OVERVIEW OF VACUUM DRYING METHODS AND FACTORS AFFECTING THE QUANTITY OF RESIDUAL WATER AFTER DRYING – PUBLIC VERSION

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Prepared by

L. Miller
D. Basu
K. Das
T. Mintz
R. Pabalan
G. Walter

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 is the present report, which 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 retaining water and should be evaluated in the test plan. The second report will be the conceptual test plan itself.

Information on current industry drying practices was gathered by reviewing safety analysis reports, vacuum drying operational procedures, and design drawings. Further, visits were conducted to vendors to observe the setup and operation of their vacuum drying systems and to discuss field experience with their staff. In general, it was found that drying systems and procedures are similar throughout the industry. Most of the equipment used in the drying systems, including pumps, valves, hoses, and gauges, are available off the shelf. Provided that it is appropriate for its intended function, the selection of equipment should not affect the quantity of residual water remaining in the canister following vacuum drying. Therefore, equipment or system design variations are not recommended to evaluate in the test plan. To prevent ice formation, vacuum drying is typically performed in a stepwise manner, gradually decreasing the pressure to certain hold points, at which the canister is isolated from the pumping system for a period of time to confirm that stable pressure readings are obtained. The number of hold points and the final canister pressure could affect the quantity of residual water if they are such that ice formation is not detected. It is thus recommended to evaluate these operational parameters in the test plan.

Fuel assembly and canister designs were reviewed to identify locations where water could be trapped or difficult to remove during drying. One important case is that of a rod with breached cladding that becomes waterlogged in the core. If the hole or crack in the cladding has limited opening area, it could take a long time for water to flow out during drying or the hole could ice

over, completely blocking the exit path. The flow rate of water out of the fuel rod or the potential for icing will depend upon the size and location of holes along the length of the cladding. Other locations identified include the dashpot region of the guide thimble tube for pressurized water reactor assemblies and the water rod for boiling water reactor assemblies, both of which are hollow tubes into which water can flow, but are closed at the bottom end. Lastly, water could be difficult to remove from creviced regions around geometrically complex assembly hardware, such as grids, nozzles, and tie rods. For the canister itself, the most likely location for retaining water is thought to be on the flat surfaces of spacer disks. It is recommended to evaluate the potential for water entrapment in all of these locations in the test plan. Ice formation during drying should be more likely for fuel with a lower decay heat load, thus it is also recommended to consider the heat load as a variable in the test plan.

Finally, potential methods that may be employed in tests to measure the quantity of residual water remaining in the canister following vacuum drying were reviewed. A number of these were identified from similar applications in the pharmaceutical industry. In addition to mass balance, certain methods are based on measuring changes in the temperature, pressure, or dew point within the canister, while other techniques involve mass flow or visual observation. Most equipment that would be needed for such measurements is available off the shelf.

References

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. ADAMS ML101040620.

PNNL. “Evaluation of Cover Gas Impurities and Their Effects on the Dry Storage of LWR Spent Fuel.” PNL–6365. Richland, Washington: Pacific Northwest National Laboratory. November 1987.

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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 maintained in dry storage at a number of operating and decommissioned reactor sites and certain other facilities licensed by the U.S. 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 transferred from the spent fuel pool, water is removed from the canisters to create a dry 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, 2012b). 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 as the pressure decreases. Lowering the pressure below the saturation vapor pressure of liquid water will cause vaporization of the liquid, as illustrated in Figure 1-1. Vaporization of liquid water takes energy from the liquid water. If the pressure is decreased too rapidly, so much heat can be removed that the remaining liquid could freeze. Figure 1-2 illustrates the calculated temperature drop when the pressure of a system containing 1 L [0.26 gal] of water is decreased adiabatically. The calculation was done using OLIAnalyzer Studio™ Version 3.2 (OLISystems, Inc., 2012). As shown in the figure, liquid water is fully transformed to ice when total pressure

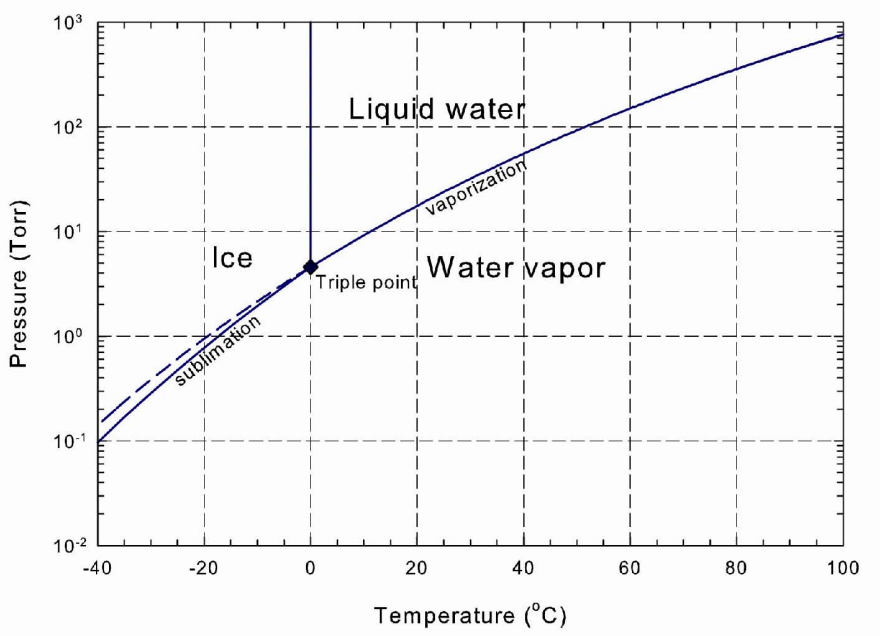

Figure 1-1. Pressure-Temperature Phase Diagram for Pure Water. Stable Phase Boundaries Are Shown by Solid Lines and a Metastable Phase Boundary Is Indicated by Dashed Line.

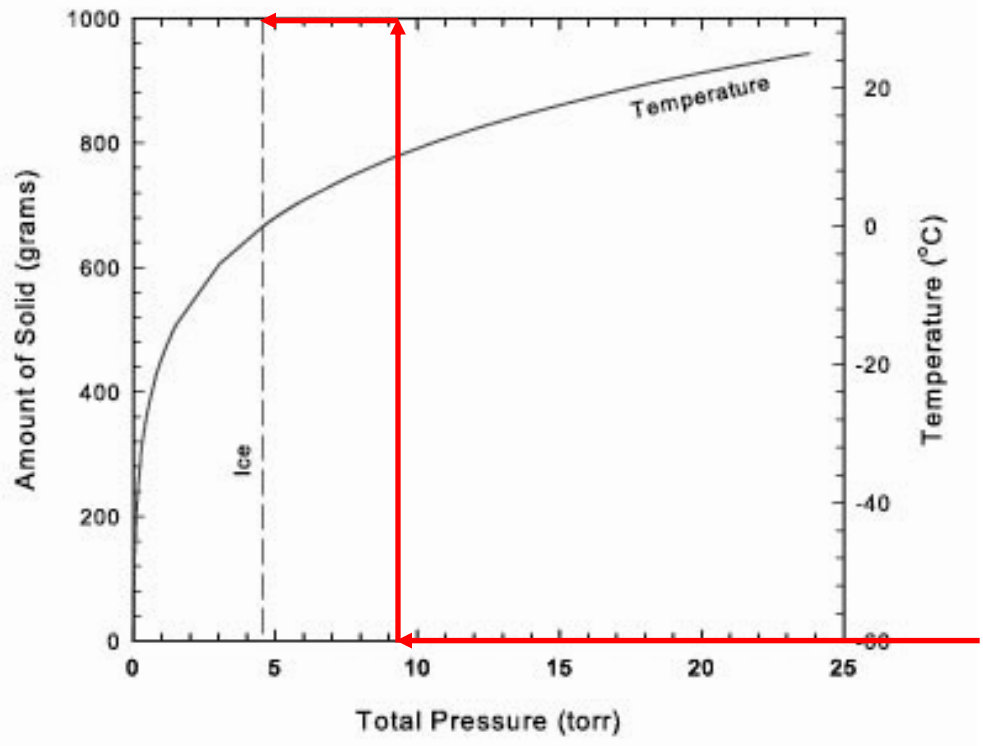

Figure 1-2. Calculated Temperature and Amount of Solid Ice (Following Red Arrow) That Forms When Pressure Is Lowered Adiabatically in a System Containing 1 L [0.26 gal] of Pure Water

is decreased below 4.58 torr [610 Pa]. The potential for ice formation may be greatest in regions of the fuel assembly or canister where water is difficult to remove because it is trapped in confined spaces.

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. 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 is the present report, which describes current industry drying practices and capabilities. It also reviews canister and fuel assembly designs to determine design features or characteristics that could affect the quantity of residual water after drying. Based on this information, recommendations are made for parameters to evaluate in the test plan. The second report will be the conceptual test plan itself. The contents of this report are as follows:

- Section 2 describes the setup and operation of typical industry vacuum drying systems.
- Section 3 describes the characteristics of fuel assemblies and canisters that may affect the quantity of residual water after drying.
- Section 4 describes measurement techniques and equipment that may be employed to measure the quantity of residual water.
- Section 5 provides a summary of the report.

2 TYPICAL INDUSTRY DRYING EQUIPMENT AND PROCEDURES

2.1 Approach

The development of the test plan for measuring the quantity of residual water after vacuum drying will require thorough understanding of equipment and procedures used in the industry. To gather such information, industry vacuum drying procedures were reviewed and visits were conducted to vendor facilities to observe the equipment and its operation in person, as well as to discuss field experience with their staff.

2.2 Equipment Used for Vacuum Drying

The equipment used for vacuum drying is relatively similar throughout the industry. The following subsections provide general descriptions of the main parts of vacuum drying systems.

2.2.1 General Setup

A typical vacuum drying system consists of vacuum pumps, a water trap, piping and hoses, valves, and a suite of pressure gauges, with the pumps and water trap tank being mounted on a rolling cart for ease of transport. The vacuum pump is connected to steel piping via flexible vacuum tubing, which allows for easier installation and connections. The water trap tank is connected in line with the steel piping, but valves are installed that allow this tank to be removed from the flow path when the system is sufficiently dry. Analog pressure gauges are mounted to the steel piping around eye level to the operator. These gauges are used to aid the operator in the blowdown and backfilling processes.

Flexible vacuum hose is used for the main lines running from the cart to the canister. These lines must be flexible to accommodate the various setup requirements seen during different drying campaigns. One of these vacuum hoses is connected directly to the canister siphon port. This siphon port connects to a tube that runs to the bottom of the canister and is used to remove the bulk water from the canister in preparation for vacuum drying. The other vacuum hose connects to stainless steel piping that is connected directly to the canister vent port. This piping is called the riser manifold or tree, and contains connections for the main pressure sensors used during drying. These pressure sensors are placed close to the canister vacuum port, which opens to the top of the canister, in an effort to obtain accurate measurements of the internal pressure.

2.2.2 Pumps

Commercially-available, off-the-shelf pumps are generally used for vacuum drying. A typical main pump is a Leybold Sogevac SV 100, which is a rotary vane pump with the ability to reach pressures around 0.5 torr [67 Pa]. In addition to the main vacuum pump, a roots blower, which is a positive displacement air pump, may be used to increase the pumping speed and efficiency in the lower pressure ranges. The roots blower is mounted to the inlet side of the vacuum pump and uses positive displacement of air to increase the air pressure at the inlet of the vacuum pump, thus increasing the vacuum pump efficiency. A typical roots blower is a Ruvac WA 251.

2.2.3 Water Trap

In a vacuum drying system, the water trap tank is used as a means of protecting the vacuum pumps from damage. Rotary vane vacuum pumps use the compression of fluid to force air from the inlet of the pump to the outlet. If fluids that are considered incompressible, like water, enter this type of pump the pump internals will fail and the pump will need to be replaced or repaired. Early in the vacuum process, water left after blow down enters the vacuum lines and can work its way toward the vacuum pump. During this time the water trap tank is valved into the vacuum path and the air-water mixture in the vacuum lines is routed through the inlet of the water trap tank. Liquid water is deposited in the tank while allowing the gasses to continue through the exhaust port and on to the vacuum pump. When no visible water droplets are apparent in the lines, this tank is valved out of the vacuum system. The removal of the tank from the vacuum system shortens the vacuum path, increasing the pumping efficiency. These water trap tanks usually have some form of sight glass to give an indication of when the water in the tank needs to be drained.

2.2.4 Piping, Hoses, and Connections

The piping on the vacuum cart and the vacuum tree or manifold is constructed of stainless steel and the pipe is connected via Klein Flange/Quick Flange (KF/QF) style flanged connections. The lines running from the vacuum cart to the vacuum manifold and siphon port are high temperature reinforced vacuum hoses connected via barbed fittings and hose clamps. These flexible hoses are required due to the varying configurations used at different vacuum drying locations. In addition, these hoses are used to connect the vacuum pump and the water trap tank to the rest of the piping. These hoses are typically transparent to aid in the visual confirmation of water removal. The vacuum tree and siphon port lines are connected to the vent port and siphon port of the canister with straight pipe nipples and a KF/QF fitting. This connection is used for all but the final vacuum step, in which the pipe nipples are replaced with quick disconnect couplings that will stay with the canister through the rest of the storage.

2.2.5 Valves

Most valving in the systems surveyed consisted of manually actuated 90 degree ball valves. The only dissimilar valve is the vacuum pump inlet valve, which is a throttling valve used to control the pump down speed. The throttling valve is required to avoid depressurizing the system too quickly and forming ice in the lines or the chamber.

2.2.6 Gauges, Sensors, and Transducers

The canister pressure is monitored during the drying process and at the final hold pressure to meet the technical specification. Digital vacuum sensors can be mounted on the vacuum manifold for the canister presser measurements. A Pirani gauge may be used for measuring the higher pressures during operation and an absolute pressure transducer for precision measurement of the lower pressures. The gauges are usually positioned as close to the vent port opening of the canister as possible in order to reduce the pressure drop seen by the gauges and provide a more accurate reading of the canisters internal pressure.
Additional pressure/vacuum gauges may be incorporated on the vacuum drying cart to aid the operator in activities such as performing blow downs or backfilling with dry helium. These may not be calibrated because they are not used for the technical specification measurement.

2.3 Procedures

The procedures used for vacuum drying also seem to be similar among various vendors, with the general concept to decrease pressure in a slow or step-wise manner to prevent ice formation by providing time for the system to equilibrate. The following subsections provide a general description of the vacuum drying process.

2.3.1 Setup and Checkout

In this step, the equipment is pre-staged for the actual operation, all the pumps are warmed up and ready, and a system pull down test is performed. In the system pull down test, a vacuum is pulled on all the hoses and piping of the system in an effort to detect any leaks that may be present in the flanges, the hose connections, or in the actual hoses and pipes. If any leaks are detected they are promptly repaired and the system is rechecked. This sequence is repeated until the cask loading supervisor or system operator is satisfied that the system is airtight. Some good practices for the vacuum drying setup include

- Run the vacuum hoses downhill from the siphon and vent ports to help drain water from the lines and decrease the chance of freezing water in the lines.

- Check and replace the seals on the KF/QF connections often. Over time the seals in these connections will compress. The compression of these seals increases the chance of air in leakage from these connections.

- All vacuum steps prior to the final pull should use straight pipe nipples at the vent and siphon ports, not the quick disconnect (QD) couplings. The QD couplings cause an orifice type effect which can lead to icing and incorrect pressure readings.

- Plastic hoses and most thread sealants will off-gas under a vacuum, so use hoses and sealants that have low off-gassing, and pull a vacuum on the system a few times before use.

2.3.2 Initial Pump Down and Blow Down and Vacuum

In this step, a self-priming centrifugal pump is connected to the siphon port of the canister, and the bulk water is pumped out until air starts to enter the lines. At this point the pump is disconnected and the canister is hooked up to the vacuum drying system using straight pipe nipples to increase air and water flow. The canister is pressurized with dry helium, then an exhaust valve, which is hooked to the siphon port, is opened and the pressure is allowed to drop to a specified point. The exhaust air and water is directed into the water trap tank which passes the air and water through a drain valve. This blow down process is repeated until a minimum amount of water is observed in the siphon hose. At this point the initial pump down and blow down of bulk water is complete.

During the initial vacuum pull down steps, described in the next section, the water trap tank is kept in line with the vacuum system. The water trap tank separates the water from the air, capturing the water in the tank and allowing the air, which is now free of water drops, to proceed to the vacuum pump. This process prevents any large water particles from entering into, and

damaging the vacuum pumps. When no visible water is present in the lines, this water trap tank is valved out of the vacuum system.

2.3.3 Vacuum Drying

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. The numbers of hold points vary by vendor, but three to seven may be typical. The final pressure to which the canister must be evacuated is specified in the technical specification, usually in the range of 3 to 10 torr [400 Pa to 1.33 kPa], with demonstration that the canister will not exceed that pressure after being isolated from the pumping system for up to 30 minutes. Operational procedures may direct that the canister should be pumped to an even lower pressure, accounting for uncertainties in the accuracy of the pressure gauges.

After the final pressure is reached, the canister is given an initial helium backfill to slightly above ambient pressure and the straight pipe nipples are replaced with QD couplings. This positive pressurization ensures that no moist air enters the canister while changing to the QD fittings. The canister is again evacuated to the technical specification pressure, after which it is given a final helium backfill to several pounds per square inch. Typical times to dry a canister are in the range of 12 to 48 hours, depending on the characteristics of the canister and fuel. The process of drying tends to increase the cladding temperature, so drying time limits are established to ensure that that the allowable peak cladding temperature is not exceeded.

2.4 Test Plan Considerations for Vacuum Drying System and Operational Procedures

Provided that it is appropriate for its intended function, the vacuum drying system itself, including the selection of pumps, valves, hoses, connections, and sensors, would seem to 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 are not recommended to be included in the drying test plan. Operational variables, however, such as the number of hold points and the final canister pressure could potentially affect the quantity of residual water. A lesser number of hold points may allow the pressure to be decreased fast enough to cause ice formation or may not provide sufficient time for evaporation or sublimation of water and ice in the canister. Further, a lower end pressure may remove more water from the system, but if ice forms, would give a greater margin for pressure increase by sublimation without violating the technical specification. As such, it is recommended to evaluate these parameters in the test plan.

3 FUEL ASSEMBLY AND CANISTER CHARACTERISTICS

The quantity of water remaining after vacuum drying may depend on characteristics of the fuel assembly and canister. Particularly, geometric features may cause water to be trapped in confined spaces or thermodynamic conditions may promote ice formation.

3.1 Test Plan Considerations for Fuel Assembly Designs

Fuel assembly designs for pressurized water reactors (PWRs) and boiling water reactors (BWRs) were reviewed to identify potential locations where water could be trapped. The specific case of a fuel rod that becomes waterlogged because of breached cladding is treated separately in Section 3.4. A typical 17x17 PWR fuel assembly is shown in Figure 3-1. The main components, in addition to the fuel rods, include the top and bottom nozzles, grids, and guide thimble tubes. A range of PWR assembly designs from different vendors were reviewed to identify potential locations where water could be trapped. This review identified two main locations. The first is creviced regions around the assembly hardware such as grids and nozzles where the path to the vacuum outlet may be confined or tortuous. The second region is the dashpot region of the guide thimble tubes. Guide thimble tubes are hollow tubes in the fuel assembly in which absorber rods are inserted. The guide thimble tubes are used to ensure control rod insertion with adequate damping and also provide some load bearing to the fuel assembly. The guide thimble tube is open on the upper end but plugged on the lower end. The dashpot region refers to the lower end where there is a transition to a smaller diameter tube. Small flow holes are present some distance above the dashpot region to allow water to flow out if it displaced by the control rod assembly.

A typical 10x10 BWR fuel assembly is shown in Figure 3-2. The main components, in addition to the fuel rods, include upper and lower tie plates, grids, and water rods. A range of BWR assembly designs from different vendors were reviewed to identify potential locations where water could be trapped. This review identified two main locations. As is the case for the PWR assembly, the first is the creviced regions around the assembly hardware. The second location is the water rod, which is a hollow tube with no fuel pellet. In a configuration somewhat similar to the PWR guide thimble tube, the water rod has holes along the length through which water could enter, but is closed at the bottom, providing a location for water to sit.

Based on this analysis, the test plan should include provisions for evaluating whether water could be trapped in the fuel assembly during vacuum drying at particular locations including creviced regions around assembly hardware, the dashpot region of guide thimble tubes for PWR assemblies, and water rods for BWR assemblies. These features should be included in mockups used for the test program

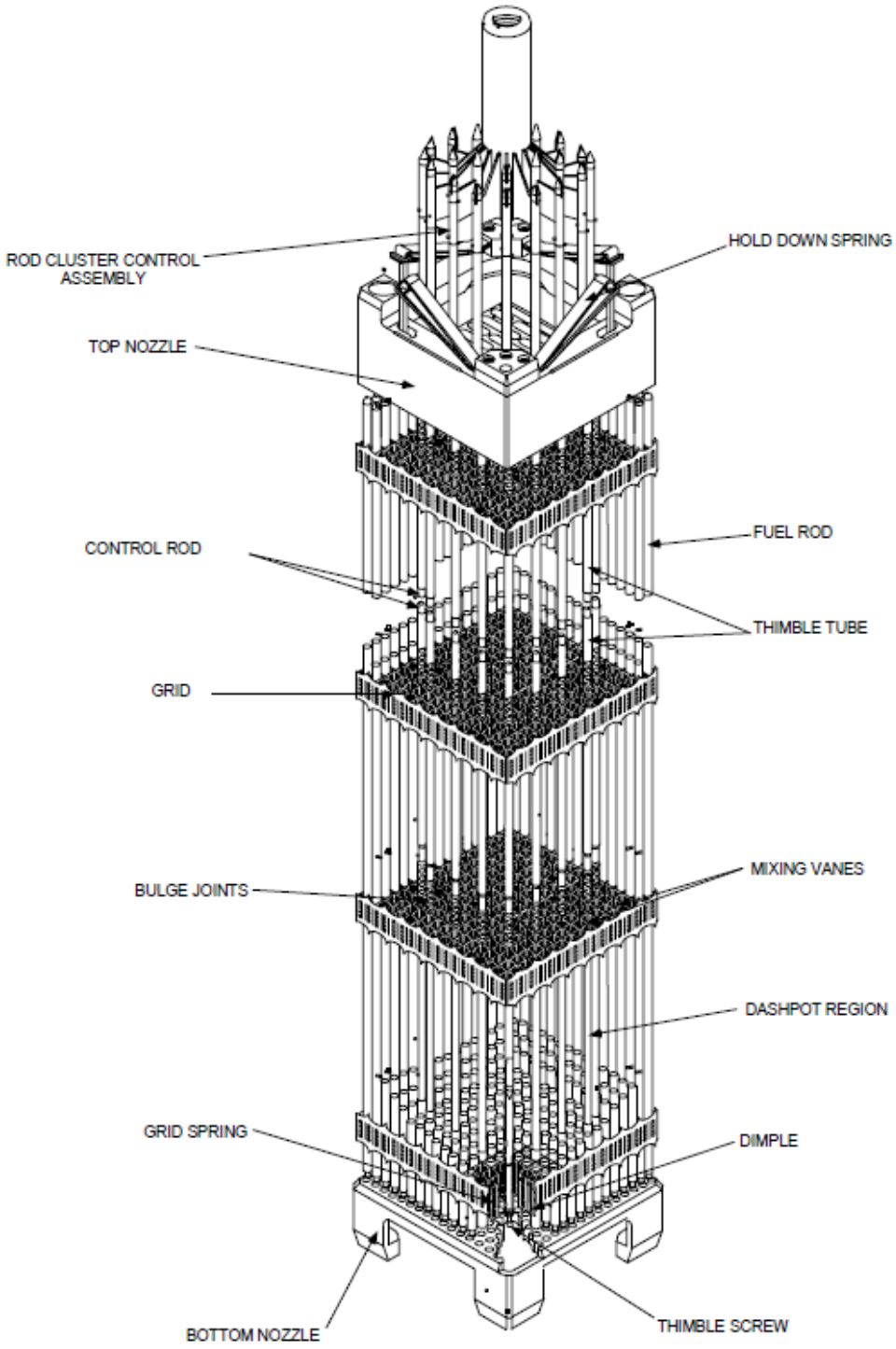

Figure 3-1: Typical PWR 17x17 Fuel Assembly (NRC, 2012a)

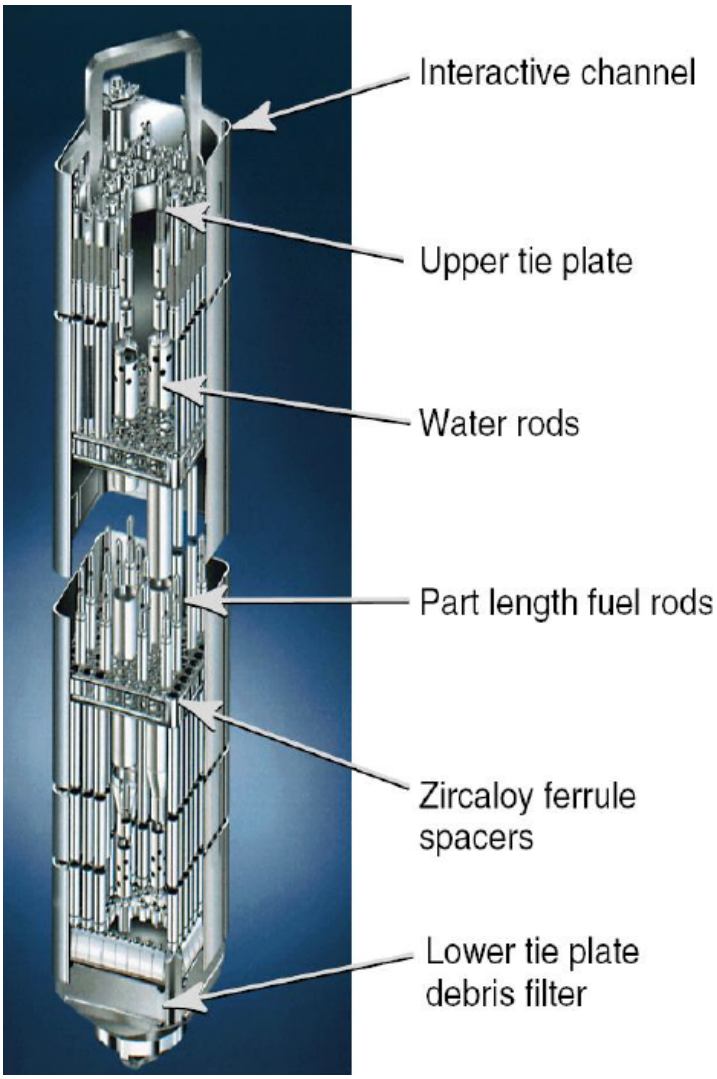

Figure 3-2: GE14 Fuel Assembly (NRC, 2011)

3.2 Test Plan Considerations for Canister Designs

Canister designs from various vendors were also reviewed to identify location where water could be trapped. As shown in Figure 3-3, spent fuel canisters include an internal basket structure to support the fuel assemblies. 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. Depending on the space between the end of the vacuum siphon tube and the bottom plate, water could also potentially sit at that location out of reach of the siphon tube. Therefore, it is recommended that the test plan include provisions for evaluating whether water could be held up on horizontal surfaces within the canister, such as spacer disks, or whether it could pool at the bottom of the canister past the end of the vacuum siphon tube.

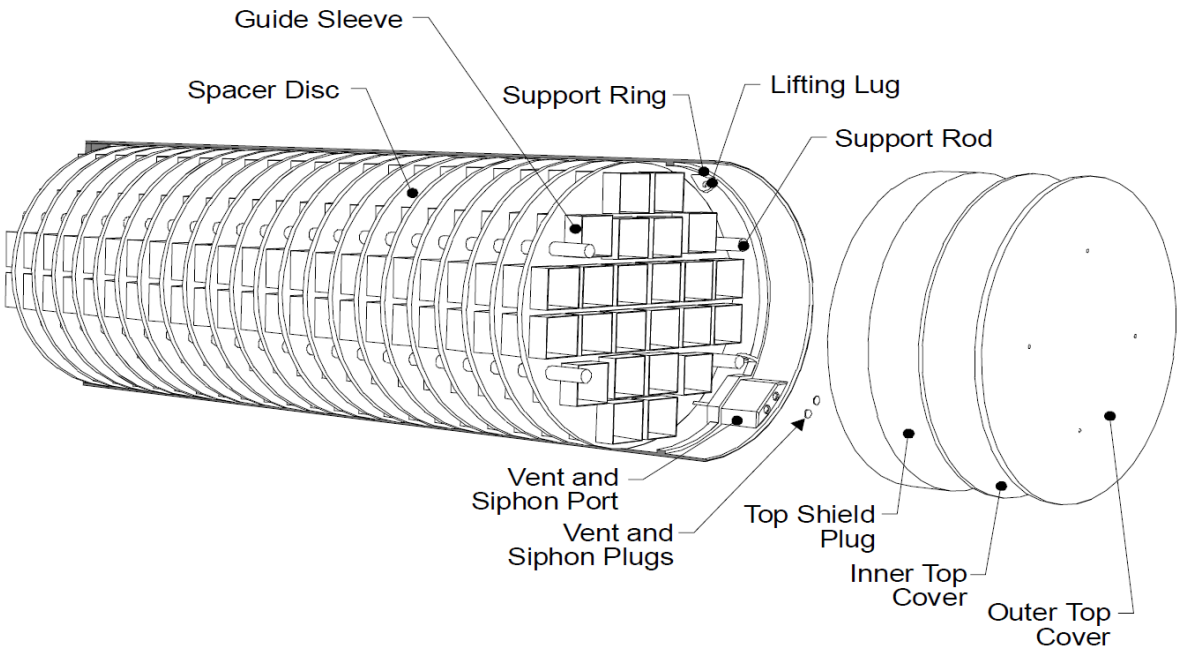

Figure 3-3: Transnuclear 24PT Dry Storage Canister (NRC, 2002)

3.3 Test Plan Considerations for Fuel Heat Load

The potential for ice formation in the canister will be affected by the temperature of the fuel assemblies, which provide a source of decay heat. The heat load of the fuel at the time of vacuum drying will depend on the in-reactor 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, as indicated in the plot in Figure 3-4, using data taken from Regulatory Guide 3.54, “Spent Fuel Heat Generation in an Independent Spent Fuel Storage Installation” (NRC, 1999). The temperature inside the canister will increase during vacuum drying. According to a review by Nuclear Waste Technical Review Board (2010), the vacuum drying process often produces the highest cladding temperatures experienced during the dry storage process. NRC guidance generally limits the peak cladding temperature to 400 °C [752 °F] under normal conditions (NRC, 2003). Licensees perform calculations to demonstrate that the peak cladding temperature will not be exceeded during vacuum drying. The temperatures are likely to remain lower when the canister contains low decay heat load fuel assemblies, suggesting that such a condition is more susceptible for ice formation. Therefore, it is recommended that the test plan include provisions for varying the heat load of the fuel assemblies to determine whether this affects the quantity of residual water.

3.4 Test Plan Considerations for Damaged Fuel Rods

Fuel rods with cladding that is breached with cracks or pinholes may be filled with water in the high pressure conditions of the reactor core. Water may remain trapped in the fuel rod after vacuum drying if the outflow is constrained, for example, by a small hole or if the hole area ices over. The drying process of a waterlogged fuel assembly is shown schematically in Figure 3-5. Water at a relatively high pressure (P1) and temperature (T1) occupies the open volume within the fuel assemblies. During the vacuum drying process, the pressure outside the fuel rods is

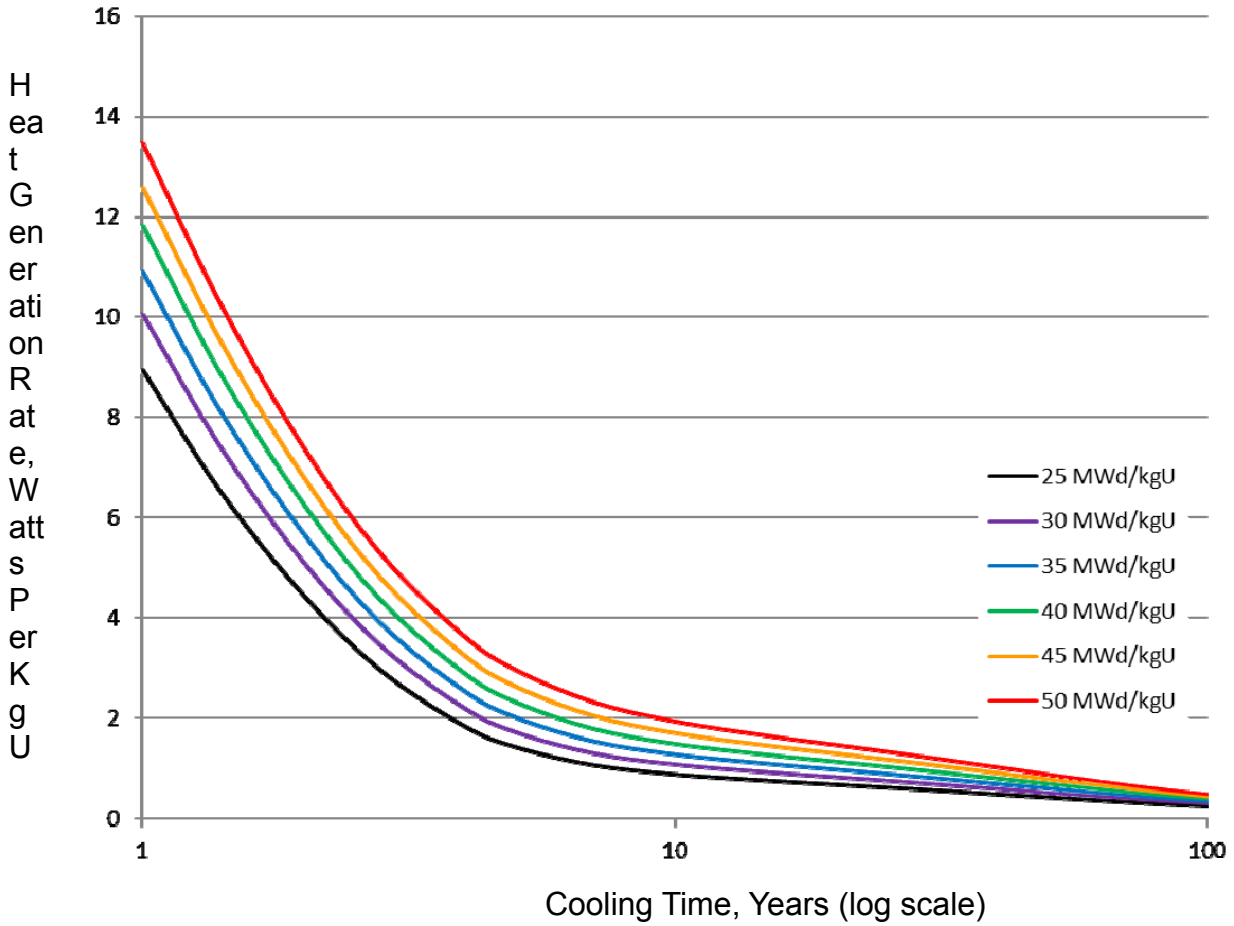

Figure 3-4: Plot of PWR Spent Fuel Heat Generation Rates as a Function of Cooling Time at Various Burnups for Specific Power 40 kW/kgU. Plot Made from Data in Table 7 of NRC Regulatory Guide 3.54, "Spent Fuel Heat Generation in an Independent Spent Fuel Storage Installation" (NRC, 1999)

reduced to a very low value (P2) and the corresponding temperature also reduces substantially (T2). Due to this high pressure differential, water from inside the fuel rods starts to flow towards the low pressure region through the pinholes and cracks. The through-wall pinholes can be conceptualized as a long slender tube. At the inlet of these tubes, water is at a liquid state and is at pressure P1 and temperature T1. Water exiting from the low pressure side will be at pressure P2, which is usually substantially lower than the saturation vapor pressure at temperature T2. This implies that the water at the outlet will be at vapor phase and the water will have to change phase while it travels from the inlet to outlet of the tube.

The phase change process depends on a number of parameters, including the hole size and pressure difference between the two sides of the hole. This change of phase requires latent heat of evaporation that is supplied by the decay heat of the SNF and convected to the phase change location by the flow of water. If the flow of water is inadequate, the total heat flow may not be sufficient to evaporate the water. In that case, any additional thermal energy needed to bridge this gap will be withdrawn from the internal energy of the inflowing water, which may cause ice formation. It is recommended that the test plan should provisions for evaluating

whether remains trapped in breached and waterlogged fuel assemblies after vacuum drying. Considerations should include both the size and location of the hole along the rod length. This may be tested by placing water in hollow rods with machined holes, then vacuum drying to see if any water remains.

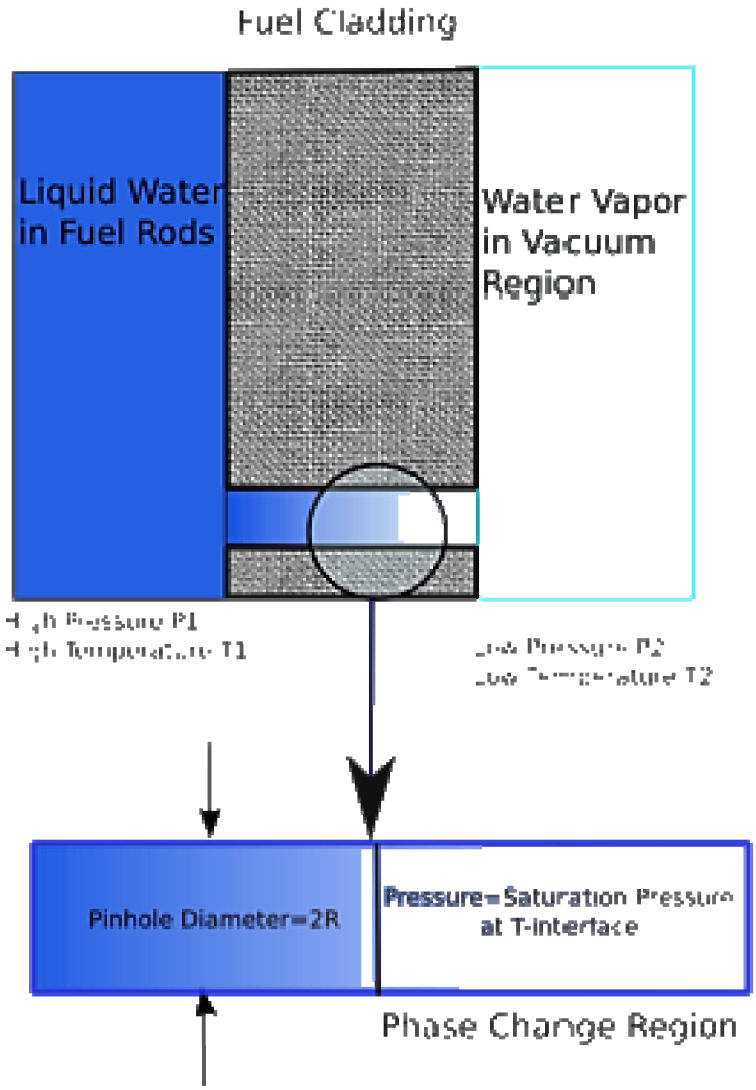

Figure 3-5. Schematic Showing the Flow and Phase Change of Trapped Water During Drying

4 CONCEPTS FOR MEASURING THE QUANTITY OF RESIDUAL WATER AFTER DRYING

This section describes the types of measurements and equipment that might be used in a test plan to measure the quantity of residual water remaining in the canister following vacuum drying.

4.1 Measurement Capabilities Needed

The issues associated with measuring the quantity of water in the canister containing a complex fuel assembly are conceptually similar to those faced by the pharmaceutical industry in measuring the completeness of vacuum drying of large numbers of small vials containing pharmaceuticals, although the pharmaceutical vacuum drying procedures are somewhat different from those used for cask drying. Patel, et al. (2010) conducted a comprehensive evaluation of techniques and instrumentation used to monitor vacuum drying of pharmaceuticals.

The techniques studied by Patel, et al. (2010) are all based on monitoring rapid changes in either the pressure, dew point (water content), or temperature that occur when ice sublimation is complete. This is because the pharmaceutical drying process involves first freezing the water in the pharmaceutical vials and then initiating the vacuum drying process. This differs from the canister drying process because any ice formed in the cask or fuel assembly would be the result of semi-adiabatic cooling of the residual liquid water due to liquid evaporation and ice sublimation. Nevertheless, the same general monitoring principles should apply because rapid changes in pressure, dew point, or temperature in the cask should occur when all of the liquid water or ice has been removed. As schematically illustrated in Figure 4-1, the total pressure and dew point in the vacuum chamber remain relatively high, controlled by the vapor pressure of water or ice, as long as water or ice are present during the initial drying phase. The temperature in the water or ice remains low because it is controlled by the heat of evaporation or sublimation.

As the volume of water or ice is reduced, a transition phase occurs when the pressure and dew point are controlled by rate-limited release of water vapor through physical constrictions in the materials to be dried (such as vial caps in the case of pharmaceuticals and pinhole defects in the case of fuel assemblies), or slow sublimation of ice. One caveat in following the pharmaceutical drying approach is that the pharmaceutical drying process uses much higher vacuum than the cask drying processes, typically less than 0.1 torr [13.3 Pa]. Thus, the pressure response in the cask drying process may be less pronounced than in the pharmaceutical drying process, although the changes in pressure and temperature should be strong upon complete drying. Another difference is that the vacuum level during the pharmaceutical drying process is regulated by bleeding nitrogen into the vacuum chamber, whereas no inert gas is introduced into the canister until the backfill after drying is complete. Therefore, the water content of the gas inside a canister should approach and stabilize at 100 percent as opposed to decreasing as it does in the pharmaceutical case. Although measurement of water content inside the vacuum chamber, in itself, may not give a good indication of the completeness of drying, monitoring water content during the evacuation and re-pressurization process would yield useful data on the rate of residual water/ice evaporation/sublimation, as well as providing an indication of leaks into the vacuum chamber.

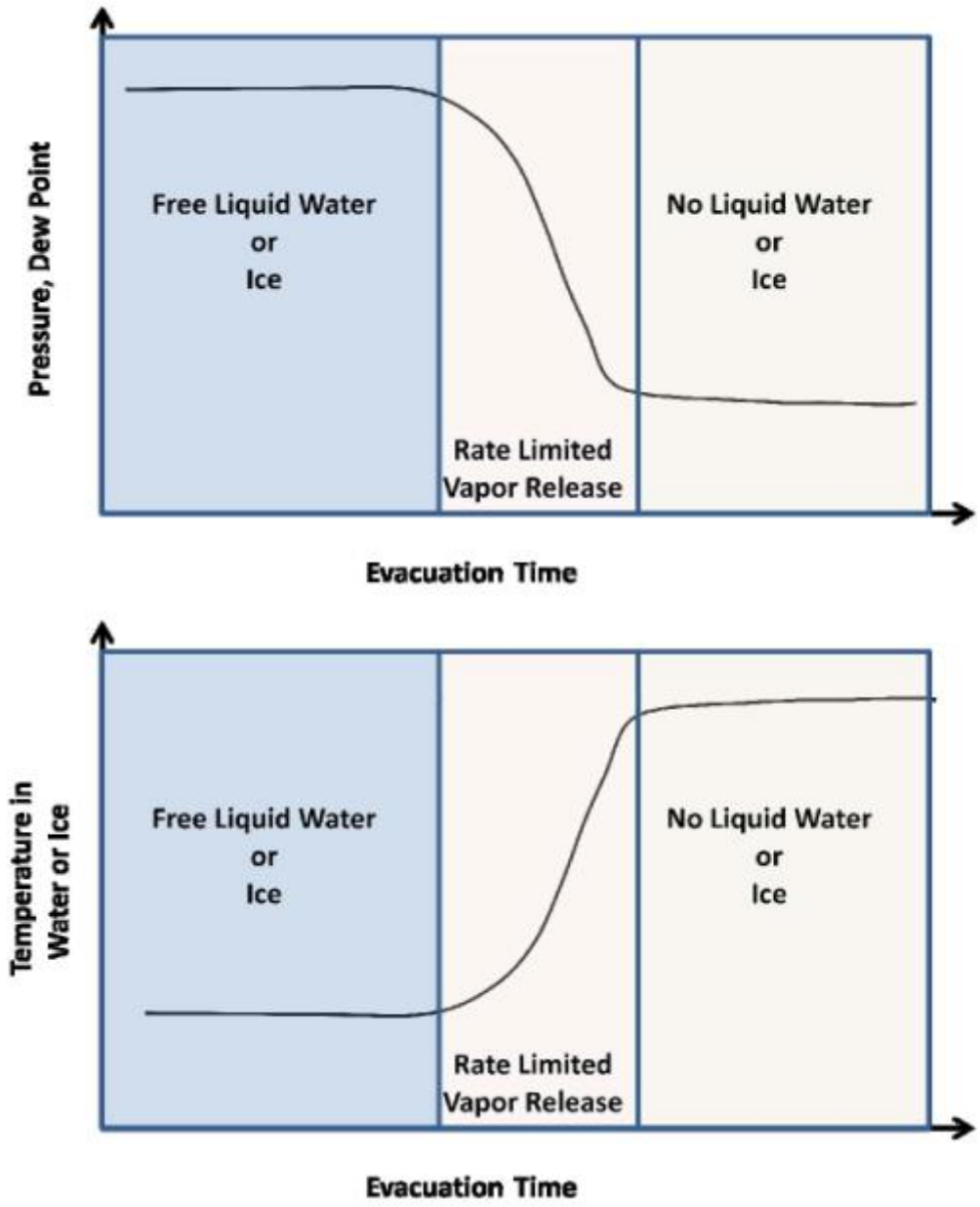

Figure 4-1. Conceptual Illustration of the Pressure, Dew Point, and Water/Ice Temperature Response Indicating Complete Removal of Free Water

4.2 Potential Measurement Techniques

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 prior to drying, then to measure the quantity of water remaining after drying. For instance, a fuel rod with pinhole could be filled with water prior to drying, and then drained after drying to determine how much water remains. Additional methods that would require more sophisticated setup or instrumentation are summarized in Table 4-1. The first column lists the technique and the next columns describe the type of instrument that would be needed for such

a measurement, how that instrument would be used, and associated challenges, respectively. The general types of measurement and associated instrumentation are described in the following sections. The work by Patel, et al. (2010) was used as guidance for selecting the general techniques and instrumentation that might be used.

Table 4-1. Possible Measurement Techniques and Considerations

Measurement Technique	Instrument	Use	Challenge
Visual observation	Window or camera	View ice formation	Limited field of view
Internal temperature distribution	External IR camera	View temperature deviations due to evaporative cooling and ice formation	IR transparent glass window required
	Internal IR camera	View temperature deviations due to evaporative cooling and ice formation	Vacuum rating
			Calibration for emissivity of internal fixtures
Internal temperature reading	Thermocouple	Detect presence of residual water/ice	Thermocouple wires can affect ice nucleation/sublimation rates
Internal water vapor content	Dew point sensor	Monitor drying process and water vapor rebound during 30-minute hold period	Water vapor partial pressure may be less than 3 torr [400 Pa] if other volatiles are present
External in-line water vapor concentration	Dew point sensor	Monitor drying process and water vapor rebound during 30-minute hold period	Water vapor partial pressure may be less than 3 torr [400 Pa] if other volatiles are present
	Cold plasma spectrometer	Provide direct measurement of water vapor content	Will require custom instrumentation and calibration
Vacuum measurement	Vacuum gauges or pressure sensors	Monitor total pressure during drying process and hold period	Accuracy over wide range of pressures
Mass flow	Mass flow meter	Monitor rate of water removal	Multiple meters for various flow rates
			Measurement sensitive to changing gas composition if multiple gasses present

Instrumentation consisting of an external, in-line dew point sensor and mass flow meter to measure water removed from the vacuum chamber will allow the possibility of making water balance calculations if the initial water volume in the vacuum chamber is known, as it might be in a controlled experiment. Internal measurement of dew point, temperature, total pressure, and

water vapor content will allow the degree of disequilibrium between free water or ice and the average water vapor concentration in the chamber to be estimated. These data may be useful for validation of numerical simulations of the vacuum drying process, in the same way that numerical models of pharmaceutical drying have been developed, such as Pikal, et al. (1984). Infrared (IR) imaging of the components within the vacuum chamber may be used to identify cold spots where water evaporation is occurring and where ice formation may slow the evaporation process. The IR imaging and visual observation may also indicate the locations that retain free water during the re-pressurization process.

4.2.1 Gas Water Content Measurement

Review of product literature indicates that impedance-type dew point sensors will be best suited for monitoring dew point and relative humidity both inside and outside the vacuum chamber. Impedance-type dew point sensors work by measuring changes in the impedance of an active porous insulating layer sandwiched between two layers of conductive material deposited on a ceramic substrate. These sensors have been used to monitor water vapor content in industrial vacuum drying chambers. Although chilled mirror dew point sensors offer higher accuracy than impedance-type sensors. Chilled mirror sensors work by electrically cooling and heating a mirror to alternatively condense water vapor on the mirror and re-evaporate. The heating and cooling process is electronically controlled until the temperature cycle converges to a narrow range. The formation of dew or frost on the mirror is optically sensed. Chilled mirror sensors are unlikely to work well in a vacuum environment due to the limited density of water molecules in the gas that leads to slow and/or unstable response.

Cold plasma spectroscopy was the only technique identified for directly detecting water vapor in a mixed gas environment inside a vacuum chamber (e.g., Mayeresse, et al., 2007). Cold plasma spectroscopy works by using a radio frequency microwave generator to ionize water vapor and measuring the emission spectrum of the plasma. However, this technique only works for vacuum below 3 torr [400Pa], so it could not be used to monitor the full range of water vapor content expected in the vacuum drying process.

Although the tunable infrared laser diode sensor has the capability to directly identify water vapor in a mixed gas environment. These sensors operate by measuring the unique infrared absorption spectrum of water vapor. The currently available instruments require an active flow of gas through the instrument that would not exist inside a vacuum chamber. The tunable infrared laser diode sensor has been used for in-line monitoring between the vacuum chamber and the vacuum pump (Kuu, et al., 2009; Kuu and Nail, 2009).

4.2.2 Temperature Measurement

Microthermocouples are available for monitoring the temperature at specific locations within the vacuum chamber. Thermocouples have been used in the pharmaceutical industry to measure freeze-drying completeness by monitoring the temperature in specific vials within a multi-vial batch drying process. Completeness is judged by a rapid increase in temperature when the ice is completely sublimated from a vial, that is, when the temperature is no longer controlled by sublimation of ice. The same principle could be used to monitor the evaporation of water or sublimation of ice in initially wet portions of a fuel assembly with the vacuum test chamber. However, thermocouples inserted into liquid water accelerate the freezing process by nucleating ice formation, thus the temperature history in liquid water monitored with a thermocouple is different than that of water without a thermocouple (e.g., Patel, et al., 2010).

An IR camera could also be used to monitor water evaporation or ice sublimation by imaging cold spots within a complex fuel assembly. Due to the complexity of operating an IR camera with the test vacuum chamber, this method would most likely require a vacuum chamber with an IR transparent glass window with the camera operated outside the chamber.

4.2.3 Vacuum Pressure Measurement

Diaphragm type gauges are available to measure vacuum in the range of 1 to 1,000 torr [133 Pa to 133 kPa]. Convection-type gauges have a wider measurement range (10^{-3} to 10^{4} torr [1.33 x 10^{-1} Pa to 1.33 MPa]), but their response varies with the gas composition because the vacuum measurement depends on the thermal properties of the gas. The sensitivity of the convection-type gauge to gas composition could be a problem as the chamber gas composition varies from air/water to water to helium/water during the evacuation and measures below 1 torr [133 Pa] are needed.

4.2.4 Flow Measurement

Mass flow meters that use heat loss between heated wires to measure mass flow are the standard method for measuring flow at very low pressure. Because their response varies with the composition (heat capacity) of the gas, their response will vary as the gas composition changes during the evacuation and re-pressurization cycle. The apparent flow rate can be corrected if the gas composition is independently measured, possibly by using cold plasma ionization spectroscopy.

5 SUMMARY

This report is intended to provide technical background for a test program to experimentally measure the quantity of unbound residual water in spent nuclear fuel dry storage canisters dried to the criterion recommended in NUREG–1536 (NRC, 2010). The main sections of this report address the design and operation of systems currently used by industry for vacuum drying, characteristics of fuel assemblies or canisters that could affect the quantity of residual water, and measurement concepts that could be employed for the test program. Information on current industry drying practices was gathered by reviewing safety analysis reports and operational procedures, as well as by visiting vendors who perform vacuum drying services in the industry. Fuel assembly and canister designs were reviewed to identify locations where water could be trapped or difficult to remove during drying. Table 5-1 summarizes the parameters that are recommended to evaluate in the test plan. Potential methods for measuring the quantity of residual water remaining in the canister following vacuum drying were reviewed. Measurements may include the monitoring of temperature, pressure, and dew point within the canister, along with the use of cameras and mass flow meters. Necessary equipment for performing such measurements is available off the shelf.

Table 5-1. 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

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