Review of Drying Methods for Spent Nuclear Fuel

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REVIEW OF DRYING METHODS FOR SPENT NUCLEAR FUEL (U)

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1.0 SUMMARY

A practical method for drying aluminum-based spent nuclear fuel (SNF) at the Savannah River Site has been proposed. The drying methodology is based on achieving a level of dryness that allows acceptable, safe storage of SNF. Drying and stabilization techniques to prepare SNF for dry storage at other DOE sites have also been reviewed. Table 1 summarizes methods under development at the Hanford site and at the Idaho National Engineering and Environmental Laboratory (INEEL).

Aluminum SNF with minimal corrosion may be effectively prepared for extended dry storage via vacuum drying at slightly elevated temperatures (~120°F). Achieving a vacuum below ~87 torr within a heated canister will vaporize free liquid water. Achieving a vacuum below the triple point of water (4.6 torr) is within the capability of standard vacuum pump systems and will ensure dryness. High temperature drying to release hydrated water from aluminum oxide on the SNF cladding is not required because the quantity of water is insufficient to cause excessive additional corrosion. Negligible amounts of uranium hydride are expected on aluminum SNF retrieved from water storage, and further conditioning or conversion of corrosion products to eliminate an ignition hazard is not needed.

A drying demonstration with mock material test reactor (MTR) assemblies should be initiated to quantify drying system performance. A follow-up vacuum drying demonstration should be integrated into the proposed test program for dry storage and surveillance of sample MTR assemblies. Irradiated MTR assemblies will be loaded into instrumented test canisters in L Area and monitored for an extended period to demonstrate the validity of proposed storage criteria [Ref. 1, subtask 1.3]. The proposed drying demonstrations will provide operational experience and aid optimization of drying equipment and methodology. Existing surplus vacuum drying equipment can be utilized to minimize costs.

The feasibility of evaporating free water from MTR SNF via simple low humidity hot air drying is still being evaluated and may be included in the demonstrations.

2.0 INTRODUCTION

2.1 Background

SRTC is developing technology for direct disposal of aluminum spent nuclear fuel (SNF). The development program includes analyses and tests to support design and safe operation of a facility for "road ready" dry storage of SNF-filled canisters. The current technology development plan includes review of available SNF drying methods and recommendation of a drying method for aluminum SNF [Ref. 1, subtask 1.2].

2.2 SNF Disposal Issues Related to Conditioning

Conditioning SNF for ultimate disposal within a geologic repository is a primary technology development objective for aluminum SNF. Conditioning is the process whereby SNF is dried or stabilized against undesirable degradation. A one-time conditioning process for interim dry storage of SNF at SRS and subsequent disposal within the repository is desired. 10 CFR Part 60.135(b)(2) prohibits free liquids inside repository waste packages in amounts that could compromise waste package containment or cause spread of radioactive contamination. Rapid corrosion of unconditioned SNF and/or packaging materials after placement could invalidate ongoing repository performance assessments.

Formation of uranium hydride is a storage and disposal concern for uranium metal fuels. 10 CFR 60.135(b)(1) prohibits pyrophoric materials inside repository waste packages in amounts that could compromise waste isolation or performance objectives. Uranium hydride is potentially pyrophoric and can form beneath breached cladding on uranium metal SNF. Hydride formation initiates when water vapor adsorbs to uranium oxide surfaces [2]. The water dissociates into hydroxyl and hydrogen via radiolysis. The hydroxyl diffuses to the metal surface and reacts with uranium to form additional oxide and liberate additional hydrogen. Hydride forms when sufficient hydrogen accumulates at the surface of the uranium metal beneath the oxide. Elemental uranium expands greatly and breaks up into fine particulates upon hydriding or oxidizing. Uranium hydride reacts with water to form uranium oxide. Uranium hydride remains on uranium metal in water storage only if occluded from water.

Uranium hydride also reacts rapidly with oxygen when exposed to air; the kinetics of the reaction depend on the air temperature and hydride particle size. The oxidation process produces uranium oxide and water and generates significant heat. High temperatures accompanying runaway oxidation can lead to ignition of the uranium base metal.

3.0 SNF DRYING, CONDITIONING, AND STORAGE PROGRAMS

Multiple SNF drying and stabilization methods are under development at the Hanford and INEEL sites (Table 1). These methods utilize a combination of vacuum drying and high temperature passivation to remove water and reduce the likelihood of pyrophoric corrosion product formation during extended dry storage.

3.1 Hanford Uranium Metal SNF

A major program is currently underway to transfer ~103,000 SNF assemblies (~2100 metric tons uranium) from the Hanford K East and K West storage basins near the Columbia River into dry storage [3]. The SNF is primarily low enrichment uranium metal production reactor assemblies clad with Zircalloy. The assemblies are 1.4 to 2.4 inches in diameter and up to 26 inches long. Cladding damage has led to swelling from oxide formation and an accompanying volume increase. This swelling caused additional splitting of the cladding and extensive uranium corrosion during extended storage in the Basins. SNF removal from the K-Basins is currently scheduled to begin in late 1997 or early 1998 utilizing drying and stabilization processes outlined below.

SNF assemblies will first be cleaned inside a "tumbling washer" and rinsed with a high pressure spray to remove exterior crud and corrosion. Cleaned SNF will be loaded into baskets underwater and placed into multi-canister overpacks (MCO's) for subsequent drying and storage. The MCO's are 24-inch OD by 166-inch-long stainless steel canisters designed for up to 75 years storage. About 400 MCO's will be utilized to store the K Basin SNF. Each MCO holds 270 to 288 assemblies with a maximum gross weight of ~20,360 pounds flooded. The top of the MCO will be raised to the surface of the water after loading and closed with a screwed shield plug. The MCO will be placed inside a shielded cask upon removal from the Basin and transported to a new cold vacuum drying facility adjacent to the K Basins.

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The MCO holds 150-180 gallons of water after fully loading with assemblies [4]. The MCO will be purged with pressurized gas via ports in the shield plug to remove the bulk of free water. An estimated 2-4 liters (0.5-1 gal) of residual water within the MCO will be removed via vacuum drying. A 4 horsepower four-stage Balzers/Pfeiffer Unidry 050 vacuum pump has been purchased for this application. Pump capacity is 34 cfm with a base pressure of 0.04 torr (0.0007 psia). The pump chamber does not require oil lubrication and is water-vapor tolerant. Each MCO will be initially evacuated to a pressure of ~10 torr (0.19 psia) to promote vaporization of the residual water. A condenser and HEPA filter upstream of the pump inlet will remove particulates and vapor from the air stream. The vacuum pump will discharge through a second HEPA filter into a ventilation system exhaust stack. The vacuum drying system has been designed to remove a maximum of 15 liters (4 gal) of water per MCO.

Warm water will be circulated through the 1/4-inch annulus between the MCO and cask liner to prevent freezing of water within the MCO during vacuum drying. Water will enter underneath the MCO base, flow upward through the annulus, and exit at the top. Average water temperature will be maintained at 50°C (120°F).

The acceptance criteria for SNF dryness is a final pressure of 0.5 torr (0.01 psia) inside the MCO. The vacuum pump will be isolated after achieving 0.5 torr, and MCO internal pressure will be monitored to ensure all water has been removed. MCO pressure will rise if moisture, such as water trapped beneath SNF cladding discontinuities, is subsequently released. Pressure must remain below 3 torr (0.06 psia) after one hour for final MCO acceptance. The MCO will be leak checked and vacuum dried again if the pressure rises above 3 torr. For comparison, a pressure of 3 torr equates to ~2 grams of water vapor or ~11% relative humidity inside a loaded MCO with the dimensions cited above (Appendix A).

MCO's will be transported to the Canister Storage Building after drying to await further conditioning and long term storage. A new 300°C vacuum conditioning system is currently being designed to ensure long-term SNF stability by passivating the uranium metal and removing chemically bound water of hydration in the corrosion products. Removing the water of hydration will eliminate the potential for gradual moisture release and hydrogen formation inside the canister during long term storage. Hydrogen could react with uranium metal as described earlier to form additional potentially pyrophoric uranium hydrides. The initial amount of hydrated oxide and potential amount of uranium hydride produced via this process was not reported. The conditioning process includes a step to stabilize the SNF by converting existing uranium hydrides to oxides. The MCO will be purged with a small quantity of oxygen in an inert carrier gas to achieve slow, controlled oxidation and formation of an oxide film.

3.2 INEEL "At Risk" SNF

Three programs are under development at INEEL to provide improved SNF storage. The first program will transfer ~315 assemblies or handling units from the Chemical Processing Plant (CPP) 603 Basin into dry storage [5]. The seven fuel types to be transferred are at highest risk from continued corrosion within the storage basin and include UAl, UZrH, UO₂, U₃O₈ alloys and uranium metal. SNF geometries include 12-inch to 50-inch-long plates, 28-inch to 37-inch long rods, and a 220 kilogram uranium flux filter. Drying equipment installation and mockup testing have been completed, and SNF drying is expected to begin in June 1997 [6].

SNF will first be loaded into new self-draining stainless steel buckets underwater and transferred via a shielded transfer car into an existing dry handling cave adjoining the basin. The buckets will be remotely loaded into new 18-inch OD by 11-foot-long stainless steel canisters. Eighteen to twenty-one canisters will be utilized to store the SNF. Each canister is expected to contain no more than 3 liters (0.8 gal) of water after loading [7]. The loaded canister will be sealed with a temporary lid and connected to vacuum and purge lines. The lid has two thermocouples and a pressure transducer to monitor SNF drying.

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The canisters will be heated and vacuum dried at a newly constructed station inside the fuel handling cave [8]. A 5 horsepower Leybold Sogevac SV100 single-stage rotating vane pump with an oil-sealed pumping chamber will be utilized. Pump capacity is 66 cfm with a base pressure of 0.4 torr (0.008 psia). The pump will be operated with air ballast to reduce water vapor condensation within the oil. HEPA filters in the vacuum pump suction line will capture micron size and larger corrosion products. A valve in the vacuum pump suction line will be throttled to maintain canister pressure above ~5 torr (0.10 psia) and prevent freezing. The pump is located in an accessible room and connected to the canister via ~70 feet of 1-inch piping.

The canister drying well contains nine 1.5 kilowatt electric band heaters. The heaters will be cycled to maintain the canister internal temperature at 50°C during drying. The band heaters will also be utilized during subsequent baking of the fuel canister at 150°C.

The canisters will be evacuated below 4.5 torr to ensure free liquid water has been vaporized. The vacuum pump will then be isolated, and the canister interior pressure will be monitored for 1-2 hours to confirm dryness. The pressure will rise if moisture is escaping from beneath the cladding or the canister system is leaking. The canister will be leak checked and/or dried again if the pressure rises during the evaluation period.

Uranium metal SNF will be conditioned after vacuum drying to remove some of the chemically-bound waters of hydration in the aluminum oxide. High temperature conditioning will also passivate uranium hydride corrosion products as described earlier. The SNF will be purged for two hours with ~1 scfm of argon containing 2% oxygen while baking at 150°C.

A vented storage lid will be installed on the SNF canister after completion of drying and conditioning. The canister will be transported via an overhead crane into the Irradiated Fuel Storage Facility adjoining the CPP 603 Basin. This facility was originally constructed in 1974 for dry storage of graphite reactor fuel canisters. The SNF canisters will remain vented to atmosphere during extended storage in this facility. The oxygen content of air will promote oxide formation rather than hydride formation on exposed uranium during storage.

3.3 INEEL Three Mile Island SNF

A program is also underway at INEEL to transfer 343 cans of Three Mile Island (TMI) Unit 2 core rubble into dry storage [9]. The cans are currently filled with water and stored in the Test Area North Basin. Each can will be partially dewatered by injecting nitrogen gas to expel bulk water through existing ports in the lid. The cans are expected to retain 20 to 250 pounds of water intermingled with debris and trapped inside the lower head after dewatering. Vectra is currently performing vacuum drying tests to develop a technique for removing residual water. A 300°C drying process to dehydrate rubble and low density concrete liners inside the cans is being considered.

Dried cans will be temporarily sealed for transport and loaded into 29 NUHOMS dual purpose canisters for subsequent transport and storage. Each dual purpose canister holds twelve TMI cans. The canisters will be placed into passively-cooled dry storage modules and vented to prevent potential hydrogen gas buildup. Similar NUHOMS canisters and storage modules are used at commercial nuclear reactors for SNF storage.

3.4 Proposed INEEL Dry Storage Facility

INEEL has prepared a conceptual design proposal for a major new SNF dry storage facility to hold ~12,000 assemblies [10]. The new facility will receive, package, and store Fort St. Vrain, Shippingport Light Water Breeder Reactor, Peach Bottom, TRIGA, and other miscellaneous SNF assemblies from the INEEL storage basins and offsite research reactors. Assemblies will be loaded into dry handling buckets and placed into ~78 NUHOMS dual purpose canisters similar to the TMI units. Each canister is ~67 inches OD and ~186 inches long. Canisters will be loaded inside a hot cell and closed by installing and welding ported shield plugs.

The canisters will be vacuum dried and inerted prior to long term storage. Development of the vacuum drying process has not proceeded beyond a conceptual description. The preliminary facility design report recommends an oil-cooled pump with filters on the pump inlet and outlet. The proposed canister dryness test is similar to tests described above. The canister will be evacuated until the internal pressure is below the triple point of water. Canister pressure will be monitored after isolating the vacuum pump, and leak checks or additional drying will be performed if the pressure rises.

Each canister will be backfilled with inert gas and sealed by installing a second welded lid. The sealed canisters will be placed inside NUHOMS storage modules on a pad adjacent to the Chemical Processing Plant.

Development of a FY 1998 budget line item for the INEEL dry storage project has been halted. Privatization of the facility is currently being considered. The INEEL Spent Nuclear Fuel Task Team recently recommended consideration of smaller co-disposal canisters to facilitate eventual disposal within the geologic repository [11].

4.0 PRIOR SRS DRYING PROGRAMS

Lessons from two significant vacuum drying projects completed during deactivation of SRS reactor facilities are applicable to SNF drying. Unirradiated production reactor SNF and primary coolant loop heat exchangers were vacuum dried to remove or recover residual water.

4.1 Unirradiated SNF

Several hundred unirradiated Mark 22 fuel assemblies were removed from P and L Reactors and dried prior to deactivation of these facilities. The fuel assemblies contained four aluminum clad tubes, ~14.5 feet long and 3.7 inches OD, nested inside an aluminum sleeve housing. Each fuel assembly was separated from the sleeve housing inside a tank of deionized water and placed into an aluminum storage canister. The canisters were heated and vacuum dried at a temporary station inside the reactor room [12]. The station was equipped with four heated fuel canister cradles and two 1.5 horsepower Welch model 1397 oil-sealed vacuum pumps. Pump capacity was 17.7 cfm with a base pressure of 0.0001 torr. Each pump was connected to two canisters via 3/4-inch suction tubing and discharged into the reactor room ventilation exhaust duct. Sixteen strip heaters mounted on each canister cradle generated 1.9 kilowatts. The average cradle temperature was ~200°F.

Two fuel canisters were evacuated simultaneously with an average drying time of ~40 minutes and a final canister pressure of ~3.5 torr. Water accumulated inside the vacuum pump oil reservoir during drying, and frequent oil changes were necessary. The volume of water removed from the assemblies could not be measured, and no estimates are available.

4.2 Reactor Heat Exchangers

An extensive vacuum drying program was conducted during final lay-up of P, L, C, and K Reactor equipment in 1992-1995. Sixty two primary coolant loop heat exchangers were vacuum dried during 2-1/2 years to recover ~5700 gallons of D₂O and remove several thousand gallons of contaminated H₂O. Each heat exchanger is 33 feet long and 8 feet in diameter with a total interior volume of ~977 cubic feet. The heat transfer surface is ~33,400 square feet.

New 300 cfm Kinney vacuum pump skids were utilized in the heat exchanger drying program [13]. Each skid had a liquid-sealed vacuum pump coupled with an air ejector and booster blower. The liquid ring vacuum pump evacuated air from the heat exchanger and also served as a direct contact condenser for the moisture laden air. The pump was cooled by circulating antifreeze solution through an external heat exchanger and an air-cooled chiller.

A 1000 cfm Edwards rotary vane oil-sealed vacuum pump and blower were connected in parallel with the Kinney skid to expedite final drying. The Edwards pump was utilized at ~1 torr after the Kinney pump had removed most of the water. A 20 kilowatt air heater/blower and seven 6 kilowatt radiant heaters warmed the tube bundle, heads, and shell during drying.

Multiple vacuum gages were installed to monitor heat exchanger pressure and vacuum pump inlet pressure. Heat exchanger shell and head temperatures were also monitored. Thirty one parameters on the vacuum drying equipment and heat exchanger were checked and recorded every 30 minutes. Each heat exchanger was vacuum dried until condensate removal ceased and a vessel pressure of 0.9 torr (0.02 psia) or lower was achieved. The last eleven heat exchangers dried contained an average of 209 gallons of water each before drying, and the average drying time was 193 hours each.

5.0 STORAGE CRITERIA FOR ALUMINUM SNF

Acceptance criteria for 50-year dry storage of aluminum SNF were published in 1996 [1]. Specific acceptance criteria for aluminum SNF include:

- 200°C cladding temperature limit during drying and storage.
- Drying temperature may be increased to 250°C for 2 hours on SNF with non-breached cladding.
- No more than 1 milliliter of free water per 0.1 square meter of cladding surface.
- Sealed storage in nonreactive gas, air, vacuum, or
- Non-sealed storage with flowing ambient air around SNF.

These criteria were established to limit general corrosion and pitting to 0.003 inches and local deformation (creep) to 0.1 inch. Sealed canisters are recommended for road-ready interim dry storage [14].

5.1 Aluminum SNF Corrosion

Three sources of water potentially contribute to corrosion of aluminum SNF:

- Free water on the SNF surface and in pits, crevices, etc.
- Water of hydration within the aluminum oxide surface coating.
- Adsorbed water on the surface of aluminum metal or oxide.

The acceptance criteria of 1 milliliter of free water per 0.1 square meter of surface could leave enough residual moisture to generate ~0.0001 inch of uniform aluminum corrosion [1]. A protective film of hydrated aluminum oxide (Boehmite) forms as aluminum cladding reacts with water vapor. This oxide could eventually dehydrate during SNF storage; however, release of water from a 50 micron thick film of Boehmite is predicted to generate only 0.00026 inch of corrosion. Adsorbed water is much less than the water of hydration and is a negligible concern.

Calculated water contributions from each source on a cropped 18-plate MTR assembly (Appendix C), and predicted corrosion losses are:

<u>Source</u>	<u>Criteria</u>	<u>H₂O</u>	<u>Corrosion</u>
Free water	<1 ml per 0.1 m ²	16.6 gm	0.0001 in
Water of hydration	50 microns thick	42.6 gm	0.00026 in
Adsorbed water	20 molecular layers	<0.02 gm	negligible

5.2 Hydrogen and Hydride Buildup

Buildup of hydrogen inside a sealed SNF storage container is another potential concern. Hydrogen gas is released as water and aluminum react to form Boehmite. The explosive range of hydrogen in air is 4% to 75% by volume at room temperature. The SNF canisters will likely be backfilled with an inert gas prior to sealing, but air will be introduced if the canisters are reopened for inspection/fuel characterization prior to placement inside the repository. In addition, 10 CFR 60.135(b)(1) prohibits explosive materials inside repository waste packages in amounts that could compromise waste isolation or performance objectives. The 4% hydrogen threshold equates to ~17 grams of free water inside a 17-inch diameter by 10-foot long storage canister if the water fully reacts with aluminum to form hydrated oxide and release hydrogen. The water limit for hydrogen buildup is more restrictive than the corrosion limits cited above (Appendix D). Evaluation of engineering options for mitigation of hydrogen buildup is continuing.

Hydrides are not expected in corroded uranium-aluminum SNF because uranium is bound as a UAl_x aluminide. The aluminide is a stable compound and is dispersed in a matrix of aluminum which prevents uranium and hydrogen from reacting readily. The aluminum oxide film on the SNF cladding is not a pyrophoric hazard because it forms slowly, is relatively thin, and generates minimal heat during formation. Bureau of Mines tests reportedly indicate aluminum powder must reach ~500°C to ignite.

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6.0 ALUMINUM SNF DRYING

A SNF dry handling and storage facility proposed in late 1996 per Project S-7703 would have included drying equipment [15]. The current Request for Proposal for SNF handling and storage services does not specify wet versus dry SNF handling, but a vacuum drying system could be adapted to either handling mode. SNF could be dried before or after loading the storage canisters if a dry handling system is selected. A 17.5-inch diameter by 12-foot long drying chamber would accommodate the largest bare aluminum SNF currently planned for receipt at SRS. Drying prior to canister loading is feasible because water adsorbed on the SNF surface after initial drying is a negligible corrosion concern as described earlier.

6.1 Water Volume Estimate

The initial volume of free water inside an SRS SNF canister can not be accurately estimated without testing. A 17-inch-diameter by 10 to 15-foot-long co-disposal canister has been proposed. Hanford and INEEL SNF canisters of comparable size are expected to contain about one gallon of water that must be removed by vacuum drying.

Water retention can be conservatively estimated at 0.5 gallons per assembly by assuming all annuli in a cropped 18-plate MTR assembly are plugged at the bottom with debris and filled with water (Appendix B). Rough drying time estimates with this initial water loading are:

<u>Drying Method</u>	<u>One Assembly</u>
Hanford system @ 0.16 gal/hr	3.1 hrs
INEEL system @ 0.40 gal/hr	1.3 hrs
SRS heat exchanger system @ 1.08 gal/hr	0.5 hrs

6.2 Drying Test Program

A test program is highly desirable to quantify drying system performance for SRS SNF. Initial tests should focus on drying dummy test assemblies with various free water contents. Dummy assemblies can be dried and monitored inside instrumented canisters to check drying effectiveness. Some non-radiologically contaminated drying equipment is still available from the reactor heat exchanger vacuum drying program and can be utilized in this test program.

Vacuum drying should be integrated into the test program for placing irradiated MTR assemblies into instrumented dry storage canisters in L Area. This test will build upon drying experience gained with the dummy assemblies. Radiologically contaminated vacuum pumps and heaters from the reactor heat exchanger drying program could be used to dry the MTR assemblies.

Heated forced air drying may provide effective removal of gross water from SNF prior to vacuum drying or serve as an alternative to vacuum drying. Hot air (130-150°F) would be blown across the SNF assembly plates to evaporate surface moisture. Further analysis and experimentation is required to evaluate this concept.

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	Hanford K Reactor Basins	INEEL TMI-2	INEEL CPP Dry Storage Project	INEL CPP-603 AL-Clad & Sodium-Bonded SNF	SRS
Fuel	100,000 Zirc clad U metal assys 2.42" OD, 26.1" long 51.6 lbs per assy 1.25% ²³⁵ U max	Core rubble 2.95% ²³⁵ U	>4000 TRIGA assemblies, 744 FSV assemblies, plus Shippingport, Peach Bottom, and misc SS & Zirc clad SNF	Seven fuel types incl. UAl, UZrH, UO ₂ , U ₃ O ₈ , U metal assys and 220 kg U flux filter. 12" to 50" long plates and 28"-37" long rods 5.3%-93.5% ²³⁵ U	~34,000 Al-clad uranium-aluminum alloy assys
Canister Materials & Dimensions	304L SS MCO with removable baskets 24" OD Std wght pipe 25.25" OD shield plug 166" long, ~148" cavity	Existing 304L/316L stainless steel cans are 14" OD, 150" long 3 can designs: Fuel Filter Knockout Cans will be stored inside Vectra DPC's	304/316SS(?) Vectra FO-DPC is 67.25"OD, 66" ID, 186.2" long with 167" cavity. Peach Bottom SNF cans are 12.75"OD, 166" long, 161.5" cavity	SS canisters with removable buckets. Canisters are 11 ft. long 18" OD Sch 10 pipe	SS canister <17.7" OD <179.9" long
Closure	Threaded shield plug with O-ring and 4 ports Welded cap over plug?	Bolted (1) and welded can lids with 1/4" & 3/8" couplings for venting	Welded	Vented lid secured with lever arm	
Weight	19,142 lbs dry (~288 assemblies max)	2800 lbs max dewatered per can			
Quantity	400 MCO's	343 cans in ~29 DPC's	~78 DPC's	18 to 21 canisters	
Heat Load	400 watts nominal 800 watts max per MCO	20 watts avg 80 watts max per TMI can		<300 watts per canister (12 watts per ATR assy)	<14.2 kilowatts per canister
Design Rating	ASME Sec III, Sub NB 150 psig, 200°C	ASME Sec VIII, Div I 140 psig, 400°F	Not established for DPC Peach Bottom cans rated @ 15 psig, 380°C		
Free Water Inside Canister Before Drying	2-4 liters (0.5-1 gal) per MCO expected 16 liters (4.2 gal) max capacity	20-250 lbs (2.4-30 gal) per "filter" can		3 liters max (0.8 gal) per canister	
Radiation Rate		1500 R/hr @ 1 cm from top of can	300 mR/hr @ top of DPC		

	Hanford K Reactor Basins	INEEL TMI-2	INEEL CPP Dry Storage Project	INEL CPP-603 AL-Clad & Sodium-Bonded SNF	SRS
Drying Process	<p>Desludge SNF inside "washing machine" followed by high pressure rinse.</p> <p>Load MCO underwater. Transport MCO inside cask to vac dry station. Purge 150-180 gallons bulk water from MCO via gas injection and eductor.</p> <p>Dry MCO via 4-stage oil free Balzers vac pump. Condenser on pump inlet with 35°F chilled water regulates vacuum. Circulate 50°C water in annulus around canister exterior during drying. Declare SNF dry after achieving 0.5 torr, isolating and holding for 1 hr with <3 torr rise. Provisions for 350°C hot conditioning system.</p>	<p>Dewater flooded cans via gas injection. Currently performing cold vacuum drying tests.</p> <p>Considering 300°C hot drying process to fully dehydrate rubble and concrete.</p>	<p>Load DPC & install shield plug inside dry cell.</p> <p>Move DPC out of cell. Install automatic welder and weld plug to shell. Dry DPC via vent & siphon ports with oil-cooled vacuum pump. Perform 22 psia He leak test.</p> <p>2.3 psig final canister press.</p> <p>Weld caps onto ports. Install and weld outer lid.</p>	<p>Load fuel buckets underwater. Place loaded buckets into canister inside Fuel Handling Cave hot cell. Install temporary vacuum drying lid. Vac dry with Leybold pump throttled to 5 torr. Heat canister internals to 50 - 100°C via nine 1.5 kW external heaters.</p> <p>Declare SNF dry after pressure drops below 3- 5 torr and holds for 1-2 hrs when isolated. Computerized canister temperature and pressure data acquisition & control system.</p> <p>Bake @ 150°C for 2 hrs with 1 scfm purge of 2% O₂ in Argon to convert hydrides to oxides, i.e. passivate.</p>	
Drying Time	Est 24 hours per MCO. Prototype tests indicate 4-6 hours per MCO	12-24 hrs hot gas purge?		2-5 hrs drying and heatup. ~10 hrs cooling time	

	Hanford K Reactor Basins	INEEL TMI-2	INEEL CPP Dry Storage Project	INEL CPP-603 AL-Clad & Sodium-Bonded SNF	SRS
Storage Mode	Canister Storage Bldg similar to Fort St Vrain modular vault dry storage facility.	~29 DPC's holding 12 TMI cans each. Vented DPC's stored in NUHOMS modules with passive cooling.	78 DPC 's stored in NUHOMS modules with passive cooling.	Irradiated Fuel Storage Facility in CPP-603. Exhaust fan online, but not required for cooling. 80-90°C inside canister.	Modules or Monolith
Concerns	Self ignition of hydrides on severely corroded assemblies during handling. Hydrides swell cladding allowing evolved H ₂ , O ₂ to escape and pressurize MCO.	Radiolysis of residual moisture may lead to H ₂ , O ₂ generation and pressurization of cans while sealed during transport. Criticality analyses very conservative because there is no record of fissile content per can.	Corrosion & radiolysis lead to DPC gas pressurization.	Uranium hydride is pyrophoric and could ignite U metal SNF. Water released during storage decomposes into H ₂ , O ₂ leading to hydride formation.	
Status	Start loading MCO's between 12/97 and 5/98.	Contract awarded to Vectra in Summer 1996.	Privatize per 1/97 decision.	Field installation tested with mockup fuel in Summer 1996. Passivation procedures require revision. Start SNF drying by June 1997.	Request for Proposal under development.
Regulations	DOE Orders	10 CFR 72	10 CFR 72	DOE Orders	10 CFR 72

APPENDICES

Title of Project Determine mass of water vapor Project No. Appendix A
 Subject inside Hanford MCO after drying Works _____
to 3 torr Computer WS Large Date 3/17/97 Sheet No. A1

Estimate volume of free water inside MCO with final internal pressure of 3 torr.

$$3 \text{ torr} = 0.0580 \text{ psia}$$

Assume MCO has no leaks and internal pressure is due entirely to residual water vapor.

$$\therefore P_{\text{water vapor}} = 0.0580 \text{ psia}$$

Assume MCO is backfilled from 3 torr to atmospheric pressure (14.696 psia) with dry air at 80°F (~27°C).

$$P_{\text{sat}} = 0.50736 \text{ psia} @ 80^\circ\text{F}$$

The water content is unchanged as the MCO is backfilled with dry air.

$$\text{Relative humidity} = \phi = \frac{P_{\text{water}}}{P_{\text{sat}}} = \frac{0.0580 \text{ psia}}{0.50736 \text{ psia}} = 0.114 = 11.4\%$$

$$\begin{aligned} \text{Humidity ratio} = W &= 0.62198 \frac{P_{\text{vapor}}}{P_{\text{total}} - P_{\text{vapor}}} \quad \text{p 6.12 ASHRAE Fund.} \\ &= W = 0.62198 \left(\frac{0.0580}{14.696 - 0.0580} \right) = 0.00246 \end{aligned}$$

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/17/97

Sheet No. A 2

MCO is constructed of 24" ϕ standard weight stainless steel pipe per Section 1.2.3 of Performance Specification

MCO is ~ 148 " long internally per SK-2-300461

MCO ID = 23.500" for 24" Sch 10S

IA = 3.0121 ft²

$$\text{Vol}_{\text{MCO}} = \text{Area} * \text{height} = 3.0121 \text{ ft}^2 * \frac{148}{12} \text{ ft} = 37.149 \text{ ft}^3$$

MCO is loaded with 288 Mark I A fuel assemblies.

Fuel Assy Dimensions:

2.425" OD	} outer tube
1.701" ID	
26.10" long	
1.279" OD	} inner tube
0.480" ID	
26.10" long	

$$\text{Area} = \frac{\pi}{4} (OD^2 - ID^2)_{\text{outer}} + \frac{\pi}{4} (OD^2 - ID^2)_{\text{inner}}$$

$$= \frac{\pi}{4} (2.425^2 - 1.701^2) + \frac{\pi}{4} (1.279^2 - 0.480^2)$$

$$= 2.346 \text{ in}^2 + 1.104 \text{ in}^2 = 3.450 \text{ in}^2$$

$$\text{Volume}_{\text{One Assy}} = 3.44999 \text{ in}^2 * 26.10 \text{ in} = 90.05 \text{ in}^3$$

$$\text{Volume}_{288 \text{ Assys}} = 90.05 \text{ in}^3 * 288 = 25932.9 \text{ in}^3 = 15.007 \text{ ft}^3$$

$$\begin{aligned} \text{Free Volume inside MCO} &= \text{Gross Vol} - \text{Volume of 288 Assys} \\ &= 37.149 \text{ ft}^3 - 15.007 \text{ ft}^3 \\ &= 22.142 \text{ ft}^3 \end{aligned}$$

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/17/97

Sheet No. A3

Mass of air inside MCO = $\rho_{\text{air}} * \text{Free Volume}$

$$m_{\text{air MCO}} = 0.0736 \text{ lbm/ft}^3 @ 80^\circ\text{F} * 22.142 \text{ ft}^3$$

$$m_{\text{air MCO}} = 1.6296 \text{ lbm}$$

$$\text{Humidity ratio } W = \frac{m_{\text{water vapor}}}{m_{\text{dry air}}} = 0.00246 \text{ From p. A1}$$

$$m_{\text{water vapor}} = W * m_{\text{dry air}}$$

$$\approx 1.6296 \text{ lbm} * 0.00246$$

$$\approx 0.0040 \text{ lbm}$$

$$m_{\text{water vapor}} \approx 1.82 \text{ grams inside MCO}$$

Title of Project Determine surface area of cropped Project No. Appendix BSubject RINC MTR assembly

Works _____

Computer _____

WSL

Date

3/17/97

Sheet No. B

Length of cropped assembly = 25.5" per 7/18/85 Appendix A
data for Rhode Island Nuclear
Science Center

18 fuel plates per assembly with nominal dimensions of
25.00" by 2.810" by 0.060" thick per
EGG dwg 411647

Each fuel plate fits into side plate slots.

Exposed width of fuel plate is ~ 2.557" per EGG dwg 411650

Exposed surface area per fuel plate:

$$25.00" \times 2.557" \times 2 \text{ surfaces} = 127.85 \text{ in}^2$$

$$0.060" \times 2.557" \times 2 \text{ ends} = + 0.31 \text{ in}^2$$

$$\text{Exposed plate area} = 128.1568 \text{ in}^2$$

Two aluminum side plates per assembly with nominal dimensions of
25.5" (cropped) by 3.045" by 0.188" thick
per EGG dwgs 411648 and 411650

Exposed surface area per aluminum side plate:

$$25.5" \times 3.045" \times 1 \text{ outside surface} = 77.647 \text{ in}^2$$

$$0.188" \times 3.045" \times 2 \text{ ends} = 1.145 \text{ in}^2$$

$$0.188" \times 25.5" \times 2 \text{ sides} = 9.588 \text{ in}^2$$

$$25.5" \times [3.045" - (18 \times 0.066")] \times 1 \text{ inside surface} = 47.353 \text{ in}^2$$

$$\text{Exposed side plate area} = 135.7339 \text{ in}^2$$

Neglect fuel plate 0.5" shorter than side
plate for inside surface adjustment

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/17/97

Sheet No. B6

Total surface area of RINC MTR assembly:

$$\begin{aligned}
 18 \text{ fuel plates} & \times 128,157 \text{ in}^2/\text{plate} = 2306.82 \text{ in}^2 \\
 2 \text{ side plates} & \times 135.734 \text{ in}^2/\text{plate} = 271.47 \text{ in}^2 \\
 \text{Total} & = 2578.29 \text{ in}^2
 \end{aligned}$$

$$\text{Total} = 17.90 \text{ ft}^2$$

$$= 1.663 \text{ m}^2$$

Determine void volume between 18 fuel plates:

17 slots between 18 plates

Each slot is $\approx 2.557''$ wide by $25.00''$ high from sheet B1

Each slot is $2.910'' - 2.743'' - 0.060'' = 0.107''$ thick
per EGG dwgs 411648 and 411647

$$\begin{aligned}
 \text{Volume of one slot} & = 2.557'' \times 25.00'' \times 0.107'' \\
 & = 6.839 \text{ in}^3
 \end{aligned}$$

$$\begin{aligned}
 \text{Volume of 17 slots} & = 116.279 \text{ in}^3 \\
 & = 0.50 \text{ gallons}
 \end{aligned}$$

Title of Project _____

Project No. _____

Appendix B

Subject _____

Works _____

Computer _____

WSL

Date _____

3/20/97

Sheet No. B3

Estimate average water removal rates for various vacuum drying systems:

Prototype tests indicate Hanford system will dry an MCO in 4-6 hours. Expected initial water loading is 2-4 liters per discussion with John Irwin on 2/18/97.

Large average removal rate = 3 liters in 5 hours
 = 0.16 gal/hr

Expected drying time for INEL canister is ~2 hr per notes from 10/26/95 SNF Drying Station Meeting. Maximum quantity of water in fuel storage canister prior to drying is 3 liters per page 104 of Idaho Chemical Processing Plant Safety Document WIN-107-4.12, Addendum B, Draft Revision 2A.

Large average removal rate = 3 liters in 2 hours
 = 0.40 gal/hr

566 gallons of D_2O and 1736 gallons of H_2O were recovered from 11 SRS heat exchangers inside Bldg 105-C via vacuum drying. Total elapsed vacuum drying time was 2125 hours per "105-C Heat Exchanger Vacuum Drying Log" maintained by project engineers.

Large average removal rate = 2302 gallons / 2125 hrs
 = 1.08 gal/hr

Title of Project Determine mass of free waterProject No. Appendix CSubject on cropped MTR assembly per

Works

drying criterion

Computer

WSL

Date

3/17/97Sheet No. C1

Assume assembly has been vacuum dried to acceptance criterion of 1 ml free water per 0.1 m^2 of surface per WSRC-TR-95-0347.

Total surface area of 18-plate MTR asy. = 1.66 m^2
per Sheet B2

$$\text{Water volume} = 1 \text{ ml} / 0.1 \text{ m}^2 * 1.66 \text{ m}^2 = 16.6 \text{ ml H}_2\text{O}$$

$$\rho_{\text{water @ } 20^\circ\text{C}} = 0.998203 \text{ gm/cc} \quad \text{p F-4} \quad \text{Hdbk of Chem/Phys.}$$

$$m_{\text{free water}} = \rho V = 0.998203 \text{ gm/cc} * (16.6 \text{ ml}) \left(\frac{\text{cc}}{\text{ml}} \right)$$

$$m_{\text{free water}} = 16.60 \text{ grams}$$

Title of Project Determine mass of adsorbed

Project No. _____

Subject water on cropped MTR assembly Works _____

Computer _____

WSL

Date

3/17/97

Sheet No. C2

Adsorbed water is 20 monolayers thick on assembly surface at 20°C and 100% relative humidity per WSRC-TR-95-0347, Section 4.1.1

20 monolayers is 20 layers of H_2O molecules.

H_2O molecular diameter = 4.60×10^{-8} cm per attached table

$$\begin{aligned} 20 \text{ layers thickness} &= 20 * 4.60 \times 10^{-8} \text{ cm} \\ &= 9.2 \times 10^{-7} \text{ cm} \\ &= 9.2 \times 10^{-9} \text{ m} \end{aligned}$$

Total surface area of 18 plate MTR array = 1.66 m^2
per Sheet B2

$$\begin{aligned} \text{Volume of water} &= 20 \text{ layers thickness} * \text{surface area} \\ &= 9.2 \times 10^{-9} \text{ m} * 1.663 \text{ m}^2 \\ &= 1.53 \times 10^{-8} \text{ m}^3 \\ V_{\text{water}} &= 0.0153 \text{ cc} \end{aligned}$$

$$\rho_{\text{water @ 20°C}} = 0.998203 \text{ g/cc from Sheet C1}$$

$$m_{\text{water}} = \rho V = (0.0153 \text{ cc})(0.998203 \text{ g/cc})$$

$$m_{\text{adsorbed water}} = 0.015 \text{ grams}$$

(Q) is also called throughput and is work per unit time ($\frac{PV}{t}$).

C. Ideal Gas Equation

$$PV = nRT$$

P = Torr
 V = Liters
 n = No. of Moles
 R = Molar Gas Constant
 T = Degrees Kelvin

or:

$$PV = nkT$$

P = Dynes
 V = cc
 n = No. of Molecules
 k = Boltzmann's Constant
 T = Degrees Kelvin

D. Mean Free Path, for air

$$L = \frac{5 \times 10^{-3}}{P_{\text{Torr}}} \text{ in centimeters}$$

E. Molecular Velocity

$$a) \bar{V} = 1.5 \times 10^4 \sqrt{\frac{T}{M}} \text{ cm sec}^{-1}$$

$$T = K^{\circ}$$

M = Molecular Weight

$$b) \bar{V} = \sqrt{\frac{8KT}{\pi m}} \text{ cm sec}^{-1}$$

$$k = \text{Boltzmann's Constant}$$

$T = K^{\circ}$
 m = Molecular Mass in Grams

F. Pumpdown (Roughing) Formulas, excluding outgassing

$$a) P = P_0 e^{-\frac{St}{V}}$$

P_0 in Torr
 (original pressure)
 P in Torr
 S in liters per second
 V in liters
 t in seconds

$$b) t = \frac{V}{S} \ln \frac{P_0}{P}$$

X. Common Values

Acceleration-Gravity g	= 980.6 cm sec ⁻² = 32.174 Ft sec ⁻²
Angstrom Unit $\text{\AA}$	= 10 ⁻⁸ cm
Area Constant π	= 3.1416
Atomic Mass Unit AMU	= 1.66 x 10 ⁻²⁴ grams
Avogadro's Number n	= 6.023 x 10 ²³ moles per mole
Boltzmann's Constant k	= 1.38 x 10 ⁻¹⁶ ergs-deg ⁻¹ -molecule ⁻¹
Electron Charge q	= 1.602 x 10 ⁻¹⁹ coulomb
Mechanical	
Equivalent of Heat J	= 4.185 x 10 ³ Joules K cal ⁻¹
Molar Gas Constant R	= .82 liter-atmos deg ⁻¹ mole ⁻¹ = 8.31 x 10 ergs deg ⁻¹ mole ⁻¹ = 62.36 Torr-Liter deg ⁻¹ mole ⁻¹
Molecular Diameter d	≅ 3 $\text{\AA}$
Natural Log Base e	= 2.7183
Velocity of Light c	= 3 x 10 ¹⁰ cm sec ⁻¹
Velocity of Molecule $\bar{V}$	= 4.9 x 10 ⁴ cm sec ⁻¹ (1100 MPH)
Velocity of Sound S	= 3.3 x 10 ⁴ cm sec ⁻¹ (750 MPH)

PHYSICAL PROPERTIES OF GASES AND VAPORS

Gas	Chemical Formula	Molecular Weight M	Molecular Diameter (10 ⁻⁸ cm)
Hydrogen	H ₂	2.016	2.74
Deuterium	D ₂	4.028	2.74
Helium	He	4.002	2.18
Methane	CH ₄	16.04	4.14
Ammonia	NH ₃	17.03	4.43
Water vapor	H ₂ O	18.02	4.60
Neon	Ne	20.18	2.59
Nitrogen	N ₂	28.01	3.75
Oxygen	O ₂	31.99	3.61
Argon	A	39.94	3.64
Carbon dioxide	CO ₂	44.01	4.59
Krypton	Kr	83.80	4.11
Xenon	Xe	131.30	4.85
Mercury	Hg	200.59	4.26

Title of Project Determine mass of water of Project No. _____

Subject hydration on cropped MTR assembly Works _____

Computer _____

WSL

Date

3/17/97

Sheet No. C4

Assume assembly has 50 micron thick film of Boehmite oxide on surface and water of hydration is released by radiolysis per WSRC - TR - 95 - 0347, Section 4.1.1.

Total surface area of 18-plate MTR assay = 1.66 m^2
per Sheet B2

$$\begin{aligned} \text{Film Volume} &= \text{Assay surface area} \times \text{thickness} \\ &= 1.663 \text{ m}^2 \times (50 \times 10^{-6} \text{ m}) \\ &= 8.315 \times 10^{-5} \text{ m}^3 \\ V_{\text{Boehmite}} &= 83.15 \text{ cc} \end{aligned}$$

$$\rho_{\text{Boehmite}} = 3.41 \text{ g/cc per P.S. Lam} \quad 3/13/97$$

$$m_{\text{Boehmite}} = \rho V = (83.15 \text{ cc}) (3.41 \text{ g/cc}) = 283.54 \text{ grams}$$

Boehmite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) molar weight:

$$\begin{array}{rcl} 2 * & 26.9815 \text{ amu} & \text{Al} \\ 4 * & 15.9994 \text{ amu} & \text{O} \\ 2 * & 1.0080 \text{ amu} & \text{H} \end{array}$$

$$119.9766 \text{ grams per mole } \text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$$

$$\begin{aligned} \text{Moles of Boehmite} &= \text{mass} / \text{molar wt} = 283.54 \text{ g} / 119.98 \text{ g} \\ &= 2.36 \end{aligned}$$

One mole of H_2O is generated for every mole of Boehmite decomposed

$\therefore$ 2.36 moles of H_2O present

ENGINEERING COMPUTATION SHEET

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/17/97

Sheet No. C5

H_2O molar weight:

$$\begin{array}{r} 2 * 1.0080 \text{ amu H} \\ 15.9994 \text{ amu O} \\ \hline 18.0154 \text{ grams per mole } H_2O \end{array}$$

$$\begin{array}{l} \text{mass} \\ = \text{number of moles} * \text{molar weight} \\ = 2.36 \text{ moles} * 18.0154 \text{ g/mole} \end{array}$$

$$\begin{array}{l} \text{M}_{\text{water of}} \\ \text{hydration} \\ = 42.58 \text{ grams} \end{array}$$

Title of Project Determine maximum hydrogen
 Subject pressure inside SNF canister

Project No. Appendix D

Works

Computer W. S. Large Date 3/19/97

Sheet No. D1

Total amount of water on cropped MTR assembly includes:

• Free water	16.600 g	from Sheet C1
• water of hydration	42.576 g	from Sheet C5
• adsorbed water	0.015 g	from Sheet C2
	<u>59.191 g</u>	

Assume all 59.191 grams of H_2O is released and corrodes aluminum to form new Boehmite per the following equation.

WSRC-TR-95-0347
p. 24

Assuming the reaction goes to completion, 3 moles of H_2 gas will be produced for every 4 moles of H_2O consumed.

H_2O molar weight = 18.0154 g/mole from Sheet C5

$$\text{Moles of } H_2O = 59.191 \text{ g} / 18.0154 \text{ g/mole} = 3.286$$

$$\text{Moles of } H_2 \text{ produced} = \frac{3}{4} \times 3.286 = 2.464$$

The volume of 1 mole of any gas at Standard Temperature and Pressure (14.696 psia and $0^\circ C$) is 22.4 liters.

General College Chemistry p.180

$$V_{H_2 @ STP} = 2.464 \text{ moles} \times 22.4 \text{ l/mole} = 55.198 \text{ liters} \\ = 0.055198 \text{ m}^3$$

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/19/99

Sheet No. 02

Determine volume of proposed SRS SNF dry storage canister:

$$ID = 17" \quad , \quad Length = 10ft = 120"$$

$$V_{\text{canister}} = \pi/4 D^2 L = \pi/4 (17 \text{ in})^2 (120 \text{ in}) = 27237 \text{ in}^3$$

$$V_{\text{canister total}} = 0.4464 \text{ m}^3$$

Determine volume of one cropped RINC MTR assembly:

18 fuel plates with exposed dimensions of 25.00" by 2.557"
by 0.060" per Sheet B1

2 aluminium side plates with dimensions of 25.5" by
3.045" by 0.188" per Sheet B1

MTR Volume:

$$\begin{aligned} 18 * (25.00" * 2.557" * 0.060") &= 69.039 \text{ in}^3 \\ 2 * (25.5" * 3.045" * 0.188") &= 29.195 \text{ in}^3 \\ \hline &98.234 \text{ in}^3 \end{aligned}$$

$$V_{\text{MTR}} = 0.001610 \text{ m}^3$$

Assume canister contains 18 MTR assemblies:

$$V_{\text{canister free}} = V_{\text{canister total}} - 18 V_{\text{MTR}} = 0.4464 \text{ m}^3 - 18(0.00161 \text{ m}^3)$$

$$V_{\text{canister free}} = 0.4174 \text{ m}^3$$

Title of Project _____

Project No. _____

Subject _____

Works _____

Computer _____

WSL

Date _____

3/19/97

Sheet No. 03

Determine maximum H_2 pressure inside 17" by 10ft canister containing 18 MTR assemblies at $20^\circ C$:

$$V_{H_2 @ STP} = 0.055198 m^3 \text{ per assy}$$

$$V_{H_2 @ STP} = 18 (0.055198 m^3) = 0.99356 m^3$$

$$V_{\text{canister free}} = 0.4174 m^3$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{Ideal Gas Law}$$

$$P_{H_2 \text{ in canister}} = \frac{T_2}{T_1} * \frac{V_1}{V_2} * P_1$$

$$P_{H_2 \text{ in canister}} = \frac{293^\circ K}{273^\circ K} * \frac{0.99356 m^3}{0.4174 m^3} * 14.696 \text{ psia}$$

$$P_{H_2} = 37.544 \text{ psia} = 22.8 \text{ psig}$$

Alternative check:

$$m_{H_2O} \text{ on 18 assemblies} = 18 (59.1919 \text{ g/assy}) = 1065.4 \text{ g}$$

$$V_{FW} = \frac{m}{\rho_{H_2O}} = 1065.4 \text{ g} / 0.998203 \text{ g/cc} = 1067.36 \text{ cc (ml)}$$

$$FW/V = 292505 \frac{P_{H_2}}{(273.15 + T)} \quad \text{WSRC-TR-95-0347 p.24}$$

$$1067.36 \text{ ml} / 0.4174 m^3 = 292505 \frac{P_{H_2}}{(273.15 + 20)}$$

$$P_{H_2} = 2.56 \text{ atm} = 37.66 \text{ psia} \approx 22.9 \text{ psig}$$

WESTINGHOUSE SAVANNAH RIVER CO. REPORT WSRC-TR-97-0075

DISTRIBUTION

SAVANNAH RIVER SITE

T. L. Capeletti, 773-41A
N. C. Iyer, 773-A
M. R. Louthan, Jr., 773-A
J. P. Howell, 773-41A
H. B. Peacock, Jr., 773-A
P. S. Lam, 773-41A
W. F. Ayres, 773-41A
J. D. Hurd, 705-K
W. C. Bugher, 707-C
W. N. Jackson, 707-C
J. R. Murphy, 707-C
W. F. Swift, 707-C
O. J. Williams, 717-K
B. K. Coker, 707-C
J. C. Guy, 707-C
M. W. Barlow, 704-C
R. J. Skwarek, 704-C
J. M. Carter, 707-C
B. D. Clark, 707-C
W. S. Large, 707-C
D. R. Shelton, 707-C
R. L. Sindelar, 773-41A
MTS File, 773-A
Records Storage, 773-52A