Status Update of the BWR Cask Simulator

Fuel Cycle Research & Development

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SUMMARY

The performance of commercial nuclear spent fuel dry storage casks are typically evaluated through detailed numerical analysis of the system's thermal performance. These modeling efforts are performed by the vendor to demonstrate the performance and regulatory compliance and are independently verified by the Nuclear Regulatory Commission (NRC). Carefully measured data sets generated from testing of full sized casks or smaller cask analogs are widely recognized as vital for validating these models. Numerous studies have been previously conducted. Recent advances in dry storage cask designs have moved the storage location from aboveground to belowground and significantly increased the maximum thermal load allowed in a cask in part by increasing the canister helium pressure. Previous cask performance validation testing did not capture these parameters.

The purpose of the investigation described in this report is to produce a data set that can be used to test the validity of the assumptions associated with the calculations presently used to determine steady-state cladding temperatures in modern dry casks. These modern cask designs utilize elevated helium pressure in the sealed canister or are intended for subsurface storage.

The BWR cask simulator (BCS) has been designed in detail for both the aboveground and belowground venting configurations. The pressure vessel representing the canister has been designed, fabricated, and pressure tested for a maximum allowable pressure (MAWP) rating of 24 bar at 400 °C. An existing electrically heated but otherwise prototypic BWR Incoloy-clad test assembly is being deployed inside of a representative storage basket and cylindrical pressure vessel that represents the canister. The symmetric single assembly geometry with well-controlled boundary conditions simplifies interpretation of results. Various configurations of outer concentric ducting will be used to mimic conditions for above and belowground storage configurations of vertical, dry cask systems with canisters. Radial and axial temperature profiles will be measured for a wide range of decay power and helium cask pressures. Of particular interest is the evaluation of the effect of increased helium pressure on heat load and the effect of simulated wind on a simplified belowground vent configuration.

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ACRONYMS

BCS	BWR Cask Simulator
BWR	boiling water reactor
DOE	Department of Energy
NRC	Nuclear Regulatory Commission
PWR	pressurized water reactor
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TC	thermocouple

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STATUS UPDATE OF THE BWR CASK SIMULATOR

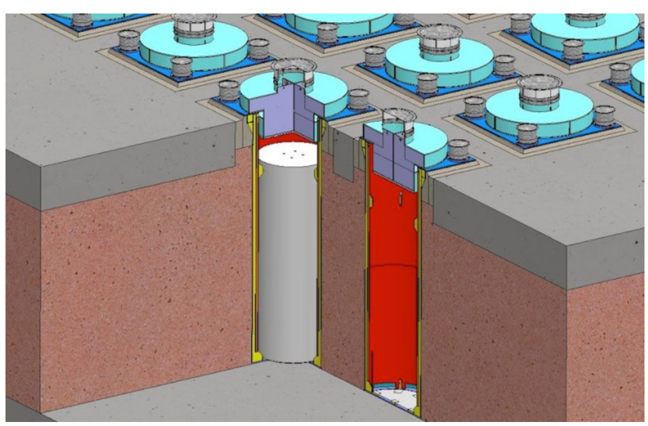
1. INTRODUCTION

The performance of commercial nuclear spent fuel dry storage casks are typically evaluated through detailed finite element modeling of the system's thermal performance. These modeling efforts are performed by the vendor to demonstrate the performance and regulatory compliance and are independently verified by the Nuclear Regulatory Commission (NRC). The majority of commercial dry storage casks in use today are aboveground. Both horizontally and vertically oriented aboveground dry cask systems are in use. Figure 1.1 shows a diagram for a typical vertical aboveground system. Cooling of the assemblies located inside the sealed canister is enhanced by the induced flow of air drawn in the bottom of the cask and exiting out the top of the cask.

Source: www.nrc.gov/reading-rm/doc-collections/fact-sheets/storage-spent-fuel-fs.html

Figure 1.1 Typical vertical aboveground storage cask system.

Figure 1.2 shows a diagram for a typical vertical belowground system. For belowground configurations air is drawn in from the top periphery and channeled to the bottom where it then flows upward along the wall of the canister and exits out the top center of the cask.



Source: www.holtecinternational.com/productsandservices/wasteandfuelmanagement/hi-storm/

Figure 1.2 Typical vertical belowground storage cask system.

Carefully measured data sets generated from testing of full sized casks or smaller cask analogs are widely recognized as vital for validating design and performance models. Numerous studies have been previously conducted [Bates, 1986; Dziadosz and Moore, 1986; Irino *et al.*, 1987; McKinnon *et al.*,1986]. Recent advances in dry storage cask designs have moved the storage location from aboveground to belowground and significantly increased the maximum thermal load allowed in a cask in part by increasing the canister helium pressure. Previous cask performance validation testing did not capture these parameters. Thus the enhanced performance of modern dry storage casks cannot be fully validated using previous studies.

1.1 Objective

The purpose of this investigation is to produce a data set that can be used to test the validity of the assumptions associated with the calculations presently used to determine steady-state cladding temperatures in modern dry casks. These casks utilize elevated helium pressure in the sealed canister or are of a design for location in the subsurface. These calculations are used to evaluate cladding integrity throughout storage cycle.

1.2 Previous Studies

1.2.1 Small Scale, Single Assembly

Two single assembly investigations were documented in the mid-1980s. [Bates, 1986; Irino *et al.*, 1987] Both used electrically heated 15×15 pressurized water reactor (PWR) assemblies and were limited to one atmosphere helium. Both also imposed a constant temperature boundary condition on the outer cask wall in an attempt to achieve prototypic storage temperatures in the fuel assembly bundle.

The present investigation differs in a number of significant ways. The present test assembly represents a boiling water reactor (BWR) fuel assembly. The canister will accommodate helium pressures up to 24 bar at 400 °C and boundary conditions for aboveground and belowground configurations. The experimental approach of the present study is different than the previous studies. Rather than striving to achieve prototypic peak clad temperatures by artificially imposing a temperature boundary condition on the canister wall, the present study represents the physics of near-prototypic boundary conditions.

2. APPARATUS

2.1 General Construction

The general design details are shown in Figure 2.1. An existing electrically heated but otherwise prototypic BWR Incoloy-clad test assembly will be deployed inside of a representative storage basket and cylindrical pressure vessel that represents the canister. The symmetric single assembly geometry with well-controlled boundary conditions simplifies interpretation of results. Various configurations of outer concentric ducting will be used to mimic conditions for above and belowground storage configurations of vertical, dry cask systems with canisters. Radial and axial temperature profiles will be measured for a wide range of decay power and canister helium pressures. Of particular interest is the evaluation of the effect of increased helium pressure on heat load for both the aboveground and belowground configurations. The effect of wind speed will also be measured for the belowground configuration. Mass flow rates and convection heat transfer coefficients will also be calculated from indirect measurements for the external cooling flows.

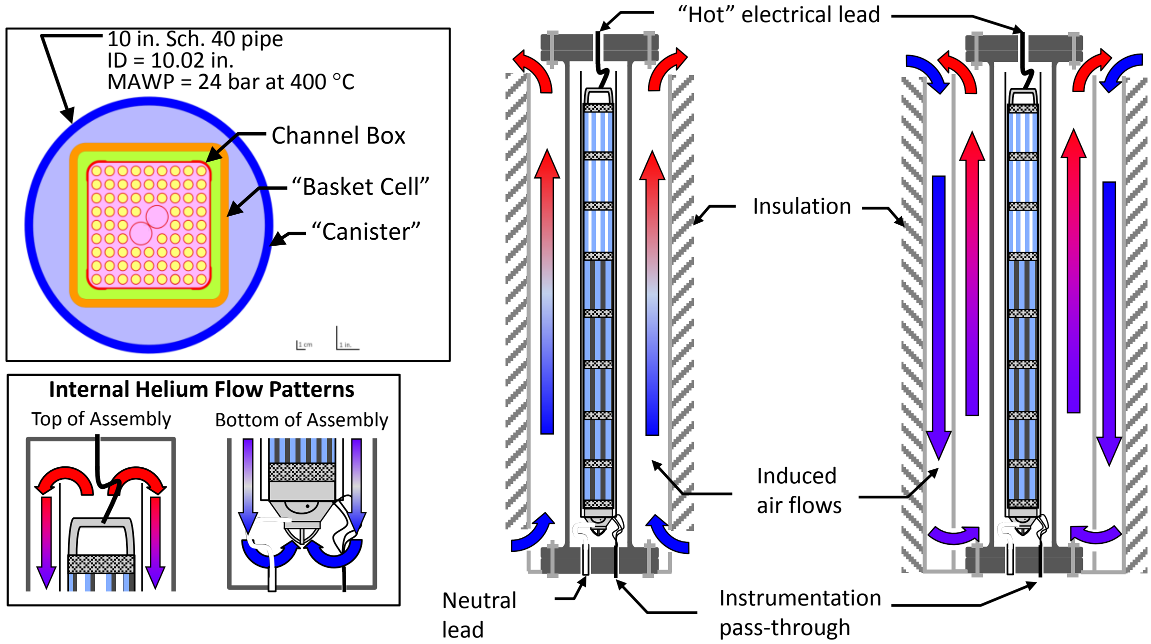


Figure 2.1 General design details sowing the plan view (upper left), the internal helium flow (lower left) and the external air flow for the above ground (middle) and below ground configurations (right).

Figure 2.2 shows some of the carbon steel components used to fabricate the pressure vessel. The 4.572 m (180 in.) long vertical test section is made from 0.254 m (10 in.) Schedule 40 pipe welded to Class 300 flanges. The 0.356 × 0.254 m (14 × 10 in.) Schedule 40 reducing tee is needed to facilitate routing over 150 thermocouples (TCs) out of the pressure vessel. Blind flanges with threaded access ports for TC and power lead pass-throughs are bolt to the top of the vertical test stand section and the sides of the reducing tee. The maximum allowable working pressure is 24 bar at 400°C. Bar stock tabs were welded inside the 0.254 m (10 in.) flange on the tee to support the test assembly and allow an insulated top boundary condition.

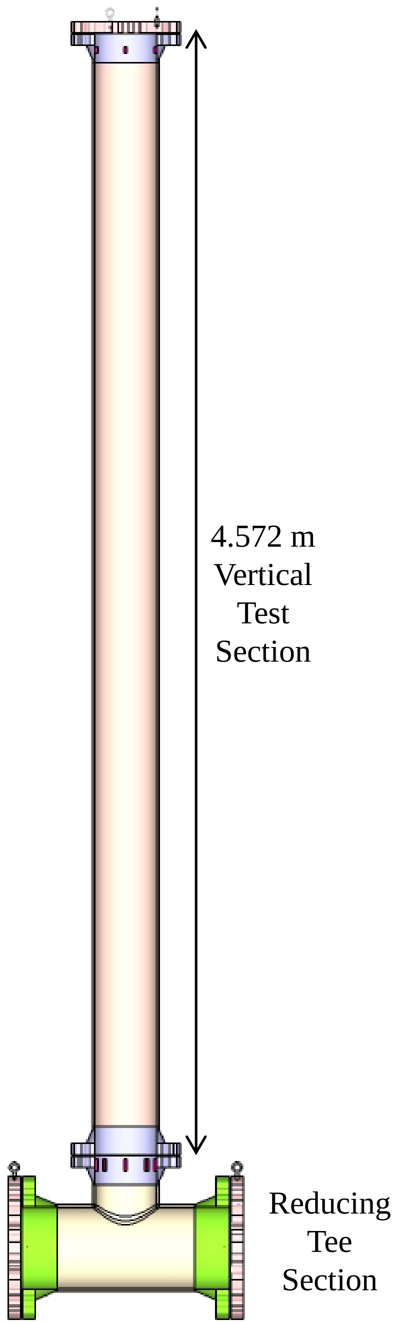


Figure 2.2 Carbon steel pressure vessel.

The test configurations will be assembled and operated inside of the Cylindrical Boiling (CYBL) test facility, which is the same facility used for earlier fuel assembly studies [Lindgren and Durbin, 2007]. CYBL is a large stainless steel containment vessel repurposed from earlier flooded containment/core retention studies sponsored by DOE. Since then CYBL has served as an excellent general-use engineered barrier for the isolation of high-energy tests. The outer vessel is 5.1 m in diameter and 8.4 m tall (16.7 ft. in diameter and 27.6 feet tall) and constructed with 9.5 mm (0.375 in.) thick stainless steel walls. Figure 2.3 shows a scaled diagram of CYBL facility with the aboveground version of the test BCS inside.

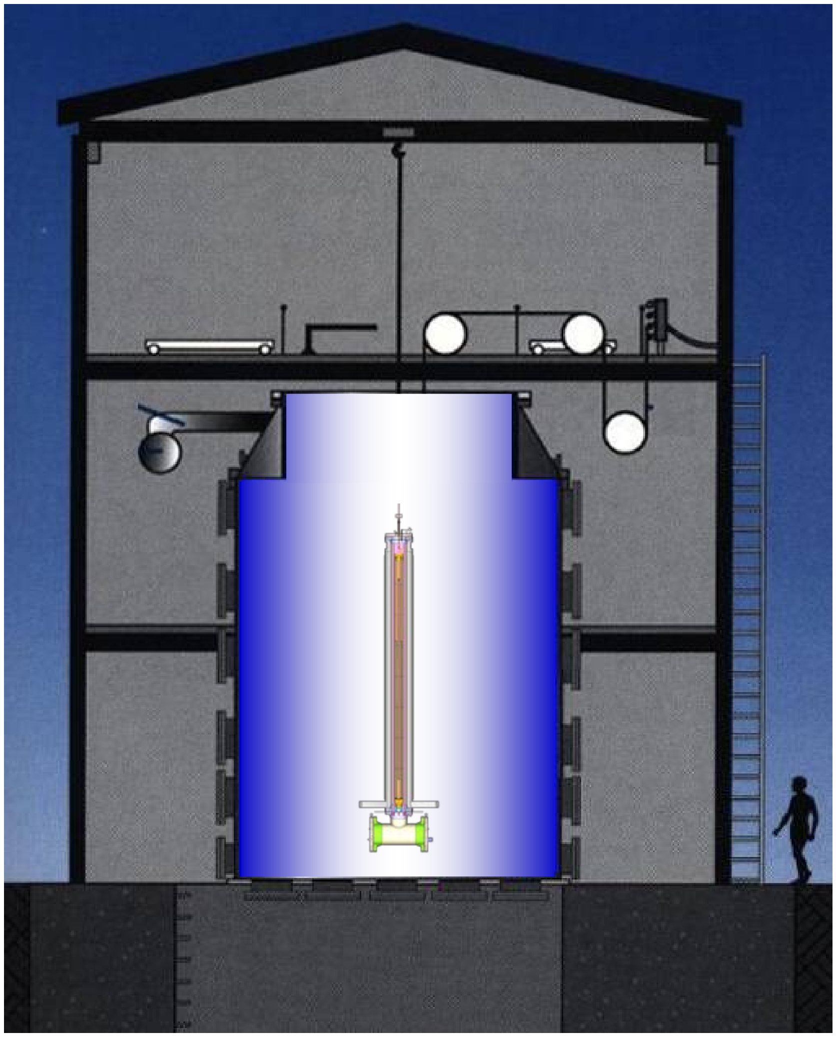


Figure 2.3 CYBL facility housing the aboveground version of the BWR cask simulator.

2.2 Design of the Heated Fuel Bundle

The highly prototypic fuel assembly was modeled after a 9×9 BWR. Commercial components were purchased to create the assembly including the top and bottom tie plates, spacers, water rods, channel box, and all related assembly hardware (see Figure 2.4). Incoloy heater rods were substituted for the fuel rod pins for heated testing. Due to fabrication constraints the diameter of the Incoloy heaters was slightly smaller than prototypic pins, 1.09×10^{-2} m versus 1.12×10^{-2} m. The slightly simplified Incoloy mock fuel pins were fabricated based on drawings and physical examples from the nuclear component supplier. The dimensions of the assembly components are listed below in Table 2.1.

Table 2.1 Dimensions of assembly components in the 9×9 BWR.

Description	Lower (Full) Section	Upper (Partial) Section
Number of pins	74	66
Pin diameter	1.09×10^{-2}	1.11×10^{-2}
Pin pitch	1.44×10^{-2}	1.44×10^{-2}
Pin separation	3.48×10^{-3}	3.48×10^{-3}
Water rod OD (main section)	2.49×10^{-2}	2.49×10^{-2}
Water rod ID	2.34×10^{-2}	2.34×10^{-2}

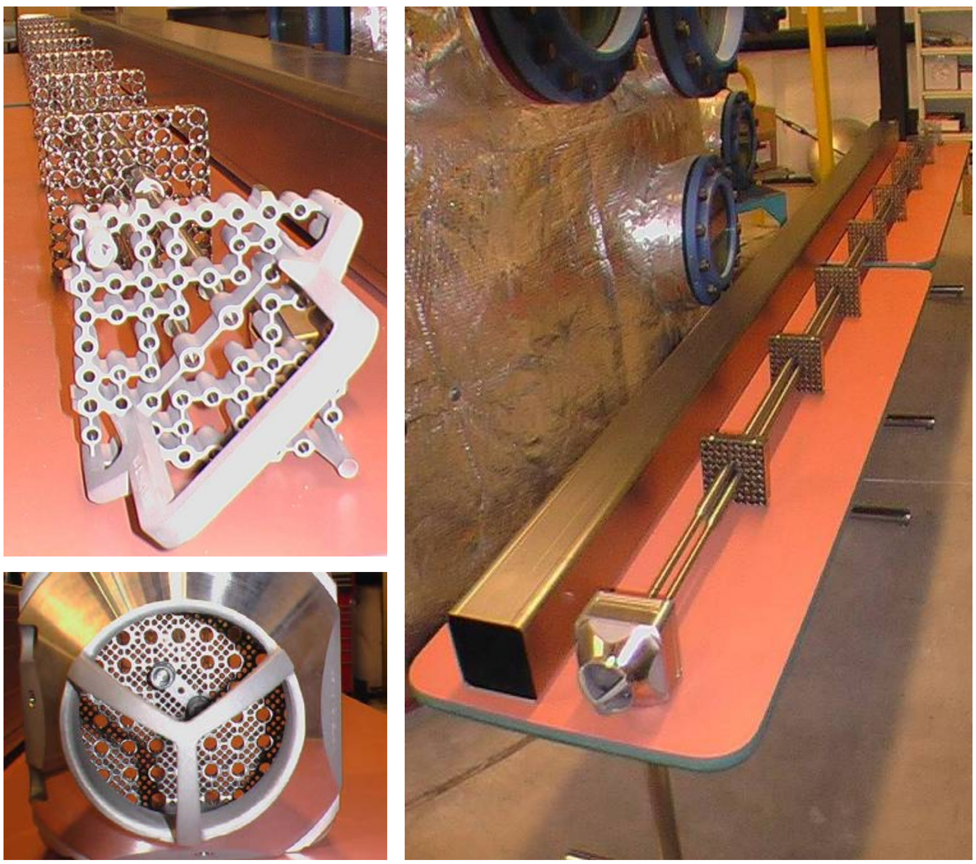


Figure 2.4 Typical 9×9 BWR components used to construct the test assembly including top tie plate (upper left), bottom tie plate (bottom left) and channel box and spacers assembled onto the water rods (left).

The thermocouples used are ungrounded junction Type K with an Incoloy sheath diameter of 0.762 mm (0.030 in.) held in intimate contact with the cladding by a thin Nichrome shim. This shim is spot welded to the cladding as shown in Figure 2.5. The TC attachment method allows the direct measurement of the cladding temperature.

Figure 2.5 Typical TC attachment to heater rod.

2.3 Instrumentation

The test apparatus will be instrumented with thermocouples (TCs) for temperature measurements, pressure transducers to monitor the internal helium pressure, and hot wire anemometers for flow velocity measurement in the exterior ducting. Volumetric flow controllers will be used to calibrate the hotwire probes. Voltage, amperage, and electrical power transducers will be used for monitoring the electrical energy input to the test assembly.

Ninety-seven thermocouples are already installed on the BWR test assembly. Details of the BWR test assembly and TC locations are described elsewhere [Lindgren and Durbin, 2007]. Additional thermocouples will be installed on the other major components of the test apparatus such as the channel box, storage basket, canister wall, and exterior air ducting. TC placement on these components is designed to correspond with the existing TC placement in the BWR assembly.

Hot wire anemometers were chosen to measure the inlet flow rate because this type of instrument is sensitive and robust while introducing almost no unrecoverable flow losses. Due to the nature of the hot wire measurements, best results are achieved when the probe is placed in an isothermal, unheated gas flow. Calibration of the hot wires will be performed by imposing a known mass flow rate of air through the ducting with the hot wires in place.

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3. TESTING

3.1 Aboveground

The inlet arrangement for the aboveground configuration is shown in Figure 3.1. Four rectangular ducts convey the inlet flow into the simulated cask. Hot wire anemometers are located in each duct and flow straightening elements at the duct entrance condition the flow.

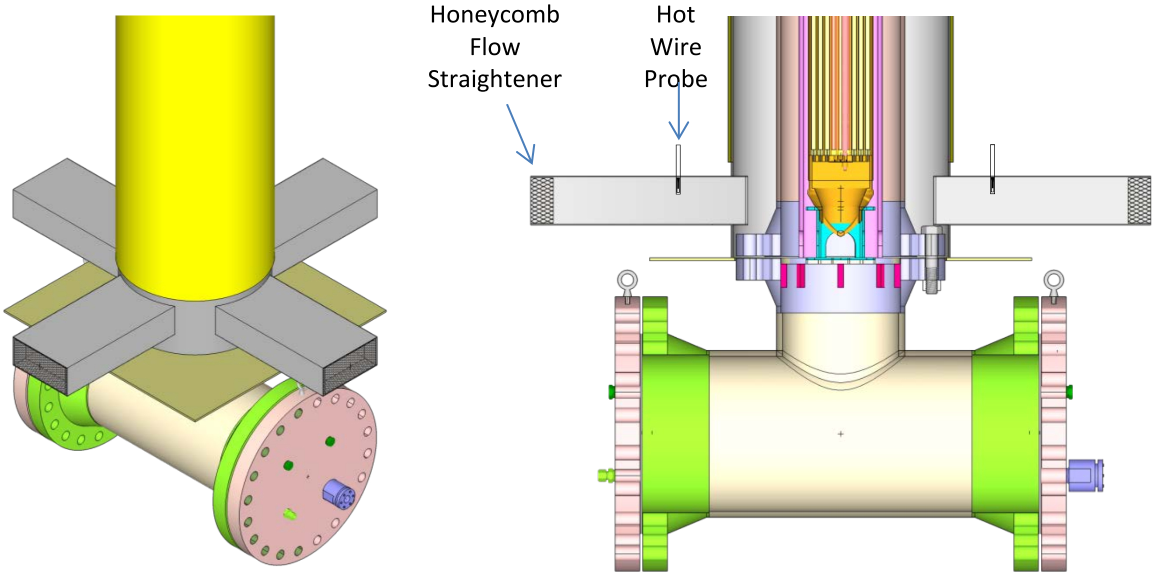

Figure 3.1 Aboveground configuration showing the location of the hot wire probes.

3.2 Belowground

Figure 3.2 shows the belowground apparatus configuration. Air is drawn into the outer duct entrance and flows downward. Insulation along the inner down comer wall prevents the air from heating. The hot wire anemometers are located in the down-comer duct at the end of the insulation near the bottom of the apparatus. The air flow turns at the bottom through the rectangular cutouts and moves upward along the hot pressure vessel wall. Hot air exits the upper central vent.

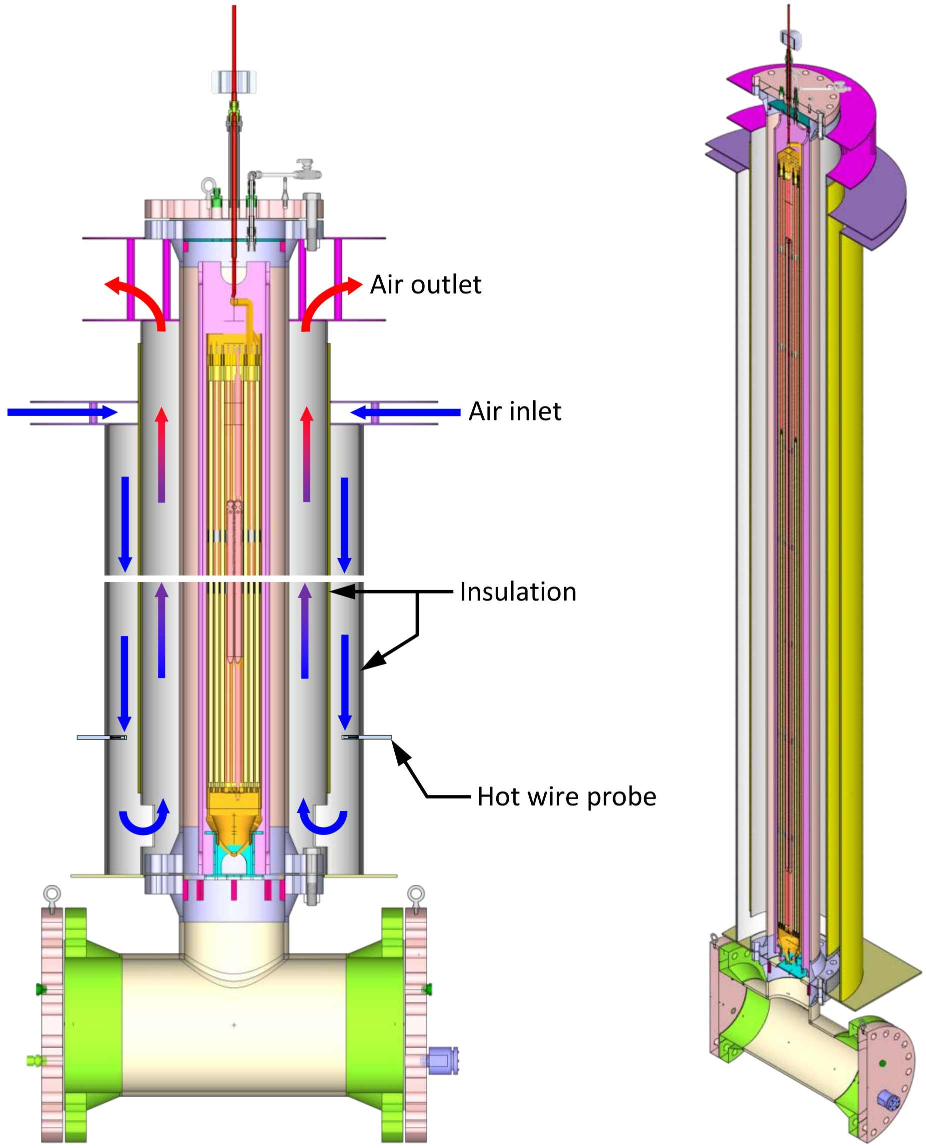

Figure 3.2 Belowground configuration showing the location of the hot wire probes.

3.2.1 Wind Generator

The effect of wind blowing across the belowground air inlet and outlet will be measured by introducing a nominally uniform velocity of air across the top of the test assembly as depicted in Figure 3.3. The wind generator consists of push-pull system: a blower section and a receiver section connected by ducting. This arrangement is intended to minimize stray air currents within the CYBL vessel. The air flow is generated by three pneumatic Venturi eductors with the suction end connected to the receiving section and the outlet end ducted to the blower section. Each educator consumes 3.54 m^3/min (125 ft^3/min) of compressed air to produce up to 101.4 m^3/min (3580 ft3/min) of ducted air flow. Baffling and flow straightening elements in the 0.76 m (30 in.) tall by 1.22 m (48 in.) wide blower section will be implemented to produce a nominally uniform wind velocity up to 5.4 m/s (12.2 mph).

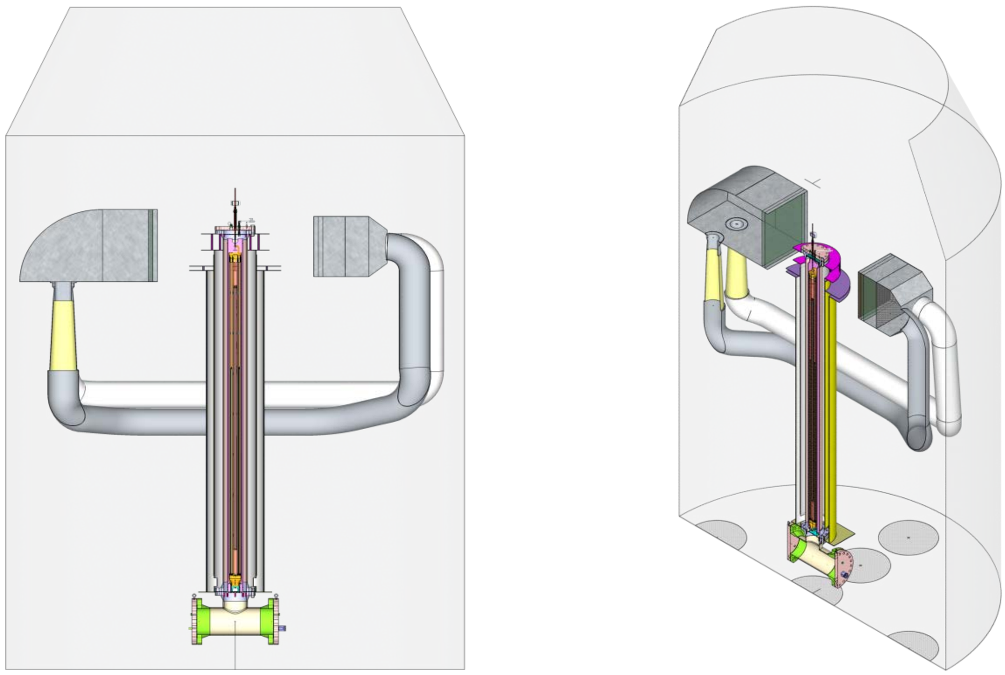

Figure 3.3 Wind generating machine across the inlet and outlet vents of the belowground test apparatus.

3.3 Test Matrix

Table 3.1 shows the test matrix. Testing will be conducted in two phases. In the first phase the experimental apparatus will be configured to represent an aboveground storage cask. Phase one testing will explore two parameters: initial helium pressure and assembly power. The pressure vessel will be filled with helium to a desired initial pressure. The test assembly will be powered at the lowest power and allowed to reach steady state. A suggested criterion for declaration of “steady state” is when the derivative of temperature with respect to time at any point within the assembly is less than 3 °C/h. Based on the data collected with the BWR assembly in previous testing steady state may require 12 to 16 hours to be established.

The data collected in the last half hour represents the steady state data for that condition. After steady state has been reached for the lowest power, the power is increased to the next level and allowed to come to steady state, which may also take up to 12 h. The process is repeated for subsequent power levels. It is expected to take one work week to complete a series of three power levels for a given pressure. The vertical dashed blue arrows represent one week of testing. Two series will be conducted for the 8 bar series. One will be from 250 W to 1000 W and another from 1000 W to 2500 W. The 8 bar 1000 W case will thus be conducted to demonstrate repeatability.

Phase 2 belowground testing will explore an additional parameter of wind speed for the higher pressure cases. The low pressure series will be conducted like the Phase 1 aboveground case. For this low pressure test series, the power will be incrementally increased. For the higher pressure cases, the wind speed will be incrementally increased. For the test series with 4.5 bar helium and 500 W, the apparatus will be allowed to come to steady state first without wind. After that steady state is achieved, the wind speed will then be set to 2.25 m/s with the assembly power kept constant. After steady state is again achieved, the wind speed will be increased again to 5 m/s. This type of test series of three steady state tests is expected to take one work week and is represented by the horizontal green dashed arrows.

Table 3.1 Test matrix for aboveground and belowground configurations.

		Belowground					
Aboveground		Wind (m/s) =>	0.0		2.25		5.0
Helium pressure (bar)	Power (W)	Helium pressure (bar)	Power (W)	Helium pressure (bar)	Power (W)	Helium pressure (bar)	Power (W)
1	500	1	500				
	1500		1500				
	2500		2500				
4.5	500	4.5	500	4.5	500	4.5	500
	1500						
	2500		2500		2500		2500
8	250	8	500	8	500	8	500
	500						
Step	1000		2500		2500		2500
through	1500		Step through wind speeds				
powers	2500						

4. STATUS

The BCS has been designed in detail for both the aboveground and belowground venting configurations. The wind generating machine for the belowground testing has been designed. The instrumented, electrically-heated 9×9 BWR remains ready for installation. The pressure vessel that represents the canister has been designed and fabricated from carbon steel components. This vessel has been pressure tested for a MAWP rating of 24 bar at 400 °C. The carbon steel components have been painted with a high temperature paint to prevent corrosion and simulate stainless steel surface properties (see Figure 4.1).

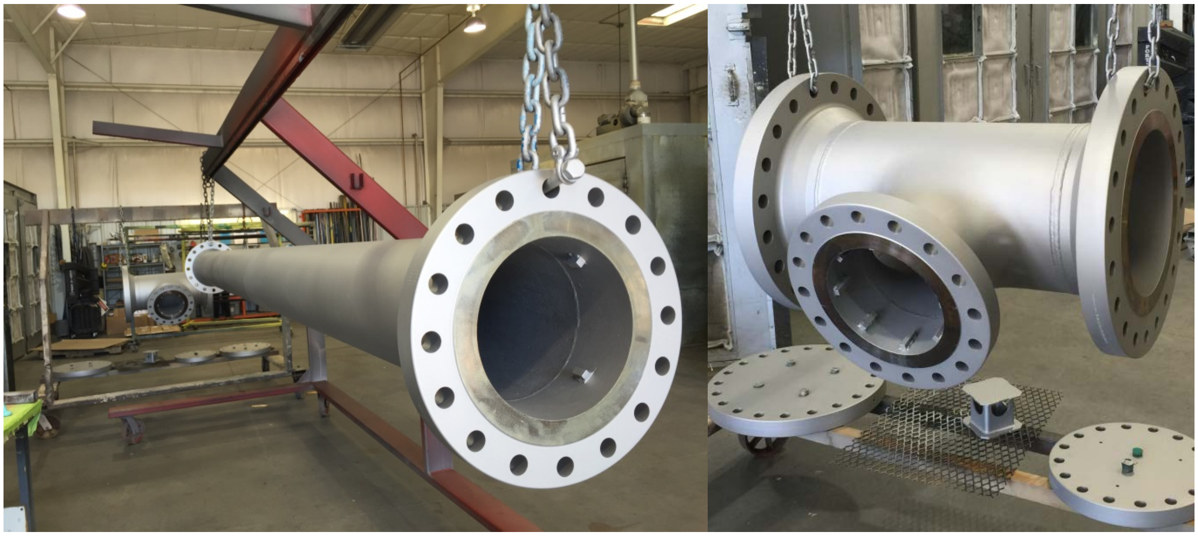

Figure 4.1 Carbon steel pressure vessel components freshly coated with high temperature paint.

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5. SUMMARY

The performance of commercial nuclear spent fuel dry storage casks are typically evaluated through detailed finite element modeling of the system's thermal performance. These modeling efforts are performed by the vendor to demonstrate the performance and regulatory compliance and are independently verified by the NRC. Carefully measured data sets generated from testing of full sized casks or smaller cask analogs are widely recognized as vital for validating these models. Numerous studies have been previously conducted. Recent advances in dry storage cask designs have moved the storage location from aboveground to belowground and significantly increased the maximum thermal load allowed in a cask in part by increasing the canister helium pressure. Previous cask performance validation testing did not capture these parameters.

The purpose of the investigation described in this report is to produce data sets that can be used to test the validity of the assumptions associated with the calculations used to determine steady-state cladding temperatures in modern dry casks that utilize elevated helium pressure in the sealed canister or are of a design for location in the subsurface.

An existing electrically heated but otherwise prototypic BWR Incoloy-clad test assembly is deployed inside of a representative storage basket and cylindrical pressure vessel that represents the canister. The symmetric single assembly geometry with well-controlled boundary conditions simplifies interpretation of results. Various configurations of outer concentric ducting will be used to mimic conditions for above and belowground storage configurations of vertical, dry cask systems with canisters. Radial and axial temperature profiles will be measured for a wide range of decay power and helium cask pressures. Of particular interest is the evaluation of the effect of increased helium pressure on heat load and the effect of simulated wind on the belowground vent configuration.

The BWR cask simulator has been designed in detail for both the aboveground and belowground venting configurations. The instrumented prototypic electrically heated 9×9 BWR is existing from a previous project. The pressure vessel that represents the canister has been designed, fabricated and pressure tested for a maximum allowable pressure rating of 24 bar at 400 °C.

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