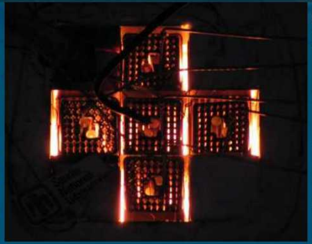
SAND2019-2358PE

Dry Cask Simulator Testing with Applications to CFD Model Validation



Sam Durbin, E. Lindgren, R. Pulido, and A. Salazar

Thermal Modeling/Testing of RAM Packages Course

March 26, 2019

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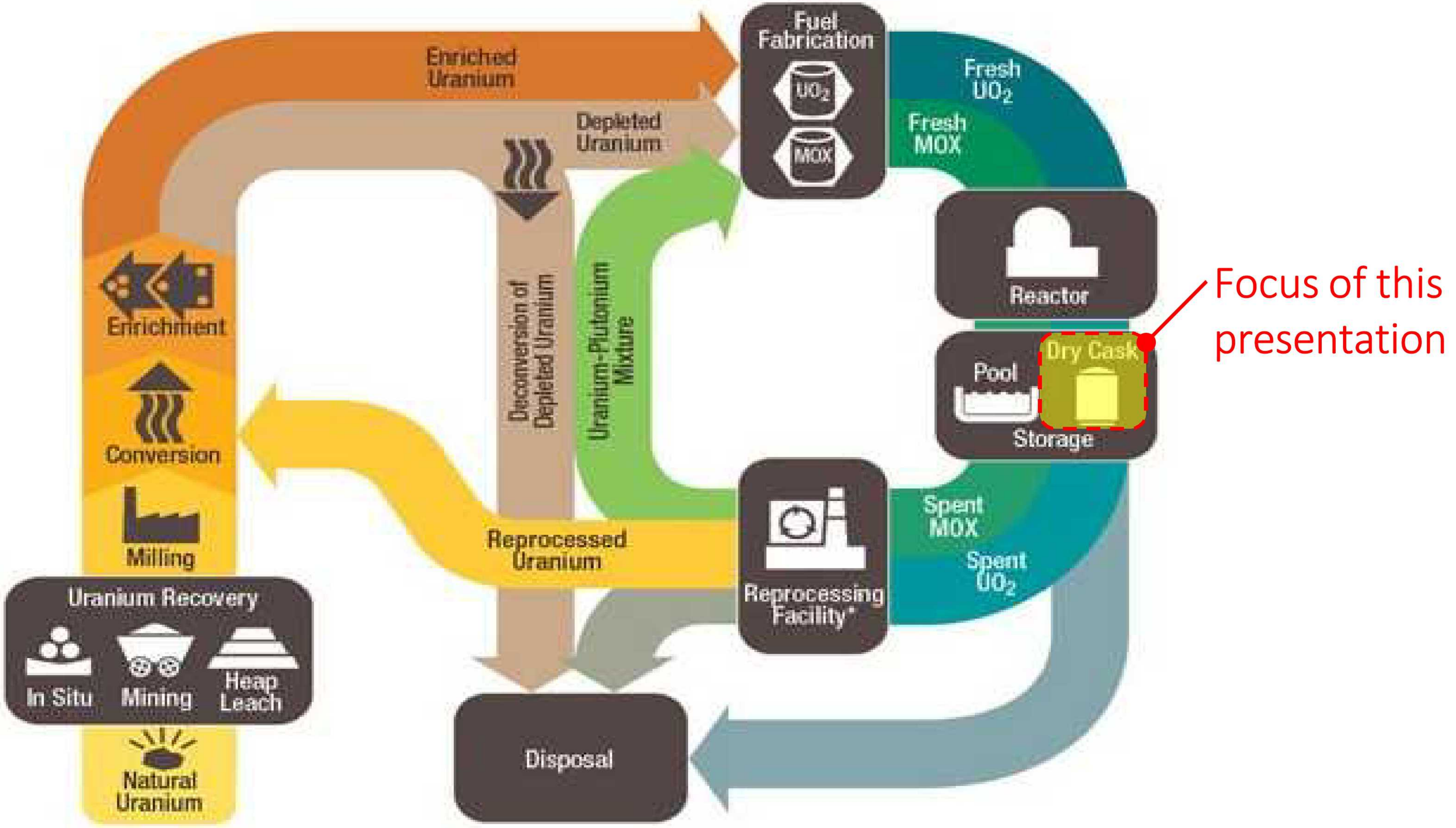
SAND2019-####

Outline

- Introduction to the back end of the nuclear fuel cycle
  - What are dry storage casks?
  - How do they work?
- Vertical dry cask simulator (DCS) tests
  - Overview
    - Hardware
    - Configurations
    - Dimensional Analyses
  - Aboveground
  - Belowground
  - Cross-wind
- Upcoming horizontal dry cask simulator (HDCS) tests
  - Overview
  - Hardware and facility modifications
  - Dimensional analyses
- Summary

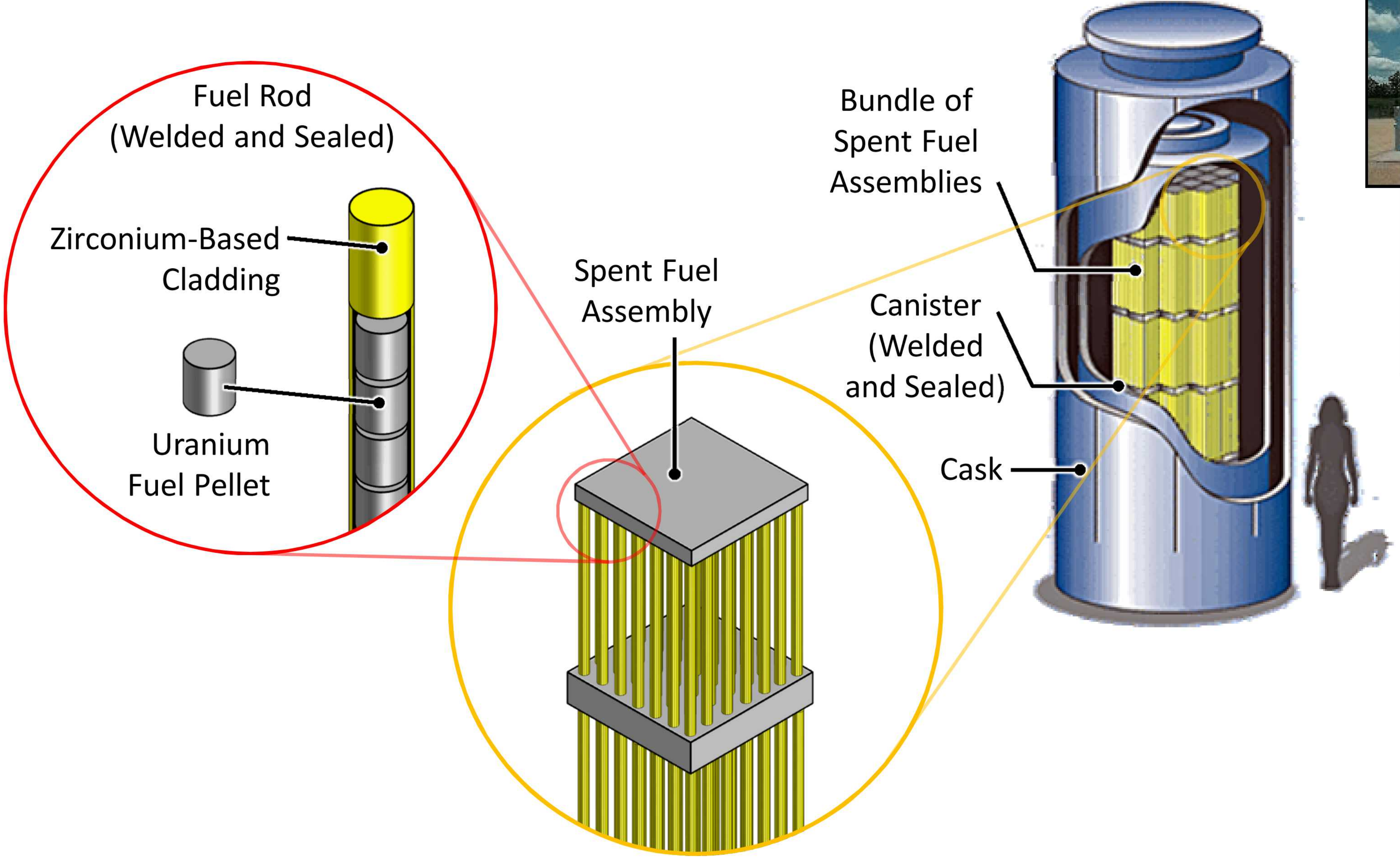
INTRODUCTION

Nuclear Fuel Cycle



* Reprocessing of spent nuclear fuel including MOX is not practiced in the U.S.
Note: The NRC has no regulatory role in mining uranium.

What Are Spent Fuel and Dry Storage Casks?

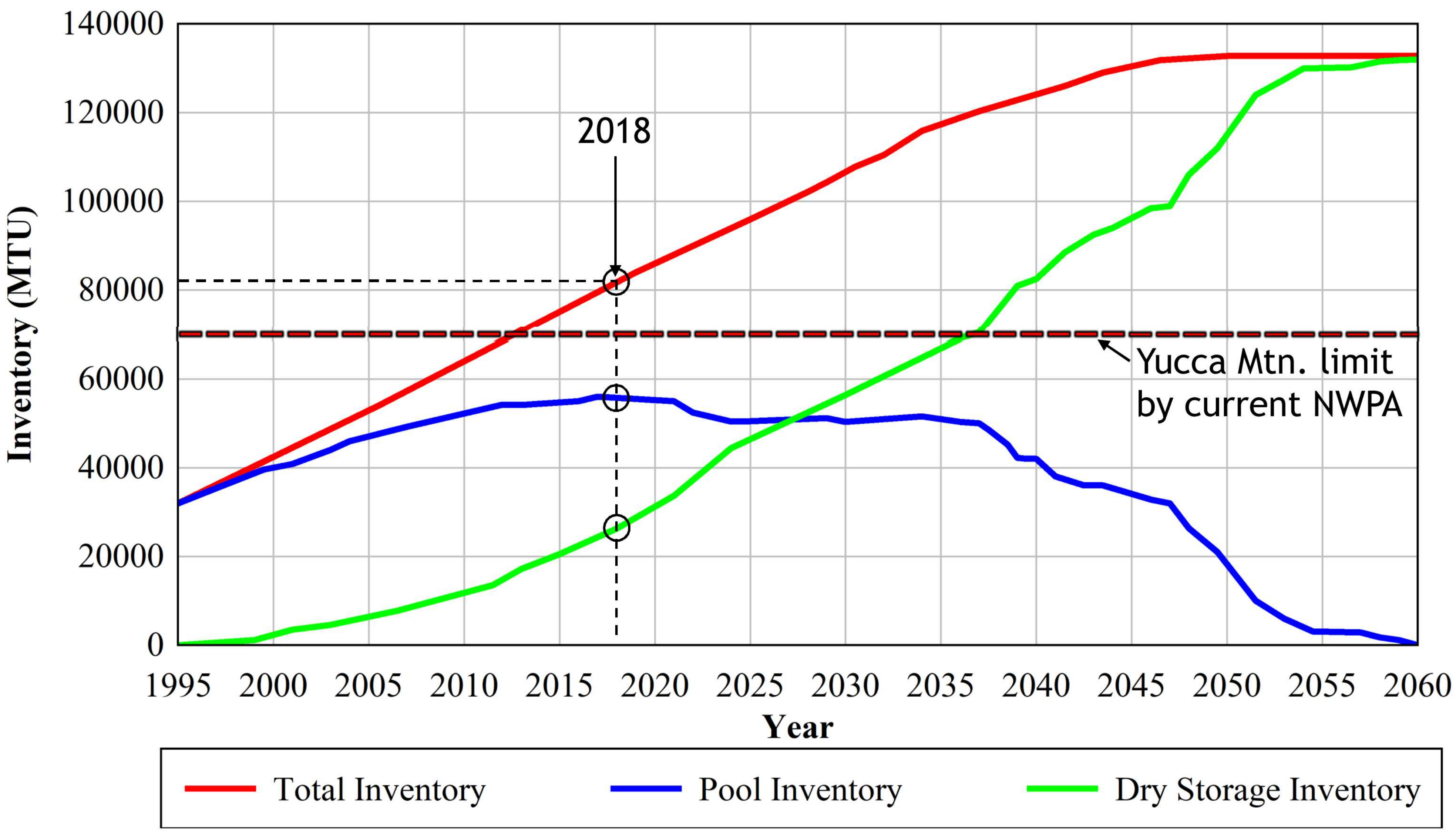


Aboveground

Belowground

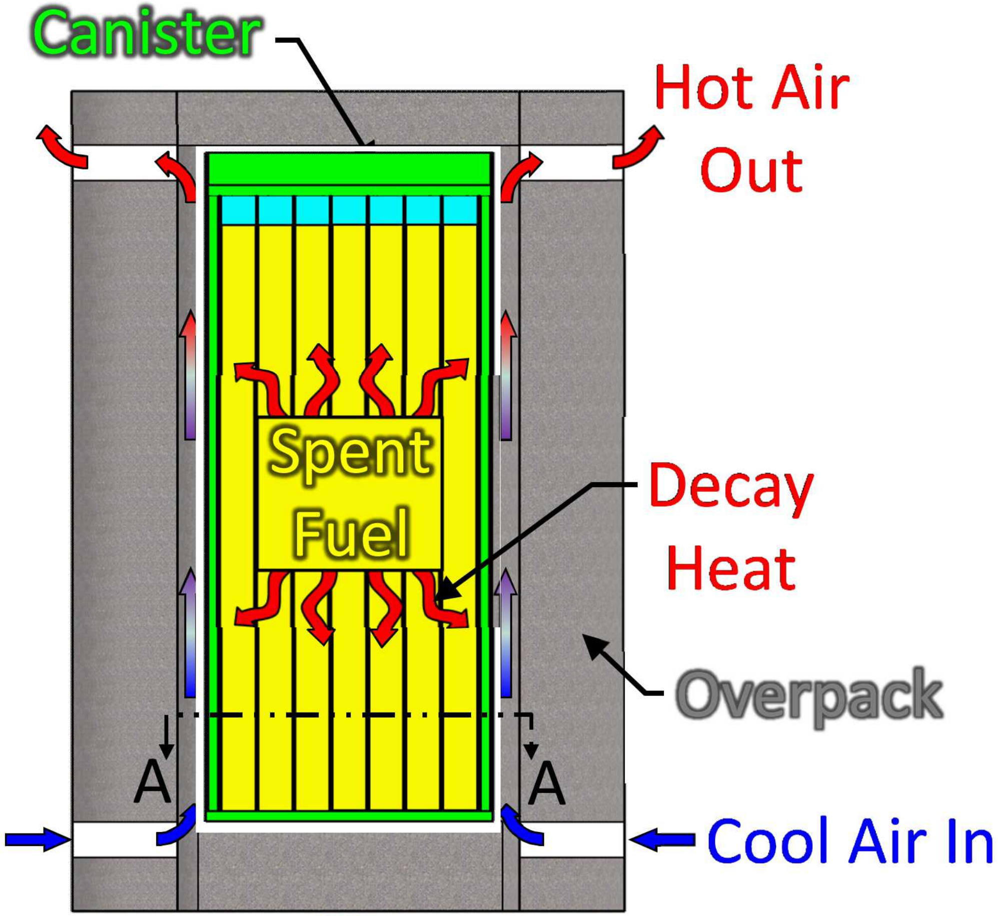
Horizontal

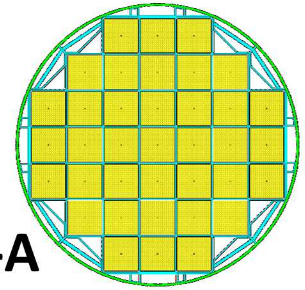
Commercial Spent Nuclear Fuel Inventory in US



Data from J. Carter, D. Vinson, and J. Wilson, Commercial Spent Nuclear Fuel and High-Level Radioactive Waste Inventory Report (U.S. DOE Office of Spent Fuel and Waste Management FCRD-NFST-2013-000263 Rev. 4 SRNL-STI-2016-00360, 2016) 176 p.

How Storage Casks Work





Section A-A

Cross-section of 39-PWR canister

- Canister holds spent fuel assemblies
  - Fuel rods individually sealed (welded)
  - Canister also sealed (welded or bolted)
  - Fuel gives off heat from radioactive decay
  - Stainless steel cylinder with regularly spaced compartments
  - Backfilled with inert helium
    - No chemical interaction
    - Good thermal properties
- Passively cooled storage
  - Decay heat conducted, convected, and thermally radiated to canister wall
  - Heat externally removed by natural air flow
  - Air not in contact with spent fuel
- Overpack provides shielding from radioactivity
  - Typically made from reinforced concrete

Dry Cask Simulator Testing

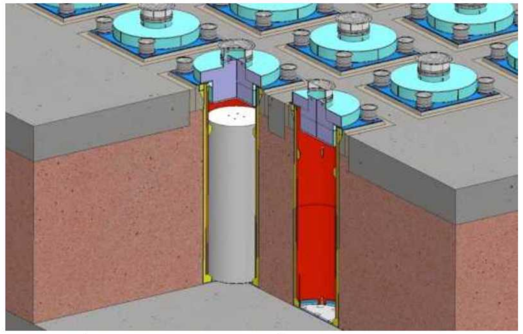
- Sandia Dry Cask Simulator (DCS)
    - Collect data for model validation
        - Simplified geometry based on real-world systems
    - Co-funded by Department of Energy and Nuclear Regulatory Commission
        - Office of Nuclear Energy (DOE)
        - Office of Nuclear Material Safety and Safeguards (NRC)
    - Wide range of parameters
        - Decay heat and internal pressures
        - Different storage configurations (above and below ground)
        - Currently reconfiguring for horizontal configuration
    - Better confidence in predictive modeling to understand fuel behavior

Vertical Dry Cask Simulator Testing

Overview of Dry Cask Simulator (DCS) Testing

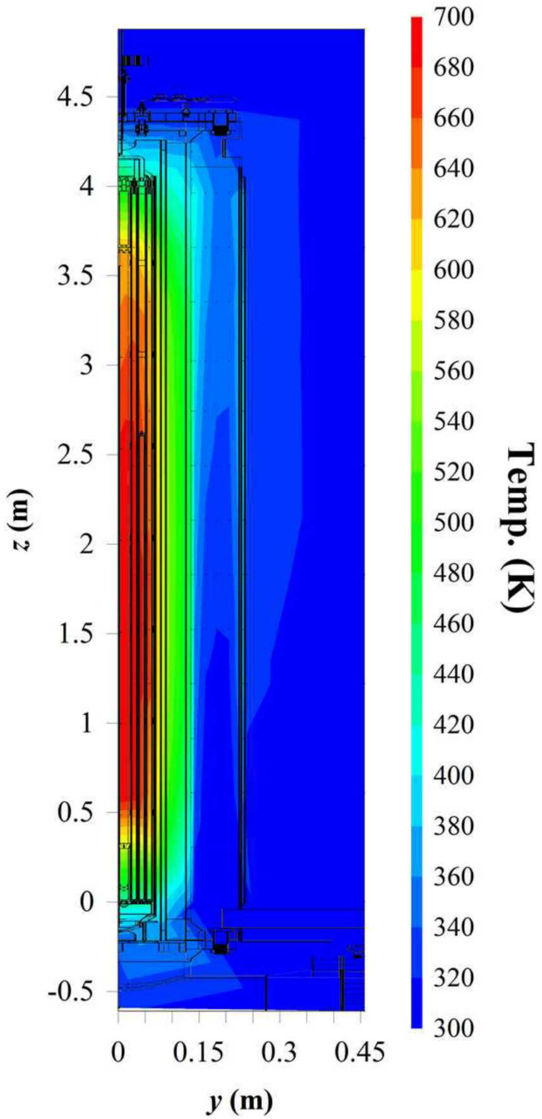
Aboveground Storage

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



Belowground Storage

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



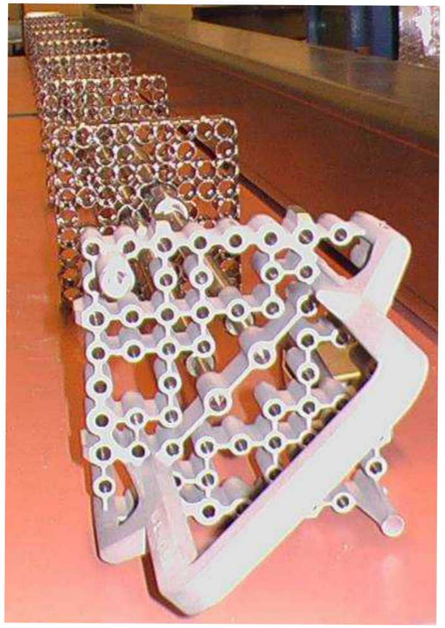
DCS Temp. Contours

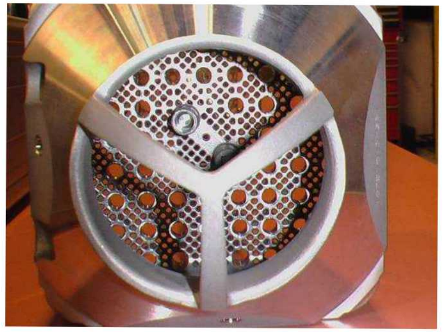
(Test Data for 5 kW, 1 bar)

- 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 cask pressures
  - 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

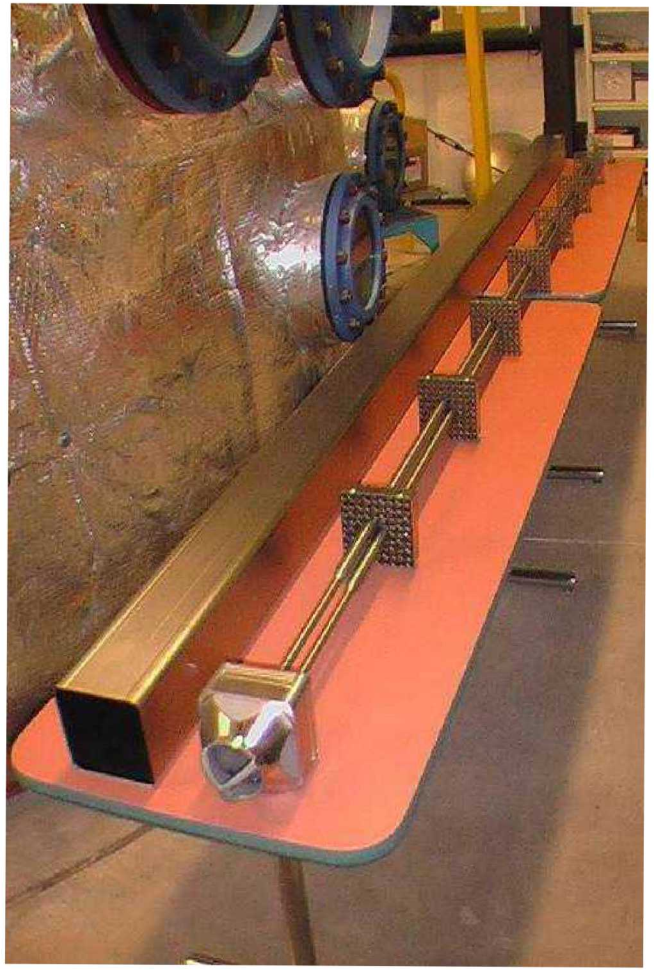
Assembly Hardware

Upper tie plate



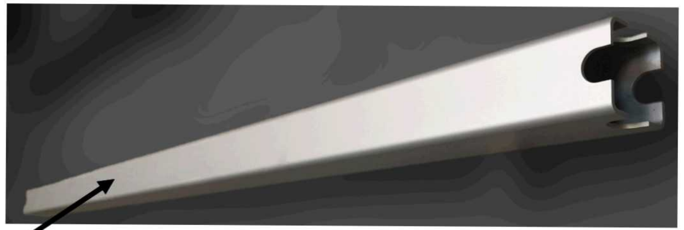


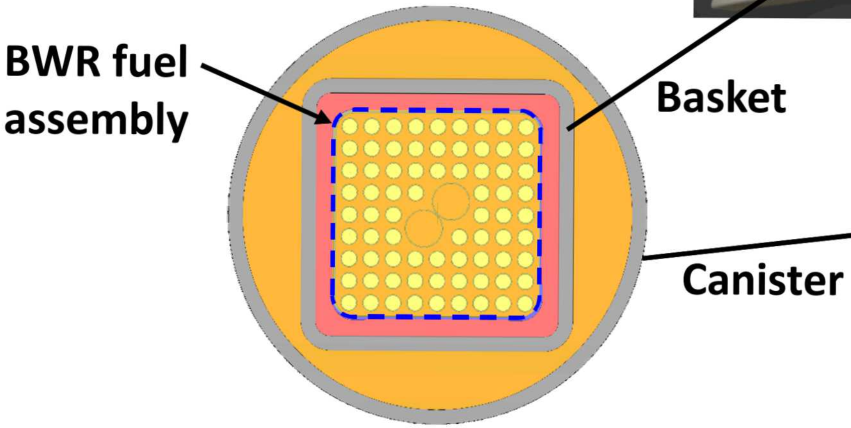
Nose piece and debris catcher

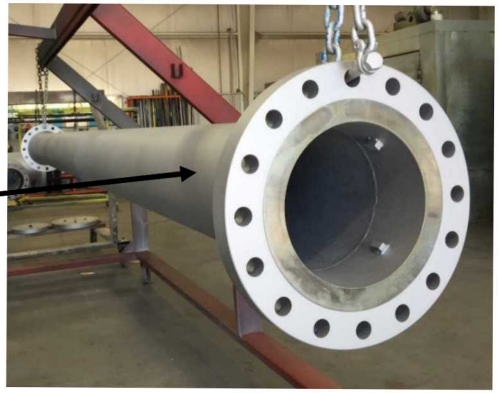


BWR channel, water tubes and spacers

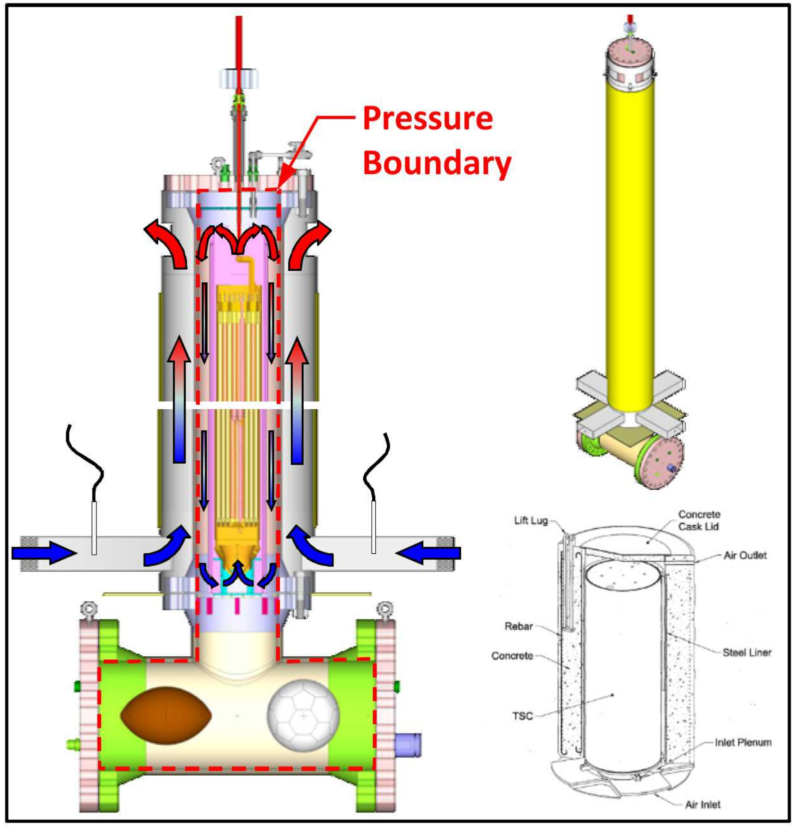
- Most common 9×9 BWR in US
- Prototypic 9×9 BWR hardware
  - Full length, prototypic 9×9 BWR components
  - Electric heater rods with Incoloy cladding
  - 74 fuel rods
    - 8 of these are partial length
    - Partial length rods 2/3 the length of assembly
- 2 water rods
- 7 spacers

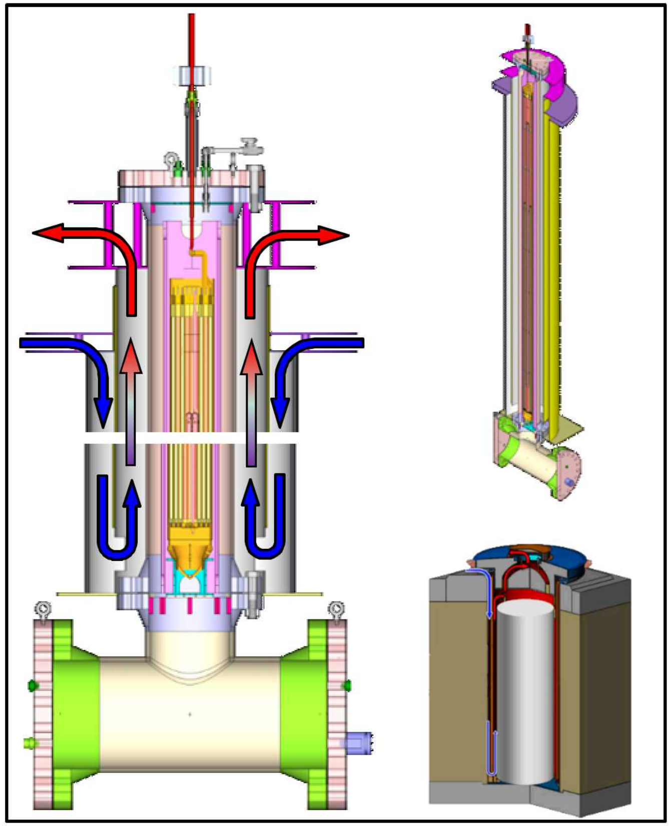


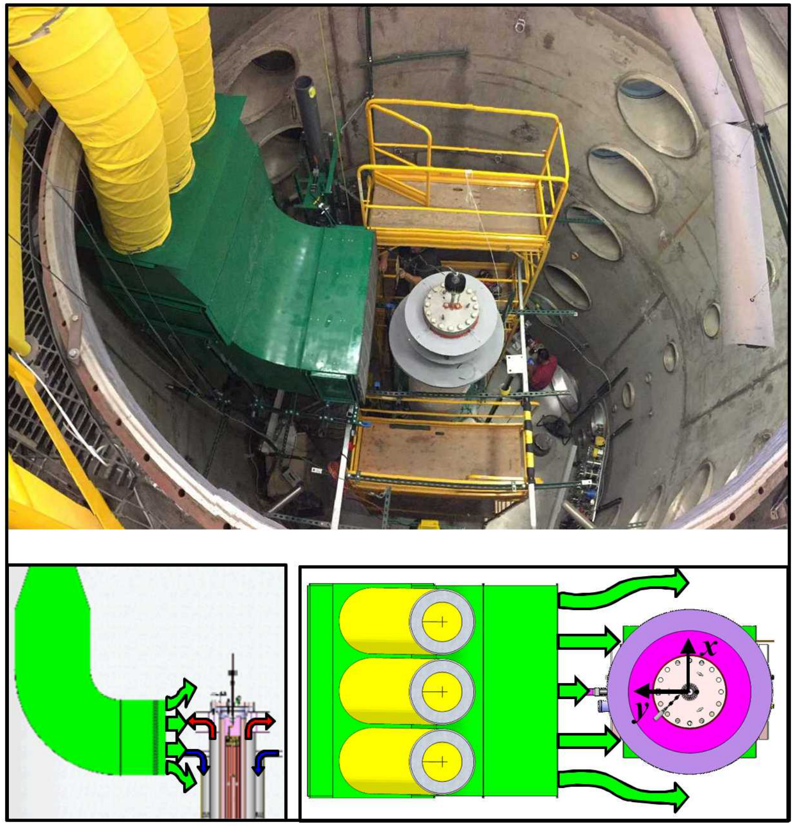




Vertical Dry Cask Simulator Configurations





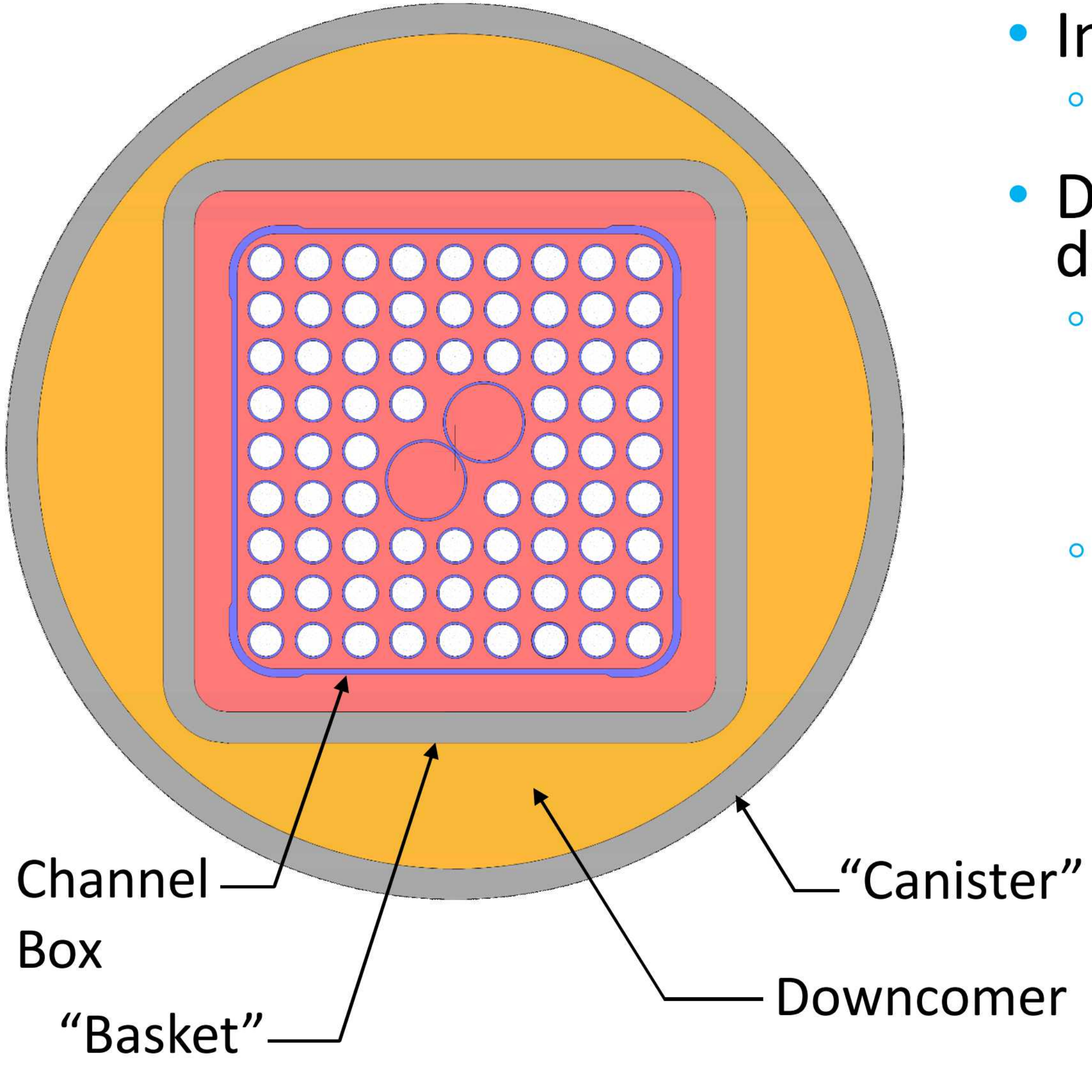


- Aboveground Configuration
  - Air inlets at bottom
  - Air outlets at top

- Belowground Configuration
  - Modification to aboveground configuration
  - Additional annular flow path
  - Inlet near top of assembly

- Cross-Wind Configuration
  - Study impact of sustained cross-winds on belowground systems
  - Custom wind machine installed in-vessel

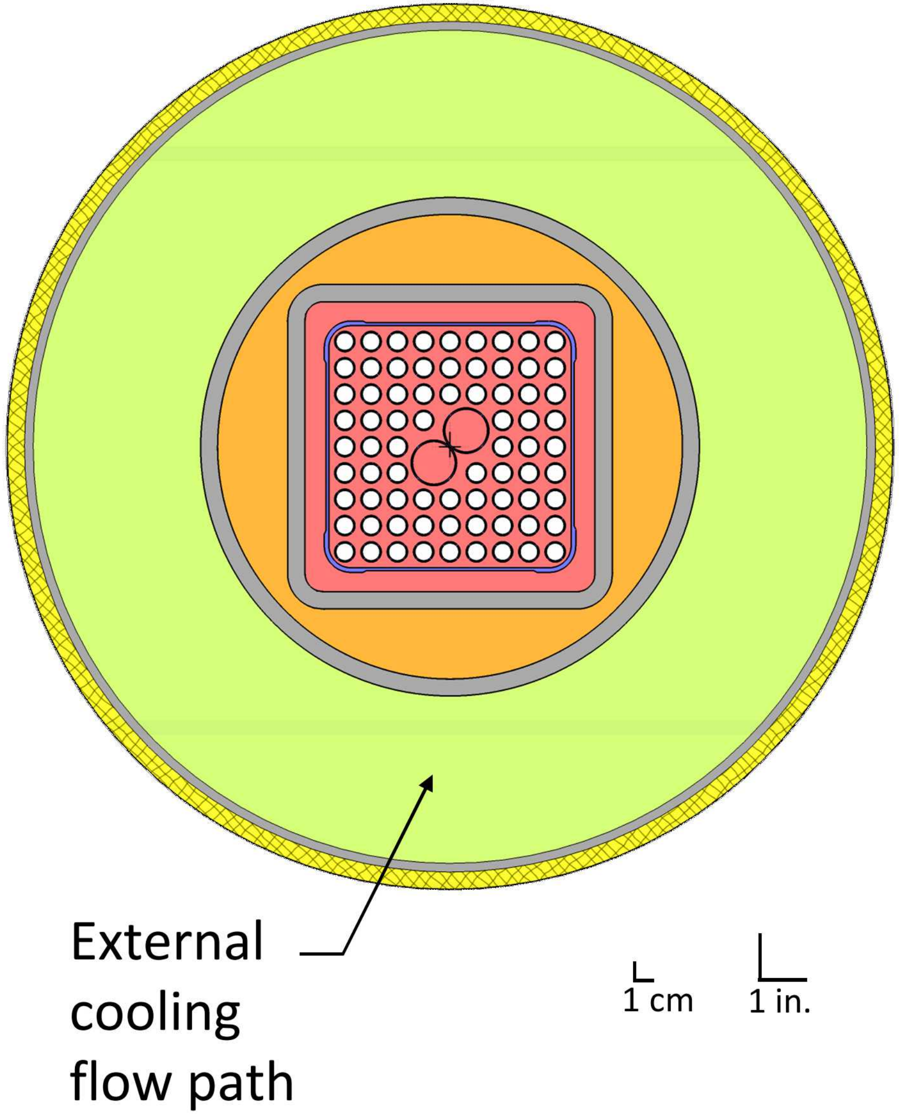
Internal Dimensional Analyses



- Internal flow and convection nearly prototypic
  - Prototypic geometry for fuel and basket
- Downcomer scaling insensitive to wide range of decay heats
  - External cooling flows matched using elevated decay heat
    - Known scaling distortion
    - Higher surface-area-to-volume ratio than prototypic
  - 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

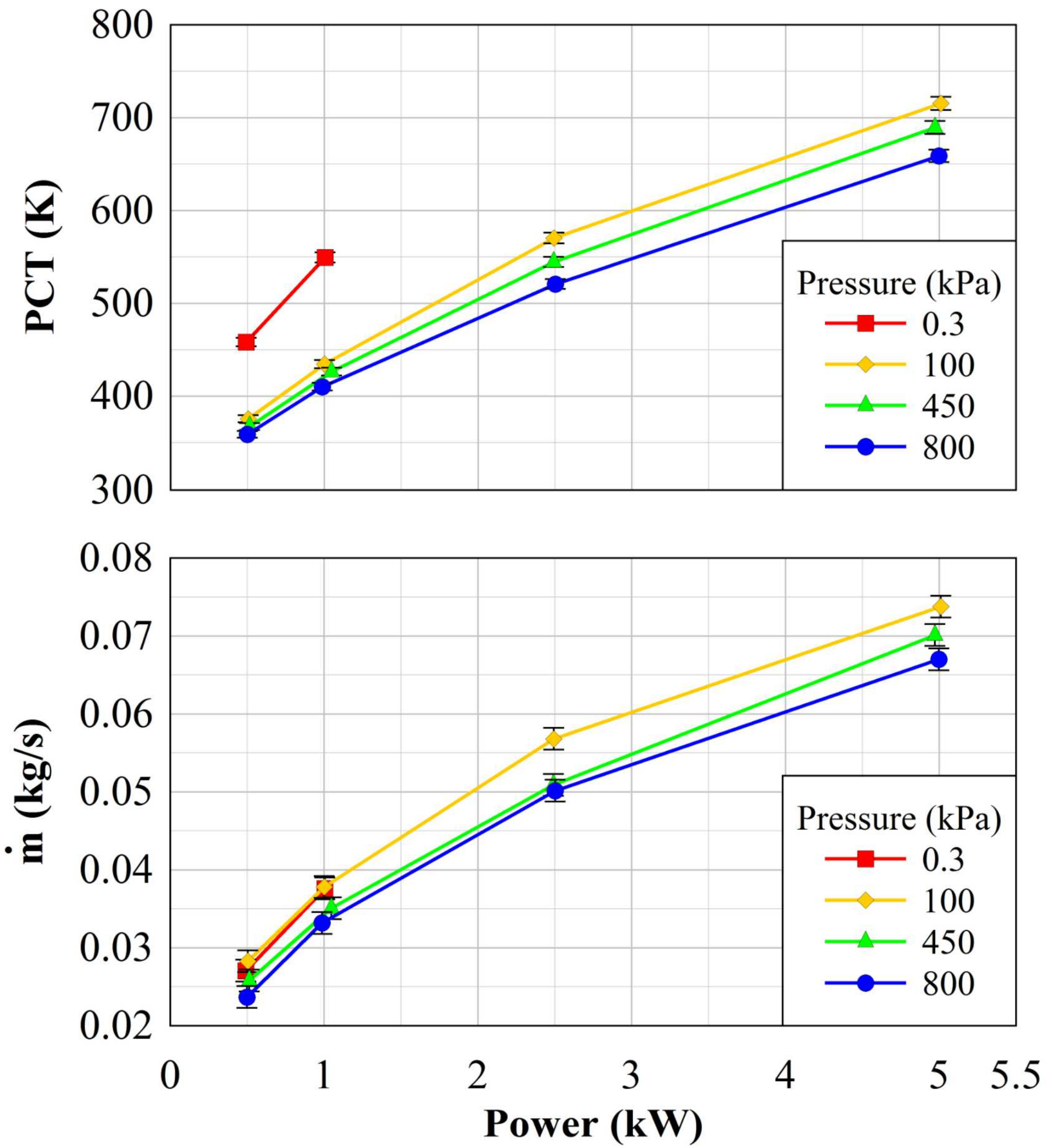
External Dimensional Analyses



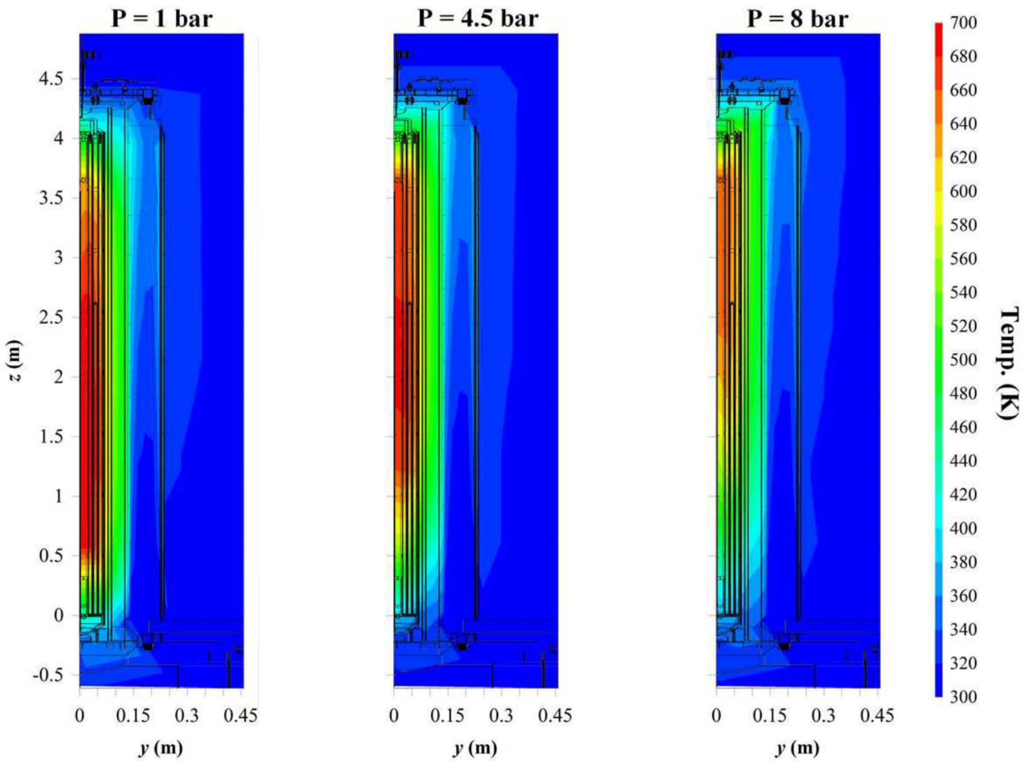
- External cooling flows evaluated against prototypic
  - External dimensionless groups

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 Steady State Values

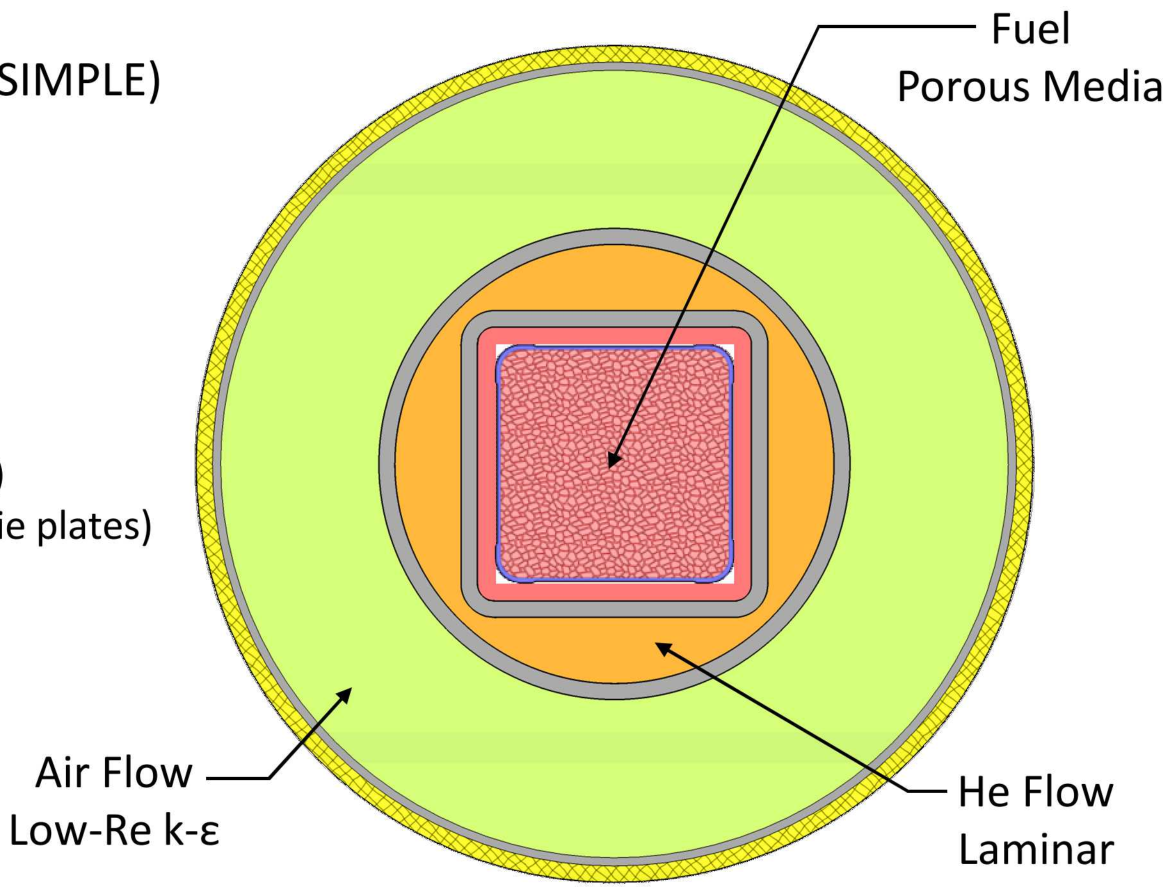


- PCT and air flow ↑ as simulated decay heat ↑
  - Significant increase in PCT for P = 0.3 kPa
    - Due to air in "canister" instead of helium

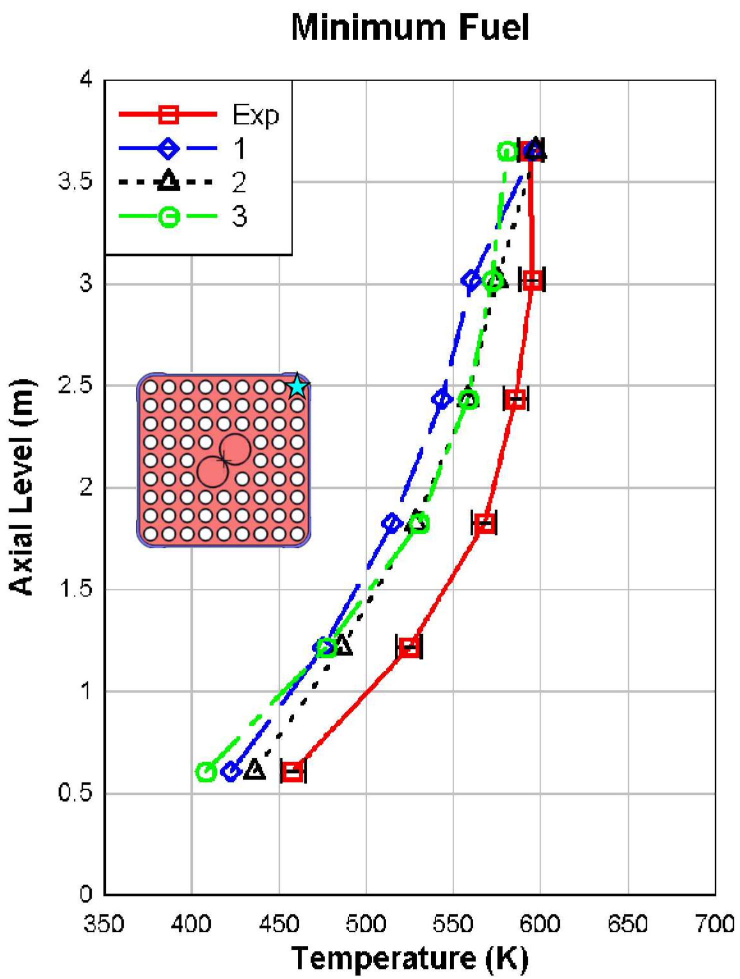


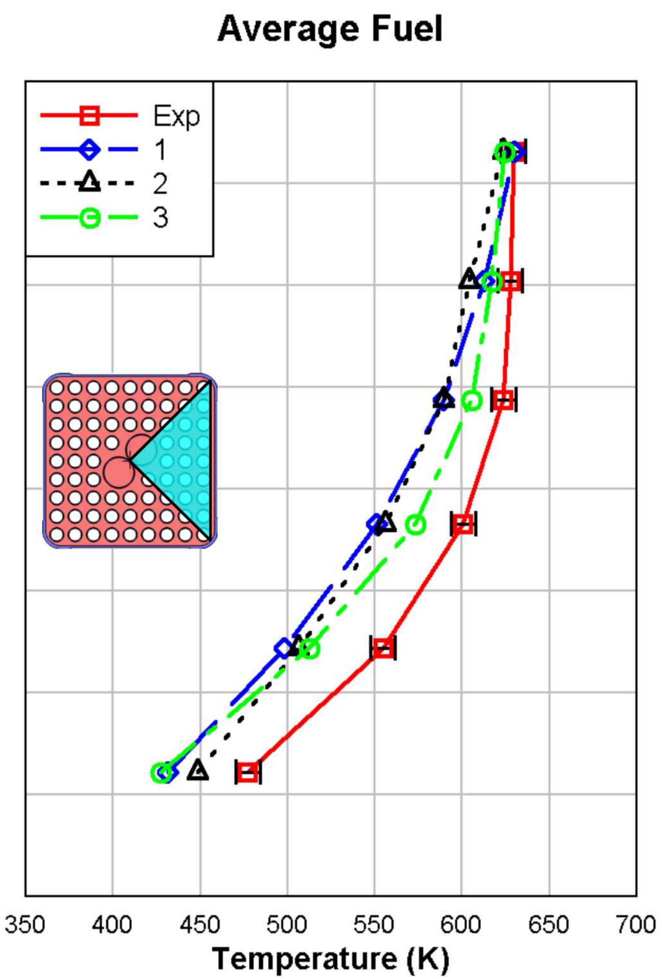
CFD Modeling Based on Best Practices

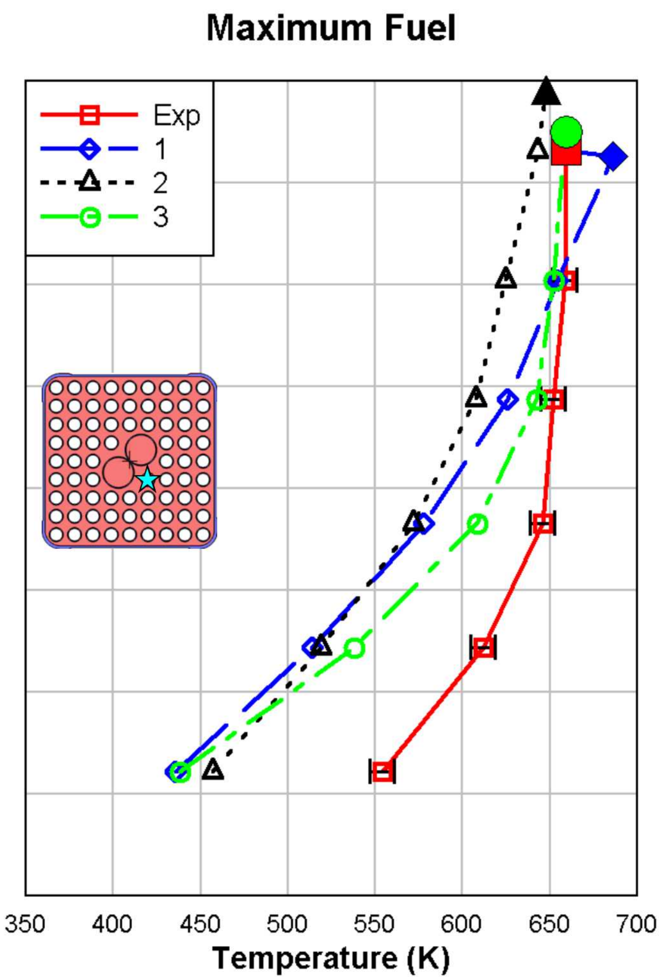
- Best practice guidelines for dry cask applications
  - NUREG-2152
- Computational fluid dynamics (CFD) modeling
  - Pressure based solver
  - 2nd order upwind discretization for all conservation equations
  - Discrete Ordinates (DO) for radiation heat transfer
  - Semi-Implicit Method for Pressure-Linked Equations (SIMPLE)
    - Link for momentum and continuity equations
- Full buoyancy effect in momentum
  - No Boussinesq approximation
- 3-D mesh with symmetric mid-plane
  - Fuel represented as porous media
    - Effective conductivities (combines conduction and radiation)
    - Effective friction factor (homogenizes bundle, spacers, and tie plates)
    - Good summary of porous media in NUREG-2208
- Internal laminar flow
- External turbulent (Low-Re k-ε)

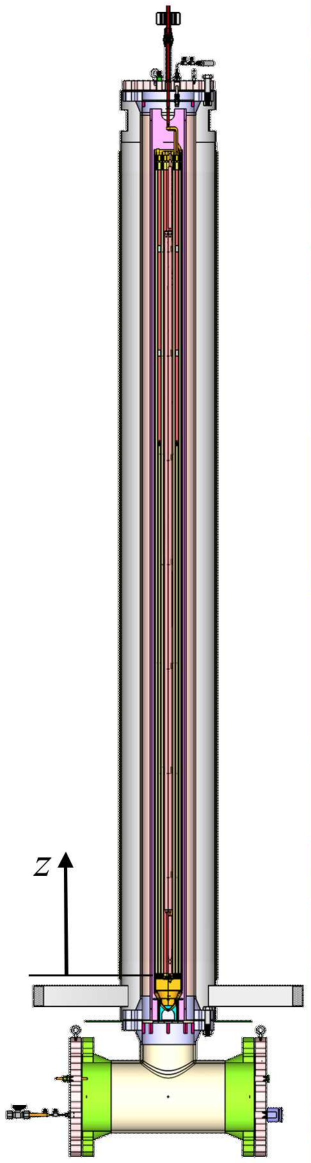


Aboveground Fuel Comparisons (5 kW, 800 kPa)

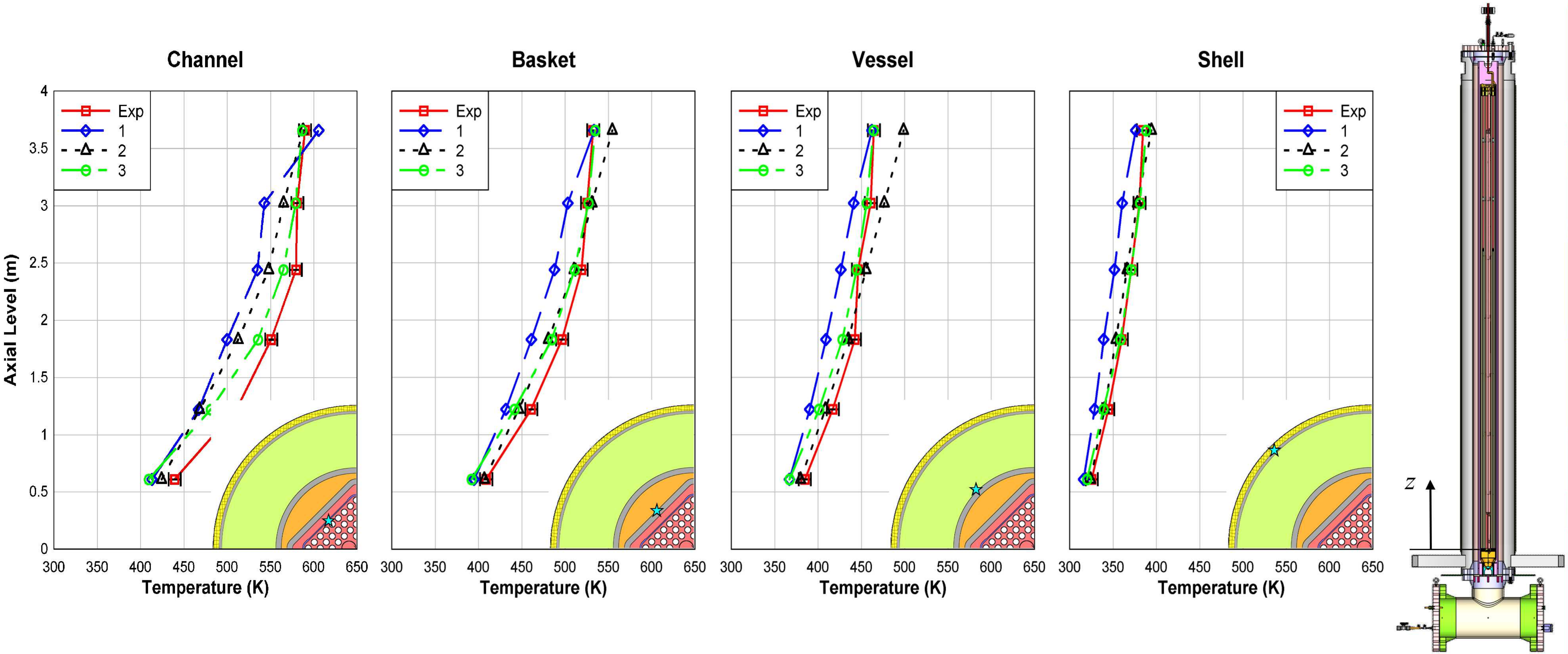








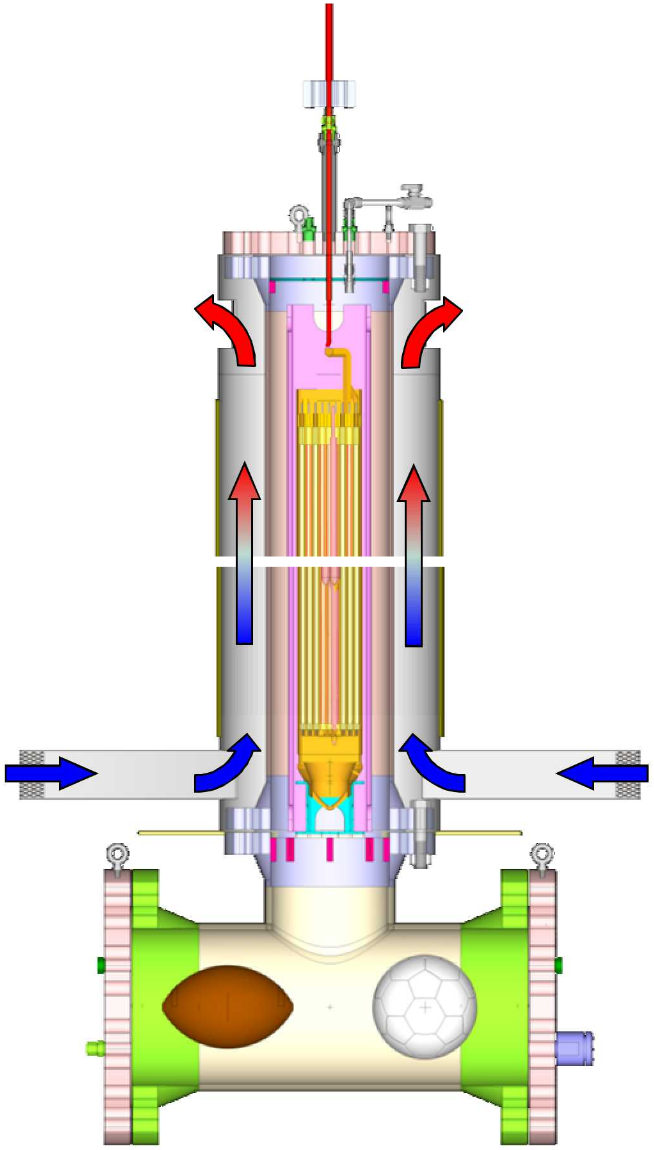
Aboveground Apparatus Components (5 kW, 800 kPa)



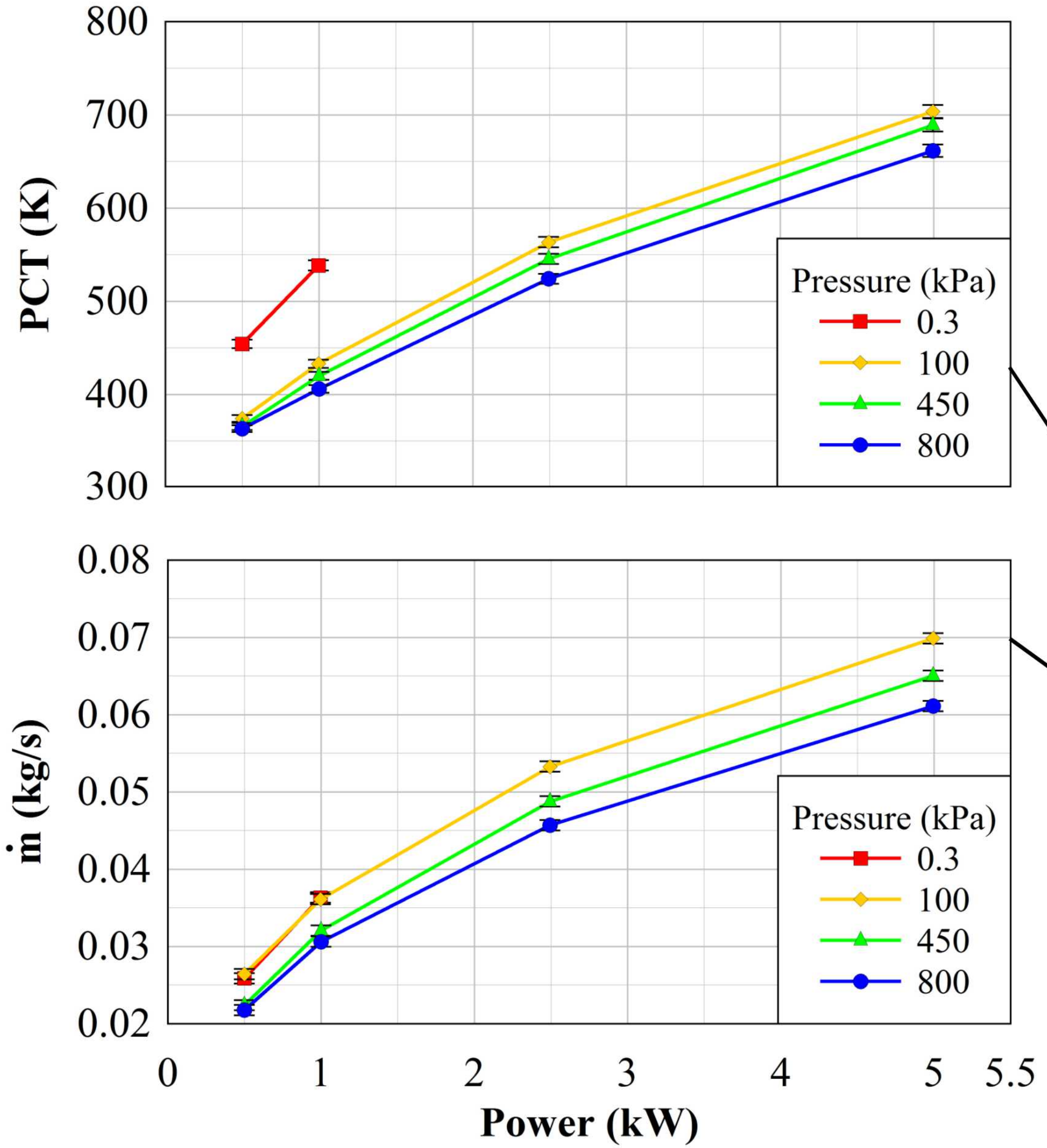
Aboveground External Air Mass Flow Rate

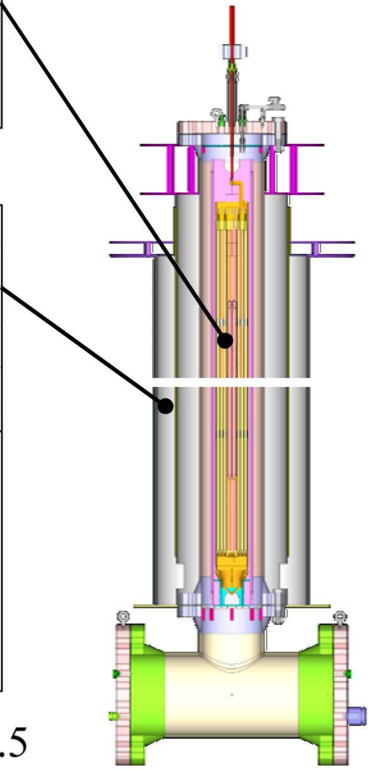
Conditions \ Model		1	2	3
Power (kW)	Pressure (kPa)	$(\dot{m}_{Model} - \dot{m}_{Exp.}) / \dot{m}_{Exp.}$ (-)		
0.5	100	0.012	-0.187	-0.023
0.5	800	-0.156	0.138	-0.010
5	100	-0.019	-0.068	0.005
5	800	-0.054	-0.042	-0.026

- Maximum experimental uncertainty $U_{\Delta\dot{m}} / \dot{m}_{Exp.} = \pm 0.08$
- Root mean square (RMS) across all values is 0.086
  - For 0.5 kW only, RMS = 0.115
  - For 5.0 kW only, RMS = 0.042

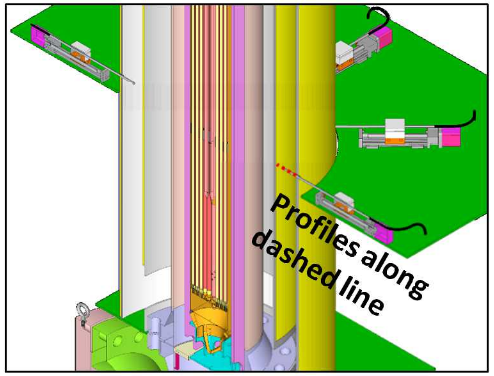


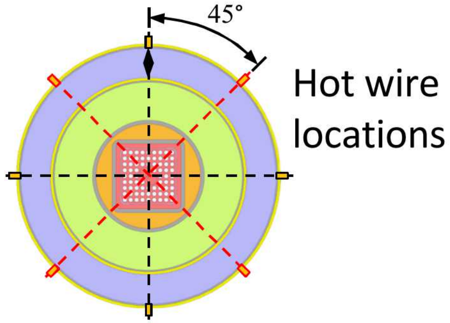
Belowground Steady State Values



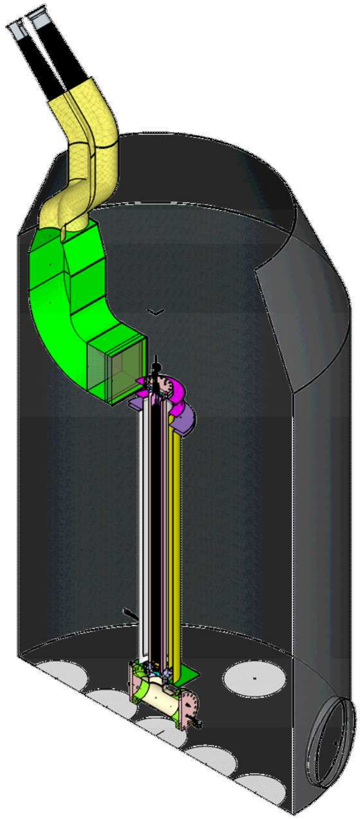


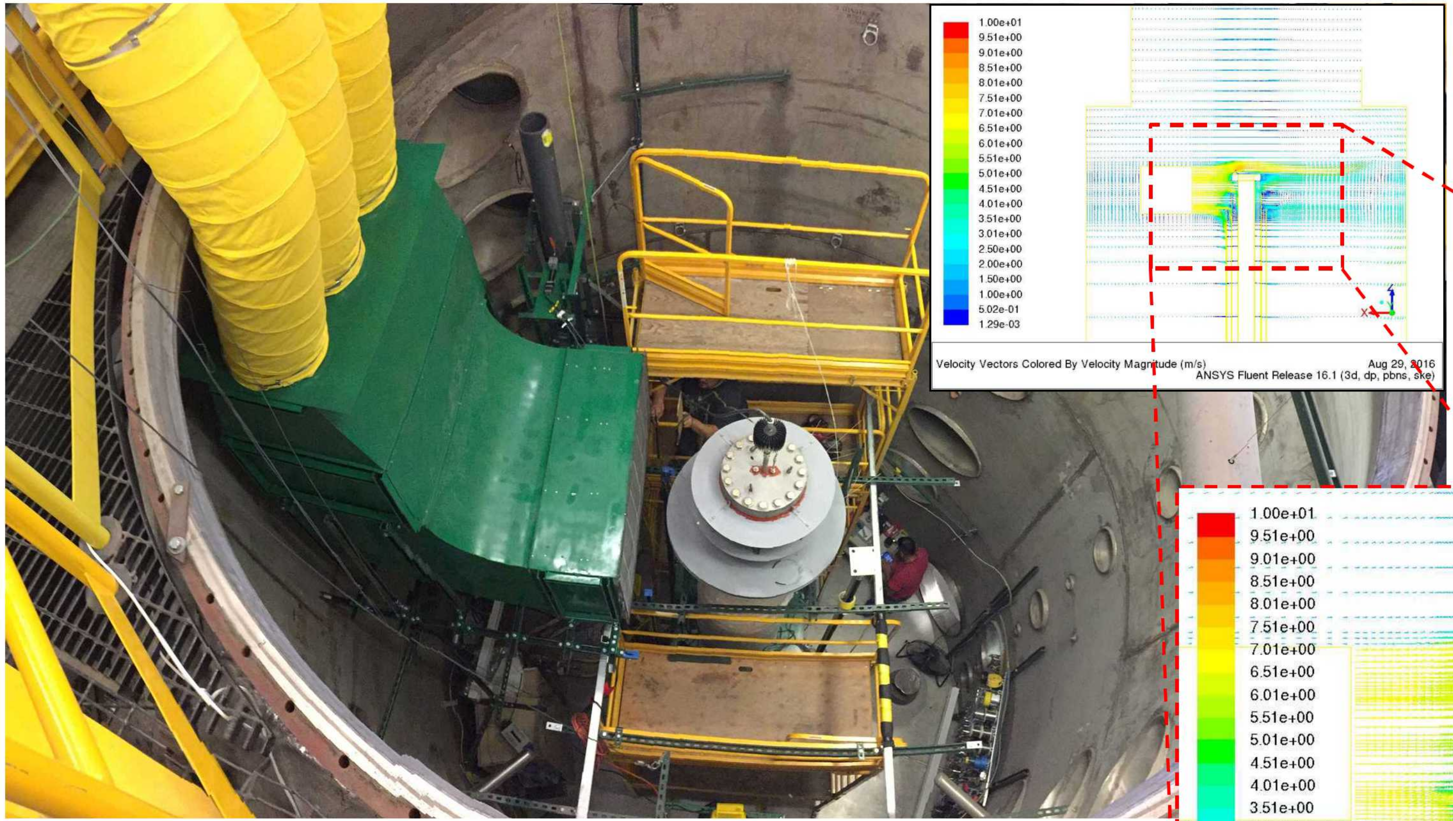
- Similar performance to aboveground configuration
  - Within 2% for PCT
  - Within 5% for ṁ

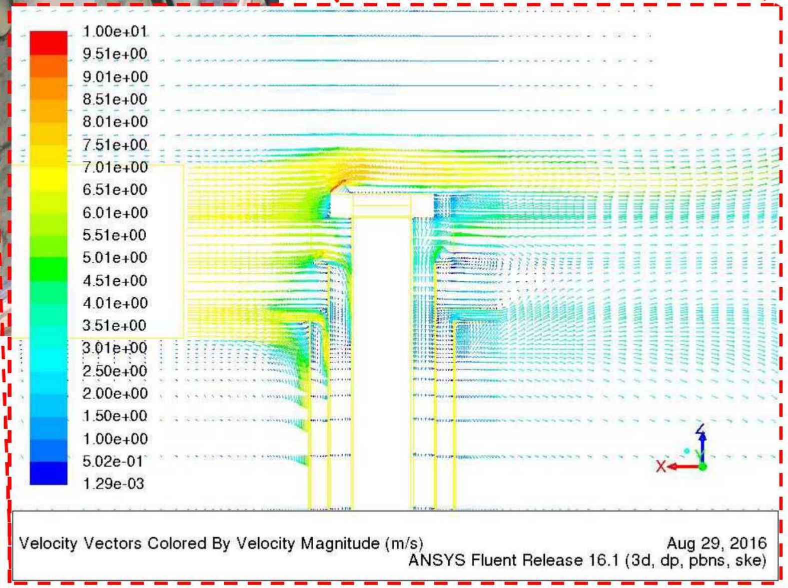




Cross-Wind Testing



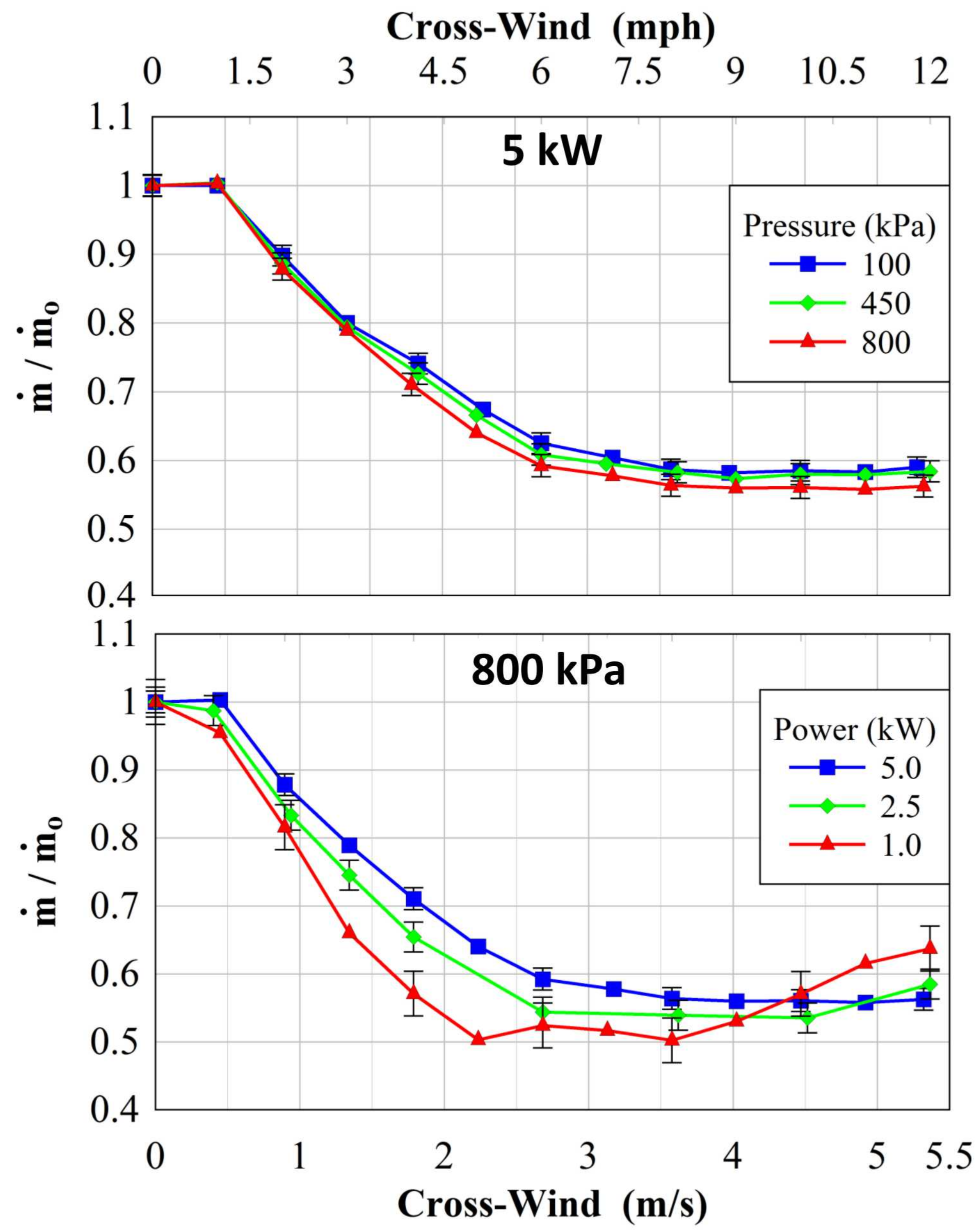




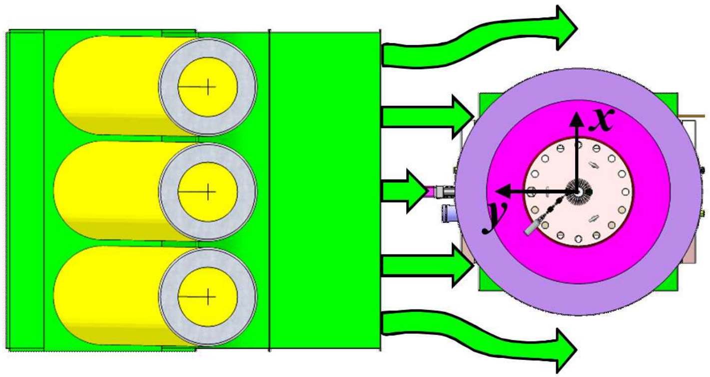
CFD simulations by A. Zigh (USNRC)

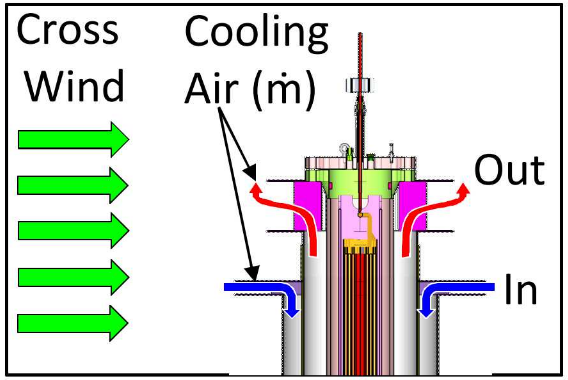
- Wind machine installed inside test enclosure
  - Three air-driven blowers
  - Specially fabricated duct with flow straightening
  - Cross winds of up to 5.4 m/s (12 mph)

Reduction of External Air Flow Rate



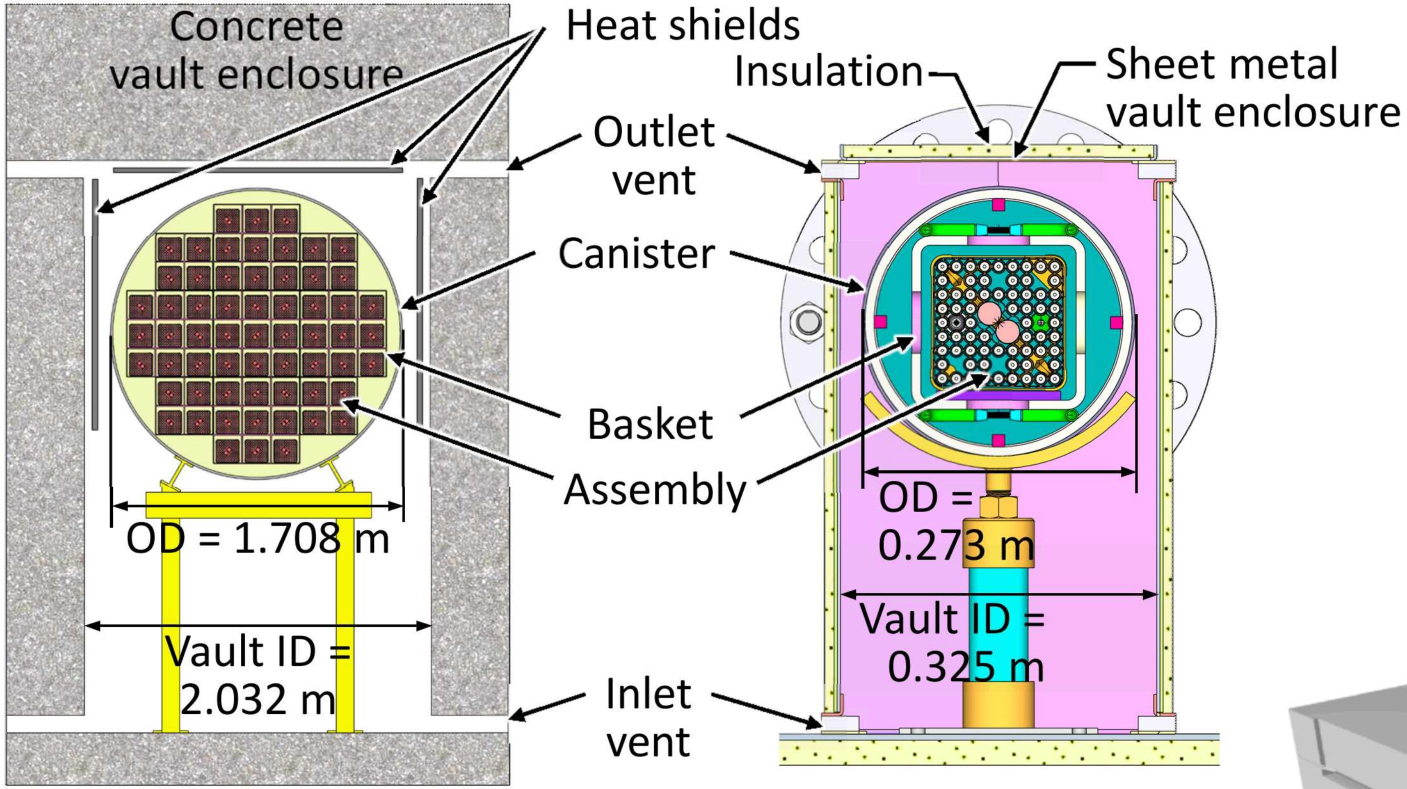
- Belowground configuration
- Moderate, sustained cross winds have significant impact on external air mass flow rate
  - Reductions of up to 50%
  - Thermal impact limited for DCS
  - Potentially more significant effect for prototypic systems





Horizontal Dry Cask Simulator Testing

Overview of Horizontal Dry Cask Simulator (HDCS) Testing

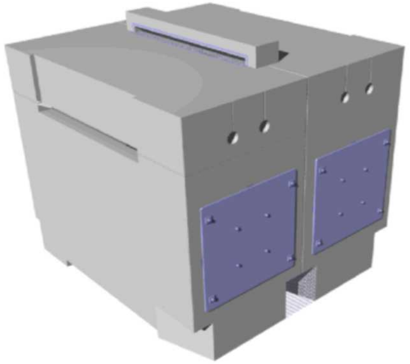


NUHOMS HSM Model 80 with 61BT canister BR = 0.84

HDCS BR = 0.84

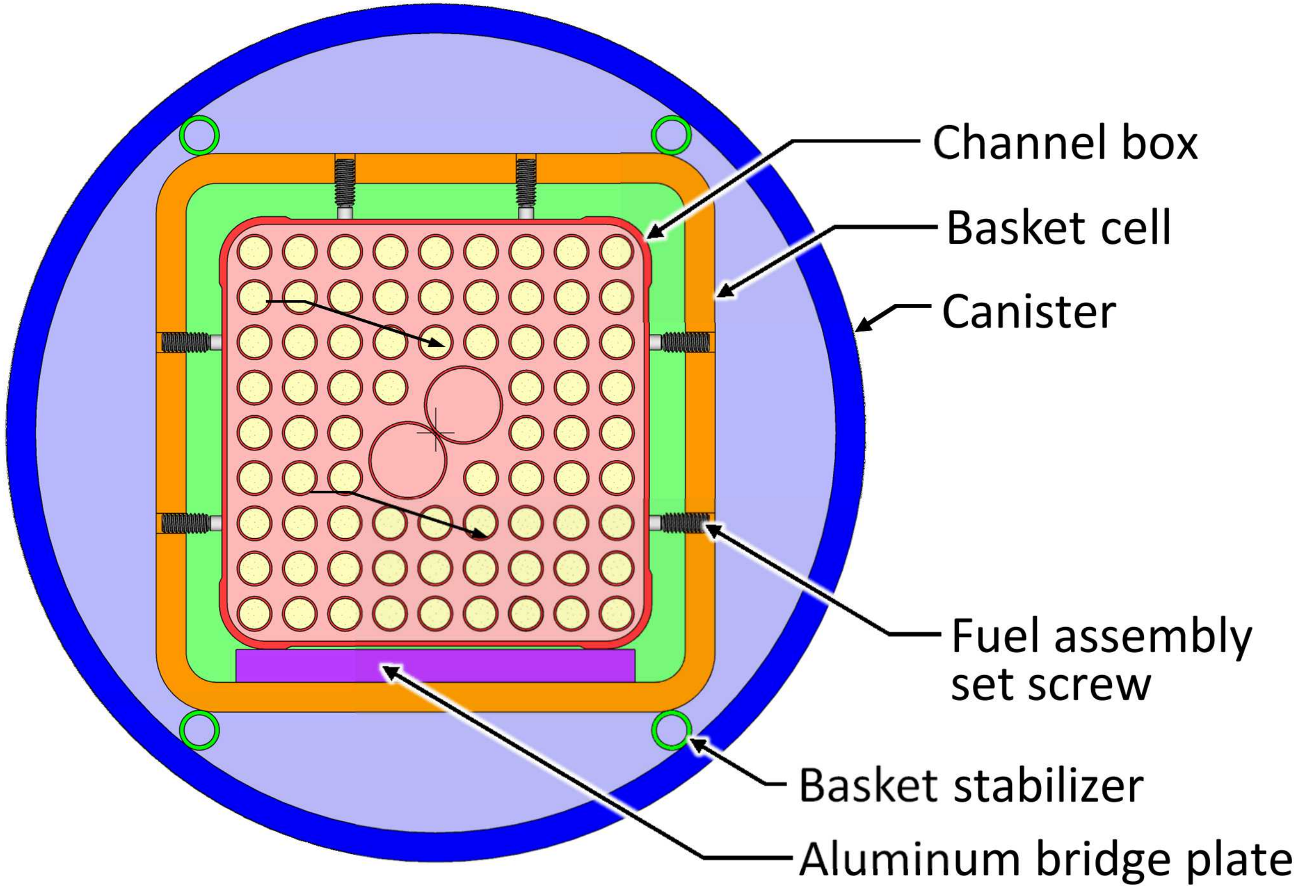
- Repeat testing for horizontal storage configuration
  - Wide range of test parameters
    - Decay heats, gas backfills, and internal pressures
  - Collect validation data
    - Temperatures and air flow rates

Depictions of horizontal storage modules



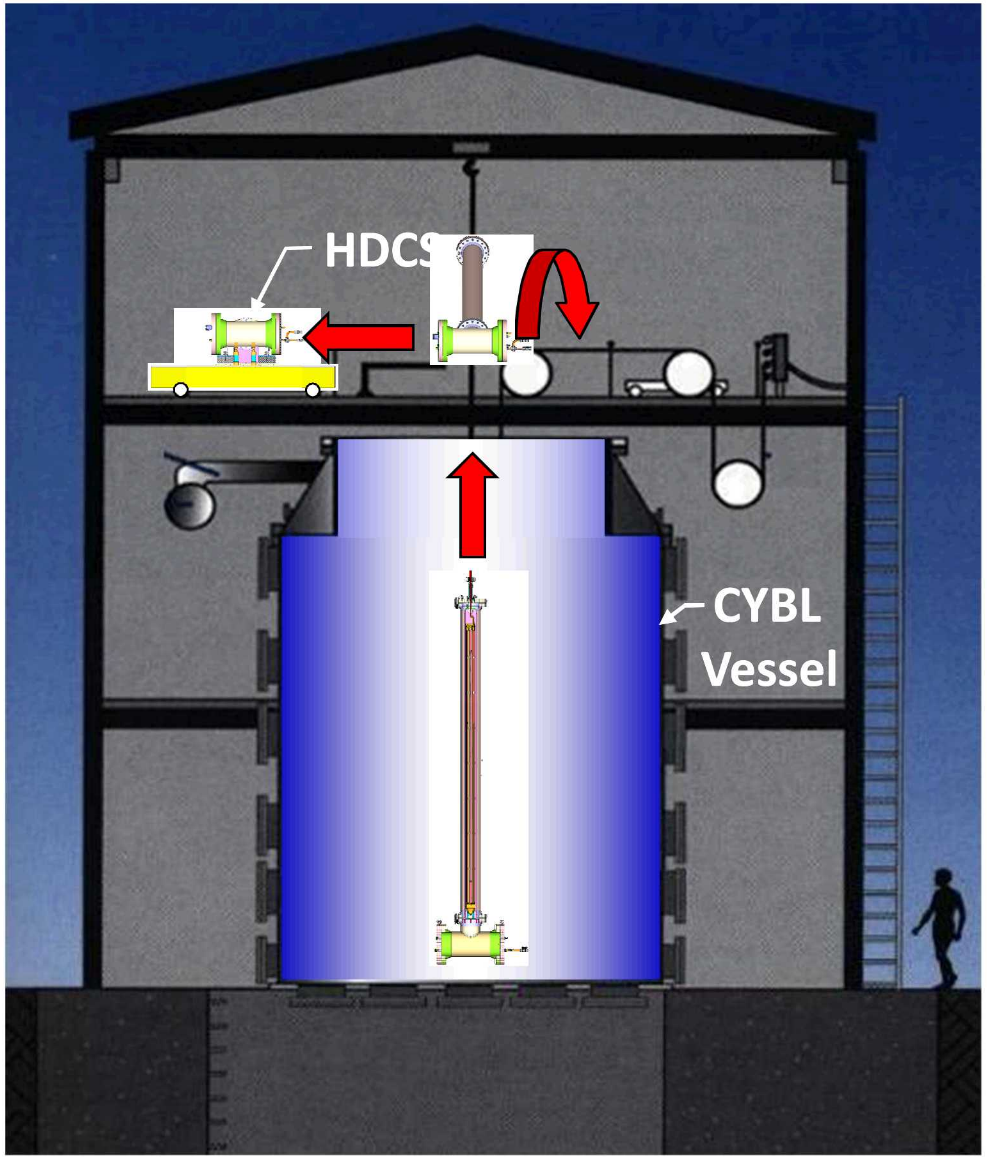
Source: http://us.areva.com/home/liblocal/docs/Catalog/AREVA-TN/ANP_U_299_V5_17_ENG_NUHOMS_HSM.pdf

Assembly Modifications



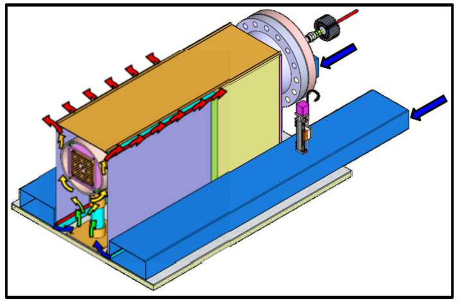
- DCS presently deconstructed
- Convert to horizontal
  - Outer shell and inner shells removed
  - Pressure vessel opened
  - Basket removed
- Maintain concentricity and enhance heat conduction
  - Add stabilizers
    - Between channel box and basket
    - Between basket and canister wall
      - Full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

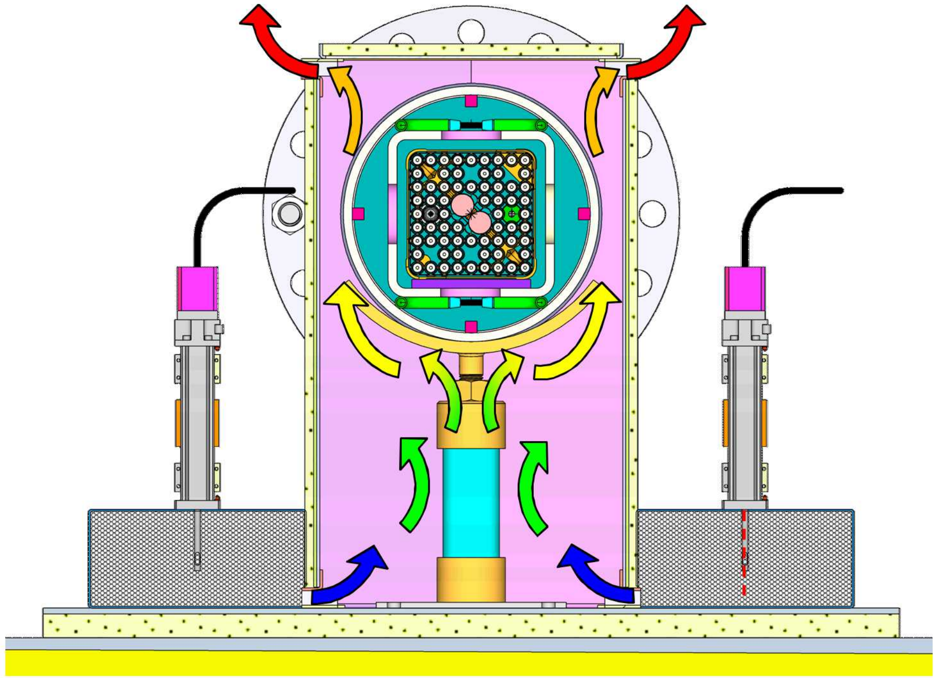
Facility Transition



- After performing in-vessel modifications
- Move HDCS 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

Dimensional Analyses





- Internal scaling within fuel maintained by matching prototypic geometry
  - Known scaling distortions
    - Power: Higher surface-area-to-volume
    - Internal heat transfer: Reduced conductivity between structures
- External dimensionless groups may appear dissimilar at first inspection, but…
  - Reynolds: Irregular regime for $270 < Re_D < 5{,}000$
  - Modified Rayleigh: 3-D wake separation (turbulence) for $Ra_D^* > 3.5\times10^9$

Parameter	Horizontal		
	HDCS Low Power	HDCS High Power	Cask
Power (kW)	0.5	5.0	24
Re_D	280	730	2,000
Ra_D^*	1.3E+09	1.3E+10	1.4E+13
Nu_{DH}	30	50	170

Summary

- Vertical testing of the dry cask simulator (DCS) 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
    - Test results documented in NUREG/CR-7250
  - Model validation efforts are ongoing
    - NRC modeling and uncertainty quantification will be reported in NUREG (Late 2019)
    - Additional comparisons (NRC, PNNL, CIEMAT, and ENUSA) to be published as SAND report (May 2019)
- Horizontal dry cask simulator (HDCS) under construction
  - Testing planned to start by mid-March 2019
  - 28 tests scheduled
    - 3 gas backfills (Helium, air, argon)
    - 4 different decay heats (0.5, 1.0, 2.5, 5.0 kW)
    - 3 pressures (100, 200, 800 kPa)