Experimental Evaluation of Drying Spent Nuclear Fuel for Dry Cask Storage Through Vacuum and Forced Helium Dehydration

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EXPERIMENTAL EVALUATION OF DRYING SPENT NUCLEAR FUEL FOR DRY CASK STORAGE THROUGH VACUUM AND FORCED HELIUM DEHYDRATION

by

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DEDICATION

To Dr. Travis Knight, who gave me the opportunity to be on his research team, entrusted me with this work, and meant far more to me than being my academic advisor. I could never repay the knowledge, experience, and support he provided in not only my academic life, but also my professional and personal life while working under him.

To my father who passed away during my graduate studies. Your desire to see me succeed in all fields of life is what kept me going through difficult times. I will never forget how excited you were to celebrate my achievements, no matter the size. I can only imagine the joy that would have been on your face when I would have told you after completing this work, I did it dad. Thank you for everything.
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Lastly, appreciation also goes to all those that aided in the operation of the 100+ drying experiments conducted in this work.
ABSTRACT

Currently approximately 80,000 tons of spent nuclear fuel (SNF) are in either dry or wet storage at nuclear power plants or designated spent fuel storage facilities. Over 2,000 tons are added to that sum each year. All SNF must be dried to an accepted Nuclear Regulatory Commission (NRC) drying criteria before being placed in dry storage. Inadequately drying SNF increases the risk of detrimental effects to the fuel while in dry storage. Two commonly used drying operations in the nuclear industry are vacuum drying and forced helium dehydration (FHD). Although these drying processes have been used for many years, there have currently been no experimental work with full-scale fuel assemblies confirming the residual water following the two drying operations.

The purpose of this work is to experimentally evaluate the performance and drying effectiveness of FHD and vacuum drying on SNF. Experimental drying tests were conducted on a full-size Light Water Reactor (LWR) fuel assembly (Framatome Atrium 10A Boiling Water Reactor (BWR) assembly) consisting of depleted uranium rods, 12 heater rods to simulate decay heat of SNF, and an interchangeable rod position to examine key features of concern such as failed fuel rods, BWR water rod, and Pressurized Water Reactor (PWR) guide thimble. The LWR assembly was housed inside a vacuum chamber with structures simulating baskets and rails that are found in industry drying canisters to center the assembly. Additional drying tests were conducted with Holtec International drying equipment on a full-size Type 1a basket containing 10 mock
aluminum-clad fuel assemblies (ASNF) mimicking fuel used in Idaho National Laboratory’s (INL) Advanced Test Reactor (ATR). The potential of freezing in spacer discs was also evaluated in both drying setups through a simulated spacer disc.

In vacuum drying tests, the formation of ice was prevented when increasing the hold time at each pressure sequence hold from 5mins to 15mins. Ice formation was also seen in areas the volume of water was large relative to the surface area of the water. Faster drying times were achieved with increase of decay heat. Industry drying criteria was sometimes found inadequate, leaving upwards of 18.5mL of bulk water. Consistency was found in complete dryness when both the vapor pressure did not rise more than 1 Torr during the final hold and the dew point inside the canister at the start of the final pressure hold was between -8 and -16°C. For FHD, the effectiveness of drying was observed to be directly proportional to the mass flow rate and temperature differential across the canister. Although improvements are needed in facility hardware to better represent industry FHD conditions, results did show the FHD drying criteria is adequate and improvements on drying time are seen when treating the siphon as an inlet rather than an outlet. Overall, the capability to control the fuel temperature through concurrent fuel cooling gives FHD the ability to further decrease drying times without exceeding fuel cladding temperature limitations.
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CHAPTER 1

INTRODUCTION AND MOTIVATION

At present, there is nearly 80,000 tons of spent nuclear fuel (SNF) in spent fuel pools or dry cask storage and discharges from current reactors amount to nearly 2000 tons per year. This used fuel is initially stored in spent fuel pools for at least 5 years. The most likely scenario is that all used fuel will be placed into dry cask storage for a period of time that could extend from 20 to more than 100 years. From the spent fuel pool, a multitude of SNF assemblies are loaded into canisters underwater necessitating a drying of the SNF before placing the canisters into a dry storage cask.

The spent fuel pool water from loading must be removed to avoid unnecessary corrosion and degradation of the fuel in storage, as well as maintain the fuel in a retrievable geometry. Radiolysis of any retained water also offers the potential to create a flammable condition [1]. The accepted drying process involves evacuation of the canister to less than 3 Torr and maintaining that pressure for 30 minutes after isolation from the pumping system [[1], [2], [3]]. An alternate approach, called forced helium dehydration (FHD), is to circulate heated helium in the canister to achieve the same water vapor pressure. This work utilizes prototypical industry practice and equipment along with a full-length mock fuel assembly to evaluate the drying operations and quantify any remaining water. Although not discussed in this study, drying tests conducted in this work were also used to develop mechanistic models and engineering computer codes to
predict the water remaining and level of dryness following drying operations on a SNF canister. This work provides the scientific basis and validation of used fuel drying predictions needed by the industry and regulators.

Surfaces of fuel rods and other structures provide the opportunity for physisorbed and chemisorbed water that must be removed. The structure of the fuel assembly and canister are such that the possibility of trapped or retained water exists in places such as between rods and grid spacers. The dashpot on guide thimbles in PWR assemblies and BWR water rods can hold water up to some height dictated by weep holes. Flat surfaces within the canister such as spacer discs also provide locations where water may collect and be difficult to remove contributing to the dryness level.

In addition to the surfaces of intact fuel rods, failed fuel rods may contain a significant amount of water that is difficult to remove. The plenum and any annular pellet spaces may be filled with water in addition to a significant amount of water may be chemisorbed and present in the form of hydrates which will be difficult to remove. This effort will examine the drying process of simulated failed fuel rods. There is a deep concern that adiabatic cooling in the vacuum process could lead to the formation of ice crystal resulting in the retention of water even if the canister may meet the typical prescribed pressure hold point criteria for dryness.
2.1 Spent Nuclear Fuel

Nuclear reactors produce electricity from the heat generated by nuclear fuel rods bundled into fuel assemblies within the reactor. These fuel assemblies are often used for about 5 years till they are depleted to a point where they are no longer economically efficient to be used and need to be replaced. The time fuel assemblies can spend in the reactor is also based on the allowable enrichment and capability the fuel cladding can withstand without failure. The used fuel, also known as spent nuclear fuel (SNF), generates a range of decay heat and radioactivity when removed from the reactor. Due to this state of the spent fuel upon removal, deep pools of water are located on every nuclear reactor site to safely store the spent fuel.

Spent fuel pools were originally supposed to be a temporary storage site to decay the radiation and heat from the spent nuclear fuel to a safe level before shipping the spent fuel to a reprocessing plant. However, the pools began to reach capacity as reprocessing was never commercially demonstrated in the United States [4]. Starting in the 1980s, the nuclear industry began to store SNF in a dry state for long-term storage. Radiation shielding is provided in the form of a storage cask with overpack shielding as the SNF is still emitting high levels of neutron and gamma sources [5].
Dry storage casks (or dry storage systems) come in all different cylindrical sizes with an interchangeable internal canister that safely contain SNF assemblies. For light water reactor (LWR) fuel, the internal canister is typically a cylindrical honeycomb-design fuel basket made of neutron absorber materials to maintain the loading configuration of the fuel assemblies [6]. The storage cask protects the canister and provides an additional layer of radiation shielding through thick steel and/or concrete [6]. A transfer cask is also used for structural and shielding protection of the SNF while loading the canister with fuel, drying the canister, and transferring the canister into the storage cask [6].

The typical commercial process of transferring SNF from wet to dry storage begins by placing an empty canister into the transfer cask and submerging both into the SNF water basin [6]. SNF is then loaded into predetermined basket slots inside the canister [6]. The SNF is kept underwater during loading to protect operators from the high dose rates of the SNF [6]. Once fully loaded, a lid is placed on top of the canister to enclose the SNF and water inside the canister [6]. The transfer cask and canister are then removed from the SNF pool and placed in a staging area [1]. The canister lid is then welded for complete seal (some designs are bolted) and two ports on the lid are connected to a drying skid [6]. The canister is then adequately dried before being placed into the storage cask for dry storage [5].

2.2 General Overview of Spent Nuclear Fuel Drying Process

SNF drying practices in the nuclear industry have evolved throughout the years and vary among the different nuclear reactor sites. However, the commercial industry most commonly utilizes vacuum drying and forced helium dehydration (FHD) to adequately dry SNF for dry storage [6]. All drying operations and criteria must be
accepted by the United States Nuclear Regulatory Commission (NRC) as the NRC regulates how much moisture content is allowed inside each licensed dry storage cask [1].

Typical commercial drying process consist of two separate stages, draining and then drying via vacuum or FHD. The first stage involves draining majority of the water through dewatering and blowdown. Dewatering is the process of removing large volumes of water from the canister typically by pumping through a siphon port (or drain port) while backfilling helium under pressure through a vent port [6]. Through blowdown, helium gas (or inert gas) under high pressure is cycled and blown through the vent port and out the siphon port to entrain water that remains inside the canister [6]. The siphon port connects to a long tube (siphon/drain tube) inside the canister that stretches to the bottom of the canister basket, terminating approximately 0.1-inches from the baseplate. The siphon tube typically has shallow angular cutouts at the bottom, preventing any flow blockages if the tube contacts the bottom of the canister. Some LWR canisters are designed with a small sump in the canister’s baseplate around the bottom of the siphon tube [6]. This design allows for the siphon tube to run full length of the canister to increase the amount of water removed during draining operations. The vent port is located on the lid of the canister, next to the siphon port, with no tube attached. An example of a SNF canister is shown in Figure 2.1, highlighting the locations of the vent and siphon port [7].

2.2.1 Dewatering & Blowdown

Before starting dewatering, connections to the vent and siphon port are made to attach the fill and suction line, respectively [6]. The fill line comprises of a series of valves and flexible vacuum hose aligning inert gas tanks, typically helium, to the vent
Figure 2.1. Transnuclear 24PT Dry Storage Canister [7].

port. Pressure transducers are also attached to the fill line, located near the vent port, to monitor the canister pressure as helium is injected through the vent [7]. Suction lines consist of connecting the siphon port to a dewatering pump used to pump out the bulk water inside the canister [6]. The water is removed through the siphon tube and typically is discharged from the dewatering pump to a floor drain located in the facility [7]. The floor drain is not an open drain and is monitored for contamination. The water that goes through the floor drain is typically directed to the SNF pool onsite [8]. Dewatering pumps vary from site to site depending on the size of the canister and setup inside the facility.

Dewatering process in the industry typically starts by allowing helium to flow through the fill line into the canister [6]. The dewatering pump is then turned on to begin removing the water through the siphon tube [6]. The canister is backfilled with helium while the pump is on to replace the volume of water being removed [9]. When determining the necessary helium flow, the industry expects a flow of 80 cfh helium will replace the volume change for a 10 gpm pumping rate [9]. This scaling relationship is
based on the rate of pumping for the canister and size of dewatering pump. Dewatering is
deemed as complete when the water discharge from the dewatering pump decreases
dramatically [6].

Upon the completion of dewatering, the dewatering pump is turned off and a
slight helium purge is maintained to prevent air being drawn inside the canister. During
this time, the suction line is detached from the canister. The vacuum or FHD system is
then connected to the siphon port to prepare for blowdown [6]. A condensate trap is
located on both drying systems, but valves are installed to allow the trap to be bypassed
or removed without effecting the systems [7]. The condensate trap also connects to a
drain line that is used for blowdown purposes only [6].

Blowdown begins by pressurizing the canister with dry helium through the vent
port [6]. Then, an exhaust valve that is connected to the siphon port, or condensate drain
line, is opened to release the pressure [7]. The water inside the canister is then blown out
the siphon port and through the drain line [6]. This process is repeated to remove as much
bulk water as possible. When the supervisor sees no more signs of moisture being
removed, blowdown is stopped to end the draining stage [9].

2.2.2 Vacuum Drying

Commercial sites begin the drying stage (vacuum drying or FHD), following the
draining stage, to remove the remaining residual water left from dewatering and
blowdown [10]. Vacuum drying in the industry is typically performed by closing the vent
port and reducing the canister’s internal pressure, with a vacuum pump, in a stepwise
manner to less than 3 Torr [1]. This method of evacuating the canister to predetermined
hold points was implemented to minimize the risk of freezing occurring [1]. Chapter 2.3
provides greater detail of what causes freezing to occur during vacuum drying. The
implemented hold points may be repeated to achieve a stable pressure acceptable to the
certainty operations. Although the number of hold points conducted during vacuum drying
may vary, the typical drying criteria used for all vacuum drying operations is maintaining
an internal canister pressure below 3 Torr for 30 minutes [1]. This requirement, although
may be stricter at some sites, is accepted by the NRC as the criteria verifies the canister
has less than 1 mole of water vapor (based on average commercial canister free volume)
before going into dry storage [1].

Depending on the nuclear facility, after the final pressure hold is achieved, the
canister is then backfilled with helium to slightly above ambient pressure and either
evacuated again or prepared for dry storage [10]. If another evacuation is required, the
canister is typically evacuated to a final prescribed vacuum level before backfilling again
with helium. After the canister meets the facility’s NRC accepted final criteria, the
canister is backfilled to approximately 4 atm [1]. The backfill pressure varies depending
on the canister’s size and total decay heat. The vent and siphon ports are then closed, and
all lines are removed to transfer the sealed canister to the dry storage cask [1].

2.2.3 **Forced Helium Dehydration (FHD)**

The process for FHD, also referred as forced gas dehydration (FGD), consist of
removing moisture in a SNF canister by circulating heated gas throughout the canister
cavity using a recirculation pump or blower [2]. Helium or nitrogen is often chosen to be
the gas used in FHD as they are dry non-reactive gases [5]. Using such gas, creates an
inert environment inside the canister which reduces the chance of fuel oxidation and
cladding failure [6]. The helium gas is typically circulated in a closed loop to reduce
helium usage and avoid the release of radioactive fission products [5].
FHD begins with a heating module on the FHD system increasing the gas temperature (150 – 260°C) entering the canister [5]. The heat from the circulating helium gas is transferred to the water molecules inside the canister, promoting evaporation and boiling. As water transitions to vapor, the dry circulating helium gas collects the water vapor and exits the canister [5]. The saturated helium gas then enters the FHD system and passes through a condenser module to condense the vapor back into liquid form [6]. This process continues to steadily remove bulk water from the canister until only water vapor is left circulating [6]. A demoisturizer module is then energized to cool the gas/vapor mixture temperature to -6°C [2]. This temperature corresponds to the partial pressure of water vapor at 3 Torr. The NRC accepts that the SNF canister contains less than 1 mole of water vapor (based on average commercial canister free volume) when the chilled gas temperature achieves -6°C for 30 minutes [2]. After the accepted drying crying has been met, the SNF canister is backfilled, sealed, and transferred to dry storage [6].

2.3 Forms of Waters (or Water Chemistry)

The intent of the drying process of SNF is to reduce the water content inside the canister to an acceptable level that complies with NRC regulations requiring SNF inside dry storage casks must remain in a retrievable state [1]. High levels of retained water poses the risk of unacceptable levels of corrosion as well as hydrogen build up from radiolysis. The free oxygen and hydrogen released from radiolysis recombine in the absence of residual air, which increases the radiolysis products generated [1]. High amounts of hydrogen gas (< 4% gas content inside canister) generated from radiolytic decomposition of residual water and corrosion could result in a flammable environment in the event the canister is opened [1]. The oxygen released from radiolysis is not enough to create flammable conditions as most of the oxygen is consumed by oxidation on the
fuel cladding and internal canister materials [1]. This oxidation poses as a risk on negatively affecting the structural integrity of the SNF. The several forms of water prevalent during SNF drying operations are unbound water, ice formation, physisorbed water, and chemisorbed water [1].

Unbound water is essentially trapped water in the form of a liquid or vapor that is not chemically or physically bound to a surface [11]. Unbound water can appear in pores, cracks, capillaries of CRUD, thin wetted surface films, and waterlogged breached rods [11]. A major concern related to unbound water is the formation of ice within the canister [1]. In vacuum drying, the internal canister pressure is lowered below the saturation pressure of the water. This is done to evaporate the liquid phase, as shown in Figure 2.2 [7]. During evaporation, it is expected the liquid water will undergo a temperature decrease due to the heat of vaporization of water, 539.6 cal/g, being substantially higher than its specific heat, 1 cal/g/°C [1]. Therefore, if the pressure is reduced rapidly inside the canister, the vaporization of liquid water will also occur rapidly. This increase in energy can remove a large amount of heat to cause the liquid water to freeze. Since the decay heat from commercial SNF is typically not capable of preventing ice formation, technical procedures such as hold points during vacuum drying are implemented to reduce the risk of freezing occurring by limiting the vaporization of water [6].

Physisorbed water is commonly found in SNF canisters, but it is the least concerning form of water. Typical water concentrations on external surfaces of the SNF and canister basket surface are approximately 0.03 – 0.05 g/cm² per monolayer [1]. With adequate drying techniques, the weakly bound water layer can be easily removed by heating the water layer to 50°C during vacuuming or FHD [1]. In contrast, chemically
bound water inside SNF canisters is far more difficult to completely remove. Chemisorbed water can exist as a hydrate or hydroxide that is often formed from water reacting with corrosion products on the fuel, cladding, or canister materials (e.g. hydrates of zirconium oxide) [11]. Although zirconium cladding was mostly used in this work, aluminum and stainless steel are also used as cladding material in the nuclear industry. Common hydroxides formed on aluminum-based fuel cladding are gibbsite ($\alpha$-Al(OH)$_3$), bayerite ($\gamma$-Al(OH)$_3$), and boehmite ($\gamma$-AlO(OH)) [1]. Stainless steel cladding corrosion is typically dependent on the chromium concentration [12]. If stainless steel cladding has low chromium concentration, iron oxides and hydroxides are formed. However, if the chromium content is high, the first oxide layer is formed by chromium oxide [12].

One primary concern is that chemisorbed water compounds can be decomposed during storage as a result of ionizing radiation and thermal energy. Radiolytic decomposition can also occur where the ionizing radiation breaks apart the water
molecules and potentially leading to hydrogen gas buildup inside SNF canisters [13]. A study on the decomposition of hydrated aluminum oxides and uranium oxides showed that vacuum drying to 3 Torr at 200 – 250°C will result in removing the chemisorbed water [14]. Another study demonstrated hydrated zirconium oxides formed from zirconium cladding can be dehydrated under vacuum conditions beginning at 150°C [11]. However, chemisorbed water may still be present after a typical drying process in the case of temperatures being high enough (greater than 150°C) for subsequent release of the water, but the duration of the drying process not being long enough [11]. This requires analysis to be conducted to show the residual chemisorbed water inside the canister will not result in negative effects and put the SNF at risk.

Temperature is generally not a controlled variable in commercial vacuum drying operations. Instead, drying temperature is a transient problem dependent on specific details of the vacuum drying process and the decay heat emitted by the SNF. This decay heat load is dependent on the fuel’s burnup and amount of time since the SNF has been withdrawn from the reactor. During vacuum drying, the temperature of the SNF is expected to increase due to conductive and radiative heat transfer. The NRC has mandated that the cladding temperature during SNF drying should not exceed 400°C to maintain the integrity of zirconium-based fuel cladding [2]. This maximum temperature was chosen based studies showing substantial hoop stress and creep strain is observed on zirconium fuel rods at temperatures higher than 400°C [2]. Studies have been conducted to estimate fuel cladding temperatures, but commercial facilities typically have minimal control during the vacuum drying operations to stay below the maximum allowable temperature. However, heat load limits are placed on canisters to prevent exceeding the
The respective licensed maximum allowable temperature for that canister [6]. The development of dewatering, blowdown, vacuum drying, and helium backfilling procedures have proven to decrease the time required to achieve adequate dryness [11]. This reduction in drying time mitigates the risk of exceeding the 400°C temperature limit.

In the case of commercial FHD, industry thermal models show fuel cladding and canister basket temperatures are controlled through the forced convection heat transfer induced by the recirculating heated helium [6]. The turbulent flow regime occurring during FHD operations ensures cladding temperatures will not exceed the recirculating gas temperature (150 – 260°C) [6]. This concurrent fuel cooling ability is why FHD is typically required for removing residual moisture inside canisters containing high burnup fuel (burnup < 45,000 MWD/MTU) with high decay heat [6].

2.4 Literature Reviews

In literature there are many works on the basis for vacuum drying and FHD, as well as their adequacy to remove water inside SNF canisters. Due to the complexity of both drying systems, evaluations have been made on typical water removal procedures to provide standard estimates of water remaining and temperature profiles. The potential for corrosion and radiolysis has also led researchers to investigate the impact of inadequate removal of water within the canisters. The studies discussed below highlights these endeavors and provides a foundation for further research to be conducted on vacuum drying and FHD.

The American Society for Testing and Materials (ASTM) C1553-16 “Standard Guide for Drying Behavior of Spent Nuclear Fuel” (2016) identifies adequate dryness during vacuum drying is achieved through a pressure rebound test, which requires the SNF canister to retain a vacuum below 3 Torr for at least 30 minutes. This indicates that
less than 1 mole of residual gas remains inside the canister. This approximation was based on BWR canister characterization test conducted by GE Morris with the REA 2023 SNF cask in 1985. The loaded canister was approximately 5 m-tall and 2.25 m in diameter, configured to hold 52 BWR SNF assemblies. The ASTM standard also explains in detail the expected forms of water and how they can be removed during vacuum drying and FHD. The standard indicates vacuum step and hold cycles are crucial in the prevention of ice formation. Types of chemically bound water and their process in forming inside the canister are also discussed. The development of neutron and gamma radiolysis are examined, as well as findings showing the hydrogen content should be limited to 4% to limit the flammable environment within SNF canisters. This standard does provide a general overview into the vacuum drying and FHD operations but does not specify the exact process that the commercial industry should follow for each operation [1].

Miller and others (2013) presented an overview of vacuum drying methods in the commercial industry to examine the differences among the vendors they visited. They discovered that vacuum drying systems and procedures from site to site are generally the same, including most of the equipment used in the facilities. Miller typically found that during vacuum drying the pressure is decreased in a stepwise manner using 3 to 7 hold points. This was done to prevent ice formation but also to provide confirmation that stable pressure measurements are being achieved. They did bring concern to the issue that ice formation could go undetected depending on the number of hold points and final pressure inside the canister, which results in a high quantity of residual water [3].
Miller also identifies possible locations where water could be difficult to remove such as breached cladding for a fuel rod so that the fuel has become waterlogged, guide thimble dashpots found in PWR fuel assemblies, water rods in BWR fuel assemblies, and spacer discs. Waterlogged fuel rods are rods filled with UO$_2$ fuel pellets that have cracks or pinholes in its zirconium cladding resulting in water filling the rod under high pressure conditions in the reactor. In PWR, guide thimbles are hollow tubes that provide the structural connectivity of the assembly tying together the bottom and top nozzles and grid spacers. They also provide adequate damping for fuel control rod insertion. These tubes have an open upper end and a closed bottom. The dashpot region refers to the bottom of the tube where the rod transitions to a smaller diameter. Water can egress through small holes that are located above the dashpot region. BWR water rods are larger hollow rods and typically occupy multiple rod locations, approximately four to nine lattice positions, near the center. These take the form of a square channel in some vendor designs. Water rods are utilized in BWR fuel assemblies for the purpose of additional moderation and have small holes which water could enter. Spacer discs (or grid spacers) are described as flat surfaces located in some canister designs between the canister wall and basket, providing structural support for basket sleeves. Spacer discs do have the potential to retain bulk water even after dewatering and blowdown [3].

Miller points out that at the time there has been no experimental tests conducted to measure the quantity of residual water inside the canisters at the conclusion of vacuum drying. This document serves as one of the main motivations for this thesis to experimentally evaluate vacuum drying procedure and quantify any water remaining following the completion of vacuum drying [3].
Ahn and others (2013) utilized an integration model to examine the extent of corrosion induced damage, hydrogen absorption, and conditions for flammability based on temperature, initial water present, and initial cladding oxidation. The transient model also accounted for rate of radiolysis and strength of internal radiation field to estimate what occurs for a given amount of residual water. Ahn found in the literature that following normal vacuum drying conditions there is approximately 1 to 5 moles of water (0.02 to 0.1 L) remaining inside the canister. They understood the uncertainties associated with quantifying the water following vacuum drying, so they decided to analyze the potential consequences if there were 5.5 to 55 moles of residual water. Results showed a flammable environment is expected for SNF that generates low heat and at 1 atm of backfill pressure. They also identified through the transient model that chemisorbed water and water in breach cladding contained majority of the remaining water following vacuum drying operation. Experimental testing was not conducted to validate the results found through the model [11].

Hurt (2009) utilized available literature and empirical data to observe the possible material interactions when assuming the canister is in dry interim storage for up to 50 years. Hurt goes into detail in calculating the amount of free water, physisorbed water, and chemisorbed water that may be present following drying operations. It is found that there are many uncertainties and unknowns to accurately determine the amount of physisorbed and chemisorbed water remaining. However, when considering a 15 ft-tall canister with an 18-inch diameter that was designed for a Type 1a basket, Hurt estimated less than 1 mL of water vapor will remain after drying. This basket design is used to dry and store aluminum-clad spent nuclear fuel (ASNF) assemblies from INL’s advance test
reactor (ATR). Hurt concludes that this is comparable to dried Multi-Canister Overpacks (MCO) that contained N-Reactor fuel, which are estimated to have 0.04 to 0.72 mL of residual free water. Note that the ASNF work discussed in chapter 6 also utilizes a Type 1a basket (1/3rd of the height) to experimentally dry mock ASNF assemblies [14].

Goode and others (2018) constructed a rig with an emphasis on comparing vacuum drying and FHD effectiveness in moisture removal. The work focuses on developing a method for drying stainless steel-clad fuels such as those used in the United Kingdom’s advanced gas-cooled reactors (AGR). They conducted experiments to measure the water content inside the drying rig during and after each drying operation. Results showed the drying rates for both methods were similar, but the team discovered FHD required a much more complex experimental setup. This was mostly due to FHD requiring an inlet gas temperature of 150°C. Therefore, Goode concluded, based on the initial work, that vacuum drying is more effective than FHD. Goode also stated that both methods can achieve complete dryness, but when accounting for energy usage, vacuum drying is shown to be even more advantageous than FHD. However, one drawback in Goode’s work is that off-the-shelf equipment was used to facilitate FHD operations. The FHD experiments were conducted at 15.75 psig with 150°C inlet gas temperature, but average commercial FHD operations are at 60 psig with 240°C inlet gas temperature. Additional work would need to be conducted to determine the impact on the change in FHD operating conditions [15].

Goode and others (2019) conducted additional vacuum drying tests to determine a true end point of the drying process. Experiments were operated on the same drying rig that they previously constructed for drying AGR fuel. The fuel geometry was ignored
when determining the end point of the drying process as experiments were conducted with small rod sections of AGR cladding without fuel. Thermocouples, dew point meters, pressures sensors, and flow meters were used to take online measurements so that dryness could be confirmed. Goode criticized the vacuum drying pressure rebound process because it only depends on remaining below 3 Torr for 30 minutes. They claim that commercial rebounds are cheating because they do not have to rely on the rate at which the pressure increases. Therefore, they can evacuate the canister to sufficiently low pressure so even though any water present is vaporizing, it is not enough to exceed 3 Torr in 30 minutes. During the experiments, they discovered that the mass flow rate was highly sensitive on such a small scale but could be useful in determining dryness on a commercial scale setup. Goode’s most notable observation was neither dew point nor pressure alone were able to determine the end point of the drying process. However, they discovered that confirmation of dryness can be achieved without rebound tests when the dew point is -10°C or less and the internal canister pressure is 3 Torr or less. The team also demonstrated rebound rates that would typically pass during commercial rebound tests would fail under their drying rig test conditions. This further shows that more work is needed to evaluate the drying adequacy of SNF canisters [16].
CHAPTER 3

EXPERIMENTAL SETUP

3.1 Test Facility and Chamber Design

A facility was constructed at the University of South Carolina to house a vacuum chamber, shown in Figure 3.1. This vacuum chamber was designed and fabricated to conduct vacuum drying and FHD experiments on a full-length mock LWR fuel assembly. The test stand built offered three different levels to accommodate the vacuum chamber and related equipment needed for vacuum and FHD. The chamber had four segments with a 1 ft-tall top section and three main sections at 5 ft-tall. Each chamber section had an inside diameter of 14-inch. The three main sections each had two large 10in diameter view ports on each side for a total of 12 view ports for monitoring and accessing the fuel assembly at various heights. The top section had eight ports for feedthroughs and instruments. Two of these ports served as vacuum ports and were taken up with the vent and siphon tube. The siphon tube was a 0.75-inch outside diameter tube that was designed to extend to the chamber bottom with a clearance of 0.1-inches. The bottom of the siphon tube had two 0.125-inch notches on each side to ensure water could enter the tube even if it sits on the chamber bottom. Vacuum ports were implemented to simulate industry SNF canisters and drying operations.
Figure 3.1. Constructed facility and test stand used to house the vacuum chamber designed for vacuum drying a full-length mock LWR fuel assembly.

Due to the size of the vacuum chamber, a wall cantilever jib crane was added to the facility to assemble the chamber segments and install the mock LWR full assembly. For ease of operations, the jib crane was mounted above and to the right of the test stand as seen in Figure 3.2. Lifting lugs were welded on to the chamber sections to provide a means to lift and position the sections in to place via the jib crane. The lifting lugs were also utilized as attachment points to the test stand to hold the chamber in the vertical position.
Each end of the chamber sections were made with a conflat flange design. This design allowed the sections to be connected and provide an all-metal seal with copper gaskets that was ideal for both drying operations. All ports on the vacuum chamber were made with a conflat flange design as well. A bottom flange was also added to provide a flat surface to represent the bottom of a canister. A diagram of the chamber sections, view ports, and vacuum ports is shown in Figure 3.3. A model and drawing of the siphon tube can also be seen in Figure 3.4.

Figure 3.2. Wall cantilever jib crane installed in the facility.
Figure 3.3. Diagram of vacuum chamber. View ports on main sections and ports on top section can be seen. Lifting lugs are also shown on the three main sections. Unit is inches.
3.2 Mock Fuel Assembly

One single, Atrium 10A, BWR 10x10 assembly with full dimensions was designed by Areva (now Framatome) to be utilized in the vacuum drying and FHD experiments. The Atrium 10A mock used fuel assembly, shown in Figure 3.5, is loaded
primarily with simulated fuel rods of depleted uranium (DU) in its lattice positions. Note that Figure 3.5 is used only as a reference to the components in the Atrium 10A BWR assembly design. The experimental Atrium 10A assembly used for the drying experiments had no part length fuel rods nor did the LWR fuel assembly have empty lattice positions.

![Diagram of Atrium 10A BWR fuel assembly](image)

Figure 3.5. Illustration of the typical Atrium 10A BWR fuel assembly design by Areva.

The positions that were not filled with the DU rods were filled with 12 heater rods and an interchangeable test rod position located in one corner. Heater rods were utilized to simulate the decay heat that would be emitted from SNF in commercial drying process. The interchangeable rod position was used to evaluate single effects of key features such
as a plugged BWR water rod, a PWR guide thimble with dashpot, and a simulated failed fuel rod filled with ceria pellets used as a surrogate for UO$_2$. Figure 3.6 shows a top view of the fuel assembly configuration where the DU rods are red, heater rods are light blue, interchangeable test rod is green, and the water channel for the assembly is orange.

![Figure 3.6. Illustration of mock fuel assembly lattice positions. Red circles indicate DU rods, light blue indicates heater rods, green indicates the interchangeable test rod location, and the orange box indicate the water channel for the Atrium 10A.](image)

Custom fabricated stainless-steel basket and rails were installed in the vacuum chamber to hold the assembly within the chamber. Basket and rails simulate the internal structures utilized in commercial SNF canister in which the basket serves to hold the assembly in the canister and the rails keep the basket structure in position. An aerial view drawing of the vacuum chamber loaded with the mock LWR fuel assembly, basket, and
rails is shown in Figure 3.7. The process in which the basket and rails were loaded into the chamber followed by the fuel assembly can be seen in Figure 3.8 as well.

Figure 3.7. Drawing of the vacuum chamber showing the loaded fuel assembly surrounded by the basket (blue) and rails (yellow).
A key feature about the internal structures was cutouts made to the BWR channel, basket, and rail. One corner of the BWR channel was cut away to expose the interchangeable rod and adjacent DU rods on either side. This was done at each of the six view port locations along the assembly. Each cutout was about 8-inches in height. Similar cutouts were made to the basket and rails at the same location of the BWR channel cutouts. This allowed for the corner rods, including the interchangeable test rod, to be visually inspected and monitored through the view ports. Cutouts of basket and rails on opposite corner were also made for thermocouple measurements.

Once the LWR fuel assembly was loaded into the chamber, it was seated on a stainless-steel pedestal, shown in Figure 3.9, that was about 12-inches in height and located at the bottom of the chamber. The design was a cylinder beneath the assembly
sitting on a square plate. The pedestal provided an attachment and grounding for the heater rods which were screwed into the plate at the bottom illustrated in Figure 3.10. Seating the assembly on the pedestal also elevated the assembly to provide the necessary offset and positioning of the heater rods in the assembly to give the correct elevation for the heated length of the heater rods. Simply for grounding the heater rods, a grounding strap was attached to the pedestal plate at one of the corners and attached to a high current feedthrough on a 2.75-inch conflat flange next to the bottom view port. The grounding strap attached to the pedestal can be seen in Figure 3.11.

Figure 3.9. Stainless-steel pedestal for the BWR fuel assembly. Holes on the bottom plate are used to screw the heater rods into.
3.2.1 BWR Water Rod

Water rods are larger and typically occupy multiple rod locations (maybe four to nine lattice positions) near the center of an assembly. In some vendor designs these take the form of a square channel. These are utilized in BWRs for the purpose of additional
moderation. Water rods are manufactured to be hollow with weep holes to allow coolant (water) to flow freely during reactor operation. However, the bottom of the rod is closed, allowing water to be trapped up to the rod’s lowest weep hole at the start of drying operations. Therefore, these rods could contain a considerable amount of water in addition to water that may be absorbed onto the surfaces. In the experiments, a single rod (full-length) was used in the interchangeable rod position. The BWR water rod was fabricated with Zircaloy-4 (Zr-4) containing a slit near the top of the rod to simulate the open top of water rods and a cap at the bottom of the rod to simulate the closed bottom. The design called for weep holes at two sets of opposing holes at right angles located 1796.3 mm from rod bottom. This allowed the simulated water rod to hold approximately 110 mL of water up to the height of the lowest set of weep holes. Figure 3.12 shows the design of the simulated BWR water rods used for testing.

Figure 3.12. Design of the simulated BWR water rod.

3.2.2 PWR Guide Thimble with Dashpot

In PWR fuel assemblies, guide thimbles tie together the bottom and top nozzles and grid spacers to provide structural connectivity for the fuel assembly. These are hollow tubes with closed bottoms. Water can egress through weep holes drilled in the sides as low as perhaps 30 cm (~12-inches) from the bottom. Like the BWR water rod, a
single rod (full-length) was used in the interchangeable rod position to simulate a PWR guide thimble. The custom fabricated Zircaloy-4 (Zr-4) guide tube required a slightly smaller than typical diameter to fit within the mock LWR fuel assembly. The guide thimble dashpot was simulated similarly to the BWR water rod with similar situated weep holes but at heights of 400 mm from the rod bottom. Approximately 24.6 mL of water can be held in this rod up to the height of the lowest set of weep holes. This was more than four times less than the water held in the simulated BWR water rod and therefore expanded the range of conditions and challenges evaluated for SNF drying. The lowest pair of weep holes were aligned with the center of a view port and arranged in a manner so that one weep hole directly faces the view port for monitoring. Design of the PWR guide thimble with dashpot is illustrated in Figure 3.13.

Figure 3.13. Design of the simulated PWR guide thimble with dashpot.

3.2.3 Failed Fuel Rod

This study utilized a simulated failed fuel rod by machining a 1 mm diameter hole that was a characteristic of a grid to rod fretting failure on the cladding. This failure geometry is considered more difficult to remove water from the waterlogged rod and thus provides a limiting case for experimentation. The hole was machined to a larger size for additional experiments conducted in this work to simulate a larger failure. The defect
hole was placed at a height of 1796.3 mm from the rod bottom so as not to be occluded by a spacer grid and therefore permit direct observation by monitoring tools. A Swagelok threaded fitting, at the top of the rod, permitted a prescribed amount of water to be added to the rod and allowed for the insertion of simulated fuel pellets. Manufactured ceria (CeO$_2$) pellets were used to fill the rod to simulate UO$_2$ fuel. These pellets were held down by a spring at the plenum inside the failed rod. Ceria had been used as a surrogate for UO$_2$ and PuO$_2$ and had similar properties of UO$_2$ which can be seen in Table 3.1. The pellets, however, were intact CeO$_2$ rather than the reality of highly fractured UO$_2$ pellets (with fission products) which would have been oxidized to U$_3$O$_8$ in a commercial failed rod. This oxidation results in substantial volume increase which causes the pellet to fragment into small particles. A drawing of the simulated failed fuel rod design can be seen in Figure 3.1.

Table 3.1. Surrogate material for CeO$_2$ for UO$_2$.

<table>
<thead>
<tr>
<th></th>
<th>UO$_2$</th>
<th>CeO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Structure</td>
<td>Fluorite</td>
<td>Fluorite</td>
</tr>
<tr>
<td>Lattice Parameter (Å)</td>
<td>5.47</td>
<td>5.41</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>10.97</td>
<td>7.215</td>
</tr>
<tr>
<td>Melting Temperature ($^\circ$C)</td>
<td>2865</td>
<td>2600</td>
</tr>
<tr>
<td>Thermal diffusivity ($m^2s^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 600$^\circ$K</td>
<td>1.82x10$^{-6}$</td>
<td>1.96x10$^{-6}$</td>
</tr>
<tr>
<td>@ 1000$^\circ$K</td>
<td>1.15x10$^{-6}$</td>
<td>1.15x10$^{-6}$</td>
</tr>
</tbody>
</table>
3.3 **Heater Rods**

Heater rods were required to raise the temperature of the mock LWR fuel assembly and hardware to simulate the role of decay heat in the drying process. The heater rods passed through the fuel assembly spacer grids and screwed into the pedestal structure previously mentioned. They penetrated the top of the chamber through a cooling gland structure and protruded above the chamber about 610 mm. The cooling gland was centered on top of the top flange and was sealed by a conflat flange. The cooling gland had penetrations for the heater rods which were sealed by a double set of O-rings (type 5-212). Vacuum grease (or petroleum jelly) provided lubrication and a means for the rods to be raised and lowered through the cooling gland. The rods had potential to axially expand up to four inches during heat up. Cooling water was flowed through the cooling gland to prevent thermal damage to the O-rings during operation. A larger cylindrical opening in the cooling gland was designed for the interchangeable rods to be inserted into the corner rod position of the LWR fuel assembly. The cooling gland and penetrations for the heater rods and interchangeable rods are shown in Figure 3.15.

![Figure 3.14. Design of the simulated failed fuel rod with designed defect hole.](image-url)
Figure 3.15. Cooling gland for vacuum chamber indicating penetrations for the heater rods and interchangeable rods.

### 3.3.1 Decay Heat Calculation

The range of decay heat that was simulated in the experiments using the heater rods was found through decay heat calculations. The analysis was based on the design of the mock LWR fuel assembly used in the experiments and the assembly containing approximately 200 kg of depleted uranium. Origen-ARP was used to calculate the decay heat for an equivalent amount of used UO$_2$ fuel with a discharge burnup of 58 MWD/kg. The decay heat as a function of cooling time is shown in Figure 3.16. The decay heat falls off so that after 27 years the decay heat is slightly less than 0.3 kW. Therefore, a lower limit of the decay heat for this experiment was chosen to be 0.25 kW. After about 3 years cooling the decay heat for this assembly would be approximately 1 kW which was thus chosen as an upper limit for drying tests. Simulating higher decay heat (< 1 kW) was possible as each heater rod was capable of 5 kW. Results from the decay heat calculations can be seen in Table 3.2.
Table 3.2. Decay heat evaluated for different cooling periods for used fuel with a discharge burnup of 58 MWD/kgU.

<table>
<thead>
<tr>
<th>Days</th>
<th>Years</th>
<th>Heat (Watt) for 1 MTU</th>
<th>Heat (Watt) per Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>2.7</td>
<td>4925</td>
<td>985</td>
</tr>
<tr>
<td>3000</td>
<td>8.2</td>
<td>2348</td>
<td>470</td>
</tr>
<tr>
<td>10000</td>
<td>27.4</td>
<td>1454</td>
<td>291</td>
</tr>
</tbody>
</table>

Figure 3.16. Decay heat as a function of cooling time for an assumed burnup of 58 MWD/kg (Note: data is evaluated for a reference 1000 kg heavy metal, adjust to total fuel mass in reference assembly).

Each heater rod was equipped with up to 8 type K thermocouples placed at varying heights along the entire rod length. Twelve heater rods were available in experiments. Eight rods (two near each corner) were used for heating. The four other rods were located further inward and were used only for measuring temperature in the inner mock LWR fuel assembly. The simulated decay heat was the total decay heat for the assembly. For example, a decay heat of 1 kW was achieved through each of the eight
powered rods being set to 125 W. The eight powered heater rods followed a cosine shaped power distribution seen in Figure 3.17. This heating distributing was atypical as commercial SNF assemblies follow a flat line peaking factor with sharp drop offs at the top and bottom of the assembly.

Figure 3.17. Power profile for the heater rods used during drying tests.

3.4 Canister Features

Several canister design features provide opportunity for water to be retained or present a challenge in drying. For this work, as previously mentioned, the bottom of the chamber was a flat surface. During flooded tests, some residual water remained here following dewatering and blowdown steps. These steps are explained in greater detail in chapter 5. The bottom of the chamber presented a slightly greater challenge for drying because of the low decay heat emitted at the top and bottom of the assembly due to the cosine shaped power distribution for each heater rod shown in Figure 3.17. The LWR
assembly’s 12-inch pedestal, previously mentioned in chapter 3.2, also created further separation from the heated length of the heater rods to the bottom of the chamber. Although the lack of heat at the bottom of the chamber was a concern for the LWR setup, Figure 3.18 shows the mock basket and rails were scalloped at the bottom to accommodate water removal and avoid water entrapment.

Figure 3.18. Illustration of the scalloped cutouts in the basket (blue) and rail (yellow) bottom structures. The radii of the cutouts are 1” (wings of rails) and 2” (main basket).

Grid spacers within the experimental mock LWR assembly allowed for water to be held in connection with the rods. Furthermore, some canister designs incorporate spacer discs between the canister wall and basket sleeves. To evaluate this feature, tests were conducted with a simulated spacer disc that holds approximately 27 mL of water. The spacer disc was a stainless-steel tray that was cut in half and placed at a slight angle to allow water to be collected. A flat stainless-steel plate was placed above the simulated spacer disc to remove temperatures in thermal imaging reflected from the assembly to the bottom of the tray. The assembly reflections caused thermal imaging to display an inaccurate temperature of the water inside the spacer disc. For testing, the simulated
spacer disc was placed inside the second to bottom view port (view port 2) and against the corner test rod. The spacer disc seated inside the vacuum chamber can be seen in Figure 3.19.

![Simulated spacer disc seated inside the vacuum chamber view port.](image)

Figure 3.19. Simulated spacer disc seated inside the vacuum chamber view port.

In all tests, the entire vacuum chamber was monitored by measurement and sensing equipment. The purpose of the monitoring equipment was to analyze drying techniques and to measure the amount of water remaining in the canister following vacuum drying and FHD. Such equipment is typically not used in commercial drying systems. The following section will discuss the equipment used in this study.
CHAPTER 4

INSTRUMENTATION AND AUXILIARY EQUIPMENT

4.1 Monitoring Equipment

The instrumentation used in this study was designed and installed to provide continuous monitoring for the duration of the drying experiments. The variables monitored were temperature, pressure, relative humidity, and gas flow rate. Infrared thermal cameras were used for imaging temperature monitoring at points of interest through the view ports. Supervisory data logging was performed by using National Instruments (NI) hardware and LabView data acquisition. A redundant measurement strategy was employed to maintain high confidence in the measurements. The measurements, such as the state in the chamber, were cross checked by multiple sensors and relationships between variables.

4.1.1 Sensors

Multiple pressures sensors were attached to the vacuum chamber as well as the vacuum line to measure the pressure throughout the drying process. Precise absolute pressure measurements were achieved by using a range of sensors that were accurate at high and low pressures. The pressure sensors used were the MKS 902B Piezo transducer (0.1 to 1000 Torr), the MKS 628F Baratron manometer (0 to 2000 Torr), and the MKS 722B Baratron manometer (0 to 2000 Torr). Teledyne 760 hasting gauge and vacuum transducer pressure sensors were also used. Again, multiple sensors were used to ensure
data redundancy during drying. In some cases, a pressure sensor for low pressure was sometimes exposed to high pressures, even when it was not operating.

Water mass flow (removal) rates were measured during drying operations using two sets of mass flow meters located upstream and downstream of a desiccator. Understanding the desiccator removed the water vapor, these measurements were combined with gas temperature, relative humidity measurement, and optical emission spectroscopy (OES) measurements to determine the water removal rate. While this setup and instruments are not used in typical industry practice, these added features were important to obtain the water removal rate for use in validating mechanistic models to be developed in this effort. The mass flow of water and the state of the chamber were monitored during the drying tests to provide a complete picture of the drying process.

The mass flow meters used were two Brooks MF63S (high flow) and two Brooks 5860 (low flow) and were calibrated for Helium since it was the gas used during operations. The original design was to have mass flow meters with different operating ranges in parallel to have the ability to switch flow meters during the vacuum drying process. However, due to flow restrictions from the two Brooks 5860 during low flow rate, only the Brooks MF63S were used during all drying experiments.

Relative humidity sensors (Vaisala HMT 334) were placed on the chamber and after the desiccators. These sensors were used with the flow meters and OES to provide information on water content in the gas necessary for computing the water removal rate as a function of time. Dew point readings were also calculated using the sensors’ gas temperature and humidity measurements. A conflat flange design was used to attach one of the relative humidity sensor probes to the chamber. A quick flange design, utilizing a
Viton O-ring for sealing, was used to attach the other relative humidity sensor probe on the vacuum line after the desiccators. Attaching one of the relative humidity probes directly to the vacuum chamber allowed for vapor content monitoring while the chamber was isolated. Measuring sensors used during testing are listed in Appendix A along with their operating ranges.

4.1.2 Thermocouples

The temperature throughout the chamber was measured by type K thermocouples installed (welded) via a spot welder radially from the center of the assembly and vertically capturing temperature gradient information in three dimensions. All thermocouples were calibrated prior to installation for accurate temperature measurements. For calibrating a thermocouple, the generated voltage was collected at several reference temperatures covering all the possible conditions from -50°C to 400°C. A mathematical tool (MATLAB) was then used to fit a polynomial function to connect voltage and temperature. The coefficients found was stored in the LabVIEW program to complete the calibration for the thermocouples.

As mentioned previously, the heater rods contained thermocouples for measuring the internal temperature of the fuel assembly. The locations of the heater rods were in the positions identified in Figure 4.1. In the figure, blue indicates heater rods, green indicates test rod position, and all remaining rods are depleted uranium rods (red). Those depleted uranium rod positions not marked red are normally obstructed at the top by fuel assembly hardware. Table 4.1 provides the axial thermocouple layout for three types of heater rods used in experimental drying tests. The axial location of each thermocouple was determined by the measured distance, in inches, from the bottom of the chamber. The
thermocouple placement was the only distinguishable difference between the three types of heater rods. For the type 4 rod shown in Figure 4.1, there were no thermocouples attached.

Table 4.1. Location of thermocouples attached to each heater rod.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Color</th>
<th>type 1</th>
<th>type 2</th>
<th>type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Black</td>
<td>162.85</td>
<td>117.85</td>
<td>97.85</td>
</tr>
<tr>
<td>G</td>
<td>Red</td>
<td>151.85</td>
<td>109.85</td>
<td>87.85</td>
</tr>
<tr>
<td>F</td>
<td>Silver</td>
<td>137.85</td>
<td>97.85</td>
<td>77.85</td>
</tr>
<tr>
<td>E</td>
<td>Blue</td>
<td>129.85</td>
<td>93.85</td>
<td>68.85</td>
</tr>
<tr>
<td>D</td>
<td>Yellow</td>
<td>117.85</td>
<td>87.85</td>
<td>57.85</td>
</tr>
<tr>
<td>C</td>
<td>Green</td>
<td>109.85</td>
<td>77.85</td>
<td>48.85</td>
</tr>
<tr>
<td>B</td>
<td>Purple</td>
<td>97.85</td>
<td>73.85</td>
<td>32.85</td>
</tr>
<tr>
<td>A</td>
<td>Orange</td>
<td>87.85</td>
<td>68.85</td>
<td>12.85</td>
</tr>
</tbody>
</table>

Figure 4.1. Illustration of the mock fuel assembly heater rod pattern. Heater rod number prefix indicates rod type, and second part indicates specific rod.
Other than the thermocouples welded on the heater rods, additional thermocouples were used to measure the temperature of different locations inside the chamber during drying operations. The thermocouples were attached at six locations along the chamber at each of the different viewports diagrammed in Figure 4.2. The locations of these thermocouples are shown in Table 4.2. Since the basket, rails, and BWR channel were cut out at all six front facing viewports, a thermocouple was attached to the basket and to the rails shown in Figure 4.3. For rear facing viewports (180 degrees opposite the front facing), one thermocouple was attached to the BWR channel at each of the 6 viewports (basket and rails only are cutout at rear facing viewports). The spot welder, displayed in Figure 4.4, was used to firmly attach the thermocouples at each location. The junction of the thermocouple was first welded. Then, the thermocouple was calibrated and welded on the location of interest. This process was repeated for all welded thermocouples.

Table 4.2. Axial location of additional thermocouples inside the chamber at different viewports.

<table>
<thead>
<tr>
<th>Viewport</th>
<th>Location</th>
<th>Relative to chamber bottom (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP6</td>
<td>Basket</td>
<td>152.5</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>152.5</td>
</tr>
<tr>
<td></td>
<td>BWR channel</td>
<td>152</td>
</tr>
<tr>
<td>VP5</td>
<td>basket</td>
<td>132.1</td>
</tr>
<tr>
<td></td>
<td>rail</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>BWR channel</td>
<td>133</td>
</tr>
<tr>
<td>VP4</td>
<td>basket</td>
<td>106.4</td>
</tr>
<tr>
<td></td>
<td>rail</td>
<td>106.5</td>
</tr>
<tr>
<td></td>
<td>BWR channel</td>
<td>107</td>
</tr>
<tr>
<td>VP3</td>
<td>basket</td>
<td>83.2</td>
</tr>
<tr>
<td></td>
<td>rail</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>BWR channel</td>
<td>82.5</td>
</tr>
<tr>
<td></td>
<td>VP2</td>
<td>VP1</td>
</tr>
<tr>
<td>--------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>basket</td>
<td>27.5</td>
<td>8</td>
</tr>
<tr>
<td>rail</td>
<td>27.5</td>
<td>8.1</td>
</tr>
<tr>
<td>BWR channel</td>
<td>27.8</td>
<td>Chamber Bottom (moved to siphon tube after 5/31/17)</td>
</tr>
<tr>
<td>Siphon tube (after 5/31/17)</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.2. Identification of the six view ports on the vacuum chamber.
Figure 4.3. Thermocouples for one viewport attached to the basket and rail (left) as well as the channel (right).

Figure 4.4. Spot welder (left) and an example of spot-welding thermocouple on stainless steel sheet (right).

Modifications were made to the chamber to install thermocouples, heating tape, and insulation on the outside of the chamber to control the chamber wall temperature. The locations of these thermocouples are given in Table 4.3. All thermocouples on the chamber wall and piping were attached using Kapton tape. Spot welding was not conducted as to not damage the chamber or piping wall.
Table 4.3. Location of the exterior chamber wall thermocouples.

<table>
<thead>
<tr>
<th>Location</th>
<th>Relative to Chamber Bottom (inch)</th>
<th>Relative to the Test Rod Clockwise (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP1-VP2</td>
<td>18</td>
<td>270</td>
</tr>
<tr>
<td>VP2-Flange</td>
<td>44</td>
<td>270</td>
</tr>
<tr>
<td>Flange-VP3</td>
<td>73</td>
<td>270</td>
</tr>
<tr>
<td>VP3-VP4</td>
<td>97</td>
<td>270</td>
</tr>
<tr>
<td>VP5-VP6</td>
<td>145</td>
<td>270</td>
</tr>
<tr>
<td>VP6-Top of Chamber</td>
<td>166</td>
<td>270</td>
</tr>
<tr>
<td>Chamber Inlet</td>
<td>189</td>
<td>270</td>
</tr>
<tr>
<td>Chamber Outlet</td>
<td>189</td>
<td>270</td>
</tr>
</tbody>
</table>

4.1.3 FLIR Thermal Cameras

Special imaging for temperature and water state monitoring was achieved with two FLIR A325sc infrared thermal cameras. These cameras provided continuous temperature measurement over an area of interest such as failure locations induced in the fuel rod and water weep holes. Thermal cameras were also placed at and near grids to understand the grids influence in the test chamber. Thermocouples were used to calibrate the thermal camera. The 10-inch view ports had a special Zinc Selenide (ZnSe) 2.75-inch conflat flange view port to minimize optical effects on temperature accuracy. ZnSe view ports, shown in Figure 4.5, were used to pass LongWaveIR between 0.3 – 17 um to the thermal camera. The spectral range of the infrared thermal camera was 7.5 – 13 um. Figure 4.6 shows the thermal camera mounted to the view port using a unique mount that
was designed for the thermal cameras. Type K Thermocouples were also placed in the field of view of the thermal camera as a redundancy check which could be seen in Figure 4.7. The instrumentation was tested for repeatability by performing multiple benchmark tests to identify instrumentation sensitivities and establish confidence intervals on measurements.

Figure 4.5. Zinc Selenide view port on the vacuum chamber for IR camera transmission.

Figure 4.6. FLIR A325sc infrared thermal camera mounted at the view port.
Figure 4.7. Thermal image of the PWR Guide Tube during testing (Top) with corresponding picture of the fuel assembly and partially cut away basket and rails (bottom).

4.2 Data Collection with LabView Data Acquisition

The data collected from each sensor and monitoring equipment was aggregated and examined for statistical trends, cross-correlation, regression models, spectral content, and joint time-frequency analysis. All the data was brought into a single data collection hub called LabView. A National Instruments PXI real-time controller was used to gather all monitoring data captured during vacuum drying and FHD experiments. The modules and chassis used for testing is shown in Figure 4.8.
Figure 4.8. National Instruments PXI chassis with real-time controller and data acquisition cards used for instrument monitoring during drying tests.

The National Instruments PXI platform in Figure 4.8 uses a PXIe-1085 Chassis (18-slot) with an integrated real-time hard drive controller along with hardware cards including analog input, 2 analog outputs, 4 thermocouple inputs, a multifunction DAQ, 6 ethernet ports, and a relay driver module. Such a setup accommodated 2 FLIR thermal cameras via the NI PXIe-8234 two ethernet ports. Also, 8 heating rods were capable of being powered and monitored using the NI PXIe-4322 and NI PXIe-4302. All data pressure sensors, relative humidity sensors, and mass flow meters were monitored using the NI PXIe-4302. Potential noise effect issues were addressed for the sensors used as they were relayed through a noise rejecting block, SCB-68A, that was wired to the PXI. The pressure sensors were powered using a Rhino PSE15-230 and the mass flow meters were powered by a Rhino PSE24-115. The relative humidity sensors were connected directly to an outlet to operate. Up to 128 thermocouple slots were available in the four NI PXIe-4353 cards to record temperature data from all the installed thermocouples in the system. Lastly, pneumatic valves that were utilized in the drying system were controlled using a NI PXI-2567 relay driver module that triggered solenoid Mac Valves.
that were connected to the pneumatic valves via air compression. The test stand used to house the PXI chassis and modules is shown in Figure 4.9. Not shown in the image is the computer that was utilized in operating LabView data acquisition software to actively monitor and control vacuum drying tests.

Figure 4.9. National Instruments PXI chassis and modules test stand used for testing.

Figure 4.10 shows the design that was used to control the power of the heater rods. The desired power setpoint controlled the power to each rod. The difference in the desired power and the measured power results in an error. This error was sent into the controller (proportional and integral) which sent a signal to the DC driver. The power output of the DC driver was sent through the watt transducers to the heater rods. The watt transducers measured the power sent to the rods. The actual power sent to the rods was then adjusted based on the control scheme to maintain the heater rod power at the desired setpoint. This strategy controlled the power of each heater rod individually at the desired level. In addition, the heater rods could be controlled based on the desired temperature by
using thermocouple feedback instead of power feedback. Figure 4.11 shows the experimental setup for this control system.

![Figure 4.10. Block diagram used to illustrate the control for heater rods.](image1)

![Figure 4.11. Experimental setup for power supplies (DPP480-48-1), DC drivers (GSD1-48-20C), and PC8 Series DC watt transducers (PC8-002-08DY05).](image2)
CHAPTER 5

METHODOLOGY

5.1 Vacuum Drying Equipment

As mentioned in chapter 2, drying systems in the commercial industry overall consist of flexible steel vacuum piping connecting the vent and siphon port to an inert gas tank and vacuum pump, respectively. The canister is connected to the vacuum pump through a series of valves and pressure gauges with a water/condensate trap aligned to prevent damage to the pump. The vacuum drying experiments conducted in this study utilized typical industry equipment and components in order to follow the standard industry practice previously mentioned. The following subsections detail the equipment and components used in the vacuum system along with general explanations of its function and operation during vacuum drying tests.

5.1.1 Pumps

Commercial vacuum drying process begins with dewatering. As mentioned previously, the process of dewatering involves pumping bulk water out of the SNF canister using a centrifugal pump. To mimic this step, a centrifugal pump was utilized in this study. Industry specifications call for a pumping rate of approximately 20 gpm, but this could be scaled down for experiments due to the size comparison of a SNF canister to the test chamber. The Dayton 2ZXT3 centrifugal pump, shown in Figure 5.1, was chosen to achieve a minimum 10 gpm pumping rate during dewatering. The quick flange
connections (KF25) made to the dewatering pump, allowed for the pump and dewatering line to be easily primed with deionized water before operating the pump. The design called for the dewatering pump to be located on the third level of the test stand.

Figure 5.1. Dayton 2ZXT3 Centrifugal pump used for dewatering. The pump’s inlet and outlet connections made to the siphon line and dewatering tank, respectively, are identified. Clear 1in ID PVC tubing was used for the dewatering line.

A Leybold Sogevac SV 300B is a typical main vacuum pump used for drying full canisters. This rotary vane pump offers a maximum pumping speed of 240 m³/h and an ultimate pressure limit of approximately 0.07 Torr. For this study, an Edwards E2M12 Mechanical Pump was chosen given the comparison between the scaled down test chamber to a full-size canister. The Edwards Pump sufficiency for this vacuum drying setup came from its maximum pump displacement of 17 m³/h. Water vapor contamination inside the pump was prevented by opening the pump’s ballast when initially evacuating the chamber. The design called for the vacuum pump to be located on the third level of the test stand. Figure 5.2 shows the E2M12 vacuum pump used for testing with vacuum pipework attached to the pump. Some industrial designs incorporate a roots blower (or booster pumps) on the inlet side of the main vacuum pump. Booster pumps are operated at low pressures to increase pumping speed and efficiency. However,
a boost pump was not implemented in this study as it was not required nor thought to have been necessary for the drying tests given the chamber size comparison to a commercial canister.

![Edwards E2M12 vacuum pump used for vacuum drying tests.](image)

**Figure 5.2.** Edwards E2M12 vacuum pump used for vacuum drying tests.

### 5.1.2 Piping, Valves, and Connections

Vacuum pipework in commercial systems often consist of flexible wire reinforced steel tubing, typically with a 1-inch ID. These flexible vacuum hoses are rated for high temperature and its flexibility accommodates for various setup requirements in the industry. For this study, 1-inch ID wire barbed PVC tubing was implemented for the dewatering and blowdown line to observe the bulk water removed prior to vacuum drying operations. Water from dewatering and blowdown traveled through the PVC tubing to a 130-gallon open tank, shown in Figure 5.3, located on the ground floor. The open tank was used to hold the water that had been in contact with the mock fuel assembly until chemical wipe tests, with liquid scintillation counter, showed no contamination.
Figure 5.3. Plastic open tank (130-gallon) used to hold water removed during dewatering and blowdown. Drainage line connecting to the dewatering pump’s outlet is identified. Not shown: the plastic tank’s drainage valve used to empty the tank.

All pipework on the drying system was connected using either Klien Flange/Quick Flange (KF/QF) or Conflat Flange (CF) connections. KF connections were sealed using clamps and viton O-rings that were reusable and bakeable to 200°C. The CF connections provided a full metal seal using copper gaskets, a bolted flange, and a knife-edge flange to cut into the gasket giving a tight seal. A majority of the vacuum and dewatering lines utilized piping with KF25 fittings which had a 1-inch ID. However, the siphon and vent port as well as some instruments in the vacuum line required 1.33CF connections that had a 0.75-inch ID. Various elbows, tees, and crosses with KF25 and
1.33CF fittings were also implemented throughout the system to accommodate the experimental setup.

One of the most important connections throughout the vacuum and dewatering line was the vacuum valves. This study employs both manual and pneumatic valves to enable the capability of opening and closing sections throughout the drying system. Manual valves were only used in this system for sections that required frequent disconnections from the pipework and places that required valve throttling to simulate industry procedure. Figure 5.4 shows several manual valves that have been installed in the vacuum piping.

![Vacuum pump](image)

**Figure 5.4.** Snippet of vacuum pipework utilizing three KF25 manual valves. Vacuum pump used for drying test is identified.

In general, pneumatic valves were controlled using compressed air. For this study, the valves were connected to Mac solenoid valves (35A Series) via air compression tubing shown in Figure 5.5. As seen in the figure, these solenoid valves were linked together to form manifolds that connected to a Kobalt 20-gallon, single stage, vertical air
compressor. Its wires were individually wired to the PXI system to allow the operator to quickly trigger the valves open or close through LabView. A total of 20+ vacuum valves were installed throughout the vacuum system. This ultimately gave the operator full control of various tasks such as isolating the chamber, bypassing equipment, sealing sections off, etc.

Figure 5.5. Mac solenoid valves (35A Series) manifolds used to trigger the pneumatic valves implemented in vacuum and FHD pipework.

Helium gas was chosen for this study to serve as the inert gas necessary for filling and purging the vacuum chamber. Helium tanks were stored and secured on the ground level of the facility. Regulators were connected to the tanks to control the gas flow between 0 to 100 psi. Stainless steel 0.25-inch OD Swagelok tubing was attached to the helium tanks, seen in Figure 5.6, and traveled up to the second level to tap into the vacuum pipework. This helium fill line was opened and closed using a 0.25-inch OD Swagelok manual valve and a KF25 pneumatic valve, which is shown in Figure 5.7. Both valves offered an ease of operation for the test operator given the PXI stand was on the third level. Swagelok tubing and adapters were also used to connect the OES system to the chamber and create the OES line. Multiple manual Swagelok valves within the OES
line allow the operator to efficiently entrap and measure a gas sample from the chamber.

The OES line’s connection to the chamber can be seen in Figure 5.8.

Figure 5.6. Helium tanks used for testing with gas regulator and Swagelok tubing attached.

Figure 5.7. Helium fill line connection to drying system with a 0.25-inch OD Swagelok manual valve and a KF25 pneumatic valve.
5.1.3 Desiccators

Commercial condensate traps were simulated by using desiccators that were implemented into the pipework to protect the vacuum pump from becoming saturated with water. The desiccators were filled with Zeolite desiccant as it offered the best performance under vacuum conditions and capable of being regenerated. Regeneration was a means of heating the desiccators while subjecting the desiccant to vacuum conditions to remove the absorbed water. Six desiccators were custom built to allow for increased drying performance and the ability to regenerate the desiccators after each test. Each desiccator had KF25 manual valves on each side for easy disconnection from the vacuum line, which can be seen in Figure 5.9. The vacuum line also consisted of KF25 manual valves to isolate the desiccators and to prevent air leaking in the system. Quick disconnection was crucial since the desiccators were frequently cycled during

Figure 5.8. OES line’s connection to the chamber with a Swagelok manual valve to isolate the OES line from the chamber.
experimental tests. A flow option to bypass the desiccators during dewatering and blowdown was also implemented.

![Figure 5.9](image_url)

Figure 5.9. Front view of the desiccators installed in the vacuum line. Inlet and outlet for each desiccator is identified.

The preceding regeneration procedure stated above relies solely on heat conduction from the outside surface of the desiccator. Given that the desiccant inside was made up of small spheres of material, the conduction heat transfer was shown to be inefficient. A heat transfer medium was required. Therefore, helium gas was chosen due to its availability in the facility as well as its superior heat transfer characteristics. The regeneration station used to regenerate the desiccators is shown in Figure 5.10 with one end of the desiccators attached to helium gas and the other end attached to a pump. The desiccators were evacuated using a vacuum pump after flowing helium for several hours. After employing this new procedure there were improvements seen from the desiccators
taking longer to become saturated during tests. Figure 5.11 observes the significant amounts of bulk water draining from each desiccator during regeneration.

![Image](image1.png)

**Figure 5.10.** The regeneration station with helium lines, cold trap and vacuum line attached.

![Image](image2.png)

**Figure 5.11.** Moisture seen upon purging the desiccators with Helium gas (left) with a close-up image (right).

### 5.1.4 Cold Trap

A cold trap was added to the vacuum line, shown in Figure 5.12, to aid the desiccators in water removal primarily for tests where the desiccators quickly became saturated. The cold trap was implemented downstream of the desiccators. In the beginning stages of utilizing the cold trap, dry ice was used. After performing
Experimental tests, it was realized the cold trap was not functioning effectively in moisture removal. Therefore, the dry ice was replaced with liquid nitrogen for future testing. A liquid nitrogen tank was stored inside the facility and appropriate protective personal equipment was used when handling the liquid nitrogen.

![Image](image.png)

Figure 5.12. Liquid Nitrogen Cold Trap implemented downstream of the desiccators in the vacuum line.

5.2 Forced Helium Dehydration (FHD) Equipment

This study also evaluated the FHD process which involved pressurized heated helium flow in the mock fuel canister. However, vacuum chambers are typically not designed to accommodate high pressure. The pressure limit for the experiments in this study’s setup was 1200 Torr. Modifications were made to the experimental design to enable recirculation of helium at pressures between 1000 to 1200 Torr and flow rates between 100 to 125 slpm.

Recirculation was made possible with a custom built KNF N01000 diaphragm pump with a maximum pumping speed of 100 slpm at 760 Torr. The custom design called for two diaphragm pumps to be connected and operated in parallel to maintain a
prescribed gas exchange rate. The working mechanism of the diaphragm pump prevented any type of possible cross contamination of oil vapor. The pump had an Edesthal pump head with the diaphragm and values fabricated out of PTFE. This custom fabricated pump was also designed to handle temperatures of up to 240°C. The high temperature operation was critical for the FHD experiments since the experiments were conducted above atmospheric conditions with heated helium and water vapor mixture.

Horizontal Inline Forced Gas Process Heaters were designed by Laco Technologies to support the heating requirements for FHD. Three inline gas heaters were added in series with each other, shown in Figure 5.13, to the FHD line between the recirculation pump and vacuum chamber. The pipework after the last inline heater was wrapped in insulation tape to prevent heat loss to the chamber. Each heater had a maximum power of 1 kW and was capable of increasing the gas temperature by ~50°C. These heaters were designed to reach and maintain a recirculating gas temperature of 150°C. Each inline gas heater had an integrated type-K thermocouple and had KF25 fittings on each end.

The temperature for each inline heater was controlled by regulating each heater’s power through the PXI system. The heaters were individually powered and controlled via a PXI module that sent a current that ranged from 4 to 20 mA DC to a Watlow Din-A-Mite Series A power controller (Model #: DA10-24F0-0000). This controller then transmitted the voltage as its output to each inline heater being powered. In order to know how much wattage was delivered to the heater, an Ohio Semitronics Watt Transducer (Model #: PC8-003-09DY18) was also integrated into the wiring system and relayed back to the PXI controller. Each inline heater’s thermocouple was also wired to a separate PXI
module to provide temperature feedback through LabView. The power sent to each heater was automatically determined on the differential of this temperature feedback and the desired set temperature given to each gas heater within LabView. Recirculating gas temperature was ultimately achieved by not sending power to the first heater, setting the second heater to 100°C, and setting the final heater to 150°C. Figure 5.14 provides a schematic used for the three heater, power, and control units. Figures 5.15 and 5.16 shows the installation of one out of the three inline heater and control units implemented.

Another Laco inline gas heater was installed on the outlet of the chamber to serve as a thermocouple to measure the chamber’s outlet gas temperature during FHD tests. This heater was not powered and was purely used as an internal thermocouple. Insulation tape was wrapped around the heater and exiting line, seen in Figure 5.17, to avoid any unnecessary heat loss. Further explanations for the insulation will be discuss in later sections.
Figure 5.14. Schematic used for each of the three inline heaters and control units.

Figure 5.15. Arrangement of components for each inline heater and control units. Note: this is an example of only one inline heater.

Figure 5.16. Inline heater installed in the FHD line.
Figure 5.17. Inline gas heater implemented on the pipework exiting the vacuum chamber to serve as an outlet gas thermocouple.

5.3 Single Effect vs. Combined Tests

Among the different parameters evaluated, the test plan evaluated single effect tests of individual design features and combined flooded tests where the chamber was filled with water. The single effect tests consisted of placing a prescribed amount of water in the simulated test articles (failed fuel rod, water rod, guide thimble, and spacer discs) to match what is typically found in commercial canisters. Deionized water was injected into the simulated rods and spacer discs via syringe.

Combined flooded tests were performed to evaluate the same simulated test articles. However, combined tests were conducted in a condition commensurate with a canister following blowdown from the initial flooded condition. These combined tests evaluated drying of water trapped in crevices, absorbed on surfaces, puddled at the bottom of the canister or flat surfaces, etc. Deionized water was also used in flooding the
chamber, but a float switch setup, shown in Figure 5.18, inserted through the cooling grand penetration was used to protect instrumentation at the top of the chamber. The float switch device functioned on two solenoid water valves on a 12-volt DC normally closed leg of a relay. It was switched via a magnetic float switch on a 5-volt DC supply once the water level inside the chamber reached the float switch. Figure 5.19 shows the deionized water tank and station that was linked to the float switch to fill the chamber. Comparison with the single effect test provided insight on the overall effects of the overall removal rate of all other trapped water.

Figure 5.18. Float switch device used to fill vacuum chamber for combined tests.
5.4 Preparing and Removing Simulated Test Articles

For this study, prepping the simulated test articles was a crucial step before beginning the drying process. Using a syringe, the simulated BWR water rod and PWR guide tube were injected with 110 mL and 24.6 mL, respectively. The simulated spacer disc was filled with approximately 25 mL of deionized water. For the mock failed fuel rod, a measured amount of water was injected via a piping device, shown in Figure 5.20, into the top of the failed fuel rod. A vacuum pump was connected to the device to vacuum the rod before the water was injected. The failure hole was sealed prior to vacuuming and the seal was removed during the lowering of the rod into the chamber so that the measured water would leak from the defect hole into the chamber.
For all single effect tests on the simulated rods, the chamber was first sealed and heated until the heater rod closest to the interchangeable rod lattice position, heater rod 1, was 100°C and the temperature of the channel at viewport 3 was 60°C. Thermocouple 1A was the thermocouple used to monitor if 100°C was reached and was located axially near the middle of the chamber. The purpose of the temperature requirement was to get the rods and chamber heated to a point that somewhat represented SNF temperature at the start of commercial drying operations. Once these temperatures were met, the test rod was inserted through the cooling gland penetration. Both PWR and BWR rods were inserted using a grapple tool that connected to its nipple end fitting. However, the failed rod required the jib crane and special clamp to be inserted into the vacuum chamber to prevent damage to the ceria pellets. Figure 5.21 shows the failed rod being inserted through the cooling gland penetration. The grappling tool used was withdrawn once the test rod was placed in the interchangeable rod lattice position and rotated to align the
defect hole with the viewport. The cooling gland penetration cap was then placed back on
the chamber to reseal the system to begin the drying process.

Figure 5.21. Clamp and jib crane used to suspend the Failed rod (left). Failed rod inserting through the cooling gland penetration (right).

A slightly different procedure was required for single effect tests that used the
simulated spacer disc. Once the temperature requirement was met, view port 2’s flange
was removed. The spacer disc was then inserted into the chamber and aligned for the
thermal camera at view port 2. The flange was then tightened back on to the chamber to
begin the drying process. During all insertions for single effect tests, helium gas was
purged out of the chamber to prevent air leaking into the system.

For combined tests, the simulated PWR and BWR rods as well as the simulated
spacer discs were not initially injected with water. Yet, they were inserted into the
chamber before the chamber had been flooded and heated. The failed rod was prepped
the exact same way as it was for single effect tests. It was also inserted into the vacuum
chamber prior to the chamber being flooded and heated. The failed rod was the only test
article needed to be initially prepped for combined test as it was incapable of being filled
thoroughly through chamber flooding.

Test articles were removed the same way they were inserted following the
completion of drying tests. Remaining water inside the chamber and test articles were
then quantified. Results on quantification will be discussed in later chapter 6.

5.5 Drying Experimental Plan

Drying tests were executed by following a test plan written specifically for this
study which contained procedures designed to reproduce industry drying conditions and
operations. This study evaluated the previously mentioned test articles under several
different drying conditions, such as:

- Single effect tests
- Combined effect tests
- **Decay heat variation**: 0.25 to 1 kW based on decay heat calculations with the
  ability to reach 3 kW heat load.
- **Vacuum drying vs. Forced helium drying**: Full scale drying procedures to
  evaluate the tradeoffs between vacuum drying and FHD. Operations for each
  method of drying was also evaluated.
- **Hold points vs. Continuous evacuation**: Evaluated methods used in the industry
  for vacuum drying. One method that had sequencing step-holds to < 3 Torr and
  the other that evacuated to < 3 Torr without step-holds.
• **Extended holds:** After the vacuum drying criteria was met, the final hold was extended to evaluate the impacts from extended holds as well as provide data for residual water quantification.

Experimental vacuum drying and FHD procedures used in this study are discussed in the following subsections. The experimental design, schematics, and procedures mentioned in the following subsections are the most evolved and up to date designs/procedures used. Images of the entire experimental setup can be seen in Figures 5.22 to 5.26. Some changes were made to the system for additional testing, but those changes and the reason for the modifications are discussed in chapter 6.

![Figure 5.22](image-url)  
Figure 5.22. Arial view of vacuum chamber and vacuum port connections. Siphon, Vent, and OES line are identified.
Figure 5.23. Full view of the entire vacuum line and PXI system.

Figure 5.24. View of the bottom level of the vacuum line. This portion is upstream of the desiccators.
Figure 5.25. Top level view of the vacuum line. This portion is downstream of the desiccators. Pipework that leads to vacuum pump is identified.

Figure 5.26. Full view of the FHD line. Vent line leading to the chamber is identified.

5.5.1 Dewatering

The dewatering operation started with the chamber filled with water. This represents the condition of the SNF canister at the conclusion of the fuel loading step. In the dewatering process, large volumes of water were removed from the chamber by pumping through the siphon port using the dewatering pump. At the same time, helium was backfilling under pressure through the vent port to replace the volume of water being removed. The dewatering line and pump were primed with deionized water before operating the pump. Helium was first bled into the chamber and the dewatering pump was then turned on once the pressure inside the chamber reached 1150 Torr. A schematic
diagram of the valves and lines used for dewatering operation is displayed in Appendix B. The end of dewatering was deemed when discharge from the dewatering pump decreased dramatically or if any cavitation occurred.

5.5.2 Blowdown

In blowdown, helium gas under higher pressure (15 psig) was cycled and blown through the vent port to entrain water that remained held in different locations in the chamber and assembly. When dewatering was deemed complete, the dewatering pump was turned off and valve M-J was closed to pressurize the chamber. The valve was opened when the pressure reached 1150 Torr to blowdown the chamber. Valve M-J was closed again to repeat this process until the operator no longer observed moisture in the clear PVC blowdown lines. After the last blowdown attempt, valve M-K and V-S were closed to stop the helium flow and isolate the chamber to begin vacuum drying or FHD. A schematic diagram of the valves and lines used for blowdown operation is displayed in Appendix B.

5.5.3 Vacuum Drying

Following dewatering and blowdown, the chamber was heated to the previously mentioned temperature requirement of 100°C and 60°C. Vacuum drying was then initiated following a series of evacuation stages from 760 Torr or slightly greater depending on the pressure of backfill following blowdown. If the test was a single effect test, vacuum drying would begin after the test article was inserted into the chamber. The individual stages with respective pressure and hold times are shown in Table 5.1. The schematic diagram indicating the valves and lines utilized during vacuum drying can be seen in Appendix B.
Table 5.1. Sequence of hold pressures and times conducted in vacuum drying tests.

<table>
<thead>
<tr>
<th>Vacuum Step, Hold Pressure</th>
<th>Isolation Hold Time for Tests Operated With 5 min Holds</th>
<th>Isolation Hold Time for Tests Operated With 15 min Holds</th>
<th>Criteria for Pressure Hold to Proceed to Next Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;100 torr</td>
</tr>
<tr>
<td>&lt;25 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;50 torr</td>
</tr>
<tr>
<td>&lt;15 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;25 torr</td>
</tr>
<tr>
<td>&lt;10 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;15 torr</td>
</tr>
<tr>
<td>&lt;5 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;10 torr</td>
</tr>
<tr>
<td>&lt;3 torr</td>
<td>5 min.</td>
<td>15 min.</td>
<td>&lt;5 torr</td>
</tr>
<tr>
<td>&lt;2 torr</td>
<td>30 min.</td>
<td>30 min.</td>
<td>&lt;2.6 torr</td>
</tr>
</tbody>
</table>

Pressure holds were conducted by closing valve V-K followed by M-A to isolate the vacuum chamber. If it was observed that condensed water vapor may be in the vacuum lines, valve M-A would stay open to remove any moisture during the hold. At the end of each pressure hold, V-K was opened followed by slowly opening M-A to reinitiate evacuation without pulling vacuum too rapidly. Vacuum drying was completed when the industry vacuum hold criteria was met. Some tests also conducted an extended holds after test completion to further evaluate the remaining moisture content.

It was discovered that some vendors were altering the procedure of evacuating to pressure hold points in favor of a continuous evacuation to < 3 Torr. Therefore, a series of vacuum drying tests were conducted that began with the same starting procedures as the original vacuum drying method. However, all hold steps were disregarded, and pressure was evacuated to < 3 Torr. This was followed by isolating the chamber for 30 minutes, then backfilling the test chamber with helium to between 500 – 900 Torr. The chamber was then re-evacuated to < 3 Torr and isolated from the pump to conduct another 30-minute hold to confirm vacuum drying was complete. If the criteria failed, the...
evacuation was repeated until the criteria was met. As with the standard procedure, the chamber was then opened to confirm removal of all water or quantify any remaining water.

5.5.4 *Forced Helium Dehydration (FHD)*

For FHD operations, the chamber was prepped in the same manner as vacuum drying experiments. However, the chamber and necessary lines were pressurized to 1000 Torr before turning on the recirculation pump. After the recirculation pump was turned on, the inline heaters were powered to heat the gas to 150°C.

For FHD testing, the desiccators were replaced/recycled and in some cases the liquid nitrogen cold trap was used to maintain a < 0.1% (lower limit) relative humidity downstream of the desiccators. Due to limitations that will be discussed in chapter 6, commercial FHD criteria was not used during FHD testing. Therefore, a method was developed using the relative humidity sensor located inside the chamber. When the sensor achieved < 1% relative humidity, the chamber was isolated, and the relative humidity was monitored. The chamber bypass line was also opened at this time to allow the recirculation pump to stay on. When the chamber still contained a significant amount of water, the relative humidity would rebound. With drying, the rebounds would become smaller. OES line that was already in use for vacuum tests, was also used when the chamber was isolated to monitor the decreasing water content with drying. If substantial water was observed in the lines during the rebound holds, the recirculation pump was turned off and the lines were evacuated. Appendix B displays the schematic used for FHD. Note the chamber was bypassed to conduct rebounds. Chapter 6 discusses how drying times for FHD tests were ultimately determined.
CHAPTER 6

RESULTS & DISCUSSION

The following subsections discuss the LWR fuel drying tests detailed in the previous sections, as well as drying tests conducted on mock aluminum-spent nuclear fuel (ASNF) assemblies. ASNF drying tests were conducted through Idaho National Laboratory (INL) with the collaboration with Holtec International. Observations and data from the ASNF drying tests were used in this work to provide information that the drying tests operated on the LWR fuel assembly could not provide. Information regarding the specifics of drying operations, equipment, and scope of work for the ASNF drying experiments can be found in “Engineering Scale Drying of Aluminum-Clad Spent Nuclear Fuel” [17].

6.1 Vacuum Drying Performance

The LWR fuel assembly’s maximum axial temperature profile observed during vacuum drying experiments at the three testing decay heat loads (250 W, 500 W, and 1000 W) are shown in Figure 6.1. Each plot was generated by averaging data from 10+ vacuum drying tests at each respective decay heat. The thermal plots confirm fuel cladding temperatures remained below the 400°C regulatory limit. However, the average peak cladding temperature when drying at 1 kW decay heat can be seen to be approximately 378°C. This is significant because the experimental LWR fuel assembly has a BWR assembly geometry and based on reports that are currently available to the
public, upwards of 1.45 kW BWR fuel is dried via vacuum drying [6]. Figure 6.2 shows that vacuum drying any BWR fuel with a decay heat > 1 kW would certainly result in the fuel cladding exceeding 400°C. Further observation of cladding temperatures for 0.25 and 0.5 kW tests indicated thermal equilibrium was never achieved for the fuel during vacuum drying. However, one could require periodically backfilling the canister with helium gas to cool the fuel rods and obtain thermal equilibration.

Although periodically backfilling with helium was not tested, several vacuum drying tests were conducted with the decay heat at 2 kW. Figure 6.3 illustrates vacuum drying at 2 kW resulted in fuel cladding temperatures upwards of 475°C. Therefore, divergence from typical vacuum drying operations would certainly be required if there was a desire to dry BWR fuel assemblies with 2 kW decay heat.

One major concern in vacuum drying is freezing as it could prolong drying times or give false readings during isolation holds. Ice formation was observed inside the simulated spacer disc during vacuum drying tests regardless of the decay heat of the LWR fuel assembly. Figure 6.4 highlights a moment captured by thermal imaging when water inside the spacer disc froze to -3.8°C with ice crystallization forming on the back wall of the simulated spacer disc. This moment occurred when evacuating from the 5 Torr pressure hold to the 3 Torr pressure hold. Although the freezing did require isolation holds to be repeated, in all instances the final drying criteria was not met until all water had been evaporated from the simulated spacer disc. Freezing was ultimately prevented by increasing the duration for each pressure hold from 5 mins to 15 mins.
Figure 6.1. Maximum axial temperature profile of the LWR fuel assembly while vacuum drying at 250 W decay heat (left), 500 W decay heat (right), and 1000 W decay heat (middle).
Figure 6.2. Peak cladding and average cladding temperature of the LWR fuel assembly during vacuum drying test operated at 1 kW decay heat and insulated chamber wall.

ASNF vacuum tests were able to capture the prevention of ice with increasing hold time as shown in Figure 6.5: the water temperature inside the simulated spacer disc for vacuum drying test 2 drops below 0°C, but not for test 3. Similar temperature drops in the ASNF drying tests were observed near the bottom of the mock ASNF assemblies (thermocouple A) as shown in Figure 6.6. However, ice formation never occurred on the assemblies as the surface area of the water exposed to the gas inside the vessel was large relative to the volume of water added to each assembly (105 mL). In the case of the simulated spacer disc, freezing was believed to be a result of the surface area of the water being small relative to the 28 mL inside the tray, requiring more heat energy to increase the water temperature for vaporization.
Figure 6.3. Maximum axial temperature profile of the LWR fuel assembly while vacuum drying at 2000 W decay heat. Red dashed line indicates fuel cladding limit (400°C).

Ice formation was also observed at the bottom of the siphon tube during some vacuum drying tests conducted on the LWR assembly. However, the atypical decay heat profile for the heater rods previously mentioned in chapter 3.3.1, as well as the pedestal that offset the heated section of the assembly from the bottom of the chamber by 12-inches were believed to be the reasons why freezing occurred in the siphon tube.

Therefore, heating tape was wrapped around the bottom of the chamber to compensate for the heat that would typically be present in commercial drying. Although cooling was still observed at the bottom of the siphon tube after this addition, temperatures below 0°C were no longer seen. To further reduce the heat lost from the chamber wall and
Figure 6.4. Thermal image from Vacuum Drying test conducted on LWR fuel assembly showing freezing of water in the simulated spacer disc. Note: Ice crystals forming up the backside of the simulated spacer disc.

viewports, the entire vessel was wrapped in heating tape (operated at 200°F) then covered with insulation.

As illustrated in Figure 6.7, applying 200°F of heat to the chamber wall increased the bottom half of the assembly and basket by approximately 25°C. Drying time was also improved by approximately 60 mins with the additional heat. It should be noted even with the added heating and insulation, the basket and wall temperatures were still within the expected temperature range for commercial drying [6].

Overall, combined (started in flooded condition) vacuum drying tests on the LWR assembly demonstrated an increase in drying time was directly related to an increase in
Figure 6.5. Spacer disc temperature for ASNF vacuum drying test 2 where 5-min pressure isolation holds were utilized (left), Spacer disc temperature for ASNF vacuum drying test 3 where 15-min pressure isolation holds were utilized (right).
Figure 6.6. Assembly temperatures of the four measured ASNF assemblies for ASNF vacuum drying test 8. Legend correlates to the assembly number, thermocouple axial location (with A being the bottom of each assembly), and whether the thermocouple is located on the exterior or interior of the assembly.

The fuel’s decay heat resulted in a decrease in the total drying time as shown in Figure 6.8. Although the improvements in drying time seem relatively small between each decay heat load, drying one fuel assembly 50 mins faster is significant when knowing there are upwards of 89 BWR or 37 PWR fuel assemblies in one canister. As illustrated in Figure 6.9, single effect (non-flooded condition) vacuum tests conducted on the three test rods used in the LWR assembly showed the BWR water rod required approximately 125 – 150 mins more time than the PWR guide tube and failed rod to meet the drying criteria. The figure demonstrates the correlation between starting moisture content versus drying time as the BWR water rod held 110 mL whereas the failed rod and guide tube contained 30 mL and 25 mL, respectively. All drying times were purely based on time elapsed from the start of the vacuum test to the end of the final 30 min pressure hold.
Figure 6.7. Comparison of maximum axial temperature profile of the LWR fuel assembly (top) and fuel basket (bottom) for combined vacuum tests operated at 1 kW with and without 200°F heated chamber wall.
Figure 6.8. Average drying time for each operating decay heat load for combined vacuum drying test with insulated chamber wall.

Figure 6.9. Average drying time for each tested rod implemented in the LWR fuel assembly for single effect vacuum drying test with 1 kW decay heat and non-insulated chamber wall.
Following the addition of heating tape and insulation around the chamber to offset heat loss, removal of all bulk water (inside chamber and tests rods) was consistently achieved for all LWR vacuum drying test types except for the simulated failed fuel rod. In several drying tests, the failed rod was seen to have 0.5 to 18.5 mL of residual water, shown in Figure 6.10, while still meeting the NRC accepted drying criteria. This was rare for combined tests (3 – 4 tests) as only the single effect failed rod vacuum tests frequently resulted in some amounts of residual water. Absence of residual liquid water following combined tests was believed to be a result of the increase in fuel rod temperatures due to the longer drying time needed to meet the < 3 Torr criteria. Although the amount of residual water in the failed rod was inconsistent, thermal imaging consistently showed water ejecting out of the failed rod’s weep hole (defect hole) until approximately 10 Torr. One theory is that the retention of water in the failed rod is a result of surface tension effects in the tightly packed rods with the fracture of the simulated fuel pellets [18]. Therefore, drying the failed rod is challenging since communication between the simulated failure hole and the top or bottom of the rod is impeded by the highly fractured pellets that developed after the first few tests. Note, pellet fracture is part of normal behavior of UO\textsubscript{2} fuels under LWR power densities and fuel temperatures [18].

The second possibility of residual water could be related to the previously referenced work by the National Nuclear Laboratory (United Kingdom), where they concluded that the current NRC accepted vacuum drying criteria is inadequate and dew point must be considered when determining the end point for drying [16]. Figure 6.11 shows the inconsistency of the current drying criteria as the vapor pressure at the end of the 30-min final hold is plotted against the residual bulk water observed for a multitude
Figure 6.10. Residual bulk water dumped from the failed fuel rod following a vacuum drying test even though the final drying criteria was met.

of LWR vacuum drying experiments. These tests varied in decay heat loads, test rod, combined or single effect, and with or without pressure step holds. No clear trend was observed when comparing the dew point at the start of the final hold to the vapor pressure at the end of the hold. However, comparing the starting dew point to the vapor pressure differential of the 30-min hold in Figure 6.12, revealed no residual moisture was observed when the vapor pressure differential was less than 1 Torr and the dew point was between -8°C and -16°C. Evaluating the same plot but separating vacuum tests with or without pressure step holds in Figure 6.13, indicated drying tests conducted without holds with residual water had substantially lower dew points. The very low dewpoints are believed to be a result of freezing. The figure shows that operating vacuum drying without sequencing holds is unreliable for complete removal of liquid water as nearly 50% of the tests resulted in false confirmation of the current NRC accepted drying criteria.
Figure 6.11. Vapor pressure at the conclusion of the final 30-min pressure hold compared to the amount of residual bulk observed following each test. All vacuum drying tests vary in decay heat loads, test rod, combined or single effect, and with or without pressure step holds.
Figure 6.12. Comparing the starting dew point of the 30-min hold to the vapor pressure differential for the 30-min hold. All vacuum drying tests vary in decay heat loads, test rod, combined or single effect, and with or without pressure step holds.
Figure 6.13. Comparing data in Figure 6.12 for vacuum tests that were conducted with pressure step holds (top) and tests conducted without pressure step holds (bottom). All vacuum drying tests vary in decay heat loads, test rod, combined or single effect, and with or without pressure step holds.
Two additional vacuum drying tests were conducted on the LWR assembly at 1 kW after discovering during the mock ASNF drying tests that Holtec International’s commercial vacuum drying process consist of pulling vacuum from both the siphon and vent port with pressure holds no shorter than 15 mins. This difference in drying operations may have been why there was never residual moisture following mock ASNF vacuum tests. However, the two additional drying tests successfully met the < 3 Torr drying criteria, yet still had 5 – 10 mL of residual water, unlike the mock ASNF drying tests. After adding data from the two tests (highlighted in gold) and data from mock ASNF tests (highlighted in blue) to Figure 6.12, it is clear in Figure 6.14 that the current < 3 Torr vacuum drying criteria is inadequate.

It is important to note that all vacuum drying tests conducted on the LWR assembly and mock ASNF fuel assemblies did not repeat the final < 3 Torr hold until very little pressure rebound was observed. Rather, the hold was considered passed if the pressure did not increase above 3 Torr after 30 mins. The NRC does state the pressure should maintain < 3 Torr for 30 mins, but there is substantial gray area in what they define “maintain” as [1]. Of course, if the final hold was repeated until the pressure rebound was equivalent to the system leak rate (indicating no pressure rise due to evaporation), then without a doubt the residual water vapor content will be less than 1 mole (~19 mL for standard commercial canisters). However, it is not publicly known whether the NRC places an emphasis on the word “maintain”.
Figure 6.14. Comparing the starting dew point of the 30-min hold to the vapor pressure differential for the 30-min hold for LWR fuel vacuum tests (red and green), ASNF assemblies vacuum tests (blue), and addition LWR vacuum tests pulling vacuum from the siphon and vent (gold).
6.2 Forced Helium Dehydration Performance

Like most published small-scale experimental work on FHD performance, the equipment for drying the mock LWR fuel assembly was not capable of achieving FHD drying operations comparable to commercial FHD. The central drying mechanism of commercial FHD is boiling and evaporating water inside the canister through forced convective heat transfer. However, commercial FHD also produces a turbulent flow regime in the canister cavity by recirculating heated helium, critical to the moisture removal process [6]. Although a standard commercial BWR canister has a free volume of 6460 L and the free volume of the LWR assembly chamber is 484 L, the scaled mass flow rate for the LWR system would need to be high enough to achieve a turbulent flow regime [6]. Details regarding commercial mass flow rates are proprietary and protected from disclosure. Due to flow rate limitations on the recirculation pump and the inability to exceed 1.5 atm inside the chamber, the maximum mass flow rate achieved during FHD test with the LWR assembly was approximately 3.5 lbs/hr.

Given the LWR FHD tests were operated at 3.5 lbs/hr with an inlet gas temperature of 150°C, the maximum heat transferred from the recirculating gas to the chamber cavity, at any given moment during operation, is only 0.3 kW. The lack of energy in the gas stream was immediately noticed from initial 1 kW FHD tests where only 7 mL of water could be evaporated from the PWR guide tube after 6.5 hrs of drying operations. Therefore, to generate enough energy to evaporate all the moisture inside chamber/test rods in a reasonable amount of time, the chamber wall was heated to 200°F and the decay heat was increased to 3 kW for all FHD tests. Figure 6.15 illustrates the LWR fuel assembly and basket maximum axial temperature profile observed during initial FHD tests (1 kW, ambient wall temperature), as well as all other FHD tests (3 kW,
200°F heated chamber wall). Increasing the heat energy from the assembly’s decay heat to compensate for the lack of heat energy from the circulating gas resulted in temperatures well above the inlet gas temperature (150°C). Fuel cladding temperatures during commercial FHD operations are not expected to exceed 260°C (current maximum inlet gas temperature for commercial FHD) as the circulating gas serves as a cooling agent for the fuel [6].

After increasing the overall heat load in the chamber, complete water removal was achieved for all single effect and combined FHD tests. However, since the outlet gas temperature never achieved superheated state (Holtec recommends 15°F higher than the saturation temperature) and uniform gas temperature inside the chamber could not be confirmed, the LWR drying tests could not use Holtec’s or NRC’s suggested drying criteria to accurately determine the end point of FHD. Therefore, FHD tests were operated at various durations to determine the time required to remove all bulk water. After 30+ FHD tests, Figure 6.16 shows the drying time for all test rods and test types were nearly identical to one another. Similarity in drying times may be a result of similarity in chamber cavity heating rates due to identical heating conditions for each test. Although the FHD tests conditions were atypical of commercial drying, the plots illustrate how the heating rate of the gas and surfaces inside the chamber cavity is the dominate parameter with respect to drying time.

The FHD tests conducted on the mock ASNF assemblies allowed for commercial FHD operations to be truly evaluated through the usage of Holtec’s patented FHD skid and drying process. Details regarding the equipment and drying process used for the experiments can found in “Engineering Scale Drying of Aluminum-Clad Spent Nuclear
Figure 6.15. Comparison of maximum axial temperature profile of the LWR fuel assembly (top) and fuel basket (bottom) for FHD tests operated at either 1 kW decay heat, ambient chamber wall temperature or 3 kW decay heat, 200°F heated chamber wall.
Figure 6.16. Comparing average drying times for each tested rod implemented in the LWR fuel assembly for single effect FHD tests (left), and for single effect and combined failed rod tests (right) with 3 kW decay heat and 200°F heated chamber wall.
Fuel” [17]. Holtec’s chiller (phase 2 of drying) was not used for the tests as the operating temperatures and durations at said temperatures were essential to the project scope [17]. No residual moisture was found inside the vessel or on the mock ASNF assemblies after any of the FHD tests.

The ASNF tests operated at 70 psig with the FHD heaters set to 260°C. A turbulent flow regime was achieved in the vessel cavity during tests by recirculating the heated helium at 105 lbs/hr. As a result, the maximum inlet gas temperature for the vessel was approximately 239°C when the FHD heaters were set to 260°C. Figure 6.17 demonstrates the forced convective heat transfer from the heated helium provided sufficient energy to heat the ASNF assemblies to 215 – 225°C. Although assembly 4 was supplied with 100 W decay heat, thermal equilibrium was still achieved through concurrent fuel cooling promoted by the turbulent helium. This aspect of the forced convection heat transfer sets FHD apart from vacuum drying. Current commercial FHD operate well below 400°C while still having comparable drying times to vacuum drying. Since fuel temperature is quite difficult to control during vacuum, the FHD process has much greater latitude for further improving drying time.

A decrease in drying time as a result of increasing the vessel’s maximum inlet gas temperature was observed in Figure 6.18 where relative humidity data from ASNF test 9 (239°C inlet gas) was compared to ASNF test 10 (220°C). Although the rate at which the vapor is being removed from the vessel seems to be identical for the two tests, it is clear the test operating at the higher inlet gas temperature begins substantially evaporating and boiling off the bulk water ~15 mins before the other test. This little difference was a result of the difference in heat energy being transferred to the bulk water molecules.
Figure 6.17. Average temperature of select assemblies for ASNF test 9. Note, assembly 4 is the only assembly supplied with 100 W decay heat.

within the first hour of each test as illustrated in Figure 6.19. As the inlet gas temperature is increasing to thermal equilibrium, the amount of heat energy transferred is identical between the two tests since the temperature differential between their inlet and outlet gas is also identical. However, the amount of heat transferred in ASNF test 9 surpasses test 10 due to the additional heat in the inlet gas further increasing the temperature differential across the vessel.

Besides seeing that an additional 19°C inlet temperature resulted in 1 kW more heat energy, the plot also demonstrates why Holtec does not operate their chiller (de-moisturizer) at the beginning of FHD operations. For the two ASNF tests, a substantial amount of water was removed within the first 3 hrs due to the significant amount of heat transferred to the water molecules to increase the water temperature for vaporization. The heat transferred levels off as the system reaches thermal equilibrium and less water is evaporated (i.e., taking energy). If Holtec operated their chiller unit at the start of the
Figure 6.18. Comparison of relative humidity measured inside the vessel for ASNF test 9 (239°C maximum inlet gas) and 10 (220°C maximum inlet gas).

Figure 6.19. Comparison of heat transfer to the vessel cavity from the circulating heat helium gas for ASNF test 9 (239°C maximum inlet gas) and 10 (220°C maximum inlet gas).
FHD process, the potential of ice blockages in their system would be high due to the large amount of vapor that would freeze. Observing no bulk water following each ASNF test without operating a chiller demonstrated that Holtec’s phase 1 process and criteria guaranteed complete removal of bulk water, leaving only moist helium recirculating the system. Even if the chiller was operated the entire time to ensure dry heated gas entered the vessel, drying rates are not expected to improve for bulk water and chemisorbed water. Holtec’s air-cooled condenser used during phase 1 is designed to de-vaporize the circulating gas at a temperature of 120°F. At this temperature, only trace amounts of vapor would remain in the gas stream.

While working with Holtec, it was discovered that Holtec recently changed their FHD operations from treating the siphon tube as an outlet to an inlet. Although very little testing was done in this work to fully understand the benefits or drawbacks of this change, two additional LWR fuel assembly tests were conducted at 1 kW to observe any significant changes in results. The relative humidity at the outlet of the chamber for the two tests were compared in Figure 6.20 and it is clear that forcing the gas through the siphon tube permitted more evaporation and moisture removal at the start of the test. This is believed to be attributed to majority of the bulk water residing at the bottom of the chamber following dewatering and blowdown. Therefore, the temperature of the bulk water at the bottom of the chamber increases more rapidly when the heated gas is entering the siphon tube. In the case of when the heated gas enters the vent, heat energy from the gas is lost (i.e., gas temperature decreases) to various surface at the top of the chamber. Therefore, the substantial bulk water located at the bottom of the chamber could not be vaporized until the entire chamber builds up enough thermal energy.
Increasing the heat transferred to the bulk water molecules by operating under commercial FHD conditions may further increase the difference between vaporization rates and drying times between the two setups.

Figure 6.20. Comparison of relative humidity measured at the outlet of the chamber for two additional, 1 kW combined FHD tests with the BWR water rod, on the LWR fuel assembly where one test the siphon tube is treated as the outlet and the other it is the inlet.
CHAPTER 7

CONCLUSIONS

The nuclear industry has turned to dry storage over the past few decades to ensure space in spent fuel pools for newly decommissioned nuclear fuel. Inadequately drying SNF increases the risk of fuel degradation, potential for hydrogen generation, and other detrimental effects to the fuel while in dry storage. Vacuum drying experiments in this work identified the formation of ice can occur near the bottom of a SNF canister, as well as on top of a spacer disc. These were locations where the surface area of the water exposed to the gas was small relative to the volume of water. Prolonging pressure sequence holds from 5 mins to 15 mins successfully prevented ice formation in all areas. Vacuum drying operation times were improved with increasing decay heat, but the NRC accepted < 3 Torr criteria was occasionally found to be inadequate and unreliable. For the systems in this work, complete dryness was consistently achieved when both the vapor pressure did not rise more than 1 Torr during the final 30-min hold and the dew point inside the canister at the start of the final hold was between -8 and -16°C.

FHD experiments in this work demonstrated the mass flow rate and inlet gas temperature greatly affected the efficacy of removing water inside a canister. Under commercial FHD conditions, the FHD drying criteria used by Holtec proved to be adequate in completely removing all bulk water. Although additional testing is recommended, water vaporization was better initiated when flowing heated helium gas
through the siphon tube rather than the vent. Comparing the vacuum and FHD processes, concurrent fuel cooling through forced convection gives FHD the ability to further decrease drying times without exceeding fuel cladding temperature limitations.
REFERENCES


# APPENDIX A

## SENSORS FOR LWR EXPERIMENTAL DRYING TESTS

Table A.1. Instruments to be used in data collection during drying tests shown with operating range and uncertainty.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model</th>
<th>Range</th>
<th>Operating parameters</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple (K-Type)</td>
<td>Apex Vacuum</td>
<td>-50 – 500 °C</td>
<td>-50 – 500 °C</td>
<td>0.75% of range</td>
</tr>
<tr>
<td>Humidity transmitter</td>
<td>Vaisala HMT334</td>
<td>0 -100 %RH</td>
<td>at +15 ... +25 °C at -20 ... +40 °C at -40 ... +180 °C</td>
<td>±1 %RH (0 ... 90 %) ±1.7 %RH (90 ... 100 %RH) ±(1.0 + 0.008 x reading) %RH ±(1.5 + 0.015 x reading) %RH</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>MKS 628F</td>
<td>0 – 2000 Torr</td>
<td>15 – 50 °C</td>
<td>0.25% of reading</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>MKS 722B</td>
<td>0 – 2000 Torr</td>
<td>0 – 50 °C</td>
<td>0.5% of reading</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>MKS 902B</td>
<td>0 – 1000 Torr</td>
<td>0 – 40 °C</td>
<td>1% of reading</td>
</tr>
<tr>
<td>Mass flow meter</td>
<td>Brooks MF63S</td>
<td>0 – 250/500 slm</td>
<td>5 – 65 °C</td>
<td>±0.9% of rate (20 – 100% F.S.) ±0.18% of F.S. (2 – 20% F.S.)</td>
</tr>
<tr>
<td>Mass flow meter</td>
<td>Brooks 5860</td>
<td>0 – 5 slm</td>
<td>5 – 65 °C</td>
<td>±1% of F.S.</td>
</tr>
</tbody>
</table>
APPENDIX B

LWR EXPERIMENTAL DRYING TESTS SCHEMATICS
Figure B.1. Schematic of the LWR experimental facility design highlighting the operation of dewatering. Valves opened and lines used are identified in red.
Blowdown Mode

Figure B.2. Schematic of the LWR experimental facility design highlighting the operation of blowdown. Valves opened and lines used are identified in red.
Figure B.3. Schematic of the LWR experimental facility design highlighting the operation of vacuum drying. Valves opened and lines used are identified in red.
Figure B.4. Schematic of the LWR experimental facility design highlighting the operation of forced helium drying Valves opened and lines used are identified in red.