to enlarging the 1 inch ID passageways in the MCO head. Additional analysis of flow resistance, or conductance, in components between the MCO and the atmosphere will be required to insure they are adequately sized when design information on these components, including the final vacuum pump selection, becomes available. The quick disconnect between the MCO shield plug and the vacuum line causes almost an order of magnitude more flow resistance than the 2 inch vacuum line.

There does not seem to be a good referenceable data source for the conductivity and viscosity of steam at low pressure/temperature. However, existing data sources, functions, and extrapolations from higher pressure/temperature conditions appear to be consistent with kinetic theory and therefore can be used with confidence. The thermal conductivity of steam is about 2/3 that for air at the temperatures of interest, and somewhat higher than a candidate purge gas, Argon. Therefore fuel temperature heatup calculations done in the past, based on conduction and thermal radiation only, from the fuel to the MCO/cask bath using the conductivity of air and or Argon, should bracket fuel temperatures in the steam environment present during vacuum drying--assuming no liquid is present and no chemical reactions are occurring. In the vacuum drying case, following the first few minutes of vacuum pump operation required to evacuate purge gas used to force drainage liquid from the MCO, the only gas left in the MCO will be steam. After dryout of all the water, the flow could potentially be in the free molecular flow regime if pressures are dropped low enough.

2.5. Estimates of Drying Time Versus Bath Temperature

Up to 14.1 liters of water can be evacuated from an MCO with a 10 C bath temperature within a 16 hour period using a 65 ft^3/min capacity vacuum pump, provided the bottom of the MCO is heated to bath temperature. Raising the bath temperature to 50 C could reduce the evacuation time to about 3 hours. This assumes that all the residual water is located in the bottom of the MCO in relatively good thermal contact with the water bath, not at thermally isolated locations within the MCO/basket/fuel thermal system. Additional analysis is also required to determine the dryout time required and the potential for freezing with the water distributed on the fuel and baskets. Futhermore, additional analysis is needed to determine the maximum fuel temperature reached for locations that are dry and not cooled by evaporating water during the vacuum drying process--including the heating effects of chemical reaction between steam and exposed metal uranium.

2.6. Relative Importance of Heat Sources and Transport Mechanisms

Only in the case of low temperature and low pressure vacuum drying, which takes considerable time to reach dryout, can the heat supplied from radiolytic decay, be a significant contributor to the quantity of heat required to evaporate the residual water. Under these operating conditions, radiolytic heat will be a major contributor if most of the residual water is uniformly distributed over the outer surface of the fuel elements. Most of the water will either drain to the bottom of the MCO, or be distributed non-uniformly throughout the fuel/basket system radiolytic decay heat. Under non uniform water distribution conditions, conduction and thermal radiation will determine the contribution that radiolytic decay heat makes in transporting radiolytic decay heat from hotter fuel zones to cooler evaporating water zones.

Stored thermal energy in the fuel, basket, and MCO structure could be a significant heat source for evaporating water provided these structures are hot (say 50 C, 122 F) prior to vacuum drying, and provided the water is distributed rather uniformly over these structures. If most of the water is non uniformly distributed, or concentrated in the bottom of the MCO, conduction and thermal radiation will determine the contribution that stored energy makes in transporting the stored energy from hotter fuel/basket zones to cooler evaporating water zones. If the vacuum drying process is initiated with the metal components at 10 C (50 F) stored energy will be of lesser benefit in evaporating the residual water.

Radial conduction and thermal radiation from the water bath to each successive ring of fuel within the MCO, combined with axial conduction within the fuel can be an important contributor towards providing heat to evaporate water. If the water bath is maintained at only 50 F (10 C), then the baths's contribution will be small. On the other hand, if the bath temperature can be increased to 122 F (50 C) then heating effect will likely be of the order of the stored energy in the metal components, or the radiolytic decay heat. The rate at which water bath heat is transported to the evaporating water zones is contingent upon the radial conduction and thermal radiation from the bath to successive inner rings of fuel, and axial conduction within fuel and basket metal.

In summary vacuum drying system design and operating procedure adequacy must be demonstrated through adequate vacuum system pumping capability, low flow resistance, and adequate heat transport from all heat sources to the evaporating water. Experiments must be designed and carried out in such a way that they represent as protypically as is economically feasible the design and operation of the WHC K-basin vacuum drying system. This will provide data which can be used to quantitatively validate the simulation model results. The model can then be used with confidence to simulate situations not evaluated by the experiments. Simulation models must include as a minimum all heat sources: radiolytic decay heat, stored energy, and water bath heating. They must also include as a minimum radial conduction and thermal radiation from the water bath to successive inner rings of fuel, and axial conduction in metal components. Background information has now been developed from which models of increasing detail can now be developed. This background information and associated modeling effort will also be used to direct and evaluate the experiments to be conducted at WHC.

3. RELATED PRIOR MSU AND INEL VACUUM DRYING TESTS

3.1. MSU Vacuum Drying Tests

Between June 1993 and January 1994 a series of vacuum drying tests were conducted at Montana State University (MSU) at Bozeman Montana [George, 1994]. These tests and related equipment are similar in some respects to the proposed WHC K Basin Fuel vacuum drying process and equipment, however, there are some significant differences.

The test equipment is illustrated in Figure 3.1. It consists of a Leybold SOGEVAC SV180 vacuum pump (110 ft^3/min), a 1.63 in ID vacuum hose, a heated and pumped circulated water bath, an outer canister, and an inner canister. The inner canister contained four 1 inch OD plus 223 .1875 inch OD stainless steel rods 35.75 inches in length which occupied approximately 60% of the free volume within the inner can. For some tests a copper tube supplied air to the outer canister. The copper tube was coiled around the outer container, and the air was heated by the water bath before entering the outer canister through the bottom flange.

Standard test conditions included:

1. initially 1.64 liters of water in the outer canister

2. initially 4.92 liters of water in the inner canister

3. stainless steel rods in the inner canister filling approximately 60% of the empty canister free volume

4. initial temperature of canisters and contents within 2 C of the specified water bath temperature

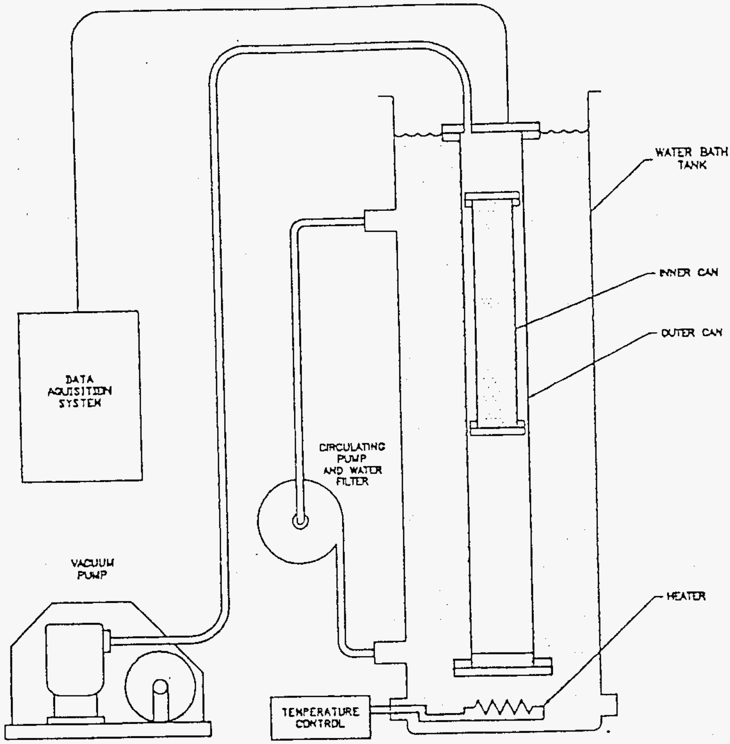

Figure 3.1 MSU Vacuum Drying System Description

There were 4 types of tests: (1) standard conditions with inner canister sealed; (2) standard conditions with inner canister upper flange penetrated with various sizes and numbers of holes; (3) tests with a 6.35 mm hole in the inner can upper flange and a larger than standard quantity of water in the outer canister, and (4) tests with controlled flow of air into the outer canister, several sizes of holes in the upper flange of the inner canister, and several different operating pressures, but otherwise standard operating conditions.

At the beginning of each test the inner canister was filled with water, plus rods. The outer canister was initiated with about 2.25 inches of water in the bottom for most tests. However for two tests the outer canister was initiated with 10 and 25 times this much water. Ten times this much water would likely have placed the water level below the bottom of the inner canister. However, 25 times this much water would have filled the outer canister.

The pump inlet, or suction, was operated without restriction during the vacuum drying process. Operation of the pump with the gas ballast valve open limited the ultimate inlet pressure of the pump to about .5 mbar above the triple point pressure of water, 6.113 mbar. This procedure was used in an attempt to prevent freezing of residual water in the canisters during the vacuum drying process.

Parameters varied in the experimental study included: (1) the temperature of the water bath, (2) sealing or variable flow resistance between the inner and outer canisters, (3) presence or absence of a controlled flow of heated air into the outer canister, and (4) the quantity of water in the outer container at the beginning of the test.

The primary findings of the study were: (1) the length of time required to dryout the outer and inner canisters, (2) establishment of measurable criteria to judge when the canisters were dry, and (3) determination of the operating conditions required to minimize the drying time.

3.2. INEL Vacuum Drying Tests

During 1994 a series of vacuum drying tests were also conducted at Idaho National Engineering Laboratory (INEL) [O'Brien, 1994]. These tests and related equipment are similar in some respects to the proposed WHC K Basin Fuel vacuum drying process and equipment, however, there are some significant differences.

Seven types of tests with some relevance to the WHC system were conducted, the first six test types were conducted in a 5 foot high 18 inch diameter vacuum vessel, and the seventh test in two 5 foot sections joined to make a 10 foot high vessel. A Leybold SOGEVAC SV100 vacuum pump (65 ft^3/min) with 1 inch piping was used. Heating was accomplished with uninsulated electric resistance band heaters positioned at the bottom of the vacuum vessel. The first type involved a 1000 ml glass graduated cylinder partially filled with water placed on the bottom of an otherwise empty and unheated, vessel and then evacuated. The second type involved a 1000 ml glass graduated cylinder partially filled with water placed on the bottom of an otherwise empty, but heated and open vessel. The third type involved a 1000 ml glass graduated cylinder partially filled with water placed on the bottom of an otherwise empty, but heated vessel and then evacuated. The fourth type involved filling a TORY fuel canister, 9.8 lbm, with 20.2 lbm of granulated aluminum oxide and 10 lbm of water, with a .09 inch hole, in a 200 C heated vessel and evacuating the contents. The fifth type used simulated ATR plate fuel, with and without simulated sludge. The sixth type involved open aluminum canisters containing 3 stainless steel rods and with water in the bottom, some of which was allowed to leak out. The seventh type involved a 10 ft high vacuum vessel with four 5 inch diameter canisters stacked above the ATR fuel. Water was placed either in the lower ATR fuel region, or above, in the canisters.

Data collected included average evaporation rates of residual water, and temperatures and pressures during the tests. Although throttling of the pump was used to prevent freezing, freezing did occur in one test.

4. Evaluation OF MSU AND INEL Vacuum DRYING TESTS RELATIVE TO WHC K-BASIN VACUUM DRYING PROCESS AND EQUIPMENT

4.1. Evaluation of the MSU Vacuum Drying Tests

A comparison of the WHC vacuum drying system in terms of vacuum vessel size, vacuum line size and pump type is illustrated in Figure 4.1. The similarities between the MSU tests/equipment and the WHC tests/equipment are:

1. the general range of operating conditions in terms of flows, pressures, temperatures, canister material and thickness, residual water, and vacuum pump are similar, and,

2. the outer canister bottom plate of the MSU system is in direct contact with the heated and recirculated bath and the plate is directly above the heating element. The WHC system MCO bottom end plate is heated by a water bath gap located between bottom of the MCO and the top of the cask bottom plate.

The significant differences are in the details which include:

1. the pump volumetric flow rate at pressures above 5 torr is about twice that proposed for the WHC system,

2. the inside surface area of the outer canister end plate is 1/10th that of the WHC MCO,

3. the simulated fuel rod outside surface are is a factor of 25 less than the WHC fuel outside surface area,

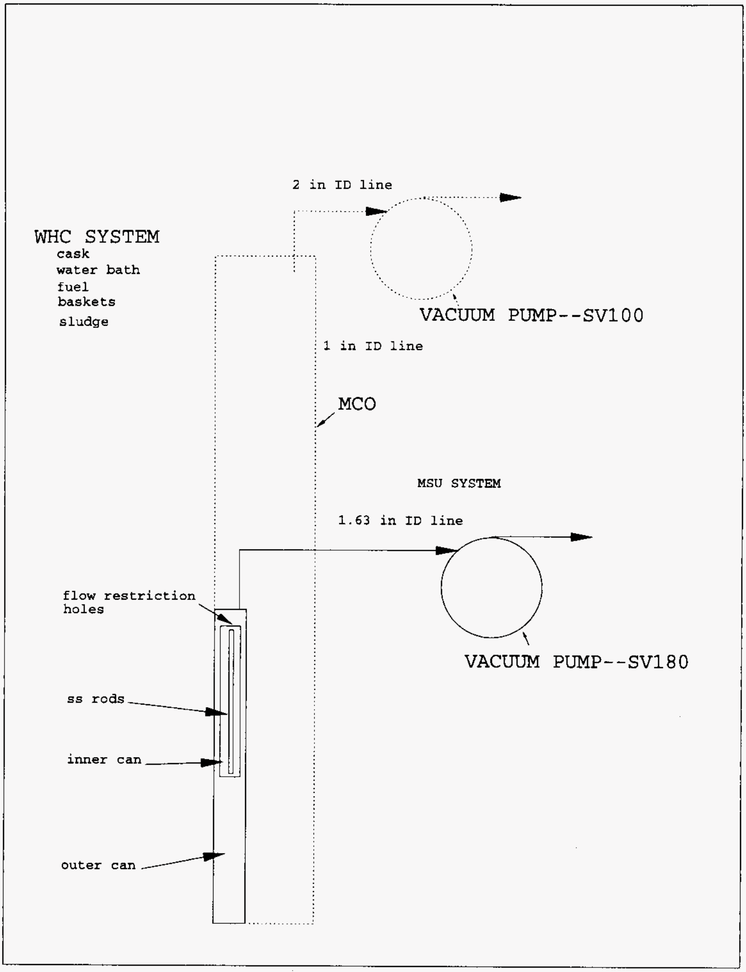

Figure 4.1 WHC & MSU Test Vacuum System & Materials Comparison

4. the vacuum line between the outer canister and the pump inlet has about 2/3 the flow area of the WHC 2 inch vacuum line. (the relative lengths have not yet been determined),

5. the MSU inner canister and simulated fuel rods are thermally isolated from the heating bath, however, this may roughly simulate water isolated from directly heated surfaces in the WHC system. It should be noted that in one MSU test the outer canister was filled with water providing good heat transfer between the water bath and the inner canister. Unfortunately there is no temperature or pressure data reported for that particular test, and,

6. the residual water in the outer canister in most tests was limited to 1.65 liters compared to estimates of up to 14.1 liters for the WHC system (however it is noted that two tests with up to 41.1 liters in the outer canister were conducted in some MSU tests),

7. for MSU tests with limited flow area to the inner canister, the flow restriction is smaller than anything expected in the WHC system, with the exception of water trapped or untrapped in corroded fuel elements. Fuel elements ejected from the pressure tubes at N reactor during refueling were damaged various ways during the ejection process. Spacer clips in some cases were broken off at the spot weld to the cladding tearing holes in the cladding at these locations. Water may be contained within cavities within the fuel elements caused by corrosive wastage. The flow of steam from these cavities during vacuum drying may be restricted due the size of the leak hole.

From a drying standpoint the MSU system will have better drying characteristics because:

a. the flow rate of the pump is higher, and,

b. there were smaller quantities of residual water in the outer canister for most tests.

The drying characteristics will be worse for the MSU system for a given quantity of water due to:

a. smaller surface area at the bottom plate,

b. possibly worse flow resistance between the canister and the pump, and,

c. for the inner canister the flow restriction is smaller in some tests and the fuel surface area is much lower.

Analytical comparisons or dynamic modeling using thermal hydraulic computer codes such as GOTH [Thurgood, 1993] can be conducted and the results compared to the MSU tests. However, there are two parameters which are not yet available to WHC, which if obtained would help this comparative analysis. The thickness of the flanges on the canisters, and the length of the vacuum hose are not known. Estimates for these parameters have been backed out using classical analysis, but it is not known how well these estimates compare to the actual geometry.

Although there are disimilarities between these tests and the associated hardware relative to the WHC system, these tests provide some valuable qualitative and quantitative insights. These include:

1. the dominant factors effecting dryout of the residual water in the bottom of a canister:

a. vacuum pump volumetric flow versus inlet pressure characteristics,

b. flow resistance between the canister and the inlet to the vacuum pump, and,

c. heat transfer to the liquid,

2. liquid can clearly be cooled to freezing if adequate precautions are not taken. There was evidence freezing occurred in one of the tests although a ballast limiting pressures to .5 mbar above the triple point of water was used to prevent freezing,

3. detection of dryout without freezing can be assisted by operating the vacuum until canister gas temperature increases to within 2 C of bath temperature following evacuation, depressurization, and cooling. Then subsequently valving off the vacuum and observing a pressure of no more than 7.5 mbar after one hour. Any ice formed would remelt and/or evaporate during the one hour waiting period thereby raising the pressure and indicating ice formation. It is possible that no ice may be present since a vacuum leak could cause a similar response, therefore this process will eliminate the possibility of ice, but not guarantee ice is present. Residual gas analysis to detect the gas species present would differentiate between the presence of ice evaporated to water vapor and the inleakage of air,

4. flow resistances, such as a limited number of small drill holes in the MSU inner canister upper flange, can greatly reduce the performance of the vacuum drying process. When combined with poor heat transfer to the liquid, the time to dryout a canister can be very large. Such circumstances my exist for damage fuel involving leak holes and internal cavities where water has collected as a result of corrosion and wastage of uranium,

5. heat supplied to water by cooldown of metal components may be significant in the initial pump down

period, but may have little impact for evaporating large quantities of water that are not uniformly distributed over all structural elements. For concentrated water volumes thermal energy required to evaporate water is large and must be supplied by some heat source other than the thermal energy stored in the canister, fuel structure, baskets, or water,

6. thermal cycling of the bath apparently occurred even during the inner canister sealed tests, which caused the lower outer canister temperature to rise in some tests after the initial cooldown. For a constant bath temperature condition, this temperature rise would not have been expected to occur,

7. an inner canister filled with water and stainless steel rods, but which is heated with a water bath isolated by an intermediate evacuated region between an inner and outer can, will become colder at the top than at the bottom of the canister due to hydrostatic pressure effects as it relates to saturation temperature. Evaporation, or boiling will occur at the top of the liquid. Limited circulation of the water will result in a significant temperature gradient from the bottom to the top,

8. reduction of liquid/metal interface area due to falling liquid levels in a canister can have significant effects on evaporation rates. Similar effects may occur due to puddling as a result of surface tension effects, and,

9. drying rates for the MSU system varied from .03-.8 L/hr depending on whether the water was in the outer or inner canister, how large the holes in the inner canister were, and the temperature of the vacuum vessel bath.

4.2. Evaluation of the INEL Vacuum Drying Tests

A comparison of the WHC vacuum drying system in terms of vacuum vessel size, vacuum line size and pump type is illustrated in Figure 4.2.

The similarities between the INEL tests/equipment and the WHC tests/equipment are:

1. the general range of operating conditions in terms of flows, pressures, temperatures, canister material and thickness, residual water, and vacuum pump are similar,

2. the INEL vacuum pump, Leybold SOGEVAC SV100, is the a primary candidate being considered for the WHC system. The alternate WHC pump is a scroll vacuum pump apparently with a nominal volumetric flow capacity of 17.5 ft^3/min,

3. the ATR simulated fuel surface area is close to half that of the WHC system fuel,

4. the TORY ground aluminum oxide tests possibly crudely simulate vacuum drying sludge, and,

5. the 10 foot vessel, wet canister tests crudely simulate long dry out times required to evaporate thermally isolated water pools.

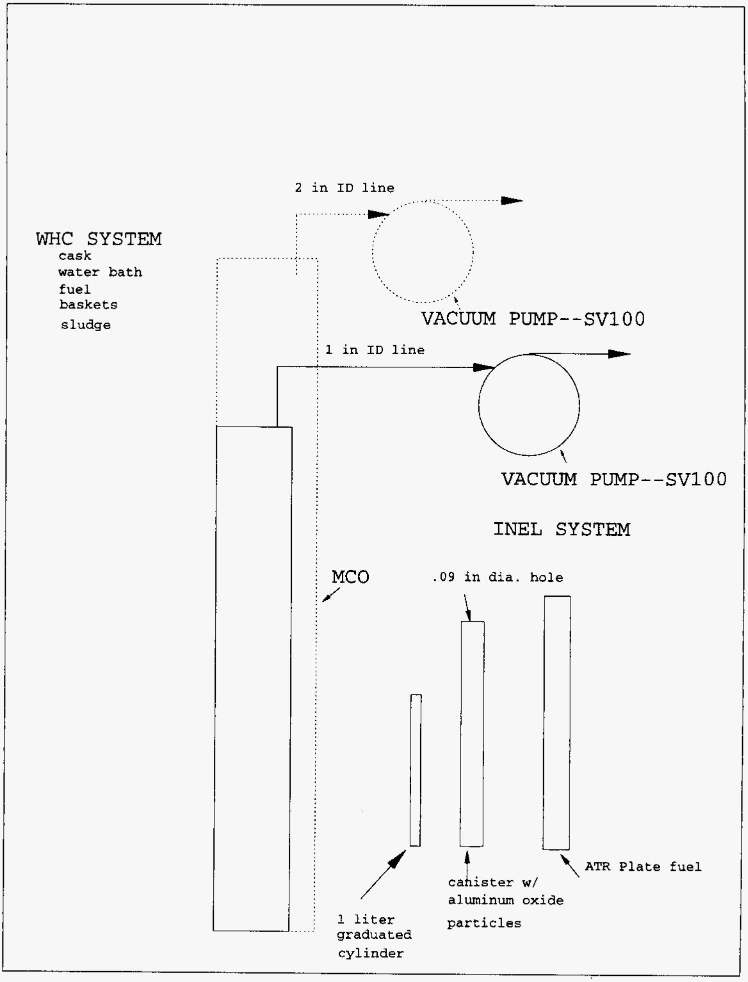

Figure 4.2 WHC & INEL Test Vacuum System & Materials Comparison

The significant differences are in the details which include:

1. vacuum vessel surface areas are smaller in the INEL facility,

2. the vacuum line is 1 inch pipe in the INEL system versus 2 inch ID vacuum line for the WHC system,

3. the INEL outer canister cylinder is heated with electric resistance band heaters, but the bottom plate is not directly heated. The WHC MCO is heated with a water bath in the annulus between the cask and the MCO's vertical cylinder and MCO bottom,

4. vacuum vessel wall temperature was maintained over a range of room temperature-200 C in the INEL vacuum drying tests compared to a bath temperature range of 10-75 C being considered for the WHC system. Since the INEL system was not insulated, the wall temperatures must have been this high only between the heaters and the vessel. At any distance from the heater location the temperatures would have been much colder.

From a drying standpoint the INEL system will have better drying characteristics because:

a. wall temperatures were higher,

b. smaller quantities of residual water.

The drying characteristics will be worse for the INEL system for a given quantity of water due to:

a. smaller surface area at the bottom plate, and,

b. possibly worse flow resistance between the canister and the pump.

Analytical comparisons or dynamic modeling using the GOTH[1] or COBRA-TF [Kelly, 1985.] thermal hydraulic computer codes can be conducted and the results compared to the INEL tests. Additional review of available geometric data would be required to determine if a model representing the facility can be adequately defined. Difficulty would be anticipated in modeling the vessel wall temperature distribution due the concentrated heat input at the heaters and the lack of thermal insulation.

Although there are disimilarities between these tests and the associated hardware relative to the WHC system, these tests provide some valuable qualitative and quantitative insights. These include:

1. the dominant factors effecting dryout of the residual water in the bottom of a canister, or on components internal to a vacuum vessel:

   a. vacuum pump volumetric flow versus inlet pressure characteristics,

   b. flow resistance between the canister and the inlet to the vacuum pump, and,

   c. heat transfer to the liquid,

2. liquid can clearly be cooled to freezing if adequate precautions are not taken,

3. detection of dryout without freezing can be assisted with the use of vacuum pressure control, however, since freezing occurred in one of the INEL tests conducted under pressure control some discussions with INEL personnel should be conducted to determine why this occurred,

4. thermally isolating liquid with limited nucleation sites can result in boiling and sporadic nucleation,

[1] GOTH is a trademark of JMI, which is derived from GOTHIC - a registered trademark of the EPRI Corp.

particularly where a significant hydrostatic pressure head can be developed within the liquid relative to the vacuum pressure,

5. drying rates for water in a glass cylinder on the bottom of the unheated vacuum vessel were of the order of .005 L/hr and .059-.079 L/hr for the vessel heated between 82-200 C,

6. drying rates for water in wet aluminum oxide granules inside a secondary canister with a flow restriction hole of .07 inch diameter was .08 L/hr with a vessel heater temperature of 200 C,

7. evaporation rates for ATR flat plate fuel were .138 L/hr with a room temperature vacuum vessel wall, .3-.5 L/hr for a 200 C vessel wall heater temperature. For a 100 C wall heater temperature rates were higher, 1 L/hr, but changes were made in the vacuum pump oil to improve its performance. However, it is not clear, why the evaporation rate increased when the vacuum chamber pressure remained the same as in the 200 C heater temperature case,

8. evaporation rates for water in cylindrical cans placed on the bottom of the vacuum vessel floor had rates of .2-.5 L/hr, for 1 can and 4 cans/vessel respectively,

9. placing an 8 inch pie plate of damp aluminum oxide in with the ATR plate fuel had little effect on water evaporation rates, and,

10. placing the canisters above the ATR fuel in a 10 foot vacuum vessel, with water in the canisters, but not on the ATR fuel, decreased the evaporation rates to .1-.2 L/hr at heater temperatures of 200 C.

Equipment used in the INEL tests conducted in 1994 has been transferred to the University of Idaho. Some rearrangement of equipment has been done following the transfer. WHC had planned to conduct some vacuum drying tests in the equipment used by INEL. However, these tests will now be conducted at Hanford with near prototypic equipment.

5. PRELIMINARY ANALYSIS AND MODELING CONSIDERATIONS OF THE WHC VACUUM SYSTEM, MCO, FUEL, AND CASK

This report section summarizes preliminary thermal hydraulic scopeing analysis and model development associated with the K-basis spent fuel MCO draining and vacuum drying system. The purpose of the draining and drying system is to remove all free water from the interior of the MCO, baskets, and fuel prior to backfilling with inert gas and transfer to the hot conditioning process. The method used involves forced drainage of water with pressurized purge gas, then drying by depressurization and heating. The design and operations criteria include:

1. removal of all free water in less than 1 day of operation.

2. prevention of freezing on any residual water during the depressurization and evaporation process.

3. prevention of heating local fuel areas to their uranium/air or uranium/steam ignition temperature.

4. minimization of radioactive aerosol generation and transport out of the MCO.

The dominant thermal hydraulic factors affecting the rate of water evaporation and the local water temperature are:

1. the vacuum pumps volumetric flow verses inlet pressure characteristics.

2. the flow resistance between the MCO and the pump inlet.

3. the quantity and distribution of water within the MCO, fuel, and basket system.

4. the available heat sources, and mechanisms and rates of heat transport from the sources to the water.

5. the potential for water filled cavities within damaged and corrosion wasted fuel elements with restricted steam outflow leak paths.

6. the propensity for aerosol generation and the mass flow pumping rates that can be achieved without aerosol generation and transport.

Preliminary results associated with the first 3 design and operations criteria, and the first 5 dominant factors affecting performance are presented and discussed below. Although these results are preliminary in nature, they should provide some guidance towards completion of the design and operating procedures for the system. Additional work remains to be done relatively to all 4 criteria items, and all 6 performance factors.

The vacuum drying process operating conditions depend on the equilibrium achieved between the pumps capability to remove steam from the MCO, and the capability to transport heat to the water being evaporated. The pumps capability to transport steam depends upon the pumps volumetric flow verses inlet pressure characteristics, and the flow resistance (or conductance) between the MCO and the pump inlet.

A preliminary schematic of the draining and vacuum drying system is illustrated if Figure 5.1.

Figure 5.2 illustrates the various components, fluid states and location, and energy transfers associated with the draining and vacuum drying process.

Potential location of the residual water within the MCO, on the baskets, and the fuel is shown in Figure 5.3.

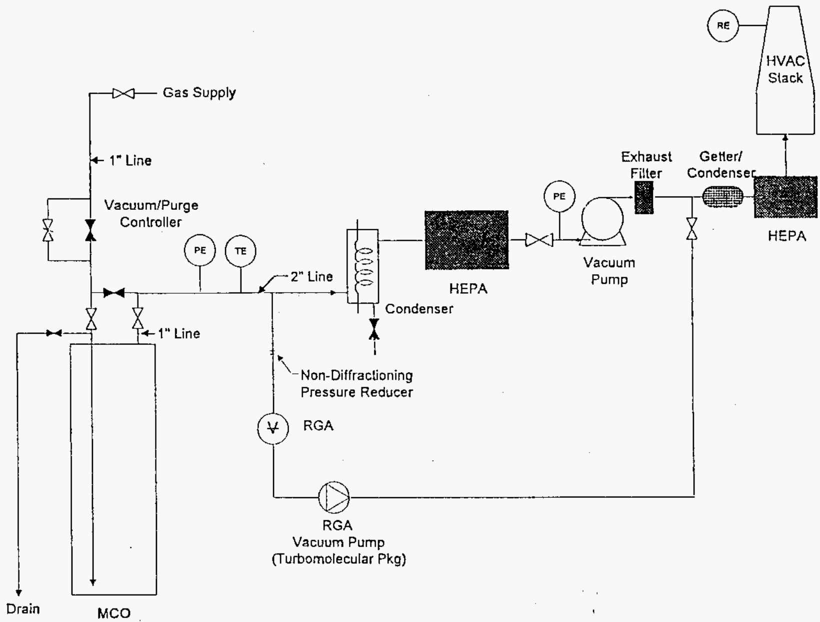

Figure 5.1 Preliminary Schematic of SNF Vacuum System.

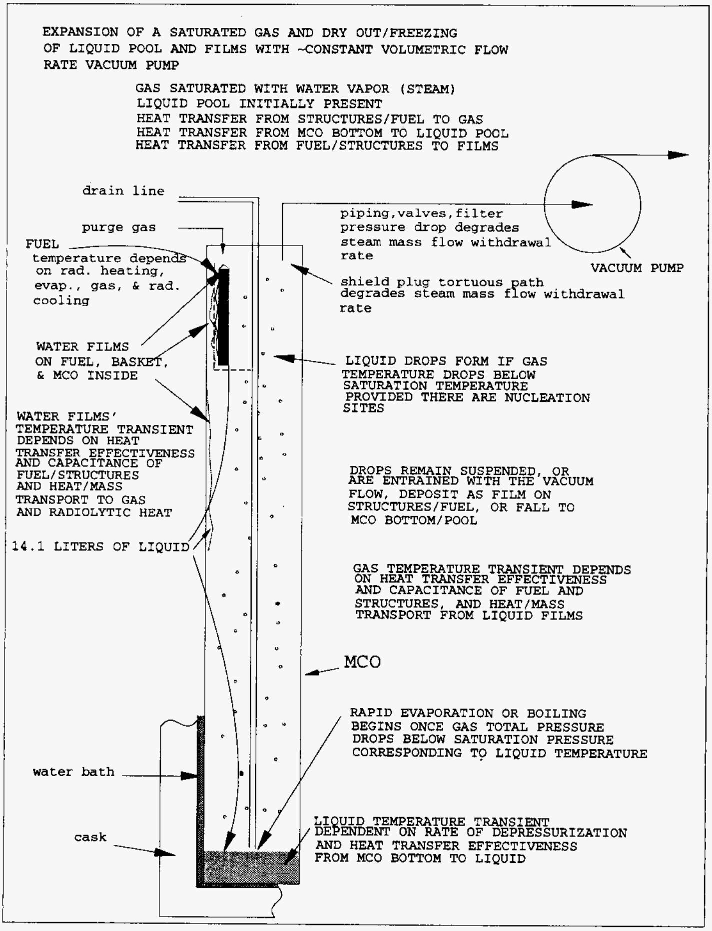

Figure 5.2 Dry Out of Pool and Liq. Films with Const. Vol. Flow Vac. Pump, and Heat/Mass Trans. Between Gas and Liquid and Between Gas/Liquid Phases and Fuel/Structures

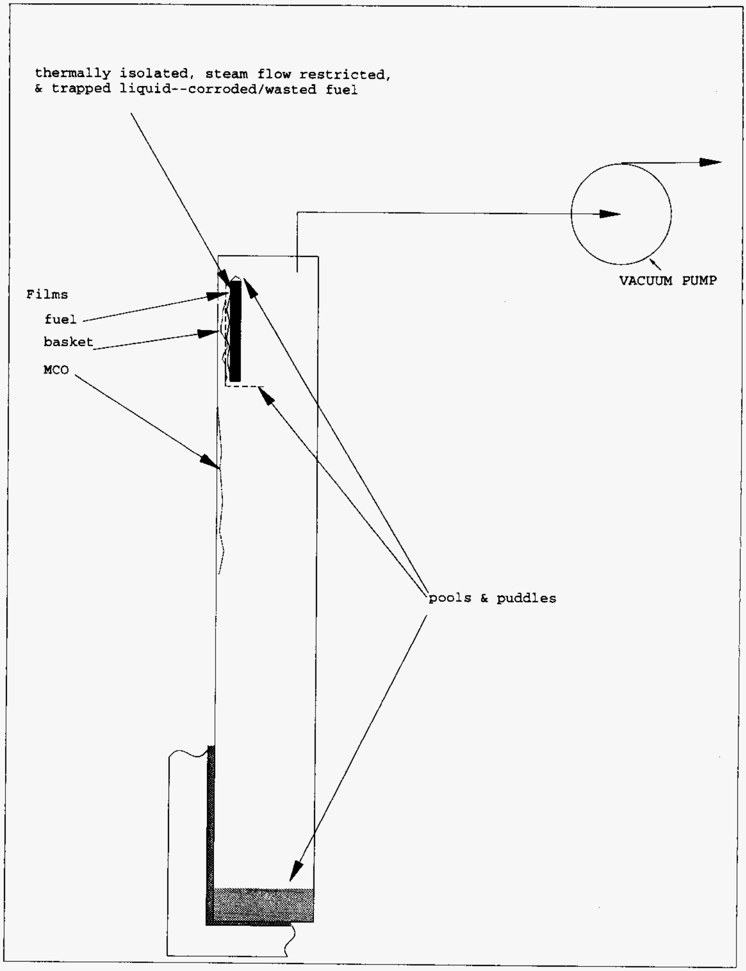

Figure 5.3 Dry Out of Pool and Liq. Films with Const. Vol. Flow Vac. Pump, and Heat/Mass Trans. Between Gas and Liquid and Between Gas/Liquid Phases and Fuel/Structures

There is not enough stored energy in the residual water to evaporate all the water. Heat must be conducted, radiated, or convected to the water from available heat sources as illustrated in Figure 5.4. Heat sources include stored energy in the structures and water, radiolytic heat, and the water bath between the cask and MCO bottom and cylindrical walls.

The draining and vacuum drying process proceeds through 5 steps or phases. These are:

1. forced purging of the liquid filled MCO with inert gas, draining the water vertically upwards through a drain or dip tube,

2. initial evacuation and depressurization of the inert purge gas which will likely become saturated with water vapor. Depressurization down to a pressure corresponding to the saturation pressure associated with the initial liquid temperature,

3. quasi-steady evaporation of liquid with slowly decreasing liquid temperature and vacuum pressure until liquid regions begin to consolidate into puddles due to surface tension,

4. final puddling and dryout, or rapid decreases in temperature and vacuum pressure leading to freezing, unless adequate heat transport is provided, or limited vacuum pressure freeze protection controls are utilized,

5. freezing of thermally isolated water filled cavities within damaged and corrosion wasted fuel elements, and,

6. delayed dryout of water filled cavities within damaged and corrosion wasted fuel elements which have steam flow restricted exit flow paths.

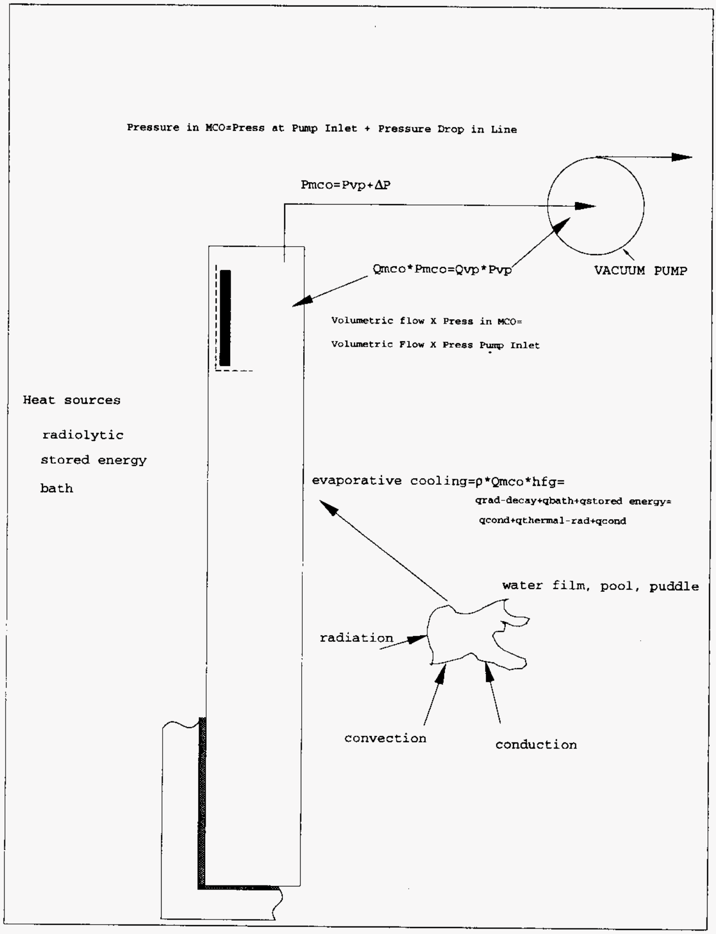

Figure 5.4 Dry Out of Pool and Liq. Films with Const. Vol. Flow Vac. Pump, and Heat/Mass Trans. Between Gas and Liquid and Between Gas/Liquid Phases and Fuel/Structures

Radioactive aerosol generation and transport may occur during this process. Potential aerosol generation mechanisms include bulk boiling, entrainment of liquid or solid particles due to excessive gas mass flow rates during initial evacuation when gas pressures and densities are high. Also aerosol generation as a result of dynamic failure of the corroded uranium/clad structure due to excessive pressure differentials between trapped water or restricted steam flow cavities and the MCO vacuum.

5.1. Vacuum Pump Characteristics

The primary vacuum pump candidate is the Leybold SOGEVAC SV100 (65 ft^3/min) [Leybold-Heraeus, 1986]. Its volumetric flow verses inlet pressure characteristic is illustrated in Figure 5.5. For pressures above about 20 torr the pump is essentially a constant volumetric flow device. After about 2 minutes of unthrottled pumping, this pump will have evacuated essentially all of the gas used to purge/drain the water from the MCO prior to vacuum drying. After this initial evacuation period the gas in the MCO will be essentially only water vapor (steam). If the steam entering the pump is nearly saturated, then for a given pump inlet saturation pressure, there is an associated inlet saturation temperature, as indicated in Figure 5.5. For example, as shown in Figure 5.5 for an arbitrary inlet pressure of 5 torr, the inlet temperature would be about 34 F.

Figure 5.5 can be replotted with temperature as the independent variable as shown in Figure 5.6. If there is minimal flow resistance between the MCO and the pump, and if the steam produced by evaporation is not heated after leaving the liquid surface, then the temperature and pressure of the steam at the MCO will be approximately the same as at the pump inlet. If there is limited heat transfer to the liquid being evaporated, it is clear the pump has the capability to reduce the temperature to the freezing level. At 32 F the saturation pressure is 4.6

torr.

The temperature and corresponding pressure operating condition will be dictated by the equilibrium between the pump characteristics and the heat transport to the evaporating liquid.

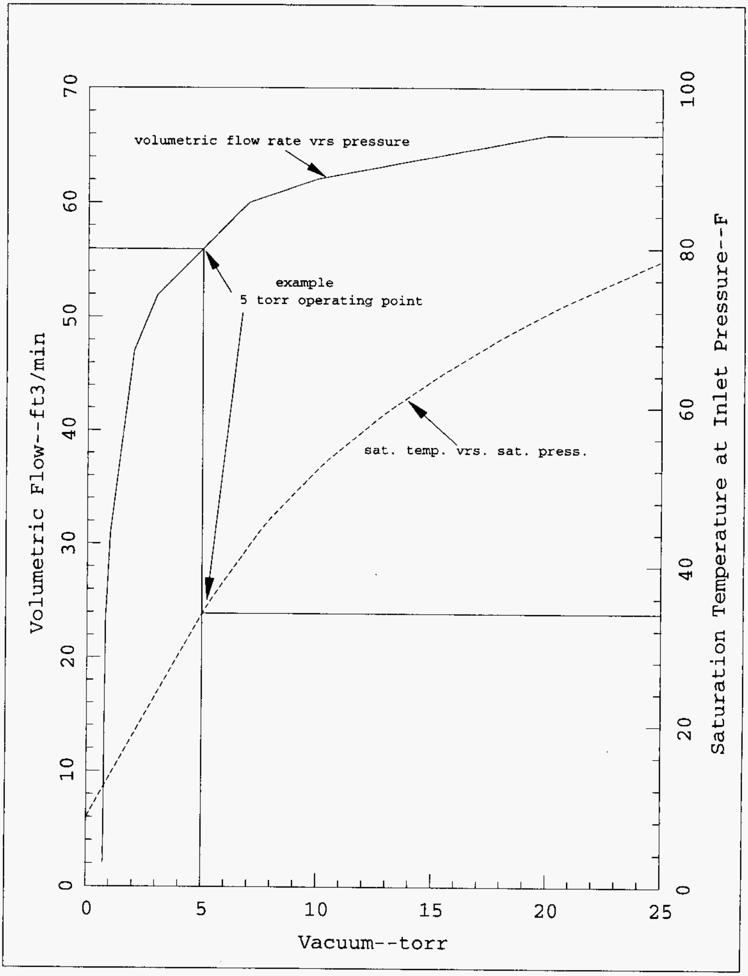

Figure 5.5 SV100 Vacuum Pump--Saturated Steam Pumping Characteristics

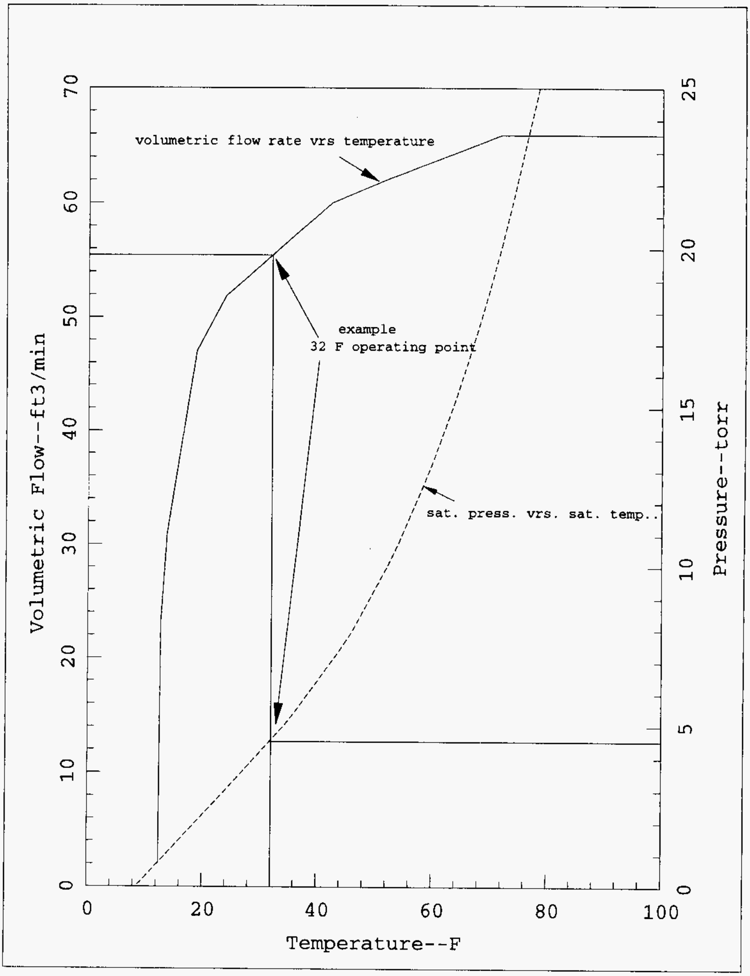

Figure 5.6 SV100 Vacuum Pump--Saturated Steam Pumping Characteristics

5.2. Required Heat Delivery Rates, Radiolytic Heat, Dryout Times, and Stored Energy in Metal Components

Estimates of heat delivery rates required to evaporate residual water, and simultaneously match pump flow verses temperature (or pressure) characteristics are provided in Figure 5.7. Also plotted is the heat generation rate corresponding to an MCO with a 400 watt radiolytic decay heat load, and the time required to dryout 14.1 liters of residual water verses MCO residual water/steam temperature. This quantity of water is a rough estimate of the quantity of residual water expected after draining of the MCO {Q-Metrics, 1995].

These curves assume there are no significant flow resistances between the MCO and the pump, that the steam and water are in equilibrium at saturation conditions, and that there is no significant heating or cooling of the steam between leaving the liquid surface and arriving at the pump inlet.

Here again the liquid/steam operating temperature internal to the MCO will be defined by the equilibrium achieved between the pumping capability and heat transfer to the liquid. As shown, at high temperatures and high associated evaporation heat removal rates, the heat available from radiolytic decay is only a small fraction of that required. However, at low temperatures and low associated evaporation heat removal rates, radiolytic heat could meet the total evaporation heat supply requirement. In order to be effective, however, the water would have to be uniformly distributed over the fuel, not concentrated at the bottom of the MCO, or concentrated at local locations throughout the fuel and or support basket structures.

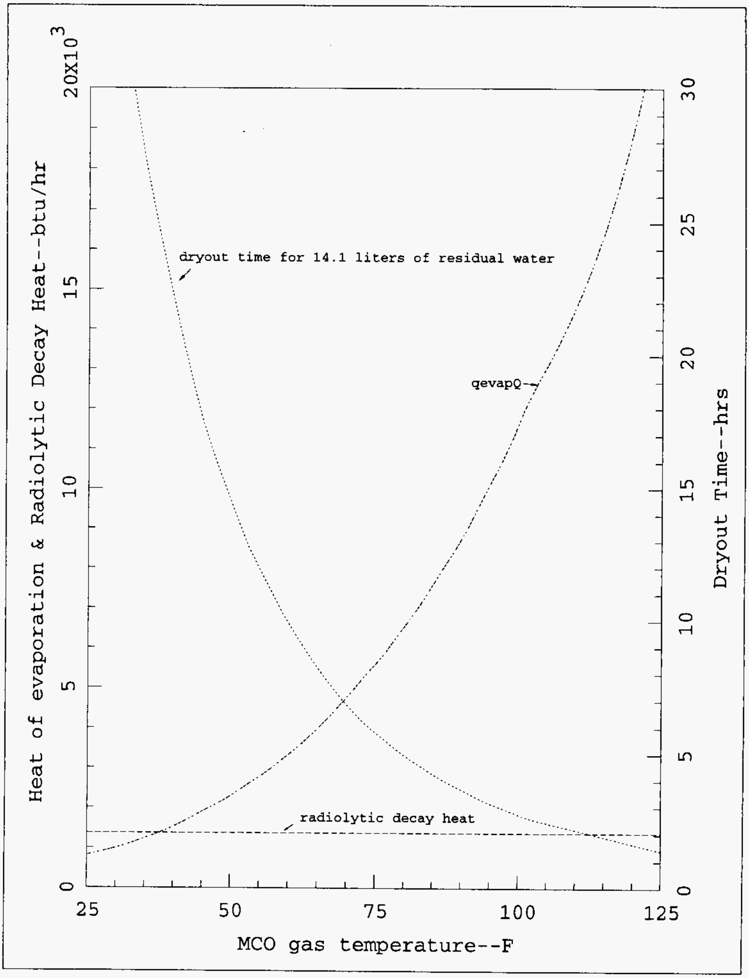

Figure 5.7 Evaporative Heat removal from liquid versus gas temperature, Radiolytic Heat Rate, and Dryout Time

The importance of stored thermal energy in the fuel, baskets, and MCO relative to the energy required to evaporate the residual water is illustrated in Figure 5.8, together with a comparison to the energy available from radiolytic decay heat over two assumed drying time periods.

Evaporation of 14.1 liters of residual water requires about 32,000 btu of thermal energy, and is only slightly temperature dependent. Cooling all metal structures by 50 F would supply adequate heat to evaporate this quantity of residual water. Supplying 400 watts of radiolytic decay power from the fuel over a period of 24 hours will also provide the required amount of heat. To obtain effective use of the stored energy, or radiolytic decay heat, requires that the water be uniformly distributed over the fuel, and/or other metal structures. Since much of the water will be somewhat concentrated in localized areas, stored energy, and or radiolytic heat may provide only limited fractions of the total heat required. Where there is a thin film of water uniformly distributed, these heat sources could be more than adequate to supply enough heat to totally evaporate the thin film. Where the water is concentrated, these heat sources will provide only a fraction of that required to evaporate the concentrated quantity of water. At these locations the heat must be supplied by thermal transport from some other source such as a water bath. Either thermal transport means from the heat source to the water must have low thermal resistance, or the heat source must be at high temperature. Otherwise, the temperature of the liquid will drop, and possibly freeze if freeze protection operating procedures or conditions are not employed, or if freeze protection schemes are used--the time to evaporate the liquid may be excessively long.

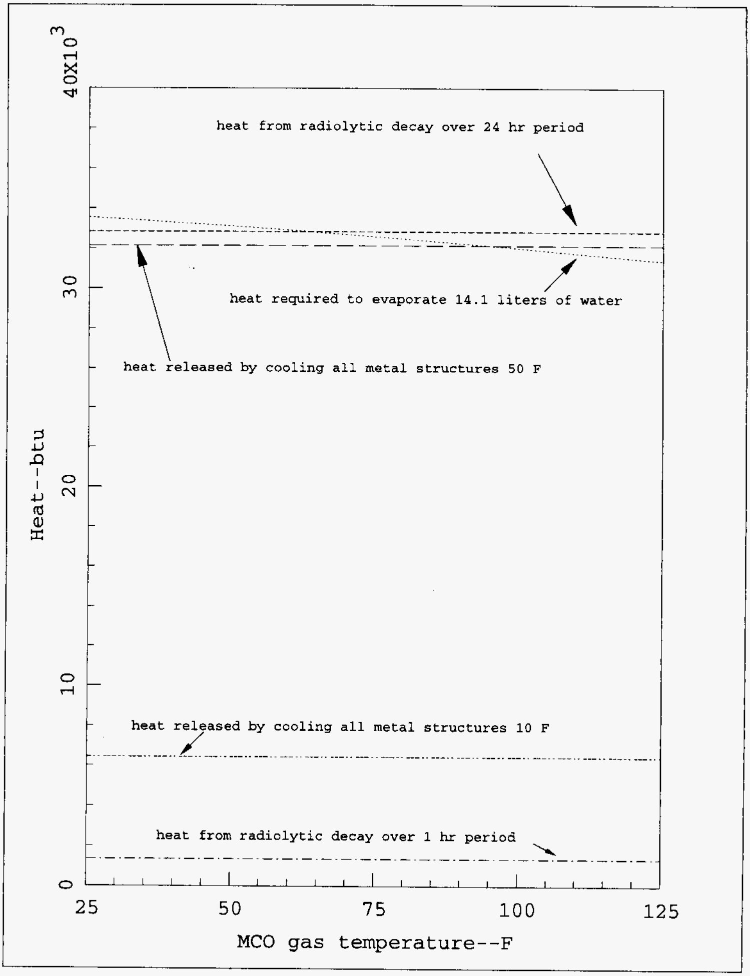

Figure 5.8 Comparison of Evaporative Heat Requirements verses Heat Source Supplies

Residual water in the MCO can provide energy to itself for evaporation by simply cooling. However, as shown in Figure 5.9 the fraction of the water than can be evaporated by cooling the remaining portion from some initial temperature down to freezing is small.

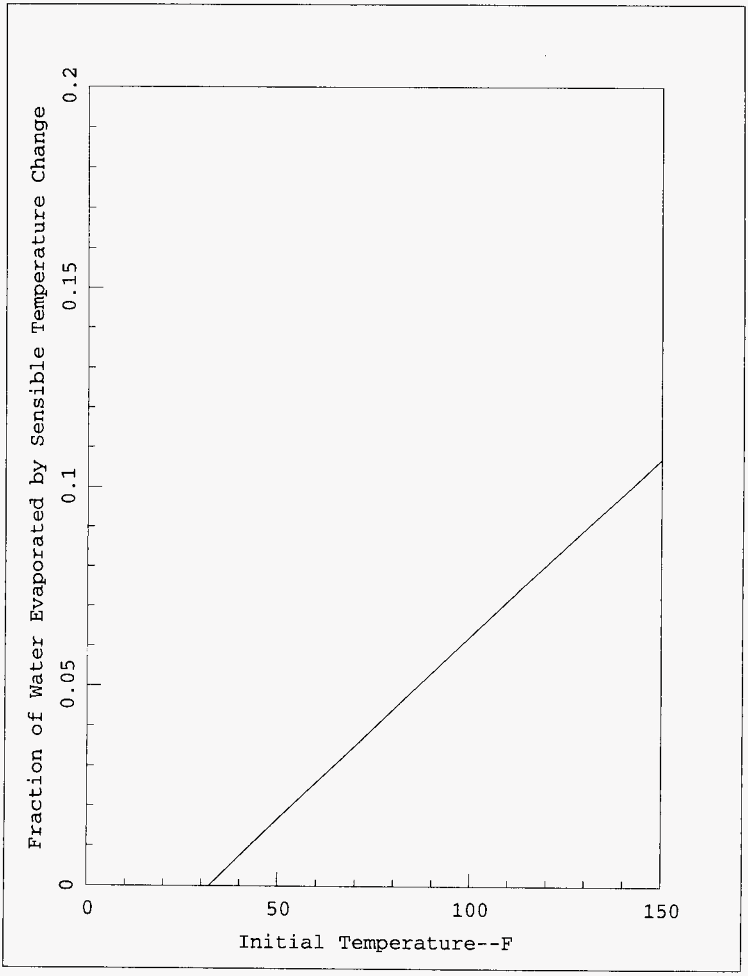

Figure 5.9 Fraction of Water that Can be Evaporated by Sensible Temperature Change of the Water From an Initial Temperature to Freezing

5.3. Flow Resistance or Conductance Between the MCO and Pump, and Thermalhydraulic Transport Properties

The pumps capability to transport steam depends upon the pumps volumetric flow verses inlet pressure characteristics, and the flow resistance (or conductance) between the MCO and the pump inlet. The flow resistance between the MCO and pump inlet depends primarily upon the sizing of the piping, fitting, valves, filters, and MCO shield plug passage ways, and also the passageway tortuosity. In vacuum systems the flow resistance also depends on whether the flow is free molecular flow, or viscous flow, and if in the viscous flow regime whether the flow is laminar or turbulent. The thermal conductivity of the residual gas during vacuum drying has a direct effect on thermal transport from the water bath, and between fuel and basket components. The thermal conductivity depends on the concentration of gas molecules, as does the flow resistance, and is therefore dependent on whether the concentration is high enough to be in the viscous or free molecular flow regime.

Details of the flow passage ways in the MCO shield plug, piping, fittings, valves, are filters are currently being developed as part of the vacuum drying system design development. Preliminary evaluation of the main piping and shield plug passageways is discussed here.

For steam vapor to be in viscous flow the ratio of the mean free path of the steam molecules to the diameter of the passageway must be less than .01. For the steam vapor to be in free molecular flow the ratio of the mean free path to the diameter of the passageway must be greater than 1. Figure 5.10 provides the Knudsen number, ratio of mean free path to diameter, verses temperature of steam vapor over the range of expected operation in the MCO and vacuum system components for 1 and 2 inch diameter passage ways. The expected flow condition for all but very low temperatures and/or pressures, and or very small

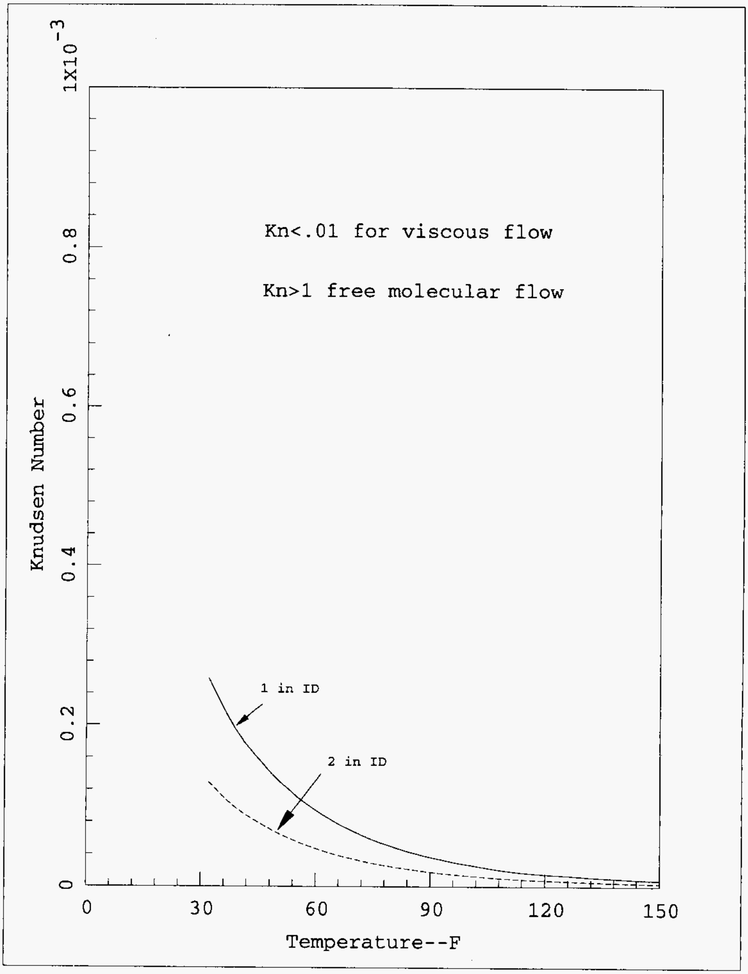

Figure 5.10 Knudsen Number versus Temperature

passageways, will be viscous flow.

There does not seem to be a good referenceable data source for the conductivity and viscosity of steam at low pressure/temperature, but still in the viscous flow regime--i.e. not free molecular flow. Existing data sources, functions, and extrapolations from higher pressure/temperature conditions are consistent with kinetic theory and therefore can be used with confidence at the lower temperature and pressure conditions to be encountered in vacuum drying of spent fuel. The thermal conductivity of steam is about 2/3 that for air at the temperatures of interest, and somewhat higher than a candidate purge gas, Argon, as shown in Figure 5.11. Gases in the MCO during vacuum drying conditions can be treated as ideal gases.

The Reynolds number of the flow within a passage way determines whether the flow can be expected to be laminar or turbulent. If the flow resistance between the MCO and the pump is low and if the steam evaporated from the liquid does not change temperature between the liquid pool surface and the pump inlet, then based on the preceeding report sections, at a given MCO liquid operating temperature there will be a given flow of steam from the MCO to the pump inlet. In the viscous flow regime the viscosity of steam is dependent on temperature, not pressure. On the saturation line, steam density is a function of temperature. Therefore for a given operating temperature the Reynolds number can be calculated for a given passageway diameter. Figure 5.12 defines the laminar, turbulent, and transition regions for 1 and 2 inch ID passageways between the MCO and pump--subject to the condition of low flow resistance and limited heating or cooling of the steam.

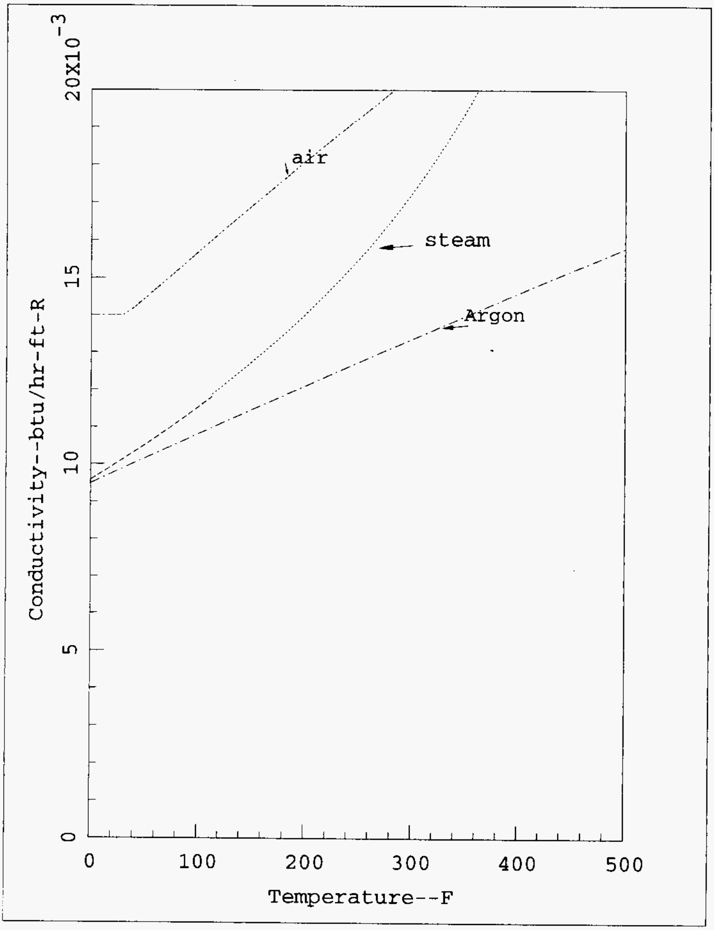

Figure 5.11 Thermal Conductivity of air, Argon, steam versus Temperature

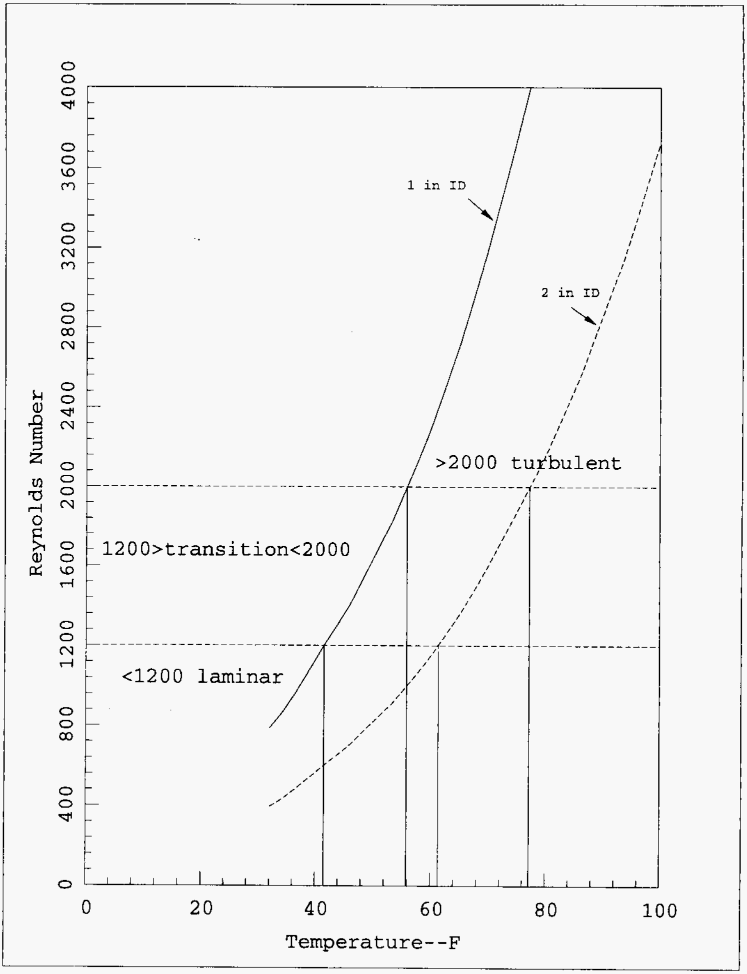

Figure 5.12 Reynolds Number versus Temperature and Laminar/Turbulent Boundaries

A similar graph of Reynolds number verses MCO operating pressure is provided in Figure 5.13 and is subject to the same assumptions.

The friction factor for flow in circular passageways is dependent upon whether the flow is laminar or turbulent, and upon the Reynolds number in both laminar and turbulent flow regimes. The relationship between the friction factor and Reynolds number for pipe/tube flow for a 2 in ID commercial pipe and smooth tube is illustrated in Figure 5.14. Over the range of operation expected in the vacuum system the roughness of the pipe/tube will have little affect on the friction factor and therefore little effect on flow resistance. Different friction factor correlations produce little difference in the calculated friction factor [Zigrang, 1985].

The pressure drop resulting from the flow produced by the vacuum pump, for a given assumed MCO liquid/gas operating temperature for 1 and 2 inch ID smooth and commercial pipe 25 feet long is provided in Figure 5.15. As shown there the pressure drop is small for the 2 inch pipe and quite large for 1 inch pipe. Also shown is the pressure drop for the quick disconnect which couples the MCO to the vacuum line. The current quick disconnect has a flow coefficient, Cv = 13 gal/min (see [Crane, 1988] for the definition of Cv) [McMcracken, 1996]. It is a significant flow resistance.

A similar result is graphed in Figure 5.16 where pressure is the independent variable rather than temperature.

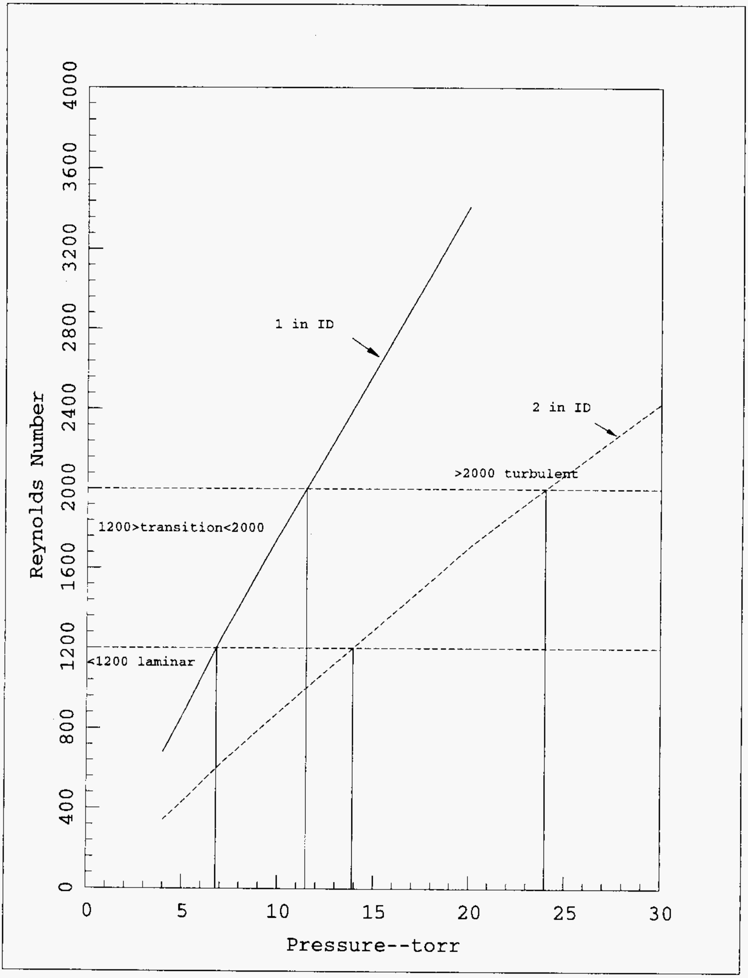

Figure 5.13 Reynolds Number verses Pressure, ID and laminar/turbulent boundaries

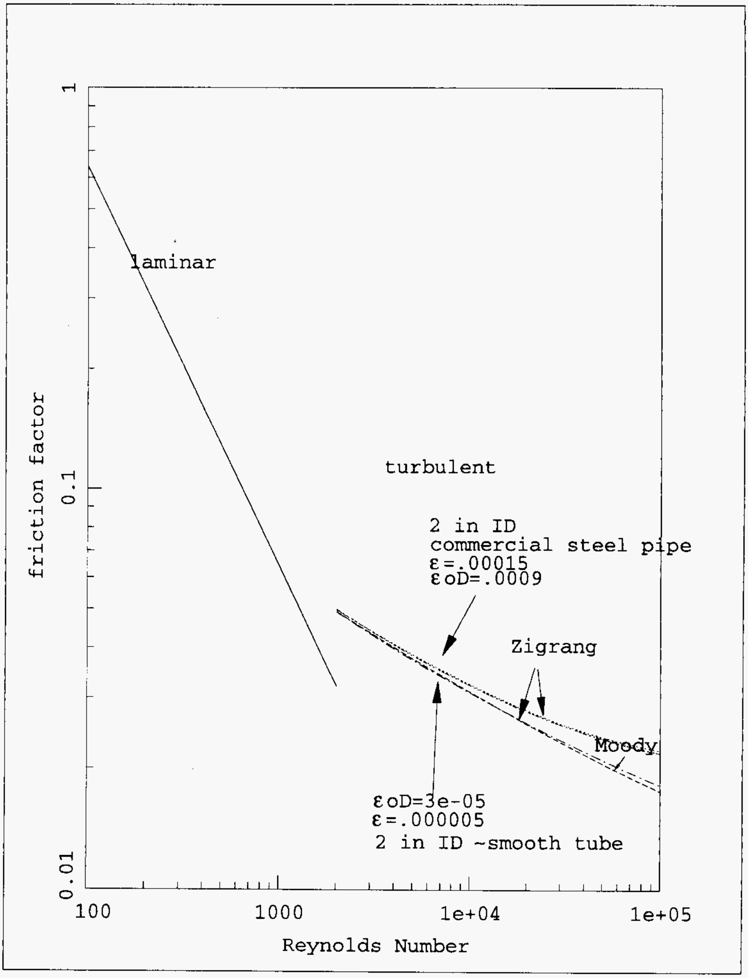

Figure 5.14 Friction factor versus Reynolds Number

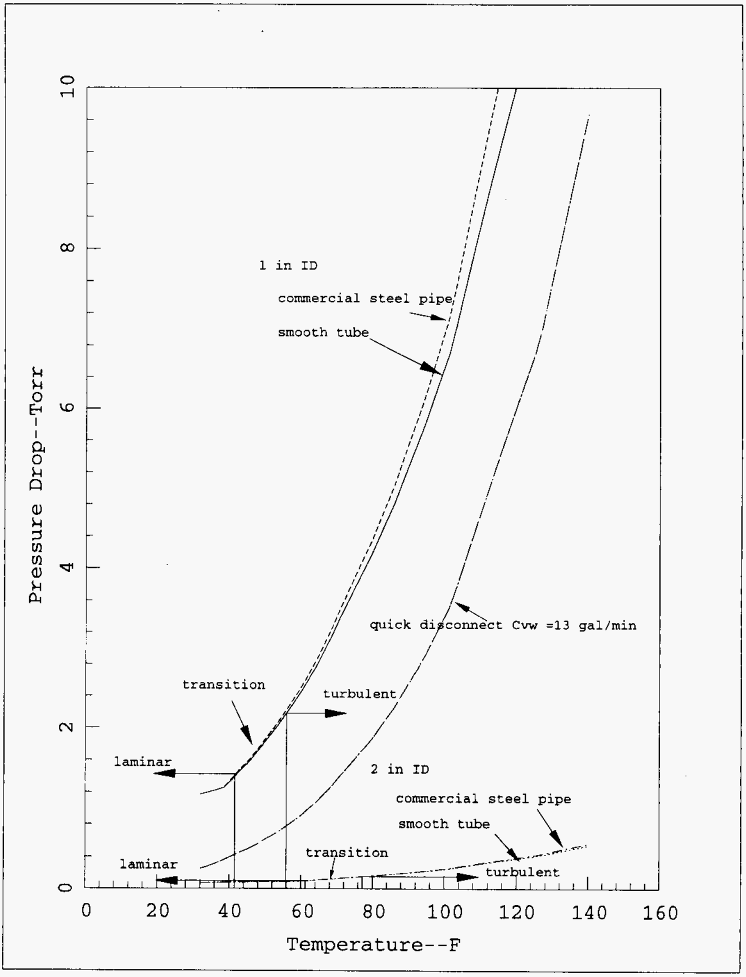

Figure 5.15 Pressure Drop versus Temperature

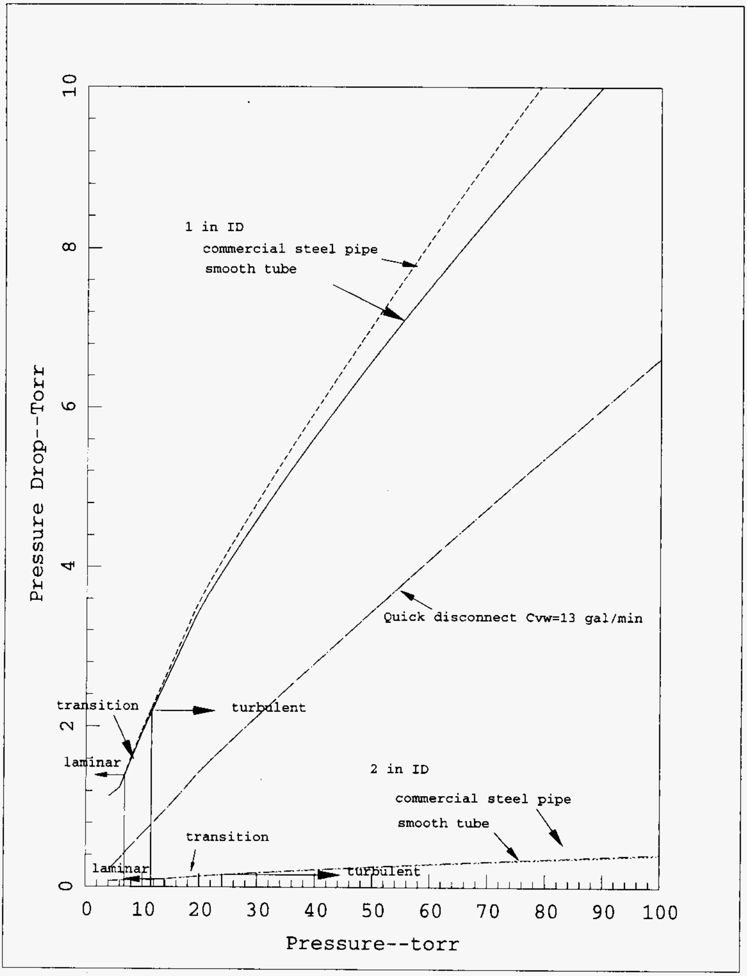

Figure 5.16 Pressure Drop versus Pressure

Relative to the flow verses inlet vacuum pressure characteristics of the pump, the parameter of importance for comparing to flow resistance is the ratio of the pressure drop due to flow resistance to the inlet pressure of the pump. This is plotted in Figure 5.17 verses MCO liquid/gas operating temperature and in Figure 5.18 verses MCO vacuum pressure. Note that this parameter is similar to the inverse of the term "conductance" used in vacuum technology. Conductance is the product of volumetric flow times vacuum pressure divided by the pressure drop. For the range of operation anticipated the volumetric flow of the pump will be approximately independent of pressure, or constant. Therefore the ratio defined in Figures 5.17-5.18 can be approximately converted to conductance by inverting and multiplying by the pump constant volumetric flow rate present above 5-10 torr vacuum pressure.

Development of the graphs presented in this report is based upon the assumptions, as previously stated, that the pressure drop between the MCO and the pump inlet is small, and that the steam vapor does not change temperature significantly between the liquid pool surface and the pump inlet. For the 2 inch ID pipe the pressure drop assumption is reasonable. For low liquid/gas MCO operating temperatures, the steam will likely be heated before reaching the pump. This will act to increase the pressure drop, as well as reduce the steam mass flow rate through the pump.

Although additional more complex analysis is needed to more accurately predict the performance of the system, including the effects of heating the steam, these simplistic results do provide considerable insight. Clearly the current preliminary selection of the 2 inch diameter pipe appears to be an adequate design choice assuming a 65 ft^3/min vacuum pumps is utilized. A 3 inch diameter pipe is not required, but a 1 inch pipe begins to compromise the pumping capability of the combined pump/piping system. Compared to the 2 inch line, the quick disconnect is a significant flow resistance. These conclusions would required modification if significantly higher, or lower flow rate vacuum pumps are finally selected.

Similar scoping calculations should be performed for other components such as fittings, valves, filters and the MCO shield plug passageways. All of these components should be sized such that the pressure drop/pressure ratio for each component is small to avoid degrading the pumping capability of the integrated pump/flow passage system.

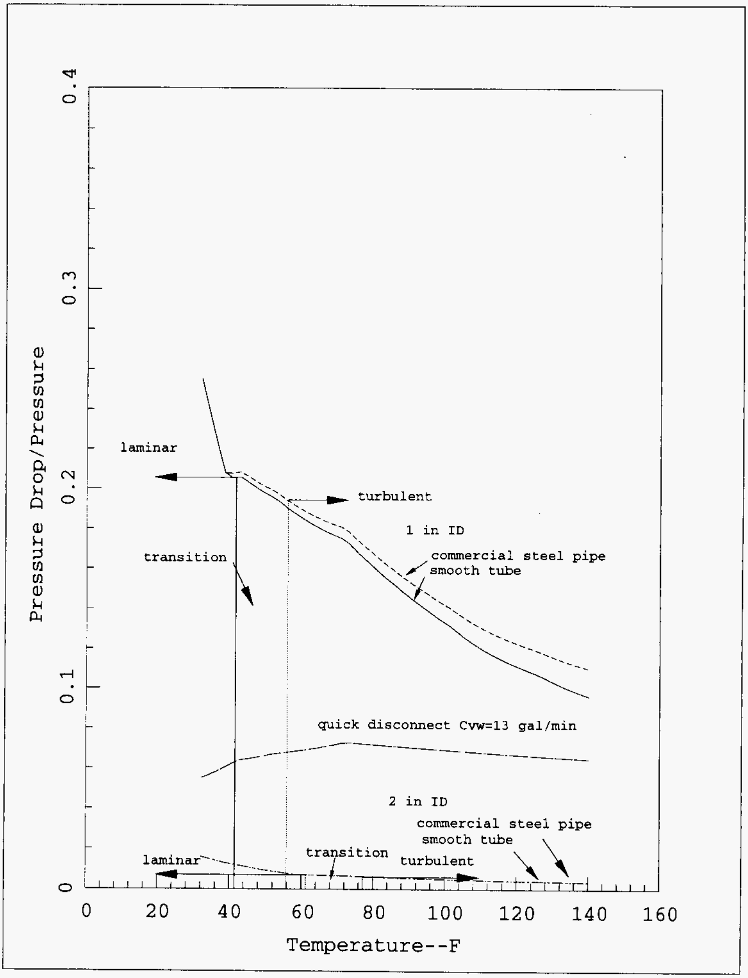

Figure 5.17 Ratio of Pressure Drop/Pressure versus Temperature

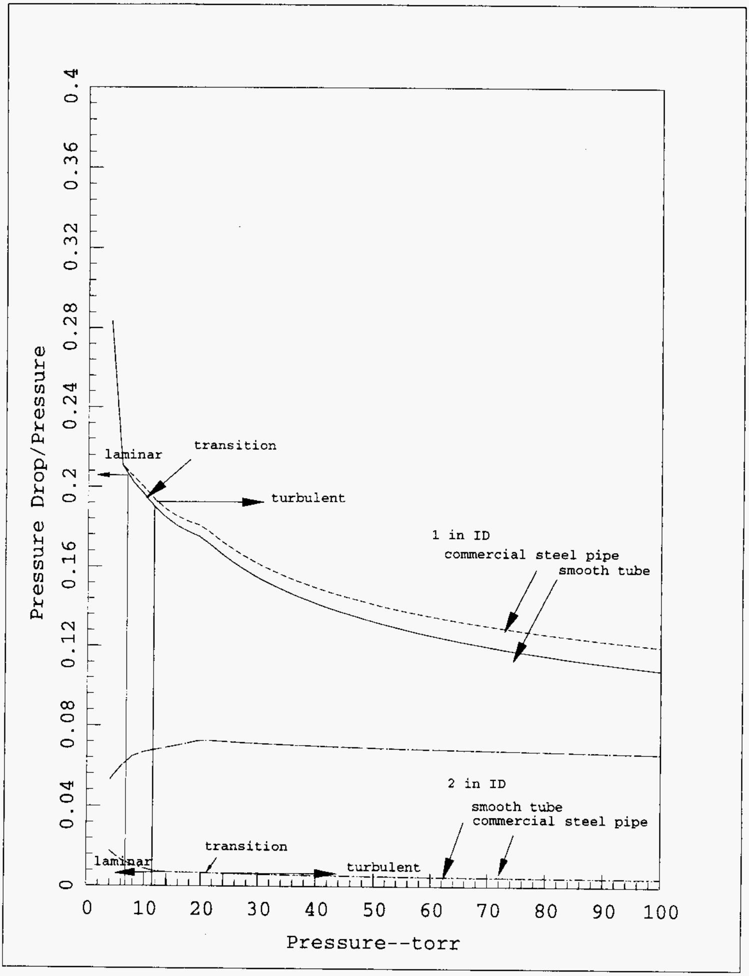

Figure 5.18 Ratio of Pressure Drop/Pressure versus Pressure

5.4. Depressurization and Drying Phases of the Process

The process of vacuum drying fuel proceeds through several phases. These phase are:

1. initial depressurization,

2. quasi-steady evaporation of water,

3. puddling and dryout, or if there is inadequate heat transfer or vacuum pressure control to limit freezing, puddling with rapid pressure and temperature decreases with potential freezing,

4. freezing of water cavities in damaged or corrosion wasted fuel elements which are thermally isolated, and,

5. long term dryout of water cavities in damaged or corrosion wasted fuel elements which are steam flow restricted.

5.4.1. Initial Depressurization

During the first phase of the vacuum drying process the inert purge gas, likely saturated with water vapor, is decompressed and cooled. The pressure is rapidly dropped to that corresponding to the saturation pressure at the initial residual water temperature. The dynamics of the temperature of the inert gas/steam mixture on the other hand will depend on how saturated the inert gas is, and how rapid the heat transport from the metal structures and water surfaces to the gas is. At one extreme the gas could heat if the initial structure temperatures are higher than the initial gas temperature. If the initial inert gas and structures are in thermal equilibrium, and thermal transport rates are high, the depressurization of the gas could be nearly isothermal. If heat transport rates are very low, then the gas will expand nearly adiabatically.

If the inert gas is initially saturated with water vapor and there are adequate condensation nucleation sites, then this water vapor will progressively be condensed and the steam partial pressure decrease, but remain in equilibrium with saturation pressure corresponding to the gas temperature.

Even if there is very limited heat transfer to the liquid, i.e. adiabatic or nearly adiabatic, the liquid will evaporate since its surface partial pressure will be higher than the gas steam partial pressure once depressurization begins. This will cool the liquid slightly. Once the inert gas is removed from the system, only steam will be present, and if it is adiabatic relative to the structures, the steam partial pressure will correspond to the saturation pressure associated with the liquid temperature--the gas temperature will now rise. Since the vacuum pump is approximately a constant volumetric flow rate device at the inlet pressures of concern, the volumetric flow of gas to the pump will not have changed significantly, but all the gas will now be steam. This increases the steam volumetric and mass flow rate--which in turn increases the evaporation rate. Increasing the evaporation rate in this hypothetical adiabatic system decreases the temperature of both the remaining liquid and gas. Ultimately the liquid will freeze before all of the liquid is evaporated.

Several of these hypothetical decompression processes have been computed with the GOTH thermal hydraulics code, and checked by classical means in some cases. The results are presented in Figure 5.19 for the first 100 seconds of decompression period for several hypothetical decompression processes. These include adiabatic decompression of dry air, adiabatic decompression of saturated air, isothermal decompression of dry air, and adiabatic decompression of 4 liters of initial residual water and air (rather than an inert gas). A constant volumetric flow pump with 60 ft^3/min flow capacity at any pressure was assumed for these cases, initial temperature was 122 F (50 C), and initial pressure was atmospheric. The vacuum vessel is assumed to have the same internal empty dimensions as the WHC vessel. No fuel or baskets are included in these calculations. The complete decompression process over an 800 second time period, which takes the 4 liter water decompression case down to freezing of the water is presented in Figure 5.20.

For the 4 liter water case the fraction of liquid remaining and evaporation rate verses time is provided in Figure 5.21.

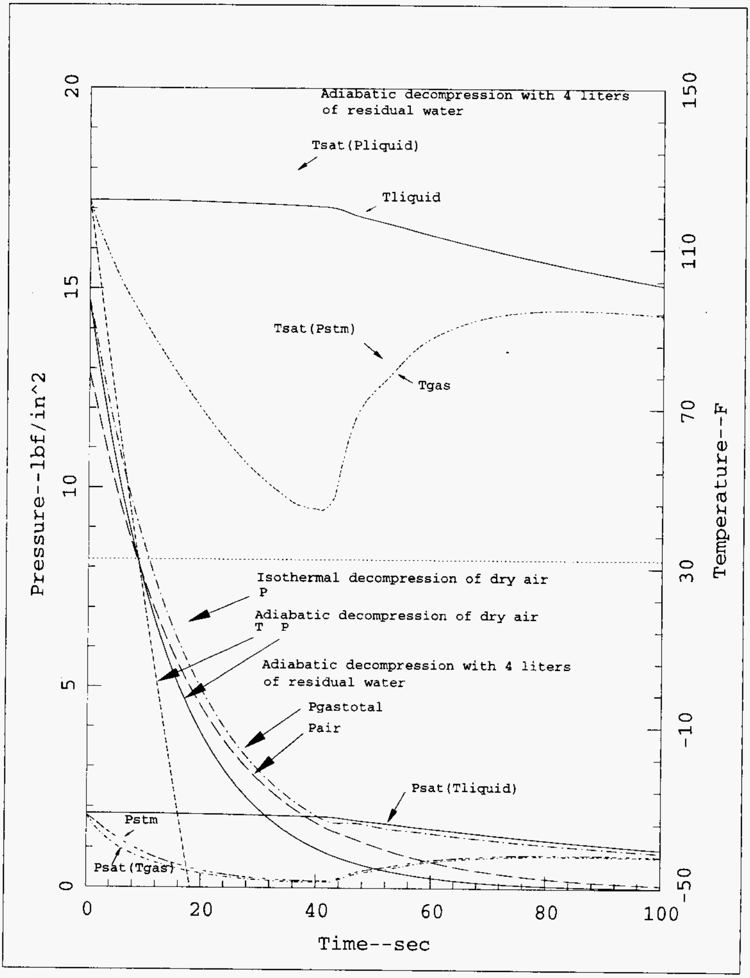

Figure 5.19 Temperature and Pressure Versus Time at a Pump Constant Volumetric Withdrawal rate of 1 ft3/sec

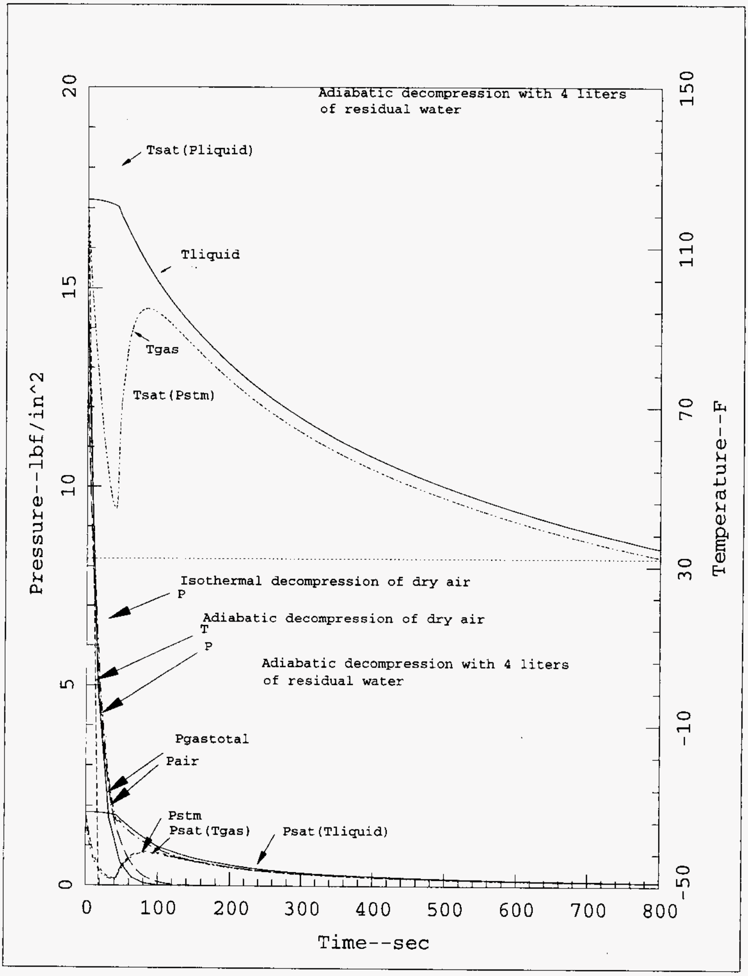

Figure 5.20 Temperature and Pressure Versus Time at a Constant Volumetric Withdrawal rate of 1 ft3/sec

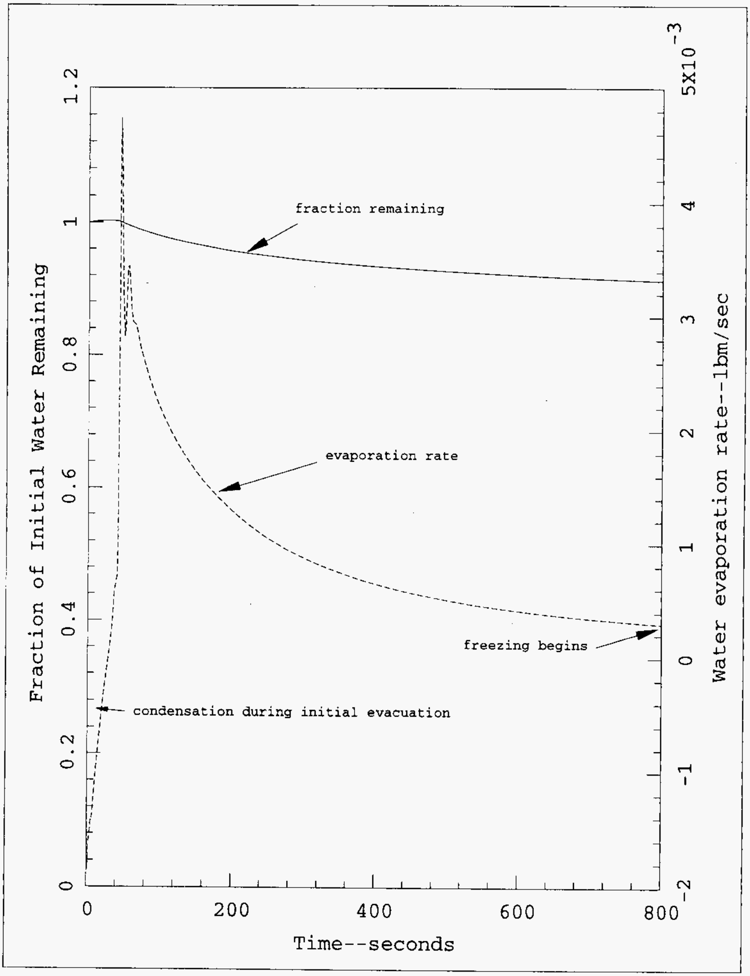

Figure 5.21 Fraction of Initial 4 Liter Quantity of Water Remaining versus Time

From these simplistic calculations several conclusions can be drawn. First regardless which of these hypothetical processes approximates the actual initial decompression, if the vacuum pump is not throttled and the flow resistance between the MCO and pump inlet is not large, all inert gas will be essentially removed from the MCO in less than 100 seconds of operation. Second, unless heat transport to the water is adequate at every location where water is present within the MCO, basket, fuel system then the water will freeze at thermally isolated locations--unless vacuum pressure at the MCO is maintained above that corresponding to the triple point of water, i.e. 4.6 torr, or saturation temperature of 32 F which corresponds to a saturation pressure of 4.6 torr. Third, there is not enough stored energy in the water such that cooling the water from 122 F to 32 F will provide enough thermal energy to evaporate all the water, only about 8% can be evaporated in this case. Fourth, even if the decompression occurs isothermally for both the liquid and the water, almost all of the inert gas will be removed in less than 100 seconds of operation. Fifth, in the WCH system quasi-equilibrium will rapidly be established between pumping capacity, MCO vacuum pressure, liquid temperature, evaporation rate, and heat transport to the water during the initial decompression if the vacuum pump is not throttled. And, sixth, depending on the initial temperatures of the residual water and structures, care must be exercised during the initial decompression to insure gas mass flow rates do not exceed levels which will lead to aerosol generation and transport.

Once quasi-equilibrium is achieved, the next phase of vacuum drying will begin.

5.4.2. Quasi-Steady Evaporation of Water, and Subsequent Puddling, Dryout, and Potential for Freezing

Once quasi-steady equilibrium between pumping capacity, MCO vacuum pressure, liquid temperature, evaporation rate, and heat transport has been achieved following the initial pump down, evaporation rates should be rather steady. There could be gradual increases or decreases however depending on the following. If bath temperature is increased then temperatures and pressures will increase as will evaporation rates. If interface areas between metal structures and liquid films, pools, puddles, and cavities decrease due to drainage, or evaporation, or agglomeration and dryout, then evaporation rates will decrease as will temperatures and pressures. Changes could occur as approximate step changes due to dryout of water regions which have good heat transport, leaving only water regions with poor heat transport.

A quasi-steady evaporation situation is described in Figures 5.22-24 based on the following hypothetical conditions:

1. WHC MCO vacuum vessel initially with 14.1 liters of water on the MCO floor (2.027 inch water level) and at quasi-equilibrium with a water bath at 10 C and the SV100 vacuum pump capacity.

2. Negligible flow resistance between the MCO and pump inlet.

3. Assumed MCO floor and wall thickness = 1 inch (actual floor 1 inch, but wall .375 inch thick) of stainless steel with k=10 btu/hr-ft-F.

4. Negligible change in steam temperature between when it evaporates from the water surface and when it reaches the vacuum pump inlet.

5. Initiation of puddling when 1/16 inch level reached.

6. Contraction of the puddle due to surface tension leading to reduced heat transfer area, vacuum pressure reduction, liquid pool temperature reduction,

evaporation reduction, dryout, and potentially freezing of the puddle.

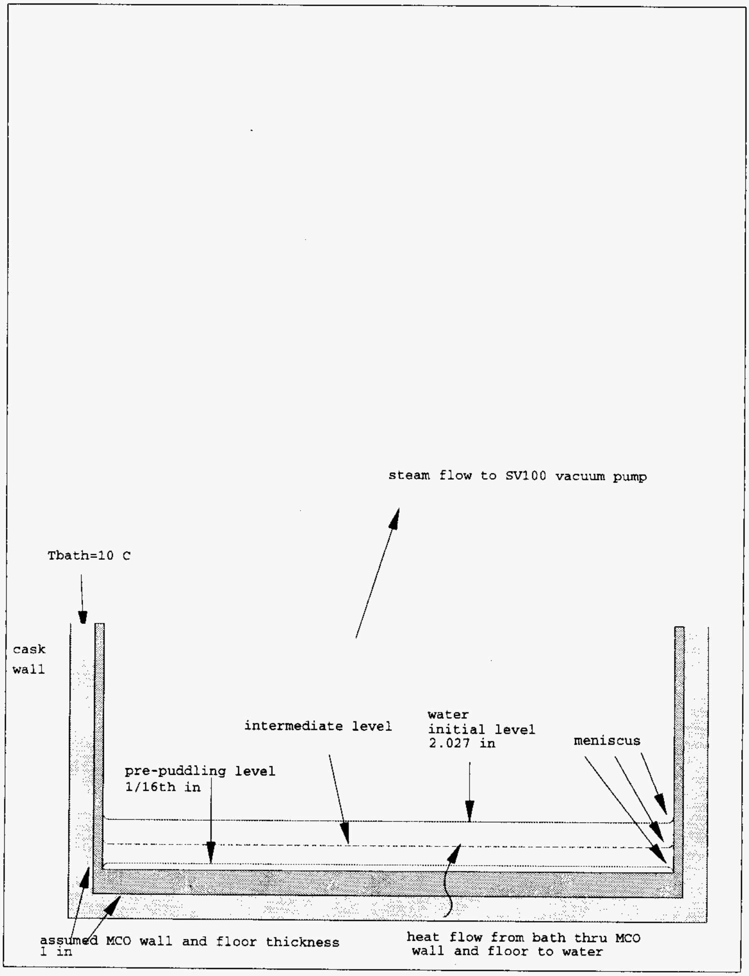

Figure 5.22 Quasi-steady Evaporation of Water Due to Wall Dryout but preceding End Plate Dryout and Puddling

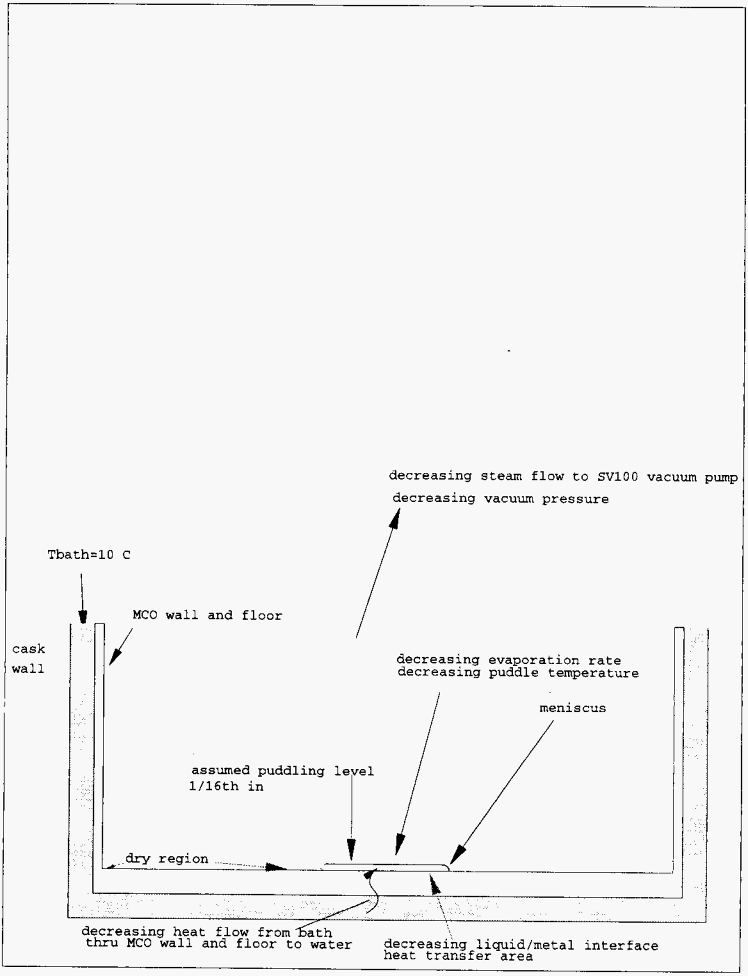

Figure 5.23 Rapid Change in Press., Temp. Liquid/Metal Interface Heat Transfer Area, and Evaporation Rate Caused by Floor Puddling and Dryout Which Could Lead to Freezing

The calculated results over the period of time which covers both the quasi-steady evaporation and pool level decrease, followed by the puddling and rapid reduction interface heat transfer area, reduction in pressure, temperature, and evaporation rate, leading to dryout, or in this case freezing is illustrated in Figure 5.25.

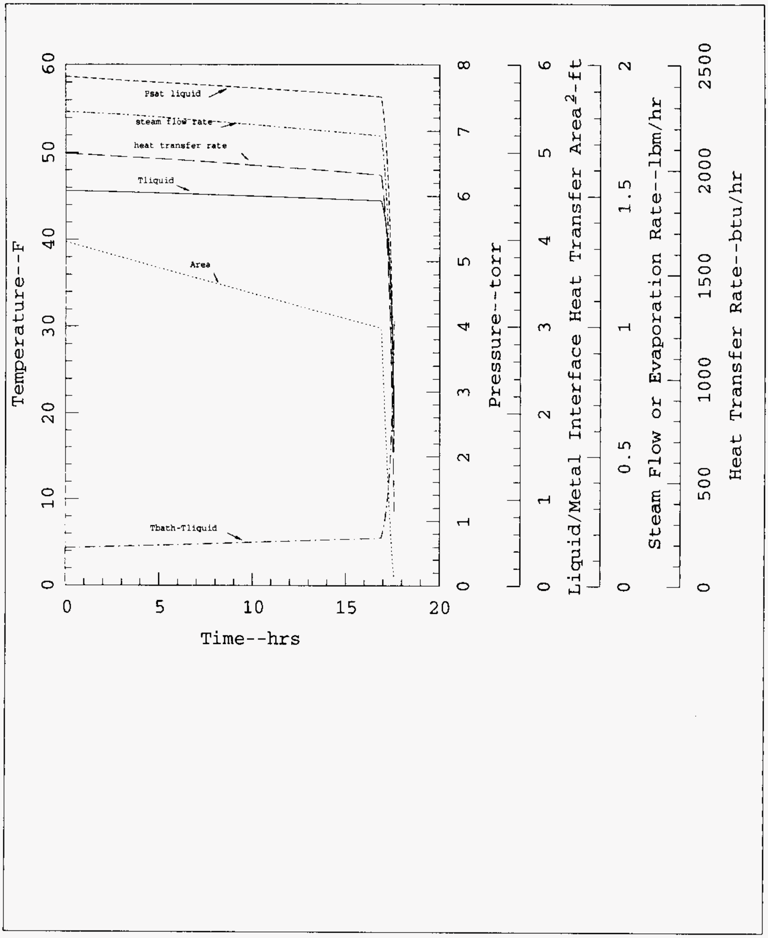

Figure 5.24 Dynamic Response of MCO and water pool during quasi-steady, puddling, and dryout/freezing phases of vacuum drying

Although 14.1 liters of water are not expected to be pooled at the bottom of the MCO following drainage as assumed in this hypothetical situation, total residual water estimates, including pools at the bottom of the MCO, and films on structures within the MCO have been this high. Water bath temperature will likely be increased from an initial starting value of 10 C up to as high as 50 C. This example does indicate, however, that if 14.1 liters of water were located at the bottom of the MCO, the current vacuum pump could evaporate all this water within about 17.5 hours. This does assume negligible flow resistance between the MCO and pump, and a water bath on the bottom of the MCO. If the bath is raised to 50 C the dryout time reduces to only 3 hours.

The actual MCO, fuel, basket, and cask thermal hydraulic system differ from this hypothetical situation--however, the potential for this phenomena exists and has been observed in the MSU tests. A somewhat similar situation could exist with damaged fuel assemblies that have been corrosion wasted leaving water filled cavities that may be thermally isolated.

The current MCO bottom plate design is flat, but includes a drainage well. There is direct contact between the water bath and the bottom plate. Sloping the flat portion of the MCO bottom plate would promote drainage thereby reducing the initial quantity of residual water, and eliminate puddling at the bottom plate, with exception of the drainage well. The addition of direct water bath heating to the bottom of the MCO will help increase evaporation rates prior to dryout. Use of vacuum pressure control will minimize the potential for freezing.

5.4.3. Thermally Isolated Water Cavities with or without Steam Flow Limiting

Water films on the inside of the MCO will be in direct contact with metal heated by the water bath and therefore not thermally isolated. The films will likely be quite thin. As are result there will likely be little difficulty in evaporating this water in a short period of time, without the potential for freezing. Water films located on external vertical surfaces of baskets and fuel will also likely be thin--but they will be thermally isolated from the water bath and MCO structure. Evaporation rates will be lower, depending on the temperature of the basket and fuel structures. Stored energy in the baskets, fuel, and water, radiolytic heat, plus radiation, convection, and conduction heat transfer will likely prove adequate to evaporate these films in a reasonable period of time with out freezing, but this needs to be verified by analysis also. Horizontal films on baskets and fuel element ends will be thicker than vertical films, requiring more thermal input per unit of liquid/metal surface area, leading to lower temperatures and increased drying times which will require additional analysis to determine expected operating conditions and drying times.

Thermally isolated water in cavities created in damaged fuel elements due to corrosion wastage of uranium is a possibility. A hypothetical situation is illustrated in Figure 5.25-26. If the uranium oxide created from the reaction of uranium and water results in corrosion wastage then possibly water filled cavities could result. Damage of fuel elements has occurred during the refueling process. One type of damage has involved the removal of spacer/clips at the spot welds between the spacer/clips and the clad as shown in Figure 5.27. This has been observed to leave holes in the clad on the order of the diameter of the spot weld diameter, estimated at 1/16-1/8 inch. If there are water filled cavities within some fuel elements the potentially large quantities of water would be thermally isolated from the heating bath, and stored energy and radiolytic decay heat within the fuel element would likely not be adequate to evaporate the large quantity of water in a reasonable period of time. The presence of uranium oxide, which is a poor thermal conductor would potentially further thermally isolate the water. In addition the leak paths between the cavity and the MCO vacuum may be steam flow restrictive. These two factors may make dryout of these regions a lengthy process. Additional analysis is required to evaluate whether this is , or is not a potential problem area.

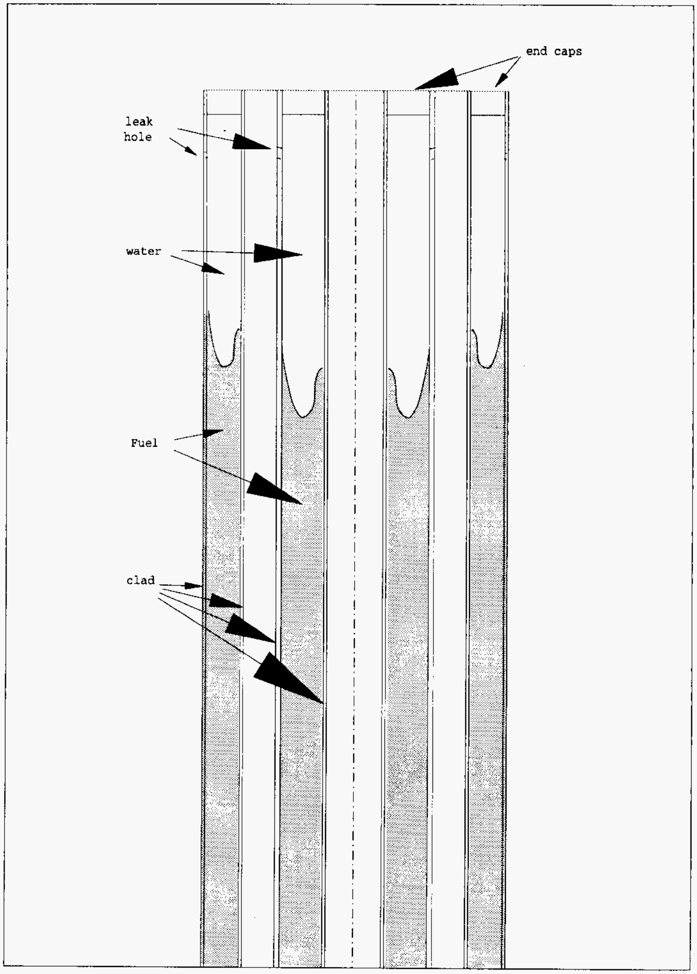

Figure 5.25 Mark-IA Fuel Element Cross Section Showing Possible Residual Water Resulting from Leak Holes and Fuel Wastage Due to Corrosion

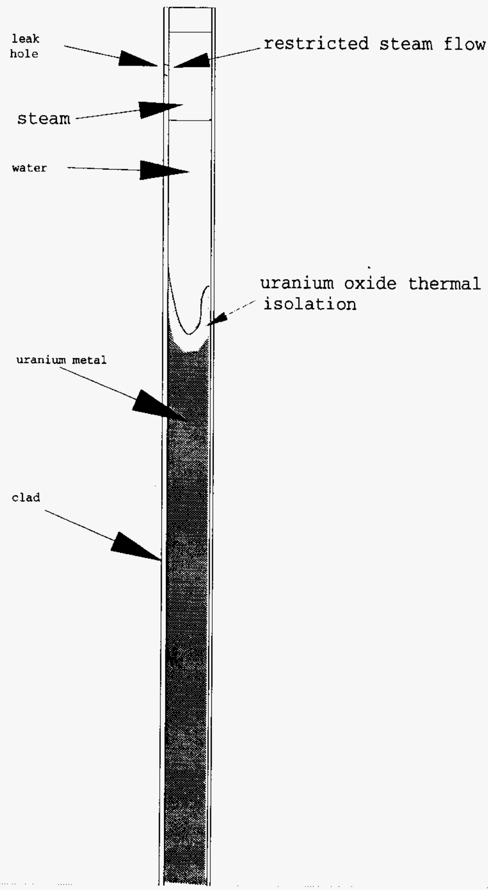

Figure 5.26 Mark-IA Fuel Element Cross Section Showing Possible Residual Water Resulting from Leak Holes and Fuel Wastage Due to Corrosion

Refueling operations knocked some spacers/clips off at spot weld locations leaving holes about the diameter of the spot welds.

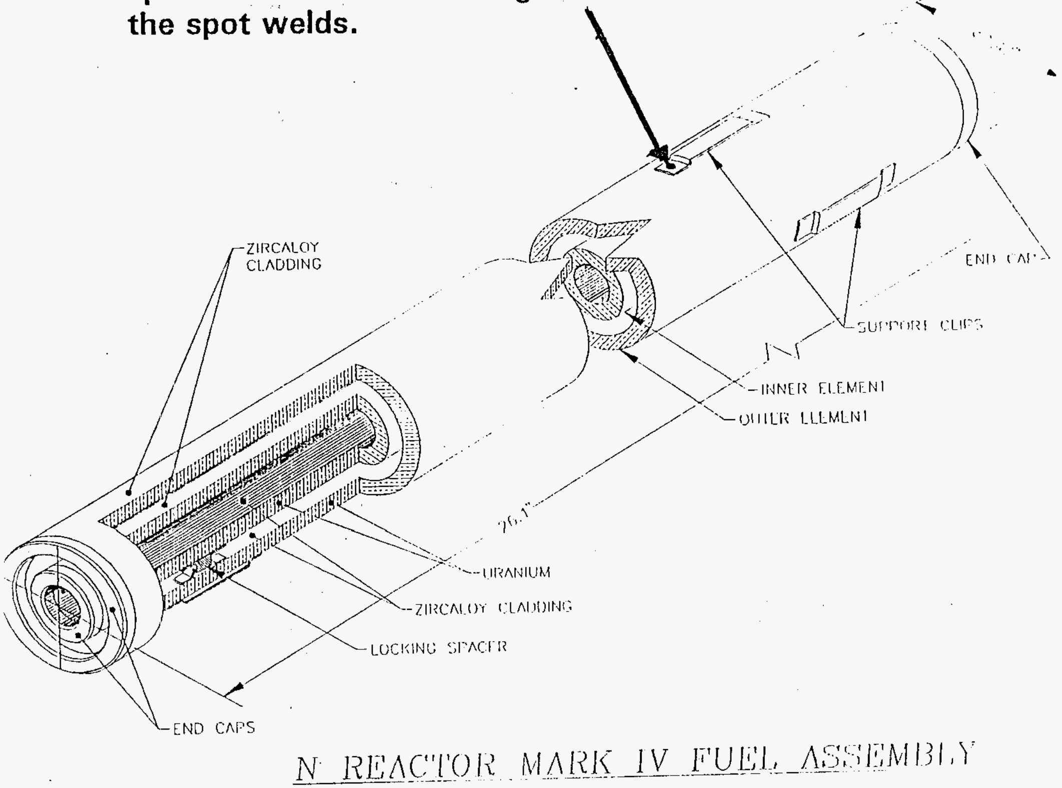

Figure 5.27 Fuel Element Showing Location of Spacer/Clips and Spot Welds

6. CONCLUSIONS

There are several main conclusions that can be drawn from this preliminary scopeing analysis and modeling:

1. Spent nuclear fuel draining and vacuum drying can be conducted successfully and safely through careful engineering design of the system and the associated operating procedures.

2. Considerable engineering analysis remains to be conducted to insure that the design and operating criteria will be met. This will include development of more detailed GOTH thermal hydraulic computer code models with coupling to even more detailed COBRA-TF thermal hydraulic computer code model.

3. The preliminary scopeing analysis and modeling conducted todate has provided the necessary background to understand what the dominant design and operating issues are, what the major uncertainty areas are, and what level of detail must be incorporated into future models. Thermal transport simulation must include as a minimum radial conduction and thermal radiation from the bath to successive rings of fuel within the MCO, plus axial conduction within the fuel. Radiolytic decay heat, stored energy, and bath heating must be included. Chemical reactions must also be included to evaluate the potential for uranium/steam ignition.

4. Prior experiments conducted at INEL and MSU provide useful insight and confirmation of conclusions drawn from the preliminary analysis and modeling effort. Evaluation of these experimental efforts has identified issues that should be avoided if possible in experiments WHC intends to conduct at Hanford. There are major non prototypic features in the INEL and MSU test apparattuses relative to the current WHC design.

5. Changes made in the WHC design thus far should reduce

the amount and distribution of residual water following draining, and improve thermal transport for evaporation of residual water.

6. Completion of the WHC vacuum system should consider in detail the flow resistances between the MCO and the vacuum pump inlet, and between the vacuum pump and exhaust stack outlet to insure the pumping capacity is not compromised.

7. Postulating realistic and bounding concepts of how much residual water will remain, where it will be located, and how heat will be transported to it is a significant remaining modeling/analysis challenge. Of major concern is developing bounding scenarios for water cavities resulting from corrosion wasting of uranium and associated steam flow limiting leak paths between the cavity and the MCO vacuum.

7. REFERENCES

George, A.H., Rogers, J., & Fleming, J., 1994, Vacuum Drying of Fuel Containers, Montana State University, Dept. of Mechanical Engineering, Bozeman, MT.

O'Brien, J., Phetteplace, D., Sprenger, M., & Welland, H., 1994, ICPP-603 Fuel Canning Project May Street South Station Test Report Document, Idaho National Engineering Laboratory, EG&G, Inc., Idaho Falls, ID.

Q-Metrics, 1995. Interim Report for Technical Services for Spent Nuclear Fuel--Thermal Analysis Support, Q-Metrics, Inc., Woodinville, WA.

Roth, A. 1983. Vacuum Technology, Elsevier Science Publishing Company, Inc., New York, NY.

O'Hanlon, J.F., 1980. A User's Guide to Vacuum Technology, John Wiley & Sons, New York.

Scott, R.B., Cryogenic Engineering, D. Van Nostrand Company, Inc., Princeton, New Jersey.

Bird, R., Stewart, W.E., & Lightfoot, E.N., 1960. Transport Phenomena, John Wiley & Sons, New York.

Irwin, J.J., 1996. Vacuum Drying System Evaluation for K Basin Spent Fuel Removal, WHC-SD-SNF-009, Rev. 0, Westinghouse Hanford Co., Richland, WA.

Crane, 1988. Flow of Fluids through Valves, Fittings, and Pipe, Technical Paper No. 410. Crane Co., Joliet, Illinois.

Zigrang, D.J., and Sylvester, N.D., 1985. A Review of Explicit Friction Factor Equations, Transactions of ASME,

Leybold-Heraeus, 1986. Product and Vacuum Technology

Reference Book, Product Information Department, Leybold-Heraeus,5700 Mellon Road, Export, PA.

McCracken, K.J., 1996. Vacuum Conductance Conversion Calculations, Kaiser Engineers Hanford, Calc. No. CVD-02.

Thurgood, M.J., et. al., 1993. GOTHIC Containment Analysis Package,Version 3.4e, EPRI TR-103053, Electric Power Research Institute.

Kelly, J.M., 1985. Analysis of FLECHT-SEASET 163-Rod Blocked Bundle Data Using COBRA-TF, NRC/EPRI/Westinghouse Report No. 15, NUREG/CR-4166, Westinghouse Electric Corporation and Electric Power Research Institute.

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution	Process Engineering Analysis	Date August 6, 1996
Project Title/Work Order		EDT No. 614687
Spent Nuclear Fuel Vacuum Drying Thermal-Hydraulic Analysis and Dynamic Model Development Status Report/LH053		ECN No. N/A

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
R. G. Cowan	R3-86	X			
J. R. Craig	K9-72	X			
J. R. Frederickson	R3-86	X			
B. C. Fryer	H0-34	X			
L. H. Goldmann	R3-86	X			
J. J. Irwin	H0-34	X			
A. T. Kee	R3-86	X			
C. R. Miska	R3-86	X			
D. M. Ogden	H0-34	X			
P. A. Scott	R3-87	X			
P. K. Shen	H0-40	X			
J. P. Sloughter	R2-54	X			
D. A. Smith	R3-11	X			
J. C. Wiborg	R3-86	X			
Central Files (Original + 2)	A3-88	X			
PEA File (Burstad 2)	H0-34	X			