VACUUM DRYING TEST PLAN –
PUBLIC VERSION

Prepared for

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Prepared by

Larry Miller
Gary Walter
Todd Mintz
Tom Wilt

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

Greg Oberson

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

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After pool loading, spent nuclear fuel canisters may be vacuum dried prior to the storage period, using a mechanical pumping system to remove the water. Water remaining in the canister could cause corrosion of the fuel cladding and internal structures or may create a flammable environment within the canister if radiolysis creates free oxygen and hydrogen. NRC provides only general guidance to licensees concerning the implementation of vacuum drying. In particular, NUREG–1536, "Standard Review Plan for Dry Cask Storage Systems," (NRC, 2010) states that NRC staff accepts vacuum drying methods comparable to those recommended in Pacific Northwest National Laboratory Report PNL–6365, "Evaluation of Cover Gas Impurities and their Effects on the Dry Storage of LWR Spent Fuel" (PNNL, 1987), which specifies less than 0.25 volume percent oxidizing gasses in the canister. When vacuum drying is implemented, licensees have a technical specification directing that the canister be evacuated to below a certain pressure with demonstration that the pressure will remain stable for a period of time after the canister is isolated from the pumping system.

There have been no experimental tests to measure the quantity of residual water that may remain in the canister following vacuum drying. If vacuum drying proceeds too quickly, it is possible that ice could form in the canister, particularly at locations where water is entrapped in confined spaces. If ice forms, the system pressure may meet the technical specification even if water is still present in the canister. To provide additional confidence that the criterion recommended in NUREG–1536 is appropriate, NRC initiated a research activity with the Center for Nuclear Waste Regulatory Analyses (CNWRA®) to develop a conceptual test plan for measuring the quantity of unbound residual water remaining in a canister following vacuum drying. This activity consists of the preparation of two technical letter reports. The first (Miller et al., 2013), describes typical vacuum drying systems and operational procedures. It also reviews canister and fuel assembly designs to determine locations or conditions that could be susceptible for trapping water. The second report is the present, which is the test plan itself.

The experimental parameters recommended for evaluation in the test plan relate to vacuum drying operational procedures, fuel assembly and canister design features, and fuel assembly heat load. The operational procedures include the number of hold steps during the evacuation process and the end pressure. The fuel assembly and canister design features are locations where it is thought that water may be trapped, including breached fuel rods, the dashpot region of the guide thimble tube for pressurized water reactor assemblies, water rods for boiling water reactor assemblies, creviced regions around assembly hardware, surfaces of spacer disks in the canister. Finally, it is assumed that ice formation will be more likely for fuel with a lower decay heat load.

Four general categories of equipment were identified as needs in the test plan: (1) the vacuum drying system such as pumps, tanks, hoses, valves, and connections; (2) the test canister; (3) the test fuel assembly; and (4) the measurement and sensing equipment. A vacuum drying system similar to those used in the industry could be built using commercially available off-the-shelf components. For the test canister, the primary consideration will be selection of an appropriate size and configuration. Options could include a full-sized canister, a canister with full diameter but scaled in length, or a canister with full length but scaled in diameter. Cost, handing, and operational challenges will probably make a full-sized canister impractical for a test program. Of the scaled canisters, the full-length, reduced-diameter configuration likely represents the better option because the vacuum siphon tube and test assembly could be maintained at normal length. A simple version of this canister may be a length of steel pipe with sufficient diameter to hold one fuel assembly, the vacuum siphon tube, and necessary internal

structures. The pipe could be sealed with bolt-on lids to allow for insertion and removal of the test assembly. Pass-throughs or ports for instruments and sensors would also be needed. Concerning the test fuel assembly, options would be to obtain mockups from vendors or to independently fabricate one or more mockups specifically for the test program. Acquiring mockups from vendors could raise issues with cost, restrictions on certain modifications or use of the assembly, or restrictions on publishing the design information. The concept for a fabricated mockup could be either a close representation of an actual assembly design or a more abstracted assembly such as a simple series of tubes or rods with holes made in various sizes and locations to represent breached fuel rods, guide thimble tubes, and water rods. Finally, equipment for such measurements as water mass balance, water vapor content, temperature, pressure, and mass flow are available off the shelf.

The implementation of the test plan involves the selection of experimental parameters, the performance of drying runs, and then the measurement of the quantity of residual water in the canister. Ideally, the parameters should be systematically selected in a manner that minimizes the number of needed drying runs while still providing meaningful results. The most efficient sequence for performing the experimental drying runs is to start with those conditions that are thought to be most likely to leave residual water. If testing in those conditions shows that there is little residual water, it would be demonstrated that NRC guidance for drying is appropriate and further runs in more favorable conditions for drying would not be needed. If residual water of sufficient quantity to be of concern is found, it would be demonstrated that NRC guidance for drying may not be appropriate and additional runs may only be needed to further bound the scope of the issue and explore the significance of various parameters. Following this logic, the first runs should evaluate the conditions of few hold points during evacuation, higher end pressure, and fuel with low decay heat load. Test acceptance criteria should be developed which take into consideration the accuracy and resolution of the measurement techniques, the effects that are introduced by scaling or other physical changes in the test system relative to a system used in the field, and the need to demonstrate that the results are repeatable.

A range of expertise will be needed for the implementation of this test program. The first would be experience with the design and operation of mechanical systems, so as to capably replicate the vacuum drying practices used in the industry. Further, knowledge of fuel assembly and canister designs will be needed to make mockups that are representative of those found in industry. A third area is expertise in the use of sensors or other measurement devices. Finally, the tests will require knowledge of thermodynamics and physical chemistry to understand heat transfer and phase changes within the canister that could contribute to ice formation.

References

Miller, L., D. Basu, K. Das, T. Mintz, R. Pabalan, and G. Walter. "Overview of Vacuum Drying Methods and Factors Affecting the Quantity of Residual Water after Drying." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2013.

NRC. NUREG–1536, "Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility." Rev. 1. Washington, DC: U.S. Nuclear Regulatory Commission. July 2010.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained in this report meet the quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: No scientific or engineering software was used in the analyses contained in this report.

1   INTRODUCTION

1.1   Background

In the United States, spent nuclear fuel (SNF) is kept in dry storage at a number of operating and decommissioned reactor sites and certain other facilities licensed by the Nuclear Regulatory Commission (NRC). In the dry storage concept, SNF is moved from the spent fuel pool to metal canister or cask systems. NRC regulates the dry storage of SNF under Title 10 of the *Code of Federal Regulations* (10 CFR), Part 72 "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste." The provisions of 10 CFR Part 72 are intended, in part, to prevent gross degradation of fuel cladding and ensure the confinement of radioactive material during storage and transportation. Therefore, after being loaded in the spent fuel pool, water is removed from the canisters to create a dry internal environment. Water remaining in the canister could cause corrosion of the fuel cladding and internal structures or may create a flammable environment within the canister if radiolysis creates free oxygen and hydrogen (ASTM International, 2008).

One method that licensees use to remove water from canisters is vacuum drying with a mechanical pumping system. NRC provides only general guidance to licensees concerning the implementation of vacuum drying. In particular, NUREG–1536, "Standard Review Plan for Dry Cask Storage Systems," (NRC, 2010) states that NRC staff accepts vacuum drying methods comparable to those recommended in Pacific Northwest National Laboratory Report PNL–6365, "Evaluation of Cover Gas Impurities and their Effects on the Dry Storage of LWR Spent Fuel," (PNNL, 1987). PNL–6365 recommends a maximum quantity of 1 mol of oxidizing gases (O_2, CO_2, and CO) in a canister with a total gas volume of 7 m^3 [247 ft^3] at a pressure of 0.15 MPa [1.5 atm], corresponding to a concentration of about 0.25 percent. In practice, licensees have a technical specification directing that the canister be evacuated to a pressure between 3 and 10 torr [400 Pa and 1.33 kPa], with demonstration that the pressure will remain stable for a number of minutes after the canister is isolated from the pumping system.

The recommendation in PNL–6365 is based on thermodynamic calculations of equilibrium gas pressures, not on physical measurements made from evacuated canisters. There have been no experimental tests to determine the quantity of residual water that may remain in the canister following drying to this level. Recently, NRC has undertaken a review of its regulatory framework for extended storage and transportation of SNF (NRC, 2012). As part of this review, NRC identified technical information gaps and research needs that warrant further consideration to ensure that SNF continues to be stored safely. It was determined that a test program to measure the quantity of residual water following vacuum drying could increase confidence that the NRC guidance in NUREG–1536 is appropriate. A particular concern for vacuum drying is the formation of ice within the canister if it evacuated too rapidly. Susceptible locations for ice include confined spaces where water could be difficult to remove. If ice forms, the system pressure may meet the technical specification requirement even if water is still present in the canister.

1.2 Purpose and Scope

NRC initiated a research activity with the Center for Nuclear Waste Regulatory Analyses (CNWRA®) to develop a conceptual test plan for measuring the quantity of residual water remaining in a canister following vacuum drying to the criterion referenced in NUREG–1536 (NRC, 2010). The test plan will be used to help NRC assess options for independently performing an experimental program or to support engagements with industry or the Department of Energy should they undertake a similar effort. While residual water may be considered as unbound or bound (i.e., physi- or chemisorbed), the focus of this test plan is only the unbound water. This activity consists of the preparation of two technical letter reports. The first report (Miller et al., 2013) described current industry drying practices and capabilities. It also reviewed canister and fuel assembly designs to determine design features or characteristics that could affect the quantity of residual water after drying. The second report of this research activity is the present, which is the description of the test plan itself. Section 2 of this report reviews the parameters that were recommended for inclusion in the test plan. Section 3 describes the considerations for the test setup and equipment selections. Section 4 describes the design and implementation of a conceptual test program. Section 5 presents the summary of this report and Section 6 lists the references.

2   EXPERIMENTAL PARAMETERS

One purpose of the first technical letter report (Miller et al., 2013) was to recommend experimental parameters that should be evaluated in the test program. It was considered that these parameters could relate to the design and operation of the vacuum drying system itself, the design of fuel assemblies and canisters, and the fuel heat load. This section will review the parameters identified in that report.

2.1 Parameters Related to Drying System Design and Operation

To gather information about industry drying system design and operation, safety analysis reports and vacuum drying procedures were reviewed. Visits were also conducted to vendor facilities to observe the equipment and its operation in person, as well as to discuss field experience with their staff.

2.1.1   System Design

The vacuum drying systems were found to be generally similar throughout the industry. As will be discussed in further detail in Section 3, the main parts include pumps, tanks, hoses, valves, connections, and gauges, all of which are available off-the-shelf. Provided that it is designed appropriately, it was determined that the system itself, including the selection of specific equipment, should have little effect on the quantity of residual water that remains in the canister after drying. Therefore, aspects of the vacuum drying equipment and system design were not recommended to be included in the test plan.

2.1.2   Drying Operation

The vacuum drying operational procedures were also found to be similar throughout the industry. Vacuum drying is generally performed in a step-wise manner, decreasing the pressure to a series of predetermined hold points prior to reaching the final pressure. At each step, the canister is isolated from the pump and the pressure is monitored for a specified period of time. The canister pressure will rise as water and other volatiles evaporate. If the pressure increases to exceed a certain value during the hold time, the step may be repeated until a stable pressure is obtained. There may be variations in the number of hold points or the final pressure to which the canister is evacuated. Given the potential for these to affect the quantity of residual water, it was recommended to evaluate these as parameters in the test plan.

2.2 Parameters Related to Fuel Assembly and Canister Design

Fuel assembly and dry storage canister licensing reports and design drawings were reviewed to identify locations were water could be trapped or difficult to remove by vacuum drying.

2.2.1   Fuel Assembly Designs

For both boiling water reactor (BWR) and pressurized water reactor (PWR) fuel assemblies, water could be trapped in fuel rods with breached cladding that become waterlogged in the core. Operational experience indicates that a single breached rod may hold several mL of water. The outflow of water from breached fuel rods during vacuum drying may depend on the size of the breached area and the position along the rod length. Therefore, it was recommended to evaluate these as parameters in the test program. Other locations identified

where water could be trapped include the dashpot region of the guide thimble tubes for PWR assemblies, the bottom of water rods for BWR assemblies, and crevices regions around assembly hardware, such as grids, nozzles, and guides. It was also recommended to consider these locations in the test program.

2.2.2   Canister Designs

For vacuum drying, a siphon tube runs the length of the canister and terminates near the bottom plate. The locations in the canister that seem most likely to retain water are surfaces of the horizontal (relative to the orientation while drying) spacer disks. Certain canister baskets are designed with drain holes in the spacer disks and the canister may also be tilted during drying to aid with draining. Therefore, it was recommended that the test plan include provisions for evaluating whether water could be held up on horizontal surfaces within the canister during vacuum drying.

2.3 Fuel Decay Heat Load

The potential for ice formation in the canister will be affected by the decay heat load of the fuel assemblies. The heat load of the fuel at the time of vacuum drying will depend on the burnup and the time in the pool since reactor discharge. Generally, the heat load will decrease with lower burnup and longer time since reactor discharge. Drying operations for fuel with a lower decay heat load fuel should be more vulnerable for ice formation. Thus, it was recommended that the fuel decay heat load be evaluated in the test plan.

2.4 Summary of Experimental Parameters

The proposed experimental parameters for this test plan, which are based on the recommendations from the first technical letter report are summarized in Table 2-1.

Table 2-1. Recommendations for Factors to Consider in Test Plan	
Operational Parameters	Number of hold points
	Final canister pressure
Physical Locations	Breached fuel rods
	Dashpot of PWR guide thimble tubes
	BWR water rods
	Crevices around assembly hardware such as grids, nozzles, and guides
	Flat surfaces of canister spacer disks
Fuel Condition	Decay heat load

3 TEST PLAN EQUIPMENT DETAILS

The purpose of this section is to give some guidance on the sort of equipment and setup that could be employed for the test program. Four general categories of equipment or materials were identified and will be discussed:

(1) Drying equipment including pumps, tanks, valves, hoses, pipes, fittings, and associated hardware;

(2) Test canister in which vacuum drying will be performed;

(3) Fuel assembly or mockup for drying;

(4) Measurement and sensing equipment for pressure, temperature, humidity, mass flow, or other parameters to determine the quantity of residual water.

3.1 Drying Equipment

The design of a typical vacuum drying system used in the industry is described in Section 2.2 of the first technical letter report (Miller et al., 2013). The main pieces and parts include the pumps, the water trap tank, the pipes, hoses, and connections (i.e., plumbing), the valves, and the pressure measurement gauges. These are described in further detail as follows.

3.1.1 Vacuum Pumps

The main pump for vacuum drying may be a rotary vane vacuum. An example pump is the Leybold Sogevac SV 100 B, which is able to pull vacuum down to around 0.5 torr [67 Pa]. As the pressure drops, the pumping speed falls off sharply. To increase the pumping speed at these lower pressures, a roots blower, such as the Ruvac WA 251 is employed. The roots blower is usually engaged around pressures of 10 torr [1.33 kPa].

3.1.2 Water Trap Tank

The water trap tank can vary in size, shape, and capacity, but the function of the tank is to remove water from the vacuum system before it reaches the pumps. Typically this tank has a capacity of around 75.7 L [20 gal]. A sight glass allows the operator to determine when the tank needs to be emptied. The penetrations in the tank consist of an air inlet and an air outlet at the top of the tank and a water drain at the bottom of the tank. This tank is usually positioned soon after the canister siphon and vent tube outlets and can be valved into or out of the vacuum system as need requires. It is usually used starting with the blow-down portion of operations and is valved out of the system once no visible water drops can be seen exiting the canister.

3.1.3 Vacuum System Plumbing

The plumbing of a vacuum drying system consists of two main parts, the Klein Flange (KF) or Quick Flange (QF) connections, and the wire reinforced flexible vacuum hose. The KF/QF connections are prefabricated connections consisting of pieces such as straight pipes, elbows, and tees, which are connected together to make the portion of the vacuum path that is mounted on the vacuum cart. In addition, the riser manifold, which is the portion of piping connected to the vent port of the canister, is also made of KF or QF connections, though these are usually sized smaller than the connections on the cart. These pipe structures provide mounting points

for the gauges and sensors used in the system. The flexible vacuum hose is connected between the riser manifold and the cart via barbed hose connections and hose clamps. This hose allows flexibility in the vacuum drying system so it can be used in various areas without requiring major component changes. Flexible hose may also be used to connect the vacuum pump to the cart piping, simplifying the routing of the KF/QF fittings. Care should be taken, when using the barbed connections, to use proper sized fittings and clamps to reduce the risk of leakage at these points.

3.1.4   Measurement Suite

This section refers only to the equipment for measurements on typical drying systems, not additional equipment needed for specialized tests to measure the quantity of residual water. Pressure measurements are typically made with sensors such as a MKS 317 series Pirani sensor. To ensure the accuracy of these sensors, they are often compared to a calibrated sensor such as the MKS Baratron 627D absolute pressure transducer. Both of these pressure sensors use a controller to digitally display the pressures, and a comparison of the variations between the two sensors is made during the vacuum drying procedure. Additional (usually 2) pressure/vacuum gauges are incorporated on the vacuum drying cart to aid the operator in activities such as performing a blow-down or backfilling with dry helium. These gauges typically measure both positive and negative gauge pressures and are not calibrated, nor do they require a high amount of accuracy in this function.

3.2   Test Canister

For the experimental program, it is envisioned that a mockup fuel assembly will be placed inside a sealed chamber or canister for the vacuum drying runs. There are a number of features or characteristics that are needed for the test canister.

- The canister must have access to insert and remove the mockup fuel assemblies, for instance by a bolt-on lid.

- The canister must be able to be flooded with water or else to have water introduced at locations where water may be trapped during drying.

- The canister must allow for instrumentation or sensing equipment to measure residual water.

- The canister must be able to withstand the expected temperatures and pressures expected during drying.

Three concepts for the chamber are described in this section. The first is full-sized canister. The second concept is a chamber scaled in length (i.e., same diameter as full-sized canister but shorter).   The third is a chamber scaled in diameter (i.e., same length as full-sized canister but narrower). The considerations for these respective concepts are described as follows.

3.2.1   Full-Sized Canister

The dimensions of a full-sized canister will vary by vendor and design, but generally have a diameter of about 1.83 m [6 ft.] and length of about 4.88 m [16 ft.]. The weight could be many thousands of kilograms, depending on the internal basket structure. The primary advantage of the full-sized canister is that it provides the best representation of canisters deployed in service.

Effects of scaling a system on interpretation of results would not be an issue. Further, the canister may have the size to hold many assemblies or mockups for a single test drying run. The primary disadvantages of the full-sized canister are the difficulties associated with handling, controlling the temperature, and instrumenting an object of that size and mass. If electrical heaters are immersed in water, electrical grounding of the canister must also be implemented and a ground fault system will need to be incorporated. Given the large surface area and thermally conductive materials, maintaining temperature control during the test would be challenging. A large number of heaters and the use of insulation may be needed to maintain the appropriate temperature profile within a full-sized canister. Given the complications associated with handling a full-sized canister, this does not likely represent a practical approach for the test program.

3.2.2   Scaled-Length Canister

A scaled-length canister is envisaged to have the same diameter as a full-sized canister but a shorter length. Certain vendors used scaled-length canisters with a height of about 1 m [3.28 ft.] for training. The primary advantage offered by the scaled-length canister is that it will be easier to handle, instrument, and maintain the temperature compared to the full-sized canister. Further, it is possible that scaled-length canisters that are already used by vendors for training could be modified to use for tests. The primary disadvantage of the scaled-length canister is the need to determine how shortening the length will affect the interpretation of the results. Shortening the length of the vacuum siphon tube inside the canister could reduce the pressure drop along the line compared to the nominal canister, thereby changing the efficiency of the drying process. Moreover, there will be differences in air flow and heat conduction inside the canister compared to the full-sized canister. The size of the fuel assembly or mockup will also be constrained by reducing the canister length.

3.2.3   Scaled-Diameter Canister

A scaled-diameter canister is envisaged to have the same length as a full-sized canister but a reduced width. The width required to accommodate a full-sized fuel assembly and associated instrumentation may be less than 0.5 m [1.64 ft.]. A concept for a scaled-diameter canister may be as simple as a segment of steel pipe fitted with bolted lids. Similar to the scaled-length canister, the advantage offered by the scaled-diameter canister is that it will be easier to handle, instrument, and control the temperature than the full-sized canister. Compared to the scaled-length canister, however, the scaled-diameter canister may be preferable inasmuch as it would allow the vacuum siphon tube and fuel assembly to remain at the same length as for the full-sized canister, mitigating such effects as pressure drop along the vacuum line. This may provide a more accurate representation of the drying process.

3.3   Fuel Assembly

The fuel assembly or mockup will be placed inside the test chamber for the vacuum drying operation. There are a number of features or characteristics that are needed for the assembly.

- The assembly must physically represent breached and waterlogged fuel rods, as well as other locations where water could be trapped, including the dashpot region of the guide thimble tube for PWR assemblies, the water rod for BWR assemblies, and assembly hardware such as grid spacers.

- The assembly must be able to be submerged in a flooded canister or to have water directly placed at the locations described in the previous bullet.

- The assembly must be heated to represent the decay heat load for irradiated fuel.

- The assembly must be instrumented to take necessary measurements during and after the drying tests.

Considerations related to the physical design and heating are discussed as follows.

3.3.1   Fuel Assembly Design

There are two general options for obtaining a fuel assembly for the test program. The first would be to acquire, by loan or purchase, a mockup fuel assembly directly from an industry vendor. The second would be to independently fabricate a mockup for the specific purpose of the test program. The practicality of acquiring a mockup fuel assembly from a vendor is uncertain and may raise issues including cost, restrictions on certain modifications or uses of the assembly, or restrictions on publishing design information or test data. Moreover, the number of assemblies that could be acquired in this manner may be limited. For example, if only one assembly could be obtained, it would need to be considered how any findings could be extrapolated to other assembly designs. Given these complications, fabricating mockup fuel assemblies specifically for the test program may prove to be a reasonable option.

The concept for a fabricated mockup could be either a close representation of an actual assembly design or a more abstracted assembly that mainly captures those features where water is likely to be trapped. Close representations of actual assemblies have been used for testing in other NRC programs, such as at Sandia National Laboratories (Lindgren and Durbin, 2013a,b). Figure 3-1 shows mockups of BWR and PWR assembly that were made using assembly hardware purchased from vendors. The abstracted representation of the fuel assembly could be a simple series of tubes or rods with holes made in various sizes and locations to represent breached fuel rods, guide thimble tubes, and water rods. The tubes could have removable fittings on at least one end to fill with water prior to the tests, and then to drain the rods and measure the quantity of water remaining after the tests.
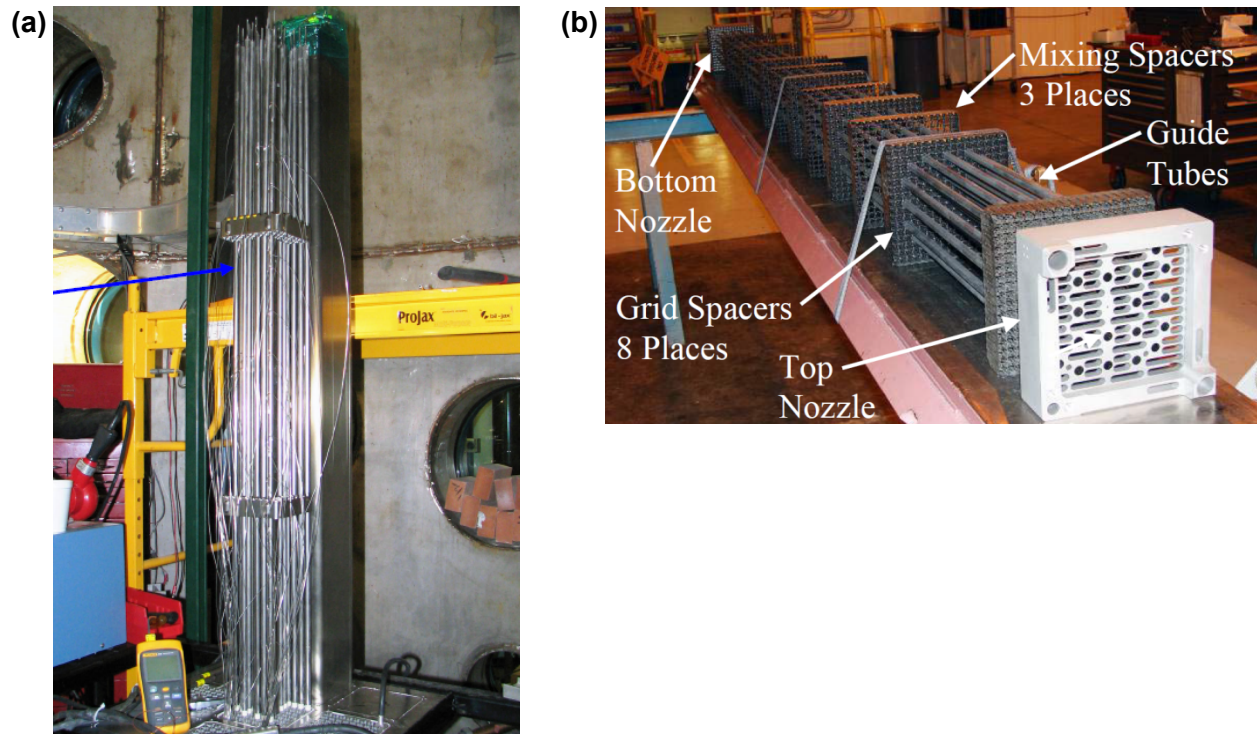
Figure 3-1. (a) Photograph of Mockup of a Prototypic BWR Fuel Assembly (Lindgren and Durbin, 2013a). (b) Photograph of Mockup of a Prototypic PWR Fuel Assembly (Lindgren and Durbin, 2013b).

3.3.2 Heating Fuel Assemblies

Spent nuclear fuel generates decay heat in an amount that will depend on the burnup and time since being removed from the reactor. The cladding temperature will also increase during vacuum drying. Given that this may affect the quantity of residual water remaining in the canister, the mockup fuel assembly should have the capability of being heated during the tests to provide a realistic representation of the drying process. Concepts have previously been developed for using heating elements to represent the decay heat of irradiated spent nuclear fuel. As part of a spent fuel pool fire study at Sandia National Laboratories, BWR fuel assemblies were made in which certain rods contained electrical heater elements (Lindgren and Durbin, 2013a). A cross-section of such a rod is shown in Figure 3-2.

Calculations were made to determine how the age of the spent fuel (i.e., time since being removed from the reactor) would relate to the power output and voltage. It was stated that the electric heater rods were designed to produce 25 W/ft at 120 volts. With this design, spent fuel assemblies between three days old to over two years old could be simulated, as shown in the Table 3-1. For the vacuum drying tests, similar calculations would need to be made to evaluate the power and heating requirements for the mockup assembly. If this approach is not practical, an alternative may be proposed for the test program.
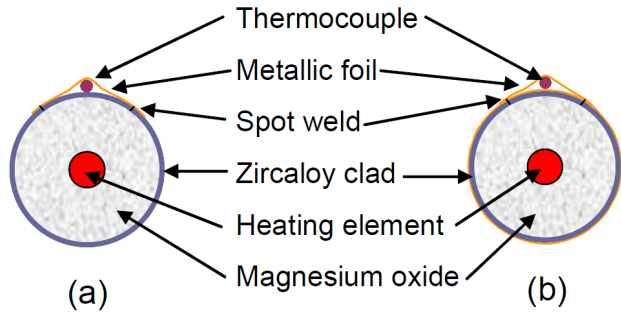
Figure 3-2. Schematic Cross-Section of Heater Rods for Spent Fuel Pool Fire Testing at Sandia National Laboratory. Figures (a) and (b) Represent Different Methods for Attaching the Thermocouple (Lindgren and Durbin, 2013a).

Table 3-1. Correlation of Assembly and Rod Power Versus Required Voltage (Lindgren and Durbin, 2013a)				
Time (Days)	Assembly Peak Power (kW)	Total Rod Power (W)	Linear Rod Power (W/ft)	Voltage (V)
3	23.93	323.40	25.87	122.07
10	15.01	202.84	16.23	96.68
100	5.17	69.80	5.58	56.72
365	2.30	31.03	2.48	37.81
730	1.33	17.91	1.43	28.73

3.4 Measurement and Sensing Equipment

The purpose of the measurement and sensing equipment is to measure the amount of water remaining in the canister following vacuum drying. Such equipment is not part of the vacuum drying systems typically used in industry. Section 4 of the first technical letter report (Miller et al., 2013) described concepts for measuring the residual water, based on similar practices that are used in the pharmaceutical industry. These measurements include:

- Water mass balance
- Water vapor content in the vacuum chamber
- Temperature
- Pressure
- Mass Flow

Further details of these measurements and equipment considerations are described as follows.

3.4.1 Water Mass Balance

What may be the simplest approach for measuring the quantity of residual water in the canister, or at least in parts of the canister, would be to place a known quantity of water in a certain location, such as a simulated breached fuel rod, prior to drying, then to measure the quantity of water remaining after drying by opening that location and emptying the contents. The only equipment needed for such measurements would be a scale or graduated cylinder.

3.4.2 Measuring Water Vapor Content

The dew point of the gas within the canister provides a direct measure of the water vapor content or partial pressure of water in the gas, which can be used to monitor the drying process. Solid state dew point sensors, which measure capacitance changes in thin films, can be used for this purpose. These sensors also measure temperature. In the absence of an external source of water vapor, the water vapor content of the gas in the vacuum chamber will be determined by the evaporation of liquid water or sublimation of ice remaining in the chamber during the drying process.

The change in dew point during the drying process is shown conceptually in Figure 3-3. During the early stage of drying, the dew point may remain relatively stable as long as liquid water or ice is present. As the water is removed, the dew point will decrease if the release of water vapor is rate limited. In the final drying phase at constant vacuum, the water vapor content should remain steady or decrease if a dry gas is bled into the chamber. The mass of water remaining in the chamber in the form of water vapor can then be calculated using the Ideal Gas Law. If the chamber is returned to atmospheric pressure using a dry gas, such as helium or nitrogen, and residual water remains in the test apparatus, the water vapor content inside the chamber should increase and ultimately reach the vapor pressure of water at the ambient temperature. Although measuring the dew point will not allow the mass of residual water to be determined, it will provide an indication of whether or not liquid water remained in the test apparatus at the nominal end of the drying process. One caveat is that back diffusion of water vapor from the water trap to the vacuum chamber may occur during final drying when the advective flow of gas is very small or zero. For this reason, the dew point should be monitored both in the vacuum chamber and in the vacuum conduit line. An alternative to using dew point sensors to monitor water vapor in the vacuum line would be to use a tunable diode laser spectrometer sensor. This sensor measures not only the water vapor content but also the water vapor mass flux.
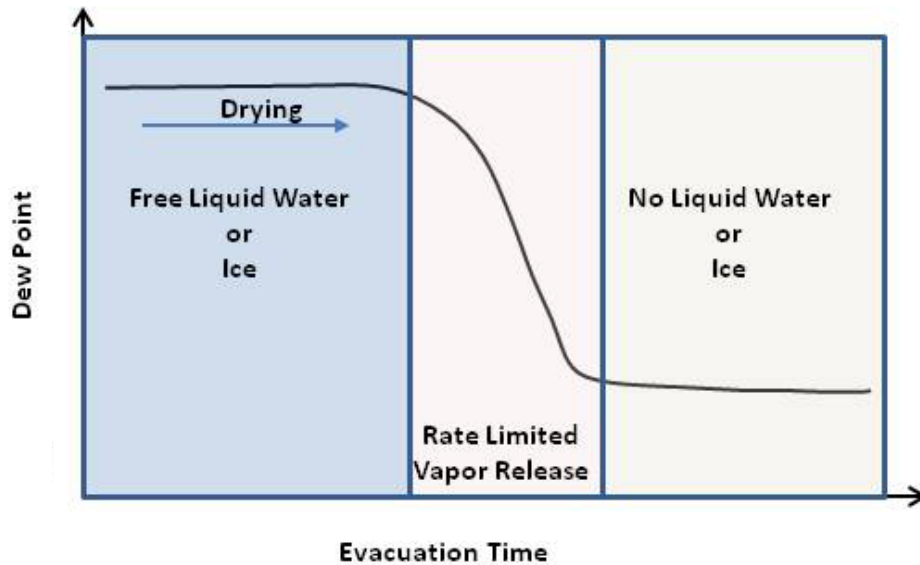
Figure 3-3. Conceptual Illustration of Dew Point Response Indicating Complete Removal of Free Water

3.4.3   Measuring Temperature

If residual water can be seen in the canister, its temperature can be monitored using microthermocouples. The temperatures recorded from the microthermocouples will be used to determine when or if the pocket completely evaporates or, for the case in which ice forms, sublimates. The concept behind these measurements and interpretations is illustrated in Figure 3-4. When the vacuum chamber is first closed and evacuation begins, the water vapor content in the chamber is likely to be out of equilibrium with the vapor pressure of water (point A in Figure 3-4). As the chamber is evacuated, water will evaporate, the temperature in the water will decrease, and the chamber water vapor content will approach and eventually follow the equilibrium water vapor pressure curve, as illustrated by the conceptual drying curve in Figure 3-4. After reaching the equilibrium curve, the temperature should be approximately controlled by the vapor pressure of water or ice as long as liquid water or ice remains in the pocket.

Once liquid water or ice is gone, the temperature of the thermocouple is no longer controlled and can increase even while the vacuum chamber remains under vacuum due to (i) conductive and radiative heat transfer or (ii) advection due to replacement of the ambient gas by air or helium. This concept of monitoring drying by monitoring temperature has been used to monitor vacuum drying of pharmaceuticals (e.g., Patel, et al., 2009; Pikal, et al., 1984) and the conceptual temperature evolution during the drying process is shown in Figure 3-5. As noted by Patel, et al. (2009), however, the presence of the thermocouple wire in the water can affect the rate at which ice forms and thus cause the temperature history to differ between the water pockets that are monitored and those that are not.

3-8
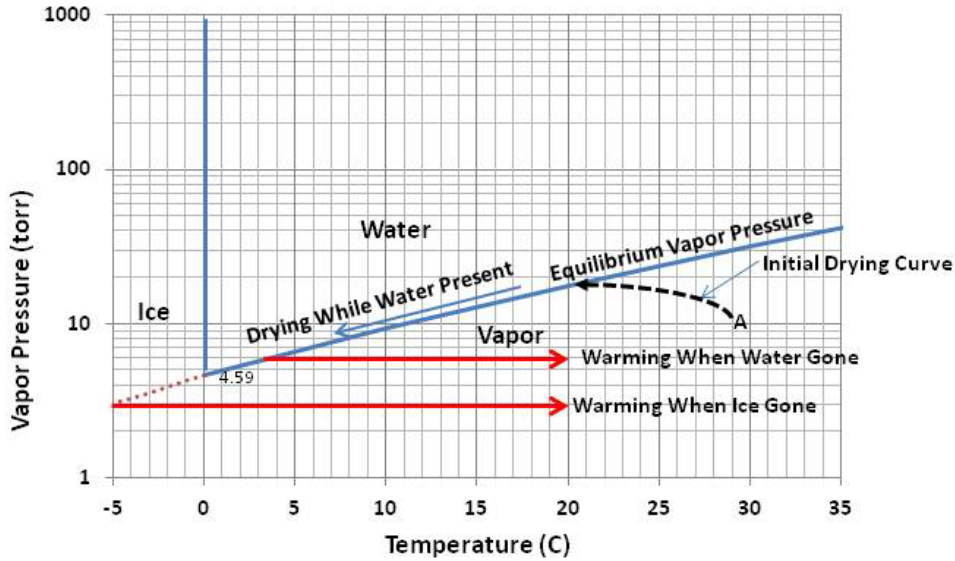
Figure 3-4. Conceptual Illustration of the Water/Ice Temperature During Vacuum Drying
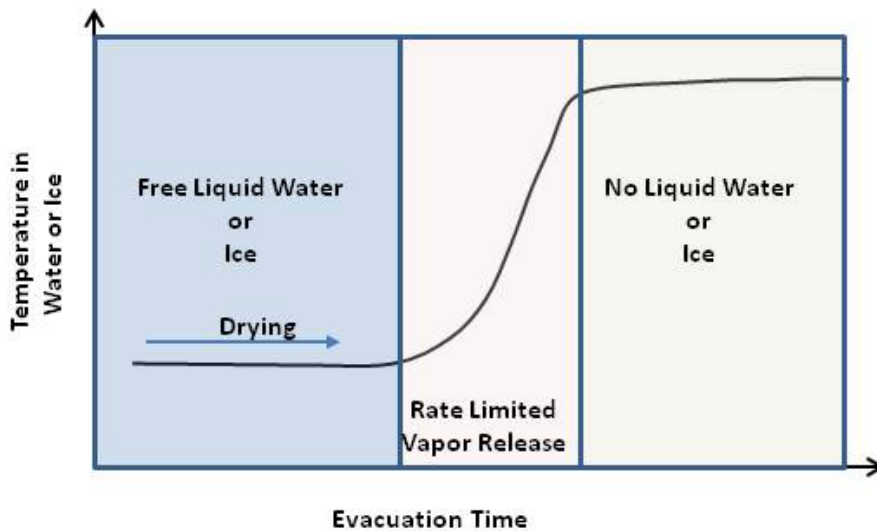
Figure 3-5. Conceptual Illustration of Temperature Response Indicating Complete Removal of Free Water

Infrared (IR) imagery can also be used to observe the temperature distribution in the canister, which may develop cold spots due to retained water and ice formation or hot spots due to reduced convective heat loss during the drying process. IR cameras are available that can be operated externally through a view port in the vacuum chamber or placed inside the vacuum chamber and operated remotely. One such camera system designed for security surveillance includes both an IR and optical camera, and can be operated inside the vacuum chamber.

3.4.4   Measuring Pressure

Chamber pressure or vacuum must be measured to control the drying process. Various pressure gauges were already described in 3.1.4. Precise absolute pressure measurements are also needed for calculating the total water vapor mass in the chamber. Diaphragm-type vacuum gauges that measure pressures in the range of 0.05 to 1,000 torr [6.67 Pa to 133 kPa] can be used for this purpose. Two vacuum gauges could be used, one directly connected to the vacuum chamber and the other on the exhaust tubing to the vacuum pump system.

3.4.5   Measuring Mass Flow

The mass flow rate out of the canister could be measured with an electronic mass flow meter. Such meters measure the flow of gases based on their heat capacity. Ideally, the desired approach would be to directly measure the mass flow of water vapor from the vacuum chamber. However, because the composition of the gas flowing to the vacuum pump will change from a mixture of air and water vapor at the beginning of the evacuation process to primarily water vapor at the end of the drying process, measuring the mass flow rate of water vapor to develop an estimate of the water vapor removed during the entire drying process is problematic. An additional consideration in measuring mass flow involves the large range in flow rates and the dimensions of tubing used to connect the vacuum pump system to the vacuum chamber.

Preliminary design considerations indicate that an insertion-type gas velocity gauge would be needed to measure the gas flow rate in a relatively large diameter tube during the early stage of the drying process. The mass flow rate would be calculated from the velocity, tube diameter, and gas composition based on the dew point water content in the exhaust tube. During the later stages of evacuation, when the mass flow rate is small, the flow to the vacuum pump can be shunted through a smaller diameter tube with an in-line mass flow meter. During this stage, the mass flow of water vapor can be directly related to the mass flow rate or adjusted, if necessary, based on the dew point in the exhaust tube.

4 IMPLEMENTATION OF TEST PLAN

The implementation of the test plan involves the selection of experimental parameters, the performance of drying runs, and then the measurement of the quantity of residual water in the canister. Ideally, the parameters should be systematically selected in a manner that minimizes the number of needed drying runs while still providing meaningful results. This section provides further details on the considerations for implementing the test plan.

4.1 Selection of Experimental Parameters

As discussed in Section 2, the experimental parameters that were recommended to evaluate in the test program related to the vacuum drying operational procedures, the fuel assembly or canister design, and the fuel assembly heat load. Within each of these categories, the parameters should be systematically varied in a manner that is reasonably bounding but representative of the range of conditions that could be expected in actual industry drying practices. The most efficient sequence for performing the experimental drying runs is to start with those conditions that are thought to be most likely to leave residual water. If testing in those conditions shows that there is little residual water, it would suggest that NRC guidance for drying is appropriate and further runs in more favorable conditions for drying would not be needed. If residual water of sufficient quantity to be of concern is found, it would suggest that NRC guidance for drying may not be appropriate and additional runs may only be needed to further bound the scope of the issue and explore the significance of various parameters. Further discussion on selection of the respective parameters follows.

4.1.1 Vacuum Drying Operational Parameters

The vacuum drying operational parameters that were recommended for evaluation in the test program were the number of hold points and the final canister pressure. The number of hold points during drying should vary from few (e.g., one to three) to several (e.g., six to eight). Since the lesser number is considered more likely to allow ice formation, this should be the first case evaluated in the sequencing of the drying runs. The final canister pressure should also vary from low (e.g., 2 to 3 torr [267 to 400 Pa]) to high (e.g., 9 to 10 torr [1.20 to 1.33 kPa]). The higher end pressure should be the first case evaluated in the sequencing of the drying runs.

4.1.2 Fuel Assembly and Canister Design Parameters

The fuel assembly and canister design parameters that were recommended for evaluation in the test program were the locations where it is thought that water is most likely to remain trapped. These were breached fuel rods, guide thimble tubes for PWR assemblies, water rods for BWR assemblies, creviced regions around assembly hardware, and the flat surfaces of spacer disks in the canister. It is assumed that these features will be represented in mockups that are designed for the tests. To encompass the range of geometries for these features that are found in the industry, it is expected that design drawings or other available information will be reviewed. It may be determined that multiple mockup fuel assemblies are needed or that the range of features could be accommodated in a single mockup with pieces that represent different assembly designs. With respect to the canister, it may be possible to insert various numbers of flat plates to represent the configurations of spacer disks. Further information about the specific design approach will be needed to determine how these will affect the sequencing of the drying runs.

4.1.3 Fuel Assembly Heat Load

As discussed in Section 2.3, the potential for ice formation in the canister will be affected by the heat load of the fuel at the time of vacuum drying. Generally, the heat load will decrease with lower burnup and longer time since reactor discharge. Therefore, loadings with lower decay heat load fuel should be more susceptible to ice formation and should be performed first in the sequence of drying runs. Abundant data are available on the decay heat load of spent fuel with various burnups and age (e.g., Hermann, et al., 1994; NRC, 1999). A representative range may be from 0.5 W/kg U for low heat load to 4 W/kg U for high heat load.

4.2 Sequencing of Drying Runs

As discussed above, the preferred sequence for the drying runs will be to first evaluate those conditions that are thought to be most likely to leave residual water and then, depending on the results of those runs, determine whether further runs are necessary. Table 4-1 summarizes this approach. The table does not consider the effects of fuel assembly and canister design features on the sequence as further information on the specific design approach will be needed.

Table 4-1. Possible Sequence of Drying Runs			
Run	**Number of Hold Points**	**End Pressure**	**Heat Load**
1	Less	Higher	Lower
2	More	Higher	Lower
3	Less	Lower	Lower
4	More	Lower	Lower
5	Less	Higher	Higher
6	More	Higher	Higher
7	Less	Lower	Higher
8	More	Lower	Higher

4.3 Test Acceptance Criteria

To draw meaningful conclusions from the tests, criteria will need to be developed for accepting the significance of the test results. The criteria should take into consideration the accuracy and resolution of the measurement techniques, the effects that are introduced by scaling or other physical changes in the test system relative to a system used in the field, and the need to demonstrate that the results are repeatable. Specific acceptance criteria based on the experimental approach should be included in a detailed test plan.

4.4 Expertise Needed for Performing Test Program

A range of expertise will be needed for the implementation of this test program. The first would be experience with the design and operation of mechanical systems, so as to capably replicate the vacuum drying practices used in the industry. Further, knowledge of fuel assembly and spent fuel canister designs will be needed to make mockups that are representative of those found in industry. A third area is expertise in the use of sensors or other measurement devices. Finally, the tests will require knowledge of thermodynamics and physical chemistry to understand heat transfer and phase changes within the canister that could contribute to ice formation.

5 SUMMARY

This report provides the description of a conceptual test plan for measuring the quantity of unbound residual water remaining in a SNF dry storage canister after vacuum drying to the criterion referenced NUREG–1536, "Standard Review Plan for Dry Cask Storage Systems," (NRC, 2010). The main concern related to vacuum drying is the potential for ice formation if the canister is evacuated too rapidly, particularly in confined locations of the fuel assembly and canister. This report consists of three main parts. The first is the identification of experimental parameters and test variables. The second is the description of options for test setup and equipment selection. The third is the discussion of test plan implementation

The experimental parameters recommended for evaluation in this test plan relate to vacuum drying operational procedures, fuel assembly and canister design features, and fuel assembly heat load. The operational procedures include the number of hold steps during the evacuation process and the end pressure. The fuel assembly and canister design features are locations where it is thought that water may be trapped, including breached fuel rods, the dashpot region of the guide thimble tube for PWR assemblies, water rods for BWR assemblies, creviced regions around assembly hardware, and surfaces of spacer disks in the canister. Finally, it is assumed that ice formation will be more likely for fuel with a lower decay heat load.

Four general categories of equipment were identified as needs in the test plan: (1) the vacuum drying system such as pumps, tanks, hoses, valves, and connections; (2) the test canister; (3) the test fuel assembly; and (4) the measurement and sensing equipment. A vacuum drying system similar to those used in the industry could be built using commercially available off-the-shelf components. For the test canister, options could include a full-sized canister, a canister with full diameter but scaled in length, or a canister with full length but scaled in diameter. Cost, handing, and operational challenges will probably make a full-sized canister impractical for a test program. Of the scaled canisters, the full-length, reduced-diameter configuration likely represents the better option because the vacuum siphon tube and test assembly could be maintained at normal length. A simple version of this canister may be a segment of steel pipe with bolt-on lids to allow for insertion and removal of the test assembly. Pass-throughs or ports for instruments and sensors would also be needed. Concerning the test fuel assembly, options would be to obtain mockups from vendors or to independently fabricate one or more mockups specifically for the test program. Acquiring mockups from vendors could raise issues with cost, restrictions on certain modifications or use of the assembly, or restrictions on publishing the design information. The concept for a fabricated mockup could be either a close representation of an actual assembly design or a more abstracted assembly such as a simple series of tubes or rods with holes made in various sizes and locations to represent breached fuel rods, guide thimble tubes, and water rods. Finally, equipment for such measurements as water mass balance, water vapor content, temperature, pressure, and mass flow are available off the shelf.

The implementation of the test plan involves the selection of experimental parameters, the performance of drying runs, and then the measurement of the quantity of residual water in the canister. Ideally, the parameters should be systematically selected in a manner that minimizes the number of needed drying runs while still providing meaningful results. The most efficient sequence for performing the experimental drying runs is to start with those conditions that are thought to be most likely to leave residual water. If testing in those conditions shows that there is little residual water, it would be demonstrated that NRC guidance for drying is appropriate and further runs in more favorable conditions for drying would not be needed. If residual water of sufficient quantity to be of concern is found, it would be demonstrated that NRC guidance for

drying may not be appropriate and additional runs may only be needed to further bound the scope of the issue and explore the significance of various parameters. Following this logic, the first runs should evaluate the conditions of few hold points during evacuation, higher end pressure, and fuel with low decay heat load. Test acceptance criteria should be developed which take into consideration the accuracy and resolution of the measurement techniques, the effects that are introduced by scaling or other physical changes in the test system relative to a system used in the field, and the need to demonstrate that the results are repeatable.

A range of expertise will be needed for the implementation of this test program. The first would be experience with the design and operation of mechanical systems, so as to capably replicate the vacuum drying practices used in the industry. Further, knowledge of fuel assembly and spent fuel canister designs will be needed to make mockups that are representative of those found in industry. A third area is expertise in the use of sensors or other measurement devices. Finally, the tests will require knowledge of thermodynamics and physical chemistry to understand heat transfer and phase changes within the canister that could contribute to ice formation.

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