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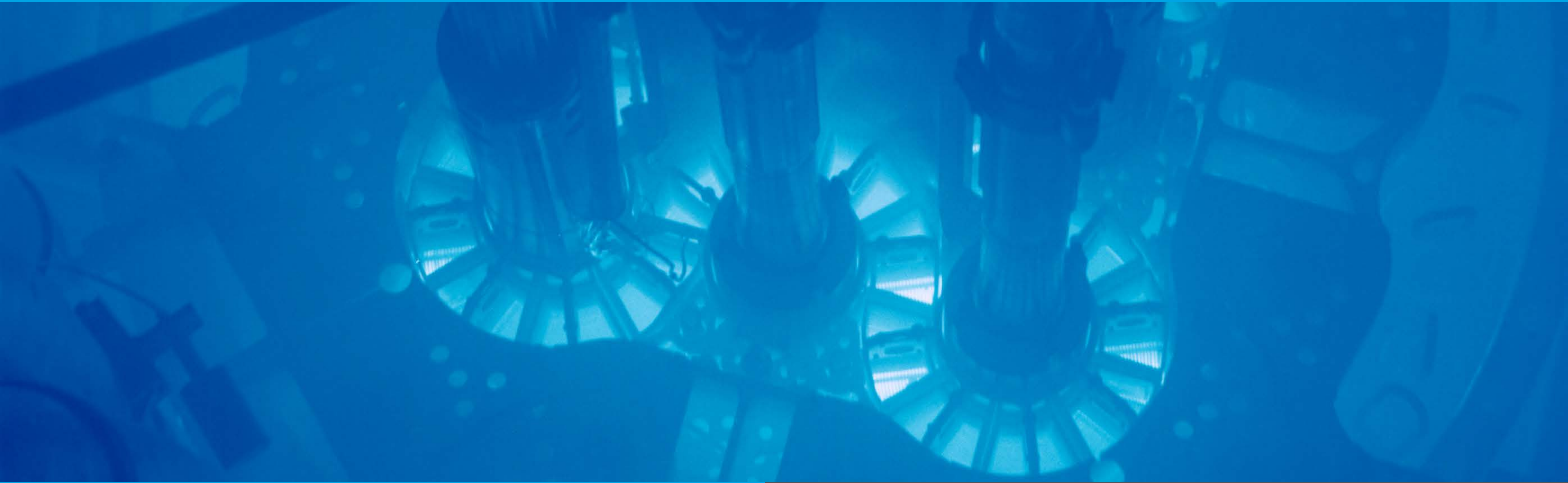

Thermal-Hydraulic Measurements in Support of Model Validation for Dry Cask Storage

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Sandia National Laboratories

Nuclear Waste Technical Review Board

Albuquerque, NM

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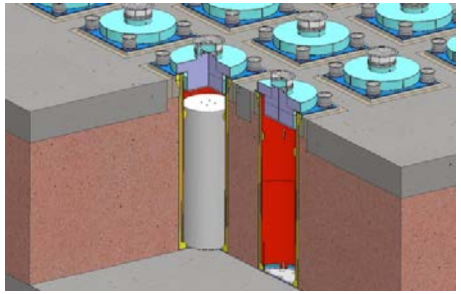
Overview

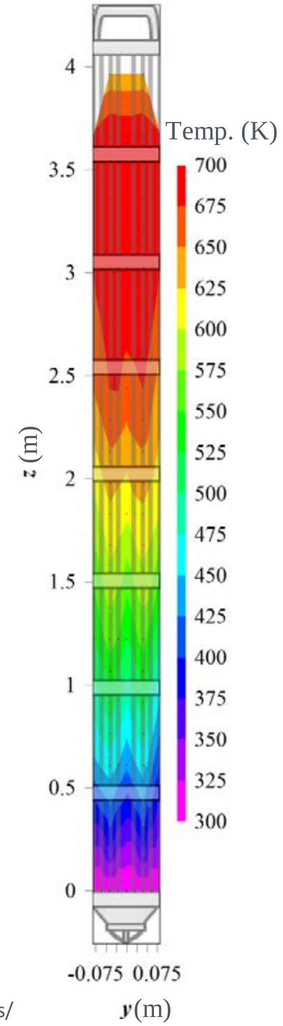
Aboveground Storage

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



Belowground Storage

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



- Purpose: Validate assumptions in CFD calculations for spent fuel cask thermal design analyses
  - Used to determine steady-state cladding temperatures in dry casks
  - Needed to evaluate cladding integrity throughout storage cycle
- Measure temperature profiles for a wide range of decay power and helium cask pressures
  - Mimic conditions for above and belowground configurations of vertical, dry cask systems with canisters
  - Simplified geometry with well-controlled boundary conditions
  - Provide measure of mass flow rates and temperatures throughout system
- Use existing prototypic BWR Incoloy-clad test assembly

Past Validation Efforts

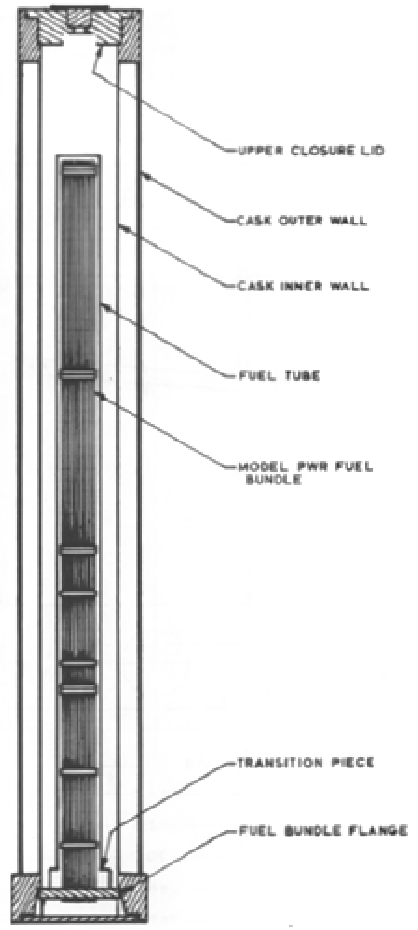
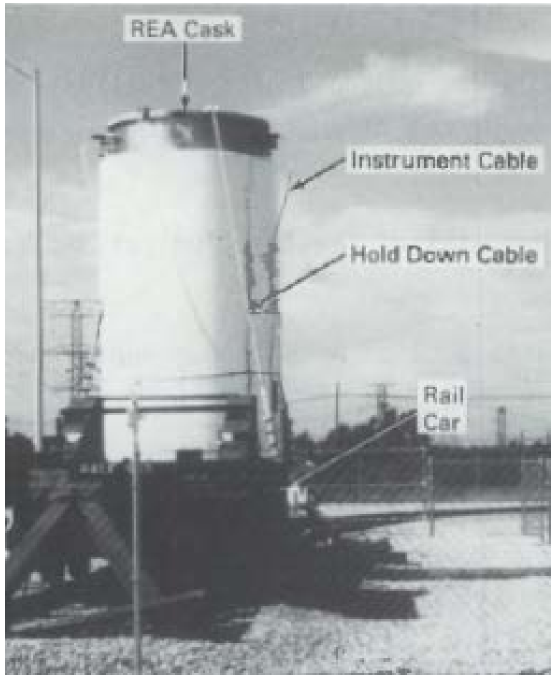
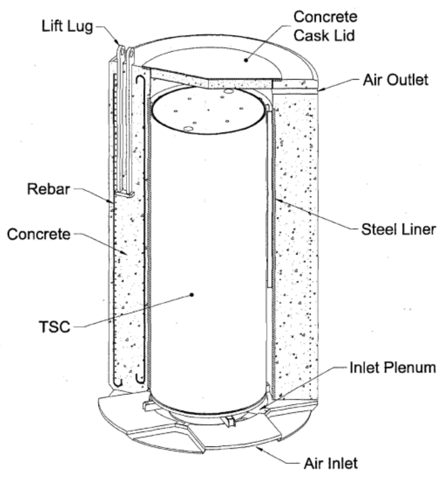


FIGURE 4-1. SAHTT Assembly

- Full scale, multi-assembly
  - Castor-V/21 [1986: EPRI NP-4887, PNL-5917]
    - Unconsolidated, unpressurized, unventilated
  - REA 2023 [1986: PNL-5777 Vol. 1]
    - Unconsolidated, unpressurized, unventilated
  - VSC-17 [1992: EPRI TR-100305, PNL-7839]
    - Consolidated, unpressurized, early ventilated design
- Small scale, single assembly
  - FTT (irradiated, vertical) [1986 PNL-5571]
  - SAHTT (electric, vertical & horizontal) [1986 PNL-5571]
  - Mitsubishi (electric, vertical & horizontal) [1986 IAEA-SM-286/139P]
  - For all three studies:
    - Unconsolidated
    - BC: Controlled outer wall temperature (unventilated)
    - Unpressurized
- <u>None</u> appropriate for elevated helium pressures or modern ventilated configurations

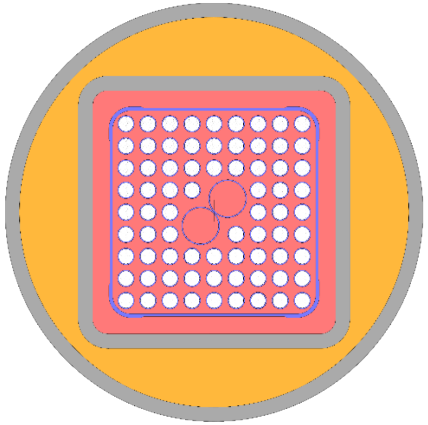


Current Approach

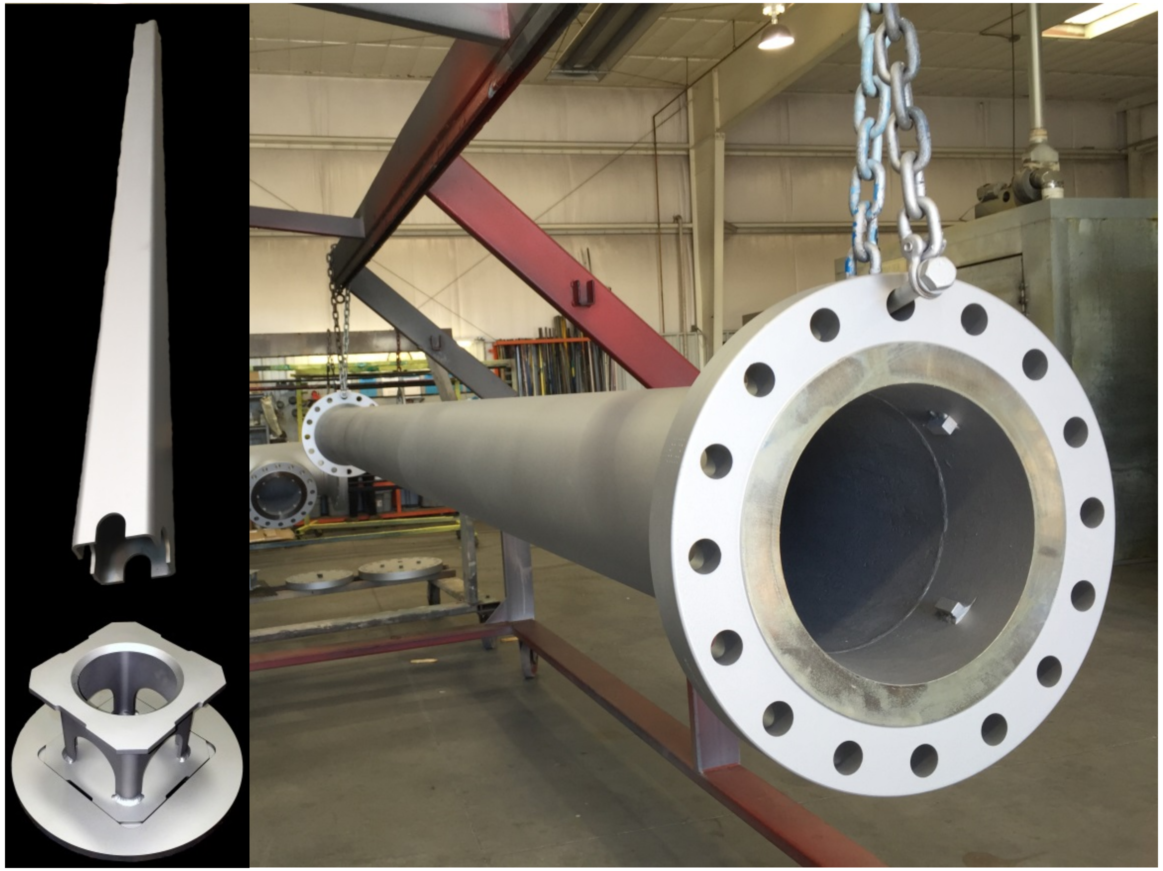


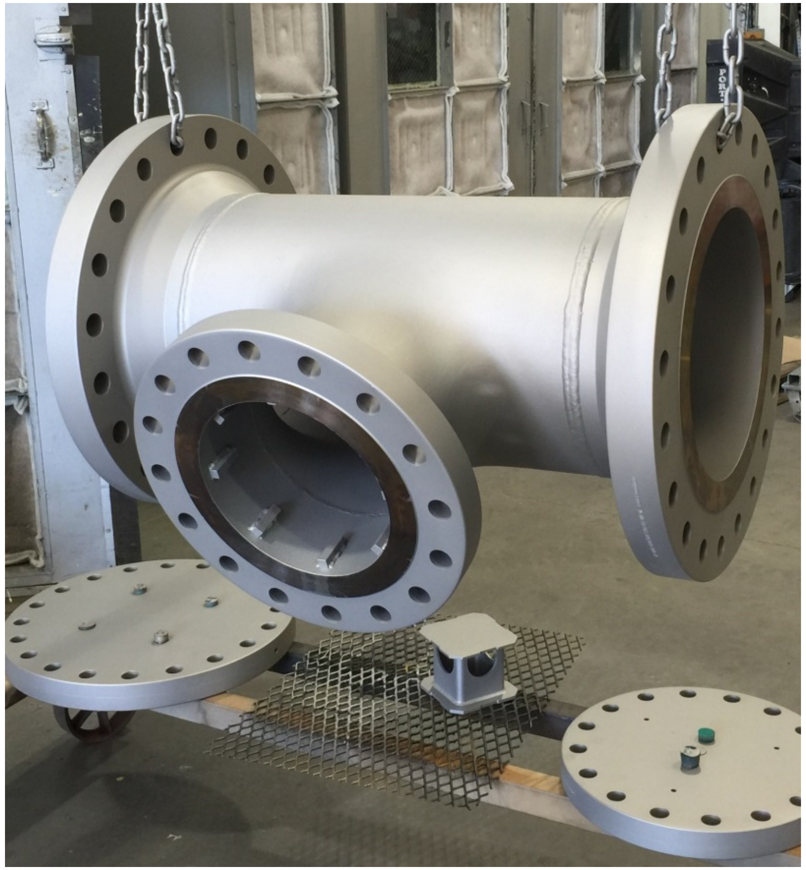
- Focus on pressurized canister systems
  - DCS capable of 2,400 kPa internal pressure @ 400 °C
    - Current commercial designs up to ~800 kPa
- Ventilated designs
  - Aboveground configuration
  - Belowground configuration
    - With crosswind conditions
- Thermocouple (TC) attachment allows better peak cladding temperature measurement
  - 0.030” diameter sheath
    - Tip in direct contact with cladding
- Provide validation quality data for CFD
  - Complimentary to High-Burnup Cask Demo. Project

DCS Pressure Vessel Hardware



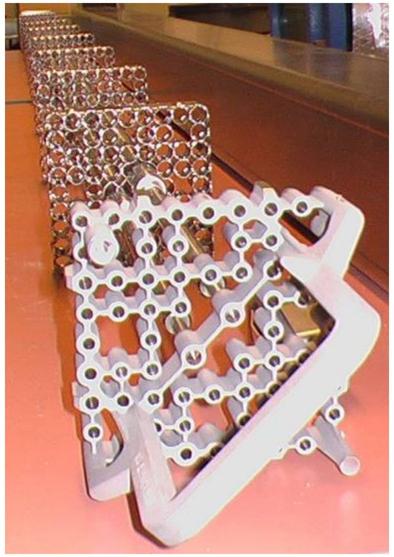
- Scaled components with instrumentation well
- Coated with ultra high temperature paint

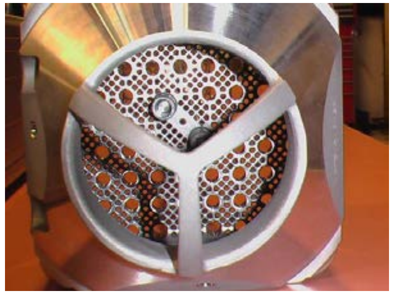




Prototypic Assembly Hardware

Upper tie plate

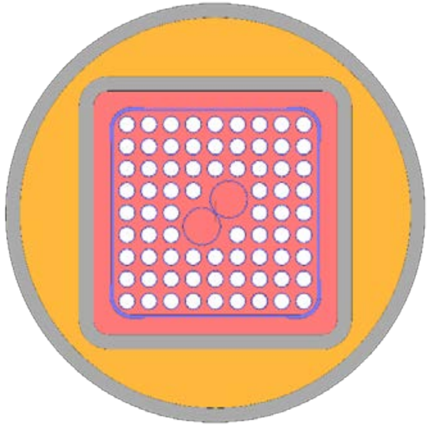




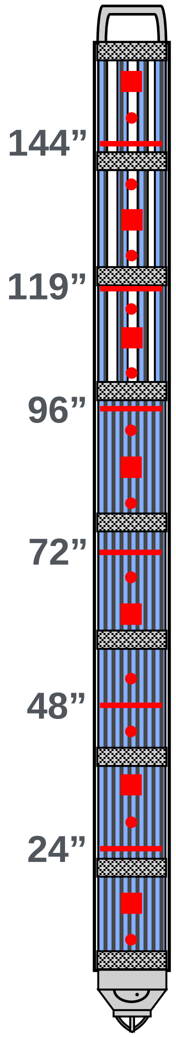
Nose piece and debris catcher

BWR channel, water tubes and spacers

- Most common 9×9 BWR in US
- Prototypic 9×9 BWR hardware
  - Full length, prototypic 9×9 BWR components
  - Electric heater rods with Incoloy cladding
  - 74 fuel rods
    - 8 of these are partial length
    - Partial length rods 2/3 the length of assembly
  - 2 water rods
  - 7 spacers



Thermocouple Layout



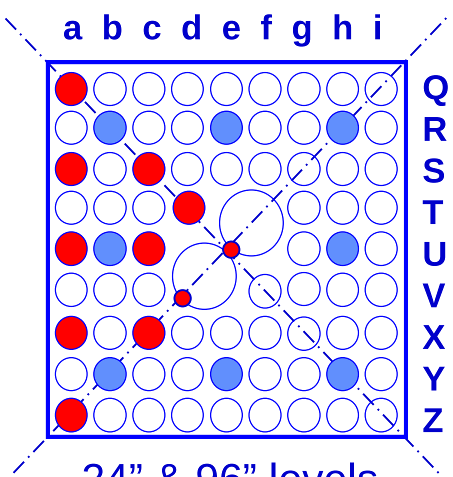
Internal Thermocouples

Radial Array
24” spacing
11 TC’s each level
66 TC’s total (details below)

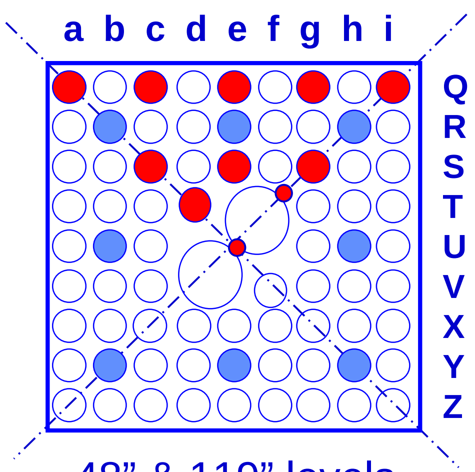
Axial array A1
6” spacing
20 TC’s

Axial array A2
12” spacing – 7 TC’s
Water rods inlet and exit – 4 TC’s
Total of 97 TC’s

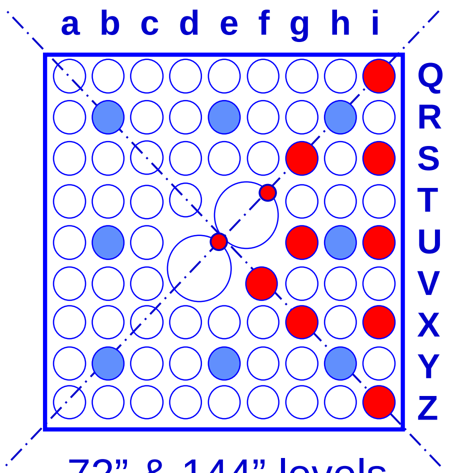
- 97 total TC’s internal to assembly
- 10 TC’s mounted to channel box
  - 7 External wall
    - 24 in. spacing starting at 24 in. level
  - 3 Internal wall
    - 96, 119, and 144 in. levels



24” & 96” levels

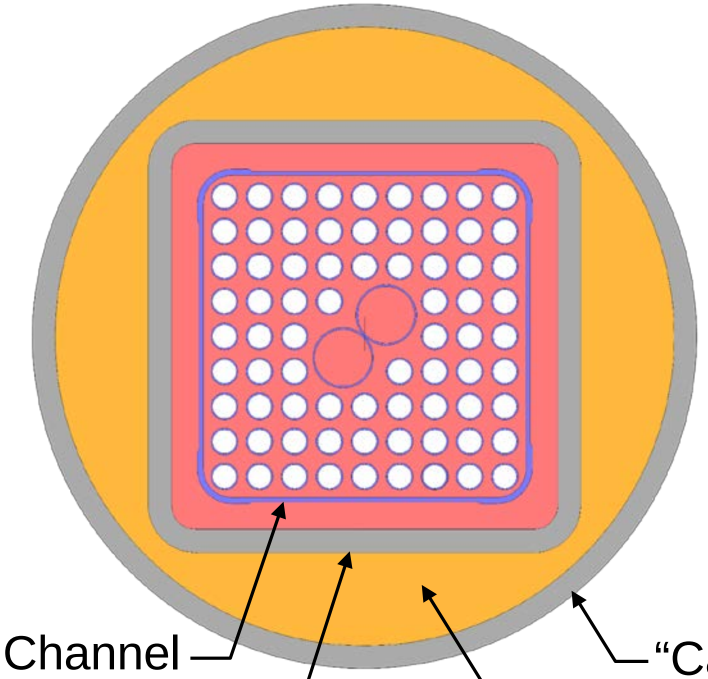


48” & 119” levels



72” & 144” levels

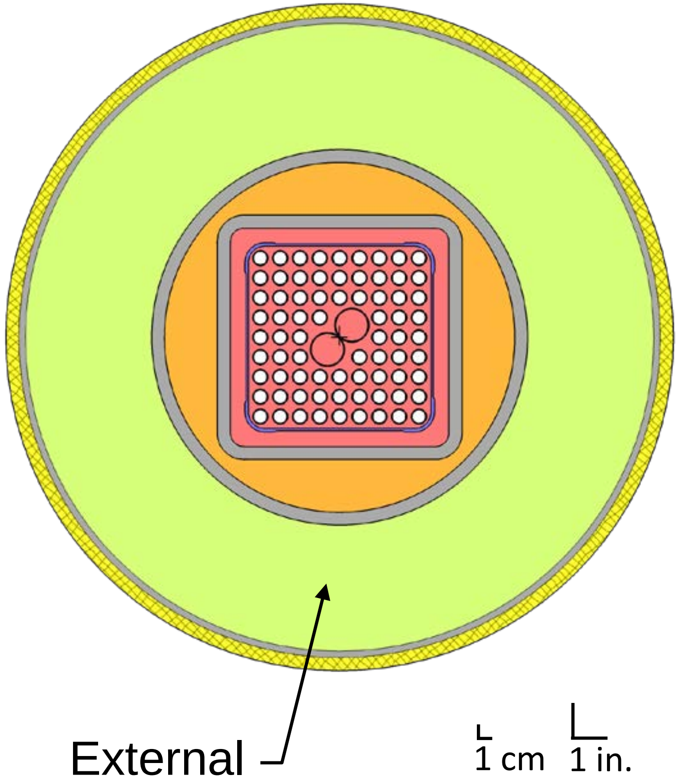
Internal Dimensional Analyses



- Internal flow and convection near prototypic
  - Prototypic geometry for fuel and basket
- Downcomer scaling insensitive to wide range of decay heats
  - External cooling flows matched using elevated decay heat
  - Downcomer dimensionless groups

Parameter	Aboveground		
	DCS Low Power	DCS High Power	Cask
Power (kW)	0.5	5.0	36.9
Re_{Down}	170	190	250
Ra_H^*	3.1E+11	5.9E+11	4.6E+11
Nu_H	200	230	200

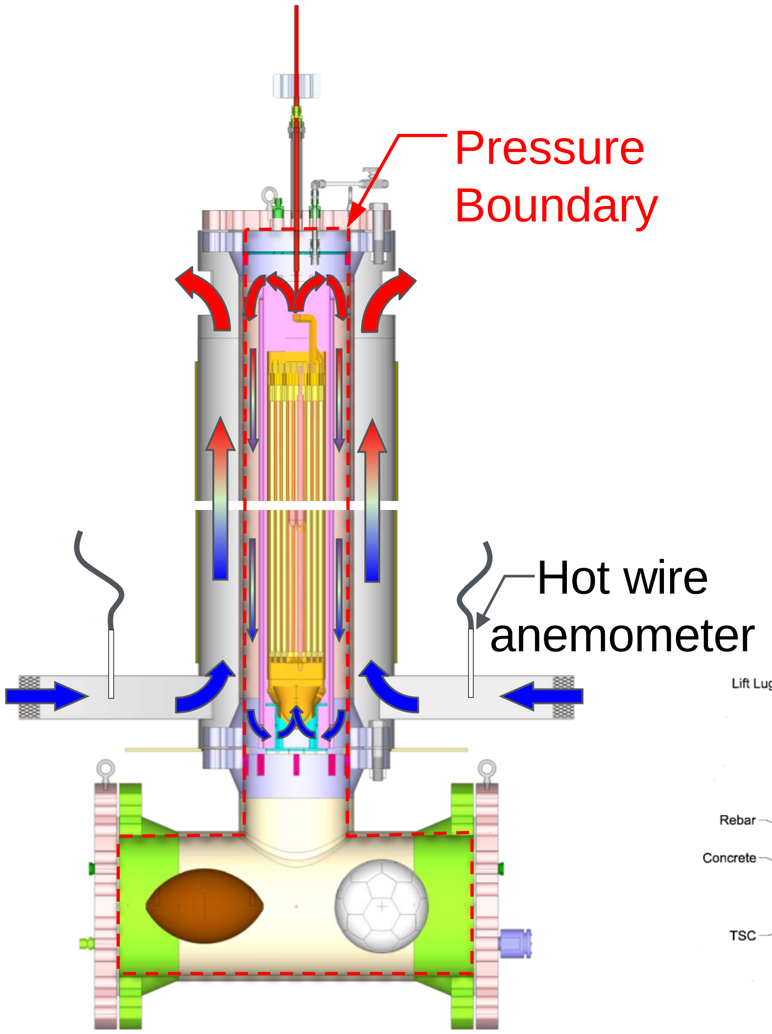
External Dimensional Analyses

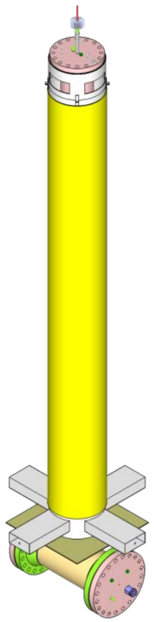


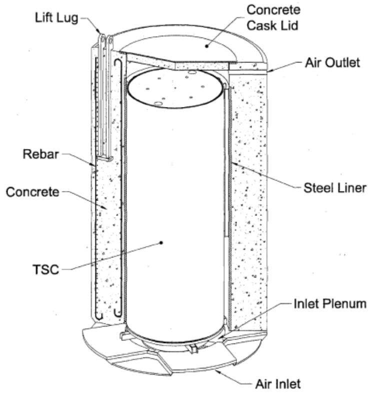
- External cooling flows evaluated against prototypic
  - External dimensionless groups

Parameter	Aboveground		
	DCS Low Power	DCS High Power	Cask
Power (kW)	0.5	5.0	36.9
Re_{Ex}	3,700	7,100	5,700
Ra_{DH}^{*}	2.7E+08	2.7E+09	2.3E+08
$(D_{H,\,Cooling} / H_{PV}) \times Ra_{DH}^{*}$	1.1E+07	1.1E+08	4.8E+06
Nu_{DH}	16	26	14

Aboveground Configuration

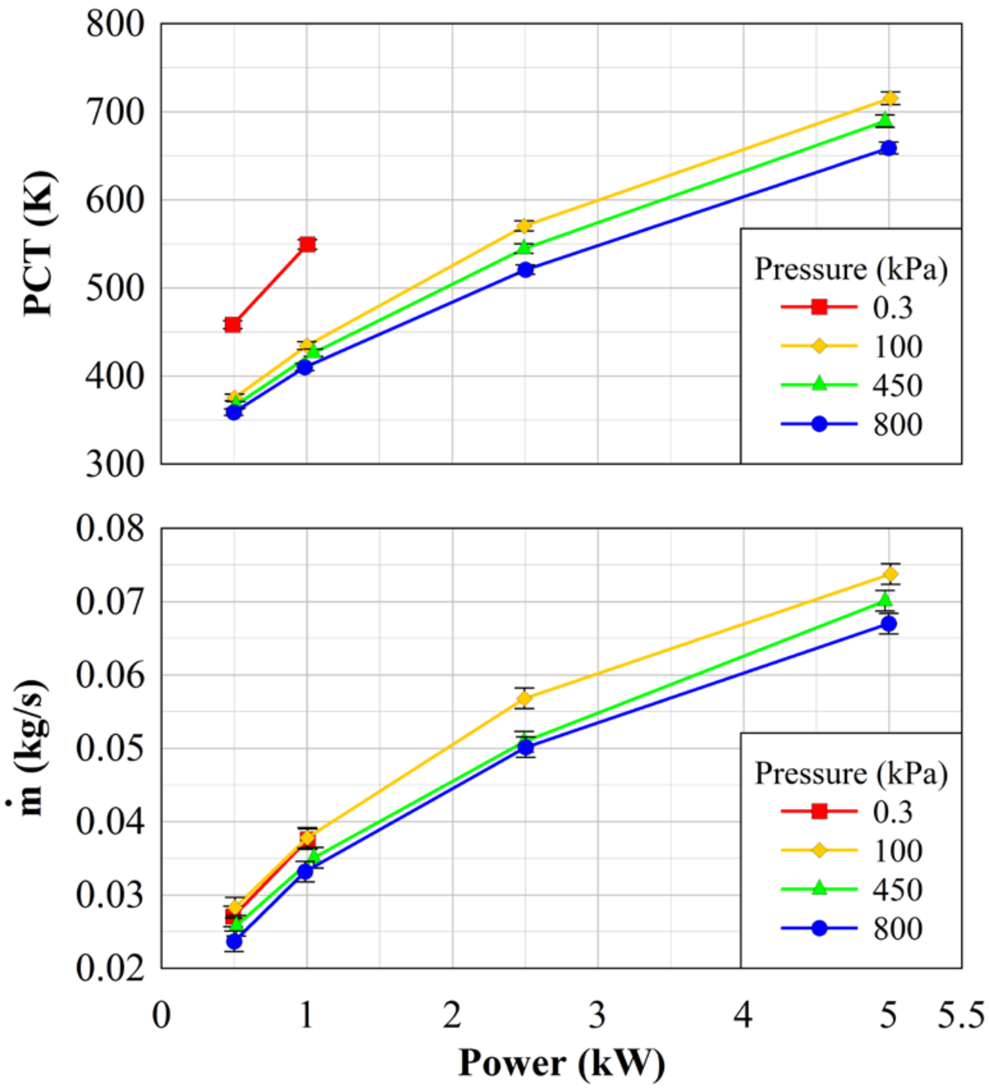




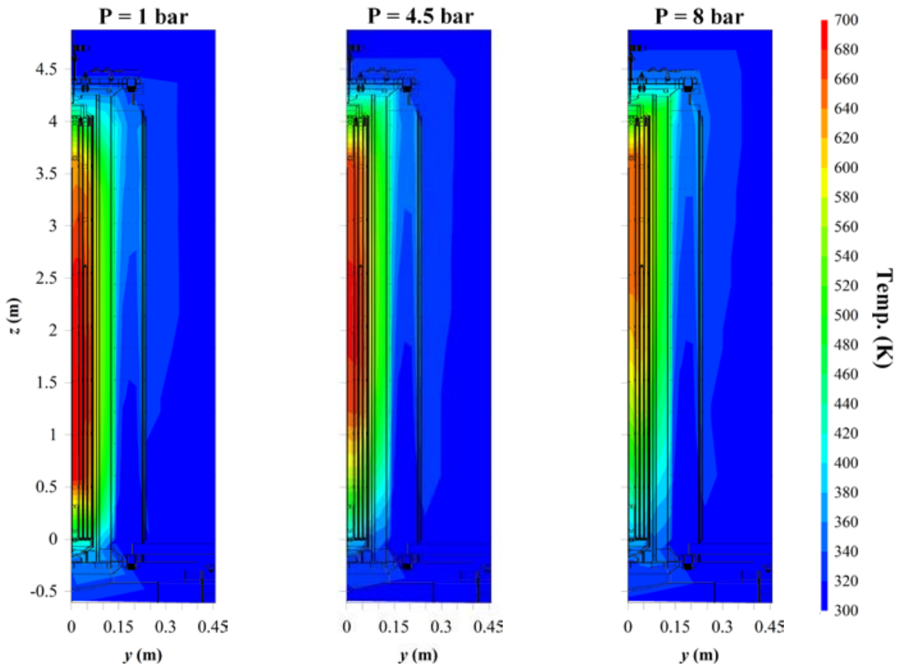


- BWR Dry Cask Simulator (DCS) system capabilities
  - Power: 0.1 – 20 kW
  - Pressure vessel
    - Vessel temperatures up to 400 °C
    - Pressures up to 2,400 kPa
    - ~200 thermocouples throughout system (internal and external)
  - Air velocity measurements at inlets
    - Calculate external mass flow rate
- *Testing Completed August 2016*
  - 14 data sets collected
    - Transient and steady state
  - Ongoing validation exercises

Steady State Values vs. Decay Heat
Aboveground Configuration

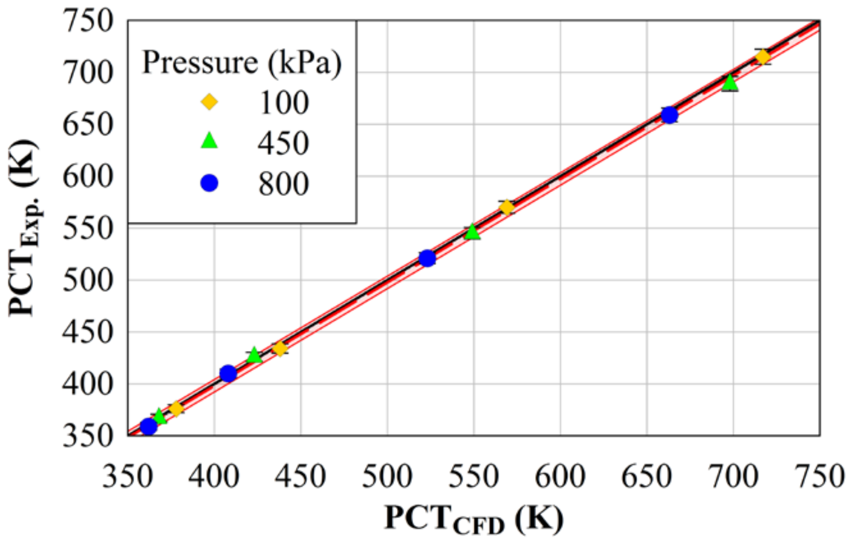


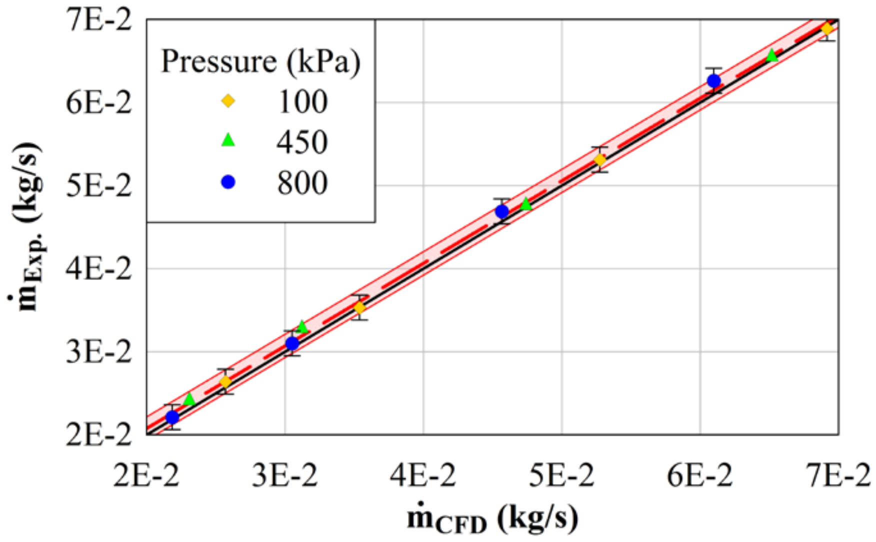
- PCT and air flow ↑ as simulated decay heat ↑
  - Significant increase in PCT for P = 0.3 kPa
    - Due to air in “canister” instead of helium



Graphical Steady State Comparisons

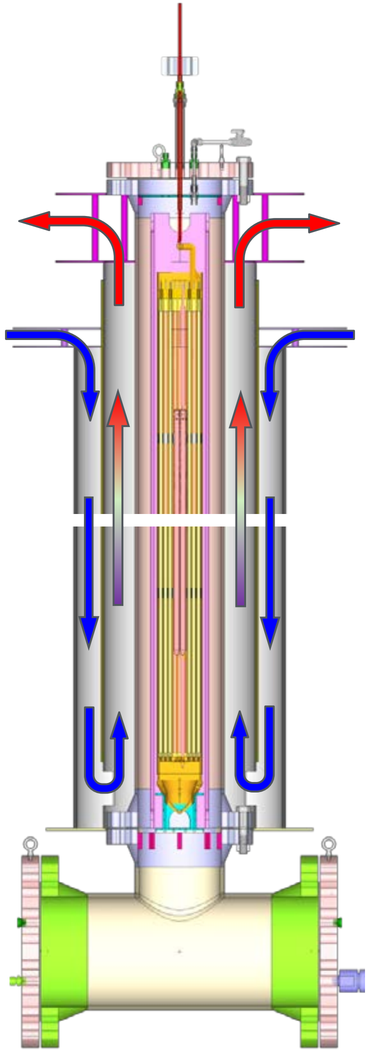
Aboveground Configuration

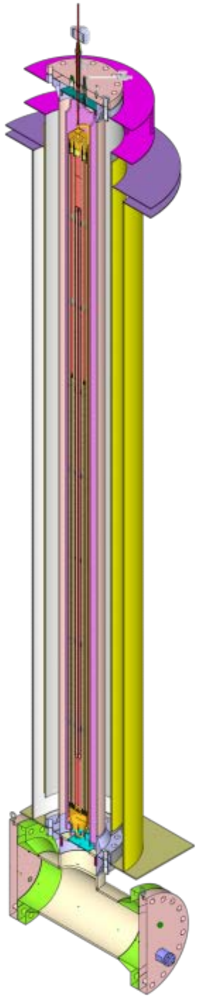


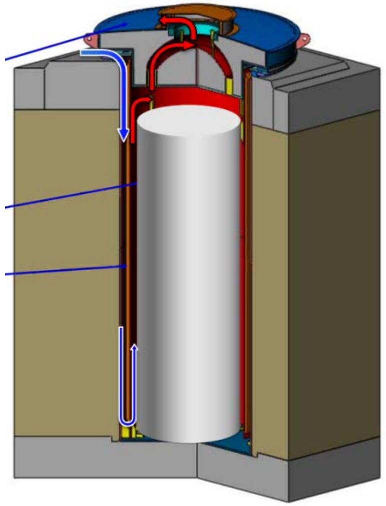


- PCT average difference of 2 K across all conditions
  - 95% exp. uncertainty
    - +/- 1% reading in Kelvin
    - ($U_{PCT, max}$ = 7 K)
  - Max. observed difference = 9 K
    - (5 kW and 4.5 bar)
- Air flow rate average difference of 6.2E-4 kg/s for all conditions
  - 95% exp. uncertainty of $U_{\dot{m}}$ = 1.5E-3 kg/s
  - Max. observed difference = -1.6E-3 kg/s
    - (5 kW and 800 kPa)

Belowground Configuration



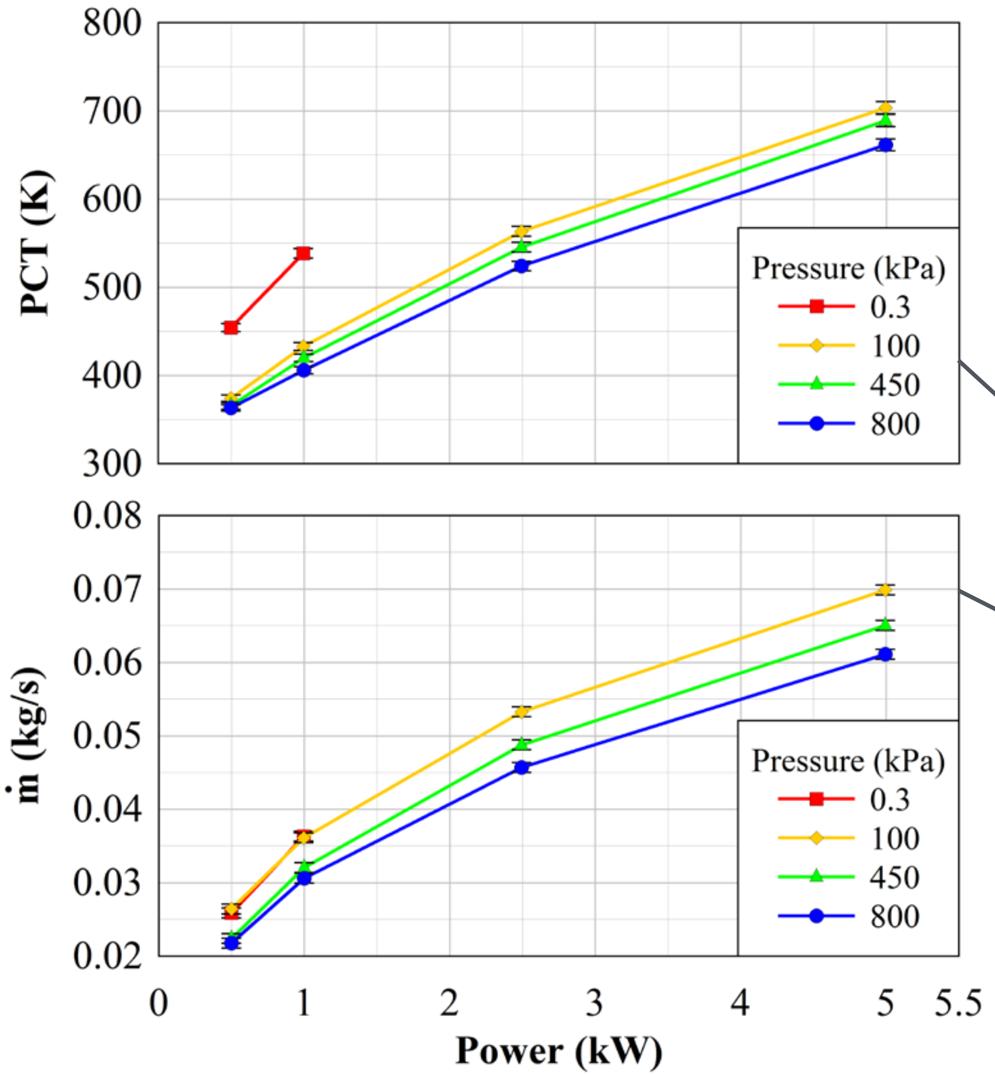




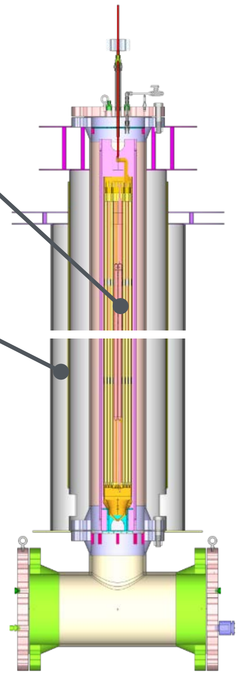
- Modification to aboveground ventilation configuration
  - Additional annular flow path
- *Testing Completed April 2017*
  - 14 data sets recorded
    - Transient and steady state

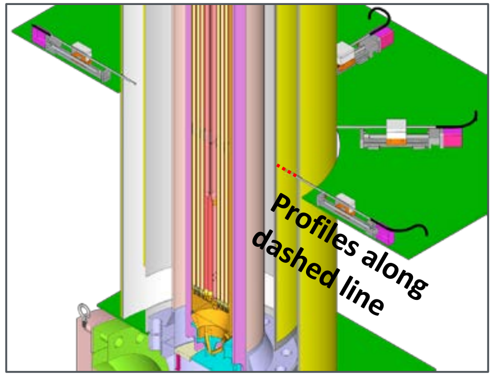
Steady State Values vs. Decay Heat

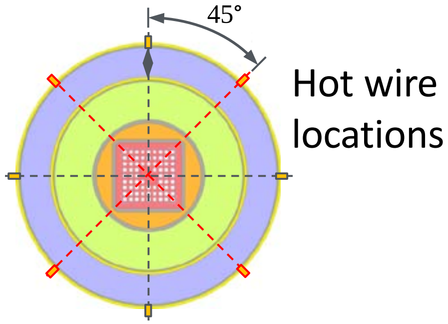
Belowground Configuration



- Similar performance to aboveground configuration
  - Within 2% for PCT
  - Within 5% for ṁ

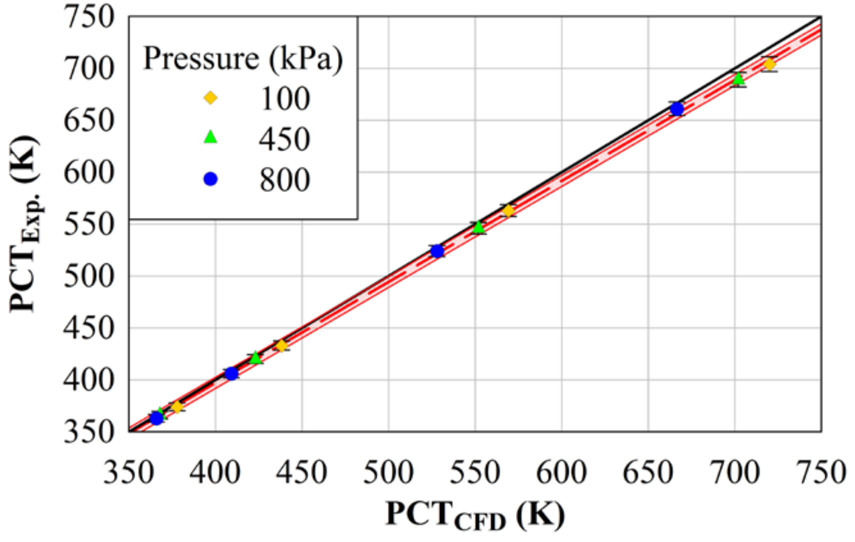


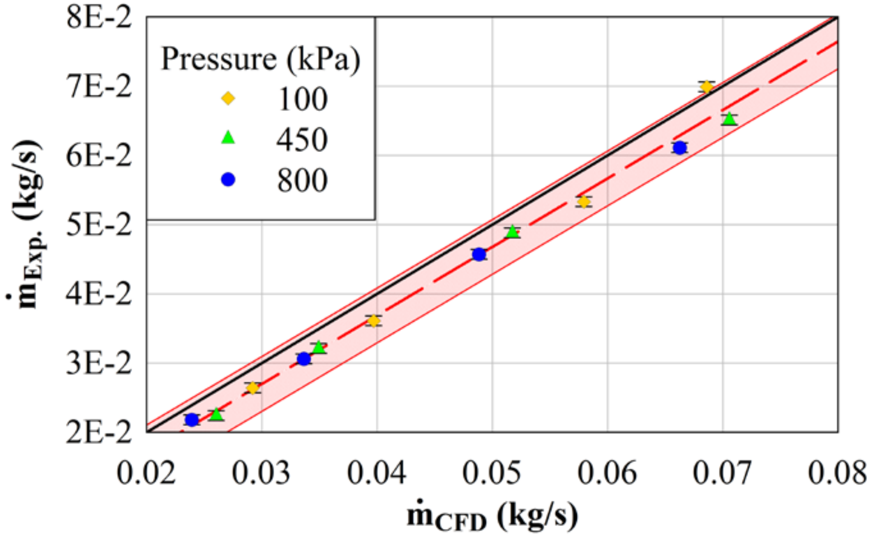




Graphical Steady State Comparisons

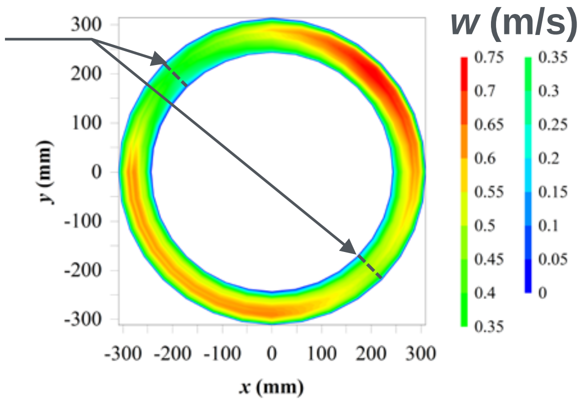
Belowground Configuration



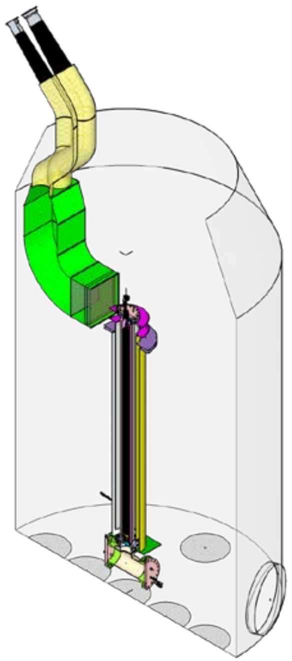


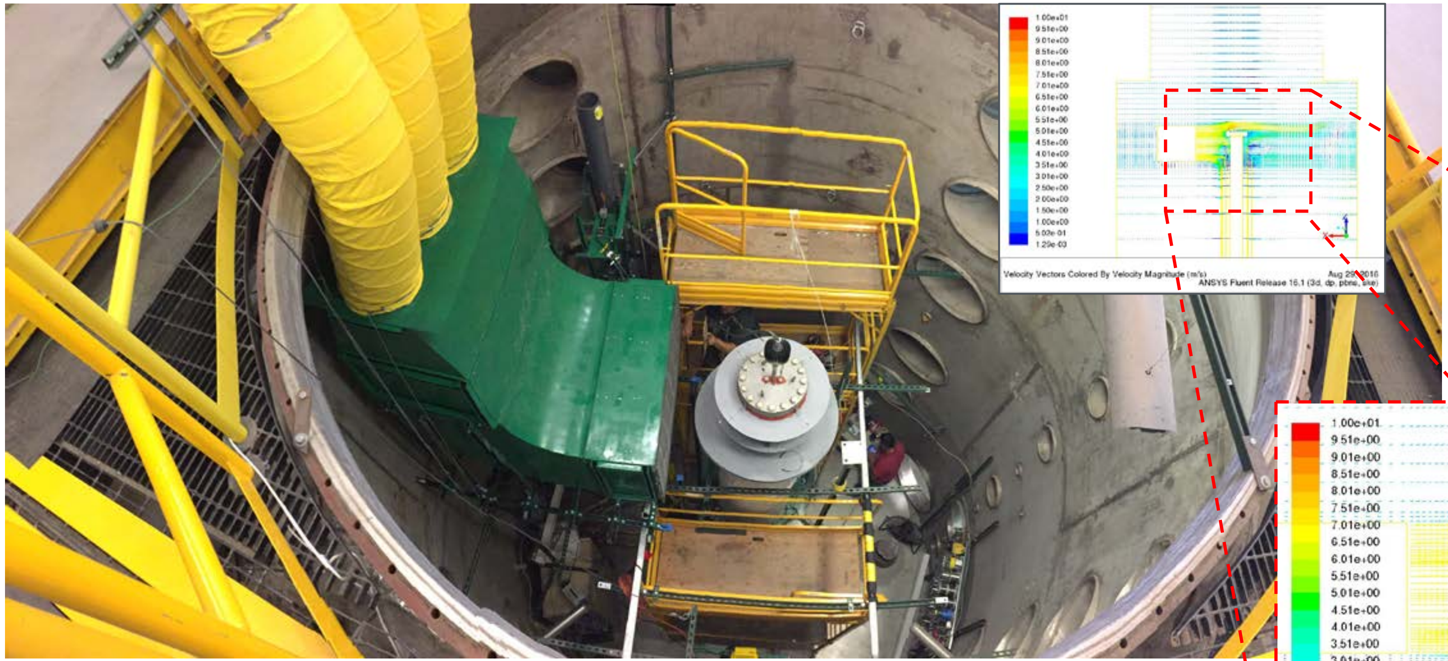
- PCT average difference of 6 K across all conditions
  - 95% exp. uncertainty of $U_{PCT,\ max}$ = 7 K
  - Max. observed difference = 16 K
    - (5 kW and 100 kPa)
- Air flow rate lower for experiment
  - 95% exp. uncertainty of $U_{\dot{m}}$ = 7E-4 kg/s
  - Max. observed difference = 5E-3 kg/s
    - (5 kW and 450 bar)

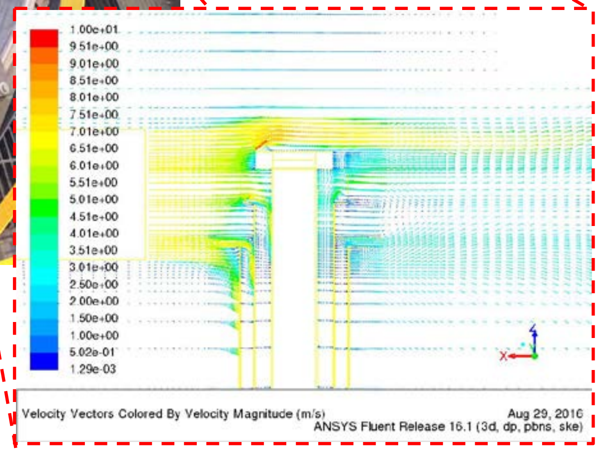
Non-uniformities at flow straightener seams



Cross Wind Testing



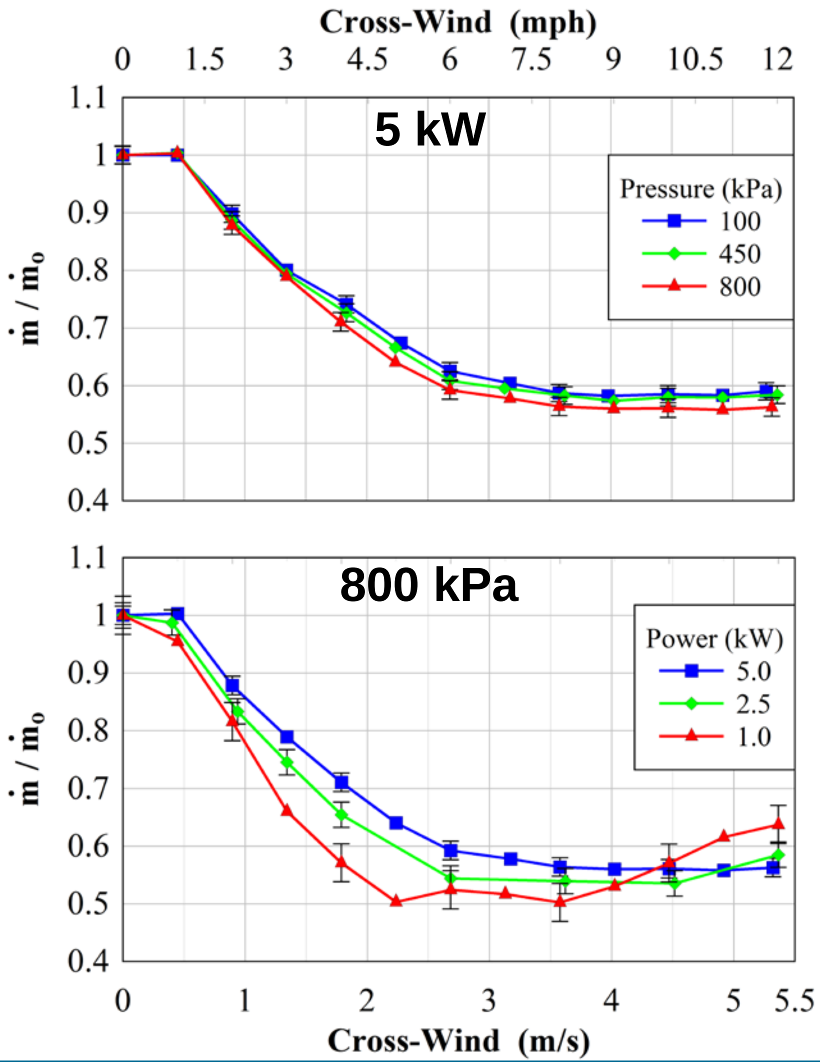




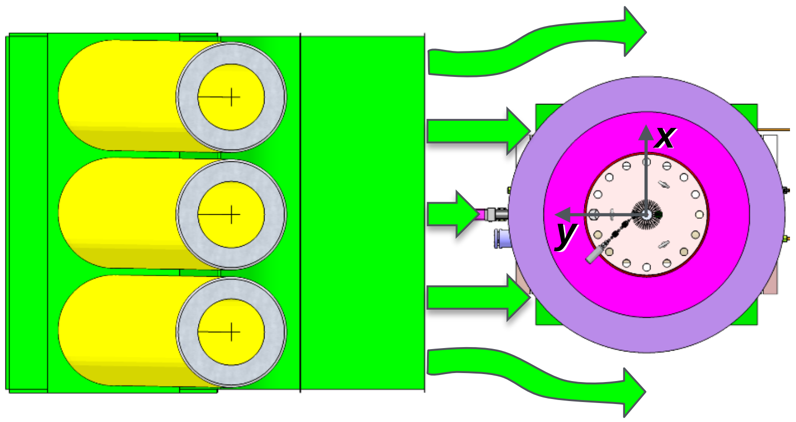
CFD simulations by A. Zigh (USNRC)

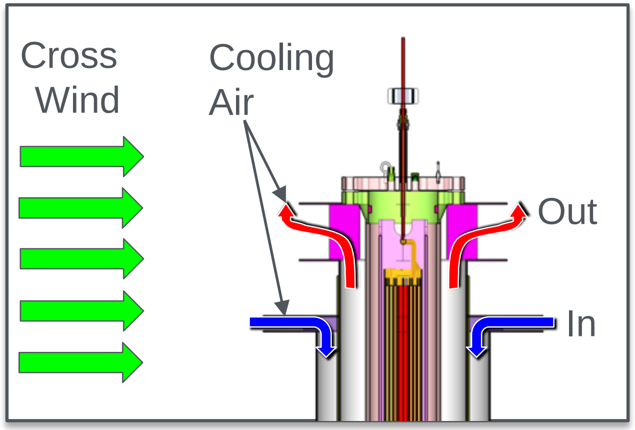
- Wind machine installed inside test enclosure
  - Three air-driven blowers
  - Specially fabricated duct with flow straightening
  - Cross winds of up to 5.4 m/s (12 mph)

Reduction of External Air Flow Rate



- Moderate, sustained cross winds have significant impact on external air mass flow rate
  - Reductions of up to 50%
  - Thermal impact limited for DCS
  - Potentially more significant effect for prototypic systems





Summary

- Dry cask simulator (DCS) testing complete for all configurations
  - Over 40 unique data sets collected
    - 14 each for two primary configurations
      - Aboveground and belowground
    - 13 additional data sets for cross-wind testing
- Comparisons with CFD simulations show favorable agreement
  - Within experimental uncertainty for nearly all cases
  - Additional steady state comparisons for basket, “canister”, and “overpack” also show good agreement

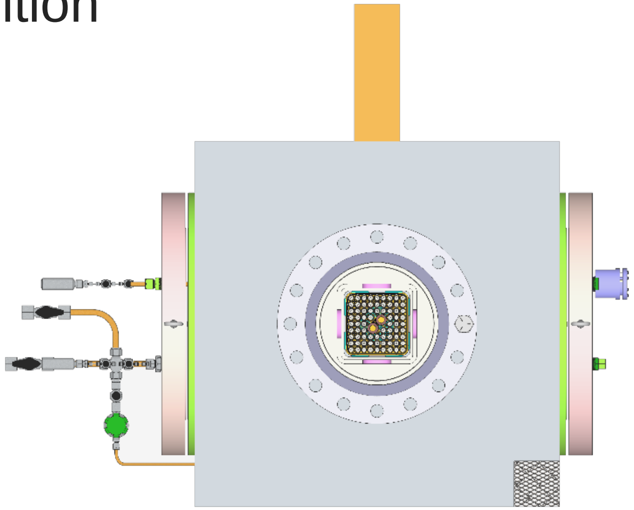
Future Testing

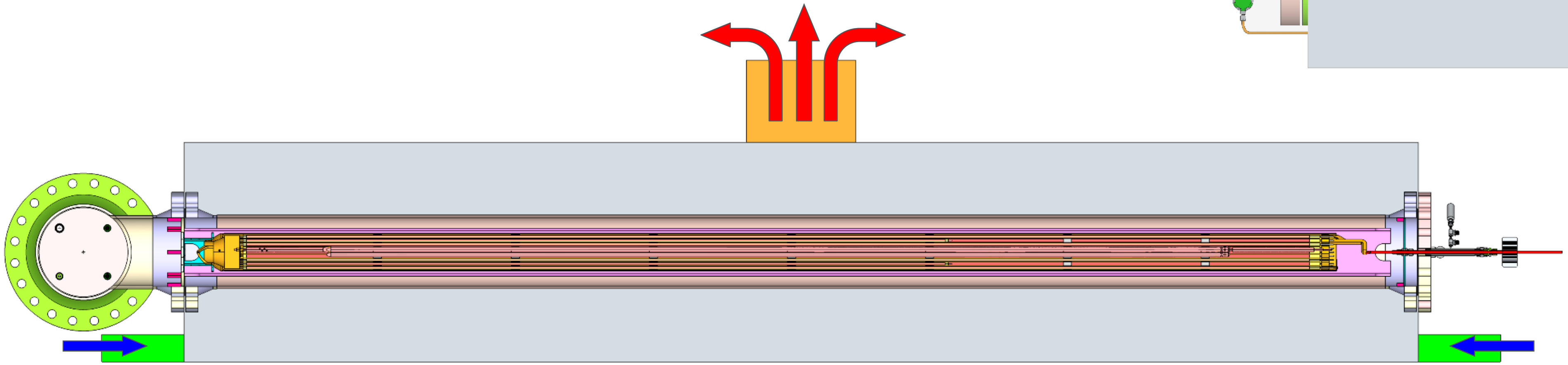
Thermal-Hydraulic Testing and Modeling Activities

- Phase I: BWR Dry Cask Simulator at SNL — Previous SNL slides
  - Mockup of 1 BWR assembly in convective heat transfer
    - Thermocouples attached directly to cladding
  - NRC has modeled the results
  - PNNL and Spain to model using the input deck provided by SNL — Ongoing Work
- Phase II: HBU Demonstration Cask — Previous PNNL Presentation
  - Multiple activities as outlined previously
- Phase III: Ongoing and Future Thermal-Hydraulic Studies — These slides
  - Horizontal Dry Cask Simulator
  - Advanced simulators
  - Potential collaboration with South Korea under the High Level Bilateral Commission studies

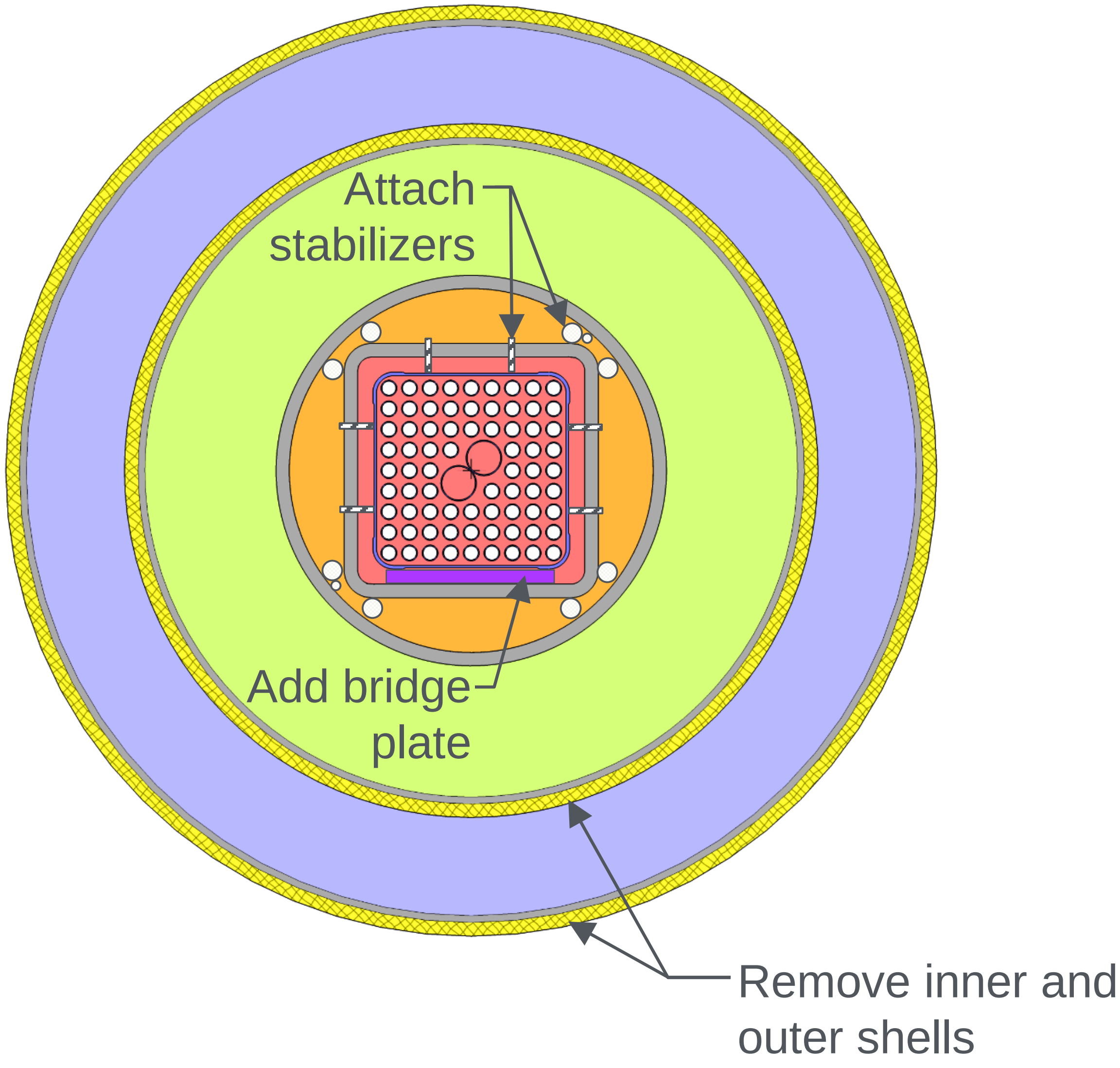
Modification of the Dry Cask Simulator

- Horizontal Simulation
  - Place single assembly dry cask simulator in a horizontal position
  - Enclose pressure vessel to simulate vault
  - Monitor air flow through inlet ducts
    - Hot wire anemometers
  - Measure temperatures for various powers
    - Fill to prototypic internal helium pressures



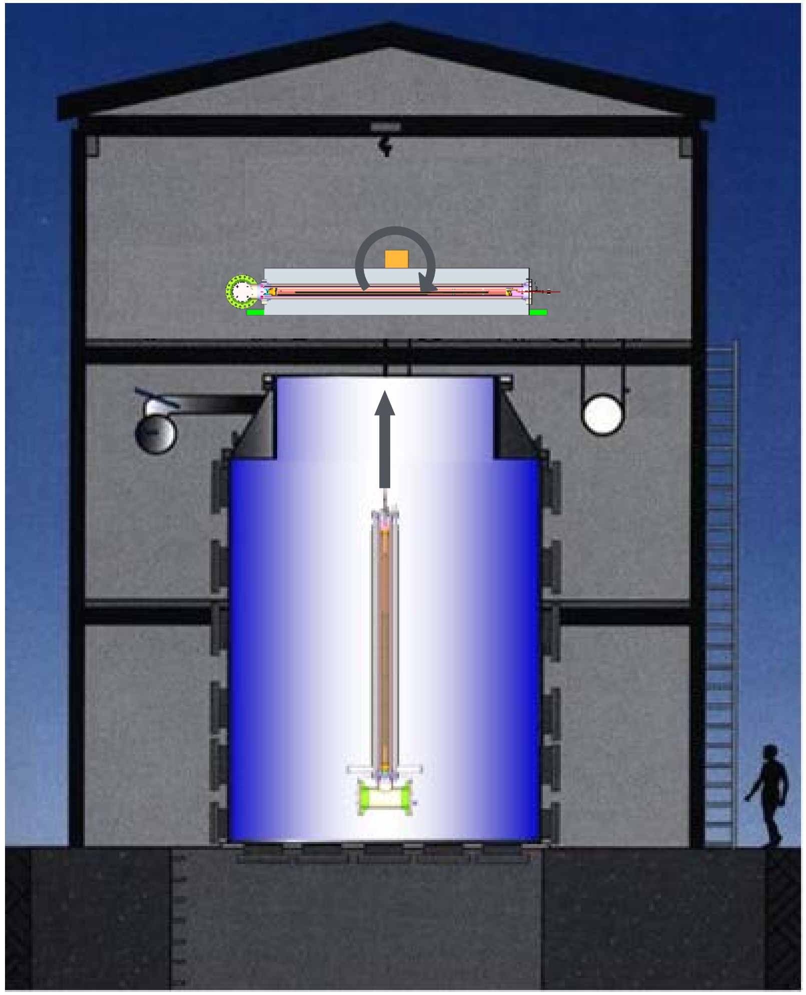


Assembly Modifications



- DCS presently deconstructed
- Convert to horizontal
  - Outer shell and inner shells removed
  - Pressure vessel opened
  - Basket removed
- Maintain concentricity and enhance heat conduction
  - Add stabilizers
    - Between channel box and basket
    - Between basket and canister wall
      - Full length to limit convective cells
  - Keep from damaging existing TC's
- Reassemble and move

Facility Transition



- After performing in-vessel modifications
- Move DCS from inside vessel to the 3rd floor
- GENTLY rotate assembly to horizontal configuration
- Construct “vault” enclosure
  - Inlet and outlets
- Install additional instrumentation
- Reconnect to DAQ
  - Power control
  - Instrumentation
- Conduct testing

Advanced Simulators

- Explore various concepts
  - Limited number of full-length assemblies
    - Inter-assembly heat transfer
  - Scaled assemblies
    - Simplified but representative mock fuel assemblies
    - Better simulation of prototypic cask loadings
- Investigate known sources of modeling uncertainties
  - Basket-to-canister contacts
  - Boral construction
- Refine best practice guidelines
  - Offer insights for selection of modeling assumptions
  - Further understanding of uncertainties