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Component Concepts for Advanced Dry Storage Investigations

Spent Fuel and Waste Disposition

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ABSTRACT

The purpose of this report is to review technical issues and previous studies relevant to the performance evaluation of dry storage systems during vacuum drying and long-term storage operations and to describe vital experimental components under development that are required for conducting advanced studies. There is a need to validate the extent of water removal in a multi-assembly system using an industrial vacuum-drying procedure, as operational conditions leading to incomplete drying may have potential impacts on the fuel, cladding, and other components in the system. Waterproof, electrically-heated spent fuel rod simulators are under development to enable experimental simulation of the entire de-watering and drying process. Specially-designed, unheated mock fuel rods are used to monitor internal rod pressures and study water removal from simulated failed fuel rods. Furthermore, single assembly studies conducted previously cannot incorporate important inter-assembly heat-transfer physics, so plans for harvesting up to five full-length 5×5 truncated assemblies from a single 17×17 PWR skeleton are described.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ACRONYMS / ABBREVIATIONS

BWR	boiling water reactor
CFD	computational fluid dynamics
CNWRA	Center for Nuclear Waste Regulatory Analyses
DAQ	data acquisition system
DOE	Department of Energy
EPRI	Electric Power Research Institute
HBU	high burnup
NRC	Nuclear Regulatory Commission
PCT	peak cladding temperature
PWR	pressurized water reactor
SFWD	Spent Fuel and Waste Disposition Campaign
SNF	spent nuclear fuel
TC	thermocouple

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COMPONENT CONCEPTS FOR ADVANCED DRY STORAGE INVESTIGATIONS

This report fulfills milestone M3SF-19SN010203033 (Advanced Thermal Hydraulic Systems for Dry Storage and Transport Applications) in the Spent Fuel and Waste Science and Technology work package (SF-19SN01020303). This work was sponsored under the Department of Energy's (DOE) Office of Nuclear Energy (NE) Spent Fuel and Waste Disposition (SFWD) campaign.

1 INTRODUCTION

1.1 Objectives

The purpose of this report is to review technical issues and previous studies relevant to the performance evaluation of dry storage systems during vacuum drying and long-term storage operations and to describe vital experimental components under development that are required for conducting advanced studies. There is a need to validate the extent of water removal in a multi-assembly system using an industrial vacuum-drying procedure, as operational conditions leading to incomplete drying may have potential impacts on the fuel, cladding, and other components in the system. Waterproof, electrically-heated spent fuel rod simulators are under development to enable experimental simulation of the entire de-watering and drying process. Specially-designed, unheated mock fuel rods are used to monitor internal rod pressures and study water removal from simulated failed fuel rods. Furthermore, single assembly studies conducted previously cannot incorporate important inter-assembly heat-transfer physics, so plans for harvesting up to five full-length 5×5 truncated assemblies from a single 17×17 pressurized water reactor (PWR) skeleton are described.

This chapter will discuss important issues relevant to continuing experimental investigations on thermal-hydraulic assessments of dry cask systems. It will be followed by a discussion of past studies that have responded to some of these concerns in some manner experimentally. This will set the stage for an explanation of several test concepts in the subsequent chapter.

1.2 Issues

1.2.1 Residual Water

Spent fuel assemblies are dried after interim storage in pools to ensure the removal of water in assembly cavities as a defense against issues related to retrievability, pressurization, and corrosion throughout the dry storage process. The evacuation of the most water and oxidizing agents contained within the canister is recommended by NUREG-1536 (NRC, 2010). A pressure of 4 millibar (3 Torr, 0.4 kPa) is recommended to be held in the cask for at least 30 minutes post water removal. A drying method similar to that developed at Pacific Northwest National Laboratory is suggested (Knoll & Gilbert, 1987), where less than 0.25 volume percent of oxidizing gases are left in the canister (1 mole in 7 m^3 at 150 kPa and 300 K).

An industry standard guide was established for the drying of spent nuclear fuel (SNF) after cooling in spent fuel pools (ASTM, 2016), although this includes no comprehensive treatment of safety concerns or measures. The main purpose is to aid in the selection of a drying system and a means of ensuring that adequate dryness is obtained. Examples of typical commercial processes are documented in the standard, where there is adherence to the aforementioned 4 mbar level.

Water remaining in casks upon completion of vacuum drying can lead to corrosion of cladding and fuel, embrittlement, and breaching. There is also some risk of creating a flammable environment from free hydrogen and oxygen generated via the radiolysis of water. The remnant water may be chemically-absorbed (chemisorbed), physically-absorbed (physisorbed), frozen, or otherwise trapped in cavities, blocked vents, breached clads, damaged fuel, etc. Chemisorbed water is bound to contents by forces equivalent to a chemical bond, such as via the formation of hydroxides and hydrates on zirconium, or corrosion products on the fuel or cladding. Physisorbed water is bound to components by weaker forces (e.g. Van der Waals, capillary) as an adsorbate, and increased surface area provided through material defects enhances this effect. For example, this may occur on spacer discs of the weep holes of boiling water reactor (BWR) assemblies.

The pressure pulled for vacuum drying lies below the water vapor pressure. Given the unique heat retention and phase change properties of water, when significant heat is removed during volatilization, some quantity of liquid may actually freeze. It is therefore important to understand under what marginal conditions ice may form during the procedure. As a preventative measure, it may be possible to use hot inert gases to create more uniform temperature profiles. Careful control of the vacuum pumps may also prevent ice formation by controlling the drying rate. This may be done by implementing pressure reduction in stages that involve bringing temperature to equilibrium with inert gases like helium prior to commencement of the next stage. Further R&D on helium dehydration has been recommended to address recently identified technological gaps (Hanson et al., 2019).

The removal of unbound water is largely dependent on the geometry and tortuosity of the components and the speed of the drying process. Cladding breaches are notable cases in that water can become trapped between fuel pellets and absorbed in cracks and voids. Water vapor may continue to diffusively release after vacuuming, and depending on the thermal profile, condensation may occur on the cooler surfaces of the cask, which may likely be at the lower extremes.

It is proposed that if vacuum is employed to remove water from a dry cask, that measurements in the pressure response to intermittent pump operation may be a good indicator of residual, unbound water (ASTM, 2016). This would involve analysis of the time-dependent pressure rebound when the vacuum is turned off. The system may be adequately dry if the 4 mbar pressure can be sustained for at least 30 minutes. Spectroscopic techniques can also be employed to measure the mass of moisture removed.

1.2.2 Cladding Performance

Cladding hoop stresses are critical for evaluating and predicting the mechanical integrity of the fuel rods. These hoop stresses have implications on stress corrosion cracking, zirconium hydride reorientation, and creep. It is recommended to maintain pressure-induced hoop stresses in the cladding below 90 MPa to reduce the probability of hydride reorientation (NRC, 2003). During commercial operation, the internal rod pressure builds from the production of fission gases and gaseous decay products along with fuel pellet swelling, and this pressure increases with burnup. If a clad is breached during operation, fission gases are released and water can penetrate into the fuel through the gap. At the end of vacuum drying, canister pressures are reduced to as low as 0.4 kPa (4 mbar), followed by pressurization to up to 800 kPa (8 bar) during storage.

A technological gap exists in understanding the evolution of internal rod pressure during full-scale, heated experiments. Such measurements can provide valuable information on the state of stress in the fuel clads as vacuum is applied during drying cycles.

1.2.3 Thermal Management

In the course of a typical vacuum drying cycle, the temperature of the fuel is liable to increase due to the reduction of thermal conductivity of the surrounding fluid. The peak cladding temperature (PCT) of the fuel should remain below 400°C to minimize the potential for hydride reorientation in the cladding (NRC, 2003) which in turn results in alternations of mechanical cladding behavior. Furthermore, temperature gradients should be analyzed to identify areas where condensation of water vapor may occur in the cask, as condensation can lead to long-term, localized corrosion issues.

1.3 Previous Studies

1.3.1 Vacuum Drying Test Plan (CNWRA)

The Office of Nuclear Regulatory Research at the Nuclear Regulatory Commission (NRC) sponsored a report from the Center for Nuclear Waste Regulatory Analyses (CNWRA) in 2013 to develop a test plan for vacuum drying using the NUREG-1536 criterion (Miller, Walter, Mintz, & Wilt, 2013). A motivating concern was the verification of water removal after drying given the potential for ice formation, liquid blockage, and other means of water retention, although the report did not focus on chemisorbed water.

The first portion of the report identified industry equipment and procedures. The industry procedures had a common goal of avoiding ice formation and allowing for the system to reach equilibrium. First, bulk water is removed from the canister via the siphon port using a centrifugal pump. The canister is pressurized with dry helium and then depressurized with exhausted water and gas directed to the water trap. This is repeated until a minimum amount of water is observed in the siphon.

The drying process is performed in steps, where the vacuum is increased in a series of predetermined hold steps before reaching a final vacuum. At each hold step, the canister is isolated from the vacuum line and the pressure is monitored for a certain period of time, during which a pressure rise may occur if water evaporates. If the pressure rise exceeds a certain range during the time period, the step is repeated until a stable pressure is obtained. Three to seven hold points were observed among the manufacturers surveyed, with final pressures between 3 to 10 Torr (0.4 to 1.3 kPa) held up to 30 minutes. Upon conclusion of drying, the canister is backfilled with helium to a desired pressure.

The report characterized components of the fuel assembly that would cause water to remain upon conclusion of drying including breached fuel rods. For PWRs, these would also include the top and bottom nozzles, spacer grids, and guide tube dashpots. For BWRs, these include the upper and lower tie plates, spacer grids, and water rods. The BWR water rods are plugged on the bottom but have holes along the lower axial length. With regards to the canister, the spacer disks and ends of the vacuum siphon tubes are likely to retain water.

The report described the experimental features needed or recommended for conducting a drying study. The recommendation was made to scale the diameter of the mock canister but not the length. The fuel assemblies must physically represent the components that may retain water listed previously. The assemblies must be heated to represent the decay heat for irradiated fuel, and the assemblies must be submergible in water at least to a depth that wets the water-retaining features. The experimental canister must therefore hold water, support a vacuum, and support final pressurization with helium. The experimental instrumentation must provide a detailed thermal characterization of the cladding through all of the drying operation steps as well as a detailed moisture balance. The previous studies discussed below are reviewed in the light of these CNWRA vacuum test plan recommendations.

1.3.2 High Burnup Demonstration

The DOE and Electric Power Research Institute (EPRI) High Burnup Confirmatory Data Project (or High Burnup "Demo") is an ongoing multi-lab demonstration of dry-storage aging effects on high burnup (HBU) fuel. It was meant to enhance the technical basis for ensuring HBU SNF integrity and retrievability during continued storage and transportation.

Prior to cask closure, twenty-five fuel rods were removed from various assemblies and sent to Oak Ridge National Laboratory and Pacific Northwest National Laboratory. Nondestructive and destructive evaluations are underway to measure the mechanical performance of these HBU fuel rods (Ahn et al., 2018). End-of-life internal rod pressures have also been measured.

A TN-32B dry cask was loaded with HBU SNF consisting of 32 PWR assemblies from the North Anna nuclear power plant in Virginia. The cask was configured with thermocouple lances in the guide tubes of seven fuel assemblies, where each lance had a leak-tight penetration in the cask lid (each lance had 9 axially-spaced thermocouples, or TCs) (Csontos, 2018). Temperatures were also measured on the cask exterior using an infrared thermometer. Ambient temperatures were also measured by thermocouples. Measurements were obtained during cask draining, drying, and storage. For the storage period, the measured PCT of 230°C was much lower than the 318°C result from the pre-test, design-basis-maximum simulation. While cask external temperatures aligned well with the models, the internal temperatures were overestimated by the models due to conservative geometric assumptions on the design of the cask internals.

Three gas samples were taken during the vacuum drying process. These samples were analyzed for residual moisture content and for the presence of fission gases. The samples indicated that no fission gases were present and that no liquid water remained in the cask (Bryan, Jarek, Flores, & Leonard, 2019).

As with most full-scale demonstrations, tight experimental control was limited. The temperatures measured during drying were lower than expected, but the final level of residual water may be higher than the recommended 0.25 volume percent. Confirmatory measurement of the residual moisture is difficult and not possible unless the cask is opened again. While providing data for a prototypic system, additional data is needed to represent other dry storage systems and a broader parameter space.

1.3.3 Scaled Assemblies (University of Nevada, Reno)

A series of scaled assembly experiments were developed at the University of Nevada, Reno to benchmark simulations of SNF cladding temperatures during vacuum drying and transfer operations (Greiner, 2017). The project aimed to investigate the effect of a low-pressure environment on the PCT using both experimental and computational assessments. Both of the University of Nevada, Reno studies summarized below used heated assemblies that were truncated in length. No prototypic components were used, and many of the water-retaining features were not included.

An early experimental apparatus was employed from 2007 to 2012 consisting of a truncated 8×8 assembly of heater rods in a square enclosure, which is described in Table 1 (Chalasani, Araya, & Greiner, 2007). It aimed to validate computational fluid dynamics (CFD) simulations by measuring natural convection in the assembly gaps and thermal conductivity in the fuel rods and enclosure using strategically-placed thermocouples and a controlled heat rate. The apparatus was truncated axially to represent the spacing between two spacer grids in a BWR assembly and was configurable in both vertical and horizontal layouts to represent different stages of storage and transportation.

Table 1: Properties of the truncated 8×8 experimental apparatus at University of Nevada, Reno

Item	Description
Assembly	8×8 heater rod array, 1/10 of prototypic BWR height
Enclosure	Square aluminum pressure vessel, 11.8 cm side, 2.54 cm thick
Heater rods (64)	• 64 Watlow tubular heater rods at pitch of 1.45 cm • 1.1 cm diameter • 67.3 cm length • Compressed MgO surrounded by 0.7 mm-thick Incoloy sheath • Nichrome heater coil with power leads o 3.2 cm unheated section on either end • 8 heaters each connected in series, and these sets are connected in parallel to 0 to 1000W DC power supply • 4 ± 0.12 Ω average resistance • Joined by two square spacer plates of 0.635 cm thickness and 11.9 cm side, with 1.15 cm holes and 1.44 cm pitch

Thermocouples	• K-type for 47 of 64 rods
	    o One of four axial locations: -17.3, 0, 17.3, 29.2
	    o Actual positions measured to ± 1.3 cm
	• 21 K-type on wall of enclosure
	• 4 K-type on each endplate

Insulation	Fiberfrax blankets of 2.5 or 5 cm thickness

Another assembly was created in 2017 with a design truncated to 7×7 (see Table 2) (Maharjan, 2018). This assembly was meant to simulate vacuum drying conditions and to benchmark CFD calculations. It also had the added capability of accommodating helium in the void space for rarefaction studies via flanges on the square enclosure, once again truncated in length to match the distance between two spacer grids. For the continuum regime of pressures (4 kPa to 200 kPa), the temperature difference between the central rod and average wall temperature was found to be nearly constant. However, in the slip regime (40 Pa to 2 kPa), the temperature difference increases with decreasing pressure because of gas rarefaction.

Table 2: Properties of Maharjan's experimental apparatus at University of Nevada, Reno

Item	Description
Assembly	7×7 heater rod array, 1/10 of prototypic BWR height
Enclosure	Square stainless steel pressure vessel, 12.7 cm side, 4.75 mm wall thickness
Heater rods	• Compressed MgO with SS sheath of 0.72 mm thickness • 1.25 ± 0.003 cm diameter • 65 ± 0.5 cm length • 3 cm unheated length at either end • 20 W ± 1 W rating • Seven rods connected in series as a group, and groups are then connected in parallel • Joined by two square spacer plates of 1.5 mm thickness and 11.5 cm side, with 1.17 cm holes and 1.625 cm pitch

Thermocouples	• One type K in each heater
	    o 1 of 5 axial locations (z = -25, -10, 0, 10, and 25 cm)
	    o ±5 cm manufacturer installation error
	    o ±3 mm error in measured positions
	• 13 TCs used in each wall
	• 14 TCs used in each end plate
	• 129 total (13·4+2·14+7·7)

Insulation	• 2.54 cm (1 in.) thick LD Duraboard Unifrax • Additional 2.54 cm (1 in.) thick Unifrax blanket on top
Vacuum system	• Ultra-high vacuum flanges with feedthroughs welded to either end of enclosure • HiCube 80 Eco vacuum pump • Helium tank • MKS 626C 1000 and MKS 622B 20 pressure gauges

1.3.4 Single BWR Assembly, Full Length (University of South Carolina)

A NEUP integrated research project was conducted at the University of South Carolina on a full assembly-scale vacuum drying experiment for dry cask storage (Knight, 2019; Shalloo, Knight, Khan, Farouk, & Tulenko, 2017). The study aimed to demonstrate the application of vacuum drying using standard industry guidelines and provide data to validate drying models using a versatile experimental apparatus summarized in Table 3. At least 120 drying tests were conducted to analyze both "single" and "combined" effects. The single effect tests evaluated drying a set amount of water in a specific assembly or cask feature, such as a failed fuel rod, spacer disc, Boral sheet, BWR water rod, or PWR guide thimble dashpot. The combined tests focused on specific features following the flooding, dewatering, and blowdown of the apparatus and prior to the drying procedure.

Freezing was observed to occur in the spacer disk outside of the basket and rails and other specific tests involving spacers. These spacers are horizontal and are capable of holding water following blowdown. Nonetheless, the water was observed to melt in the holding period, leading to the dryness test failing and water being evacuated fully in a subsequent vacuum/hold step.

Table 3: Properties of the experimental apparatus at the University of South Carolina (Knight, 2018)

Item	Description	Details
Assembly	Modified Areva Atrium 10A BWR	
Heater rods (up to 12)	Proprietary Framatome mock assembly hardware	Stainless steel sheath Ceramic filler Boron nitride internal insulation Uniform heat flux
Fuel rods (79)	Depleted uranium	
Interchangeable test rod (1)	PWR guide tube	Zr-4 tube plugged at bottom with weep holes at 40 and 43 cm height
	BWR water rod	Zr-4 tube plugged at bottom with weep holes at 175 and 178 cm height
	Defected rod with perforation at 175 cm height, water-fillable	99.99% cerium oxide pellets 1 mm diameter defect hole 33 mL H_2O pre-test injection
Thermocouples	Up to eight per heater; on inline gas heater; on channel, basket, and rails for each of six viewports	Type K
Humidity sensors	Industrial RH and temperature transmitter	Vacuum-rated High-pressure Operable at 150°C
Vacuum system	Vacuum chamber	
	Two desiccators	
	Cold trap	
	Main vacuum pump	

Tests with the failed fuel rod met test criteria for dryness (3 Torr hold) and dehydration by helium (0.1% R.H.) although between 7 to 12 cm^3 of water was still observed to be retained inside; this quantity was improved to 0.5-2 cm^3 with more carefully-controlled boundary conditions. Overall, retention was due largely to surface tension effects from tightly-packed ceria pellets, along with fractures that developed in the pellets themselves. Also, the hold-down springs in the failure test rods were mostly uncompressed and functioned as sites for liquid retention.

The heater rods were all driven with power levels meant to simulate dry cask decay heat. While remaining under the regulatory limit of 400°C, the temperatures are observed to increase under vacuum and under helium gas recirculation. Tests that successfully brought the system to dry conditions corresponded to the highest heater rod temperatures, compared to those that had residual water. Test rod peak temperatures were obtained from thermal images and varied between 85 and 190°C depending on the type of vacuum/helium test involved. Data is intended to inform predictive multi-phase, multi-physics models on vacuum drying.

Altogether, the heat flux profile and insulation played major roles in the overall behavior of results. Heat tape was added to the outside bottom of the chamber to reduce heat loss and prevent freezing in the siphon tube. It also allowed the cosine heat profile to flatten and more closely represent the typical profile of dry cask decay heat.

1.4 Desired Capabilities

Previous testing has provided a strong database and background from which to guide future test designs to meet remaining technical gaps. The desired capabilities of these designs are summarized below.

1.4.1 Compatibility with Drying

The test apparatus should be capable of replicating commercial drying cycles. These include both vacuum and forced helium dehydration drying cycles. Simulated fuel assemblies should be capable of heated operation during drying, which will likely require a submergible heater design. These assemblies should have prototypic, geometric features capable of trapping bulk water such as dashpots (PWR) and water rods (BWR). Furthermore, the apparatus should accommodate the testing of damaged fuel surrogates.

1.4.2 Prototypic Thermal-Hydraulics

The fuel assemblies should incorporate prototypic hardware and length scales to mimic the integral physics of dry storage systems. The test apparatus should be configurable to allow a variety of storage configurations to be studied. In addition, transportation configurations should be considered.

1.4.3 Monitoring of Cladding

The system should be capable of characterizing cladding behavior during drying and storage conditions. This characterization should include the measurement of cladding temperature and internal rod pressure. The impact of cladding failures from pinhole to gross breaches should be considered.

2 TESTING CONCEPTS

This chapter introduces new surrogates and techniques for testing to address gaps in the current understanding of dry storage systems during drying and storage. This involves the implementation of innovative fuel rod surrogates to evaluate water retention and internal rod pressures in a partially-submersible environment. The ultimate goal is to employ these advanced rods in multiple assemblies in a versatile dry cask simulator for thermal-hydraulic experiments.

2.1 Submersible Heater

A new heater rod concept is proposed that will enable the assessment of thermal phenomena in a wet environment. These rods will be partially-submersible versions of those in past designs, with immersion planned for up to 75% of the axial length. They will be comprised of magnesium oxide (MgO) compacted around a spirally-wound Nichrome wire with cold pins on either end, as shown in Figure 1. The coil is wound in a helix that is approximately the radius of the cold pin. Magnesium oxide ceramic is selected as a surrogate fuel material due to similar thermal mass (ρC_p) behavior with increasing temperature relative to SNF (Lindgren & Durbin, 2007).

Each heater will feature a top fitting with a hermetic ceramic-to-metal bond that will allow connection to the power source, while electrically isolating the cladding and protecting the MgO from moisture. The top fitting will be welded to the pin at the upper extreme of the threaded pin cover, along with brazing between the sheath at the clad/seal interface. The bottom fitting will have similar geometry to a bottom fuel plug, with an internal pocket containing high-temperature electrical grease to receive the neutral cold pin. This bottom plug will be circumferentially welded to the cladding, effectively bonding the cladding to the electrical neutral.

The rods can be electrically connected in an assembly by a bus plate via contact on the protruding hot pins (see Section 2.4). The cladding and guide tubes in each assembly are electrically isolated from the bus plates via the top hermetic seal. In lieu of an electrically-connected bottom nozzle, the neutral will be drawn from the top spacer grid, which has spring contracts with all the heater rods. During wetted tests, a plumbing system will be in place to prevent the water level from reaching the top bus plate and creating a short circuit as an added safety measure. Many heater rod will have K-type thermocouples installed on the cladding at various axial locations.

2.2 Internal Pressure Monitoring Rod

An unheated fuel rod can be inserted into the fuel assembly to measure the internal rod pressure. These rods can be constructed in a similar fashion as was done in a previous study (Durbin, Lindgren, & Humphries, 2016). The fuel rods are loaded with surrogate MgO ceramic pellets, and prototypic shaped end plugs are welded to the cladding. A small diameter, thick-walled tube connects the fuel rod to an external pressure source and transducer allowing the transient measurement of internal rod pressure. Figure 2 shows a schematic of a pressure-monitoring rod, where the top fitting is circumferentially welded to the pressure tube.

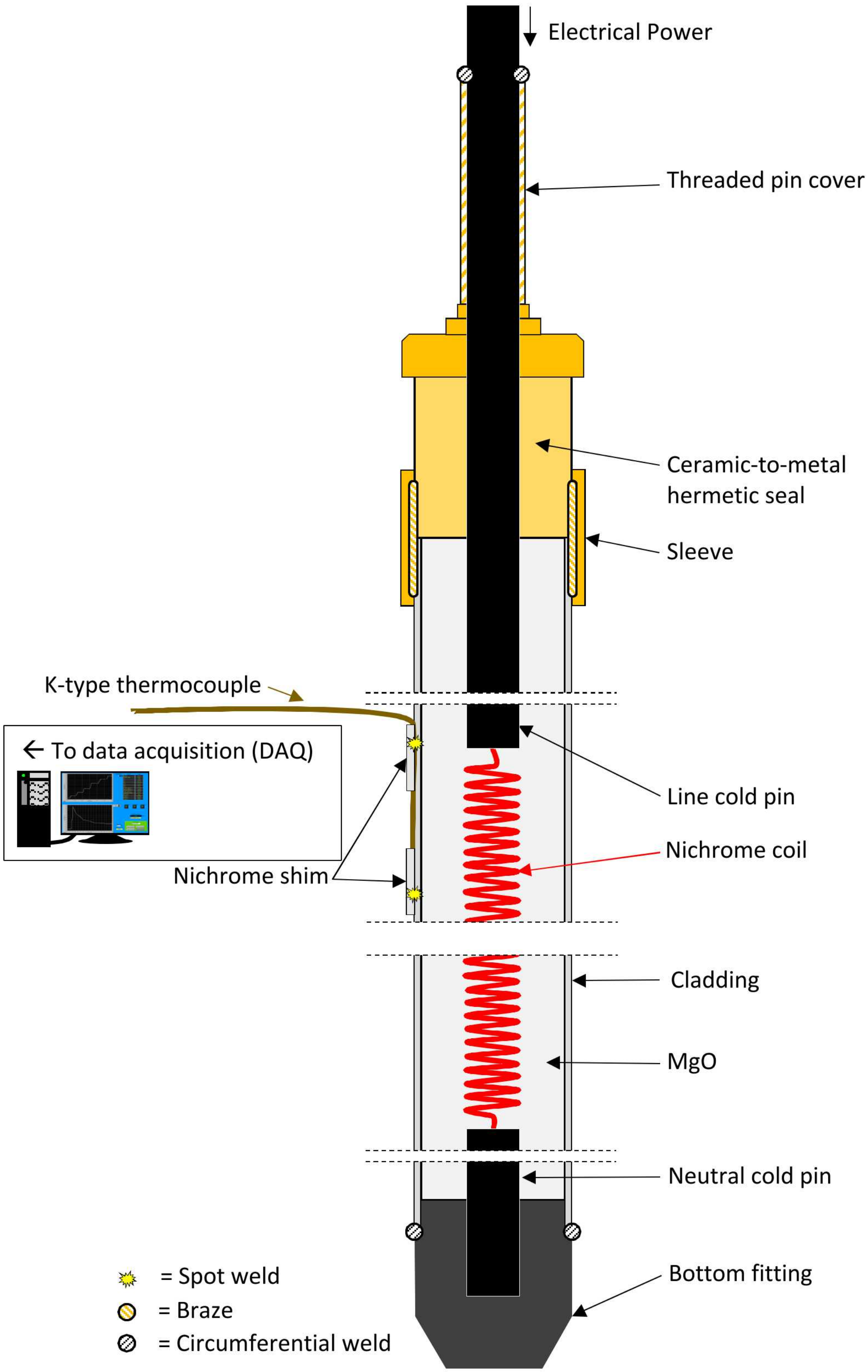

Figure 1: Heater rod schematic

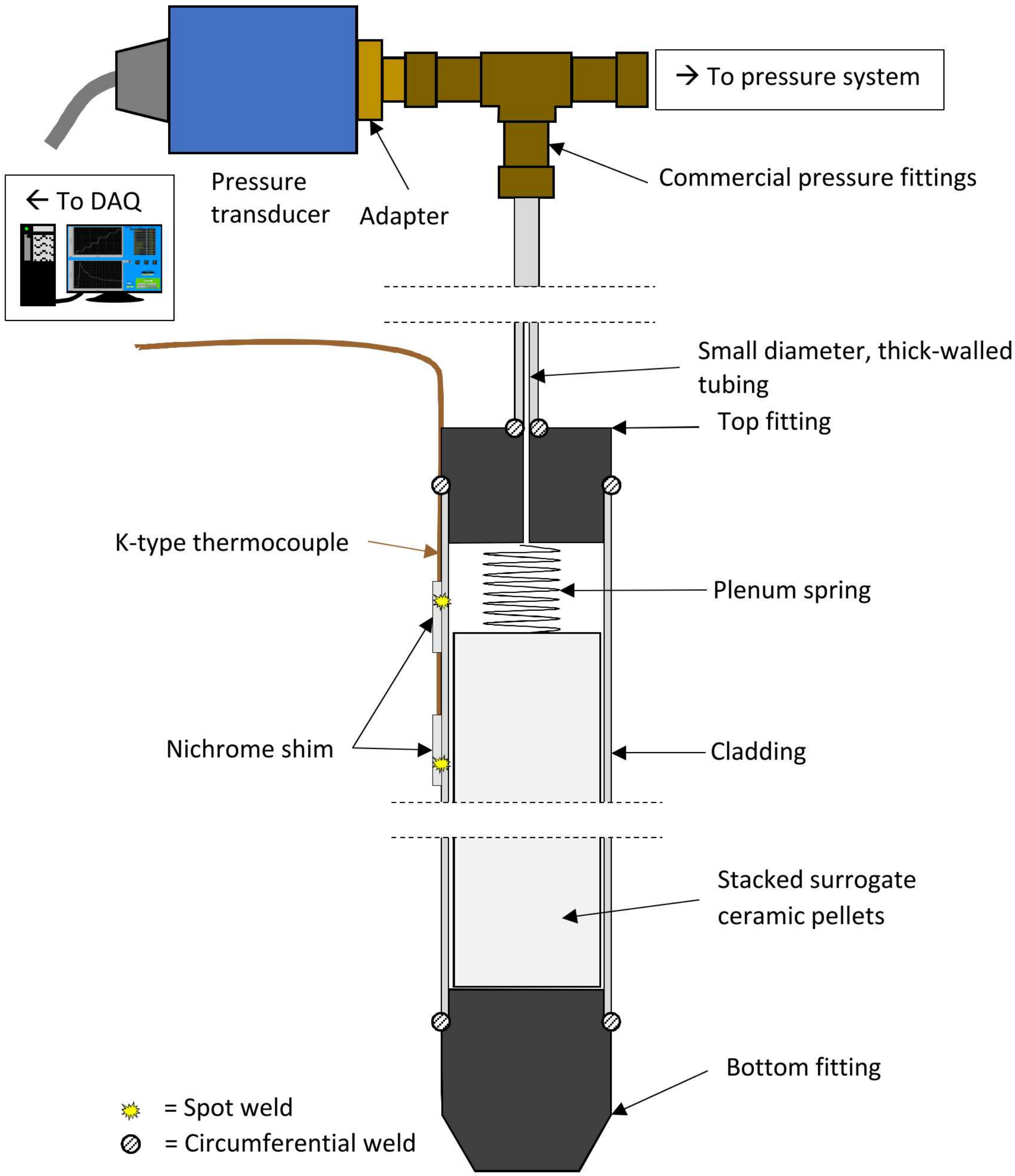

Figure 2: Cross-sectional view of pressure measurement rods

2.3 Breached Cladding Rod

Defects can be introduced to the cladding of unheated rods described in Section 2.2 and shown in Figure 2, for studies on breached fuel rods. Cladding breaches can be introduced at a specified axial location with a set geometry. A breach may include a pinhole leak, hairline crack, or gross rupture (larger than 1 mm). A breach can be machined into the cladding with well-defined geometry. Water would be metered into the breached rod through the small diameter, thick-walled tubing. The same tubing would then be used to monitor the pressure inside the rod during a heated drying test. The differential pressure between the breached rod and the pressure vessel will be used in the evaluation of the breached rod drying.

Magnesium oxide ceramic is a possible surrogate fuel material due to similar thermal mass (ρC_p) behavior with increasing temperature relative to SNF (Lindgren & Durbin, 2007). The choice of MgO will allow the heater material and pellets to be representative of the thermal mass of a fuel rod. However, the MgO ceramic is slightly porous. Therefore, the water sorption characteristics of the ceramic will need to be characterized as an input parameter for modeling. Alternative materials such cerium oxide will also be considered.

2.4 Multi-Assembly Layout Components

Building on the success of the Dry Cask Simulator (Durbin et al., 2016), a multi-assembly test would bridge the prototypic complexity of the High Burnup Demo and the controlled environment of a lab-fielded apparatus. Several concepts have been explored and are the subject of ongoing research. One promising concept would use prototypic PWR skeletons to harvest “mini-assemblies” as shown in Figure 3. The mini-assemblies would retain prototypic geometric features but would be populated with waterproof, electrically-resistive heaters and instrumentation. The fuel length would be prototypic and generate realistic temperature gradients all while maintaining the intricate features of the guide tubes and grid spacers. Although the lateral extent of each assembly would be truncated, this configuration would effectively incorporate heat transfer between assemblies as an improvement to the state of the art and offer a great deal of flexibility for future investigations.

The cross-sectionally truncated, full-length skeletons will be harvested from a 17 by 17 commercial skeleton. They will be comprised of 1 guide tube, 24 fuel pins, and all other fundamental hardware (top and bottom nozzles, spacers, IFMs, debris catcher). Figure 4 shows the rearrangement of these assemblies in a basket structure inside a scaled dry storage canister. A truncated assembly with labeled dimensions is featured in Figure 5. The use of four obliquely-cut mini-assemblies with 21 fuel rods in the corners will allow for greater economy of space in the scaled system and more closely emulate the fraction of the fuel-occupied footprint in an actual cask.

The multi-assembly cask test will feature simplified, well-controlled boundary conditions and inputs. Multiple validation exercises will be possible with a versatile configuration. In this approach, pre-test modeling is tied with the experimental design, which features prototypic length and hardware. Multiple mini-assemblies will offer a key advantage in assessing inter-assembly interactions. Furthermore, the study is intersectional of drying and cladding integrity research, allowing for a robust system performance assessment.

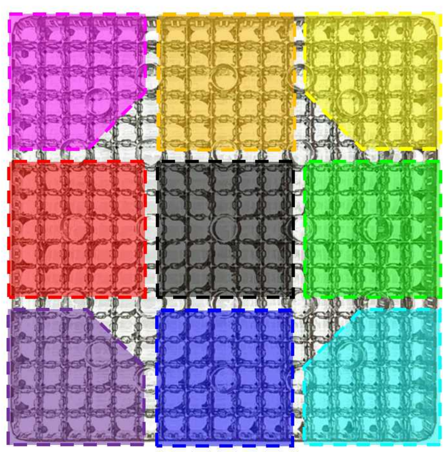

Figure 3: 5×5 subassemblies taken from a 17×17 PWR skeleton

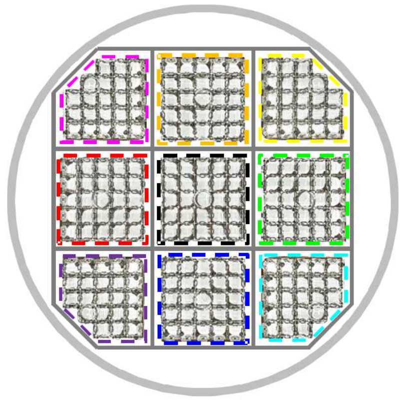

Figure 4: Reconfigured 5×5 mini-assemblies in a dry storage apparatus

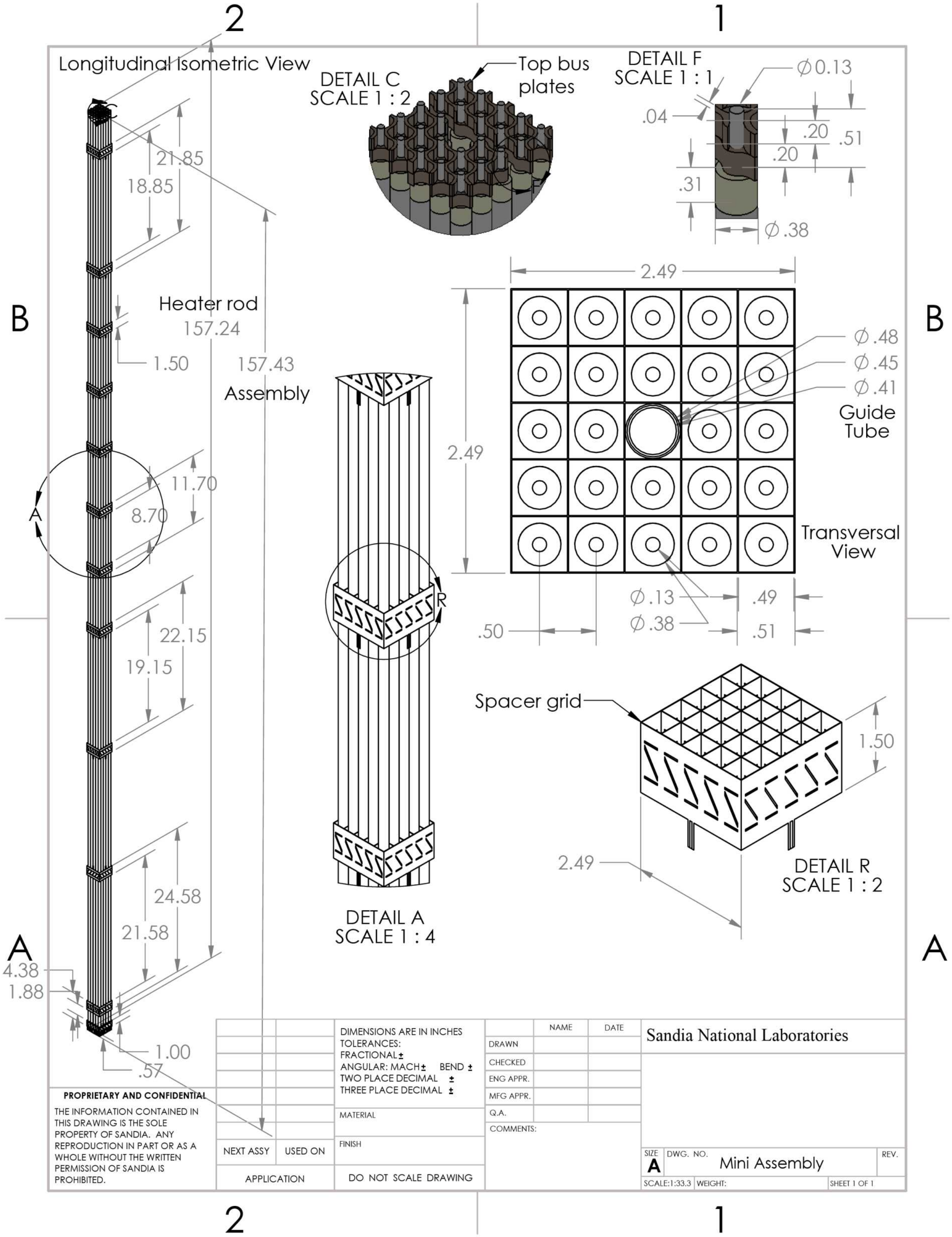

Figure 5: Schematic of truncated PWR assembly (dimensions in inches)

3 SUMMARY

Scaled and in-situ experiments to assess dry cask performance have led to greater understanding of spent nuclear fuel during drying and storage. These data sets are needed to evaluate the long-term integrity of the fuel. Several notable examples of these studies have occurred recently and have added to the existing knowledge base.

The High Burnup Demo has provided significant data on the thermal-hydraulic response of a cask during drying and storage. In addition, a limited number of gas samples have been analyzed to determine residual water content after drying. Ongoing tests of sample rods extracted from the fuel assemblies continue to offer data on end-of-life pressure and cladding mechanical properties. However, many questions remain on the exact state of rod conditions during prototypic operations.

The NEUP project at the University of Nevada, Reno was able to clearly demonstrate the role of helium rarefaction on heat transfer between heater rods and their surroundings. This was accomplished using both small-scale experiments and truncated BWR assemblies. These results were used to validate simulations with some degree of success.

The assembly-scale experiments at the University of South Carolina were able to provide a limited amount of validation data for fuel under industry-based vacuum drying conditions. Issues were encountered with non-prototypic heat losses at the bottom of the fuel assembly, and only gross breaches (1 mm) of the fuel cladding were examined. These tests of a mock BWR assembly offer several insights into future investigations with a submersible system.

To date, Sandia National Laboratories has gained specialized experience from assembly-scale experiments and related sensor installation, air flow measurements, inert gas pressurization, and automated control. This practical experience has resulted in the proposal of future testing components for the study of spent fuel assemblies under drying and storage conditions. These specialized fuel surrogates are intended as building blocks for either truncated or full-scale, mock fuel assemblies. The final test apparatus would use these surrogates to measure the response of the fuel and the interior of the dry cask with partially-submersible fuel assemblies and pressure vessel to well-controlled inputs and boundary conditions. The apparatus will provide temperature, pressure, and residual water data during wetting, drainage, blowdown, drying, and final backfill. Issues regarding bulk water retention and dryness criteria will be explored, and internal rod pressures will be monitored to characterize fuel cladding during drying and storage.

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4 REFERENCES

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