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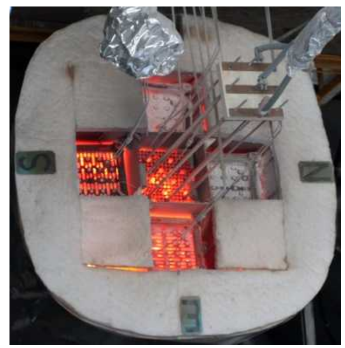

Dry Cask Simulator for a Boiling Water Reactor Fuel Assembly

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* Nuclear Regulatory Commission

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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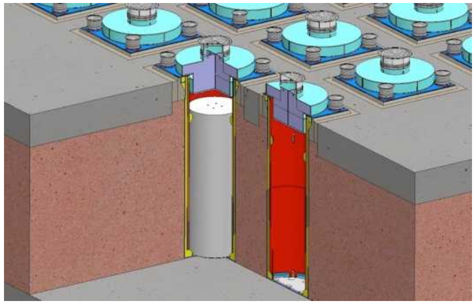
Overview

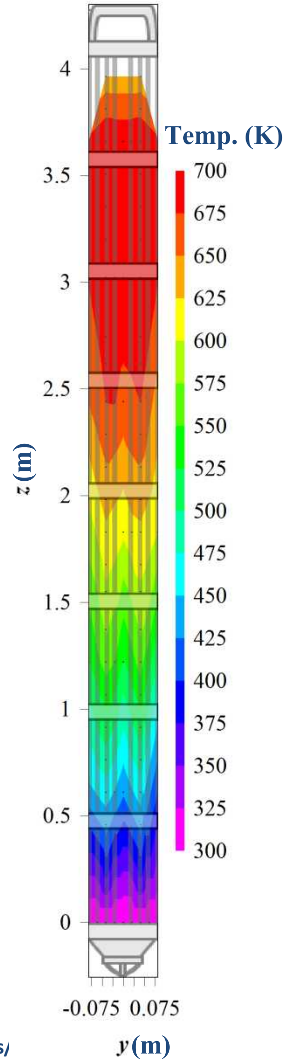
Aboveground Storage

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



Underground Storage

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



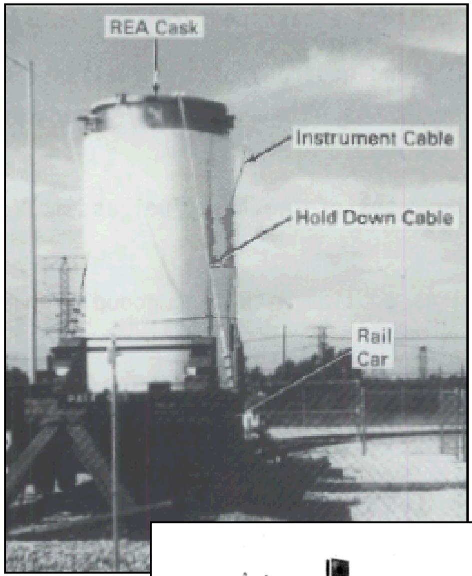
- Purpose: Validate assumptions in CFD calculations for spent fuel cask thermal design analyses
  - Used to determine steady-state cladding temperatures in dry casks
  - Needed to evaluate cladding integrity throughout storage cycle
- Measure temperature profiles for a wide range of decay power and helium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

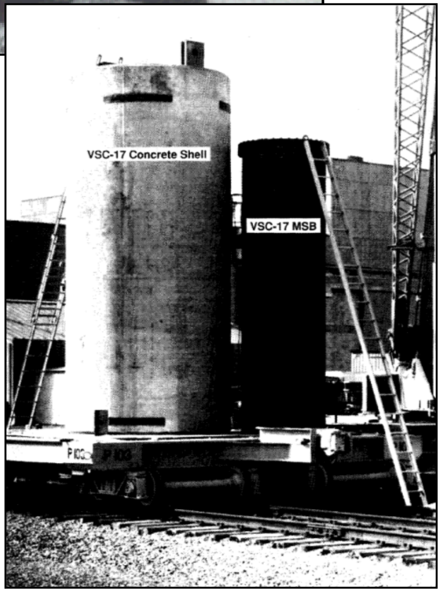
Project Structure

- Boiling Water Reactor Dry Cask Simulator (DCS)
- Partnership between USNRC and DOE
  - Equal cost sharing
  - Parallel reporting to PICS:NE and Monthly Letter Status Reports (MLSRs) to NRC
  - NRC staff has technical review lead
- Mutual benefits
  - Thermal-hydraulic data for validation exercises
  - Complimentary data for High-Burnup Cask Demonstration Project
    - Includes thermal lance comparisons to peak cladding temperature (PCT)

Past Validation Efforts

Full Scale





- Full scale, unconsolidated
  - Castor-V/21 cast iron/graphite with polyethylene rod shielding
    - 1986: EPRI NP-4887, PNL-5917
    - 21 PWRs
    - 95 Thermocouples (TC's) total
    - Unventilated
    - Sub-atmospheric (air and He) and vacuum
  - REA 2023 prototype steel-lead-steel cask with glycol water shield
    - 1986: PNL-5777 Vol. 1
    - 52 BWRs
    - 70 TC's total
    - Unventilated
    - Sub-atmospheric (air & He) and vacuum
- Full scale, consolidated
  - VSC-17 ventilated concrete cask
    - 1992: EPRI TR-100305, PNL-7839
    - 17 consolidated PWRs
    - 98 Thermocouples (TC's) total
    - Ventilated
    - Sub-atmospheric (air and He) and vacuum

Past Validation Efforts (cont.)

Unconsolidated Fuel

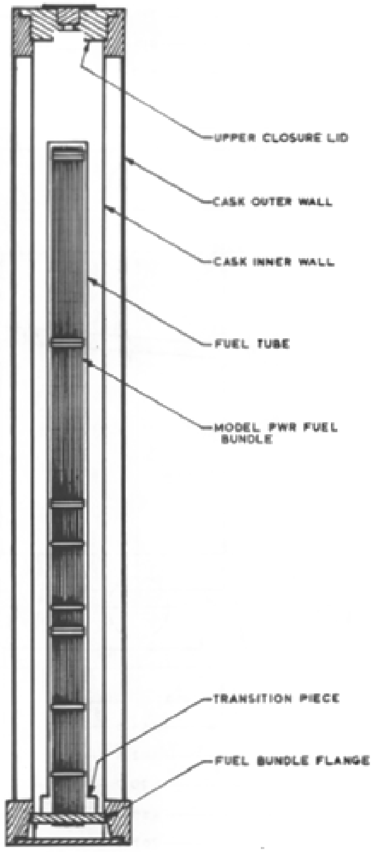
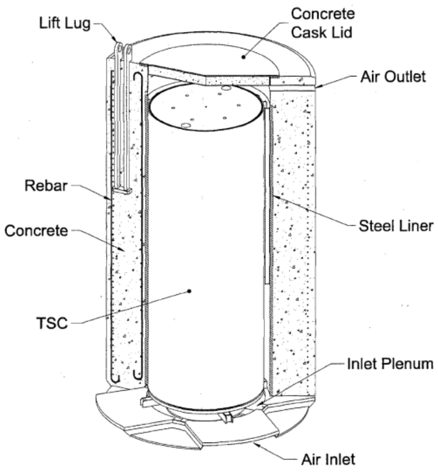
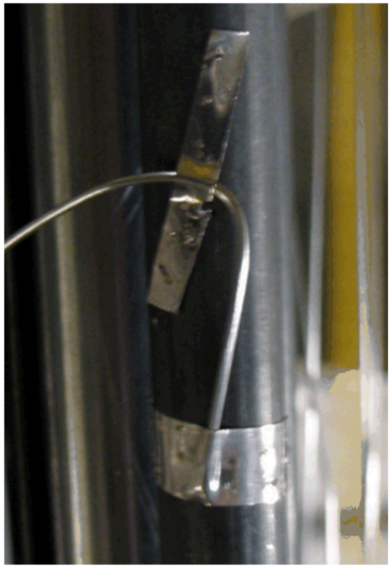


FIGURE 4-1. SAHTT Assembly

- Small scale, single assembly
  - FTT (irradiated, vertical) and SAHTT (electric, vertical & horizontal)
    - 1986 PNL-5571
    - Single 15x15 PWR
    - Thermocouples (TC's)
      - FTT: 187 TC's total
      - SAHTT: 98 TC's total
    - BC: Controlled cask outer wall temperature
    - Atmospheric (air & He) and vacuum
  - Mitsubishi test assembly (electric, vertical & horizontal)
    - 1986 IAEA-SM-286/139P
    - Single 15x15 PWR
    - 92 TC's total, all distributed over 4 levels inside tube bundle
    - BC: Controlled outer wall temperature of fuel tube
    - Atmospheric (air & He) and vacuum
- Not appropriate for elevated helium pressures or belowground configurations

Current Approach

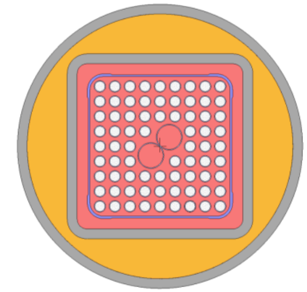


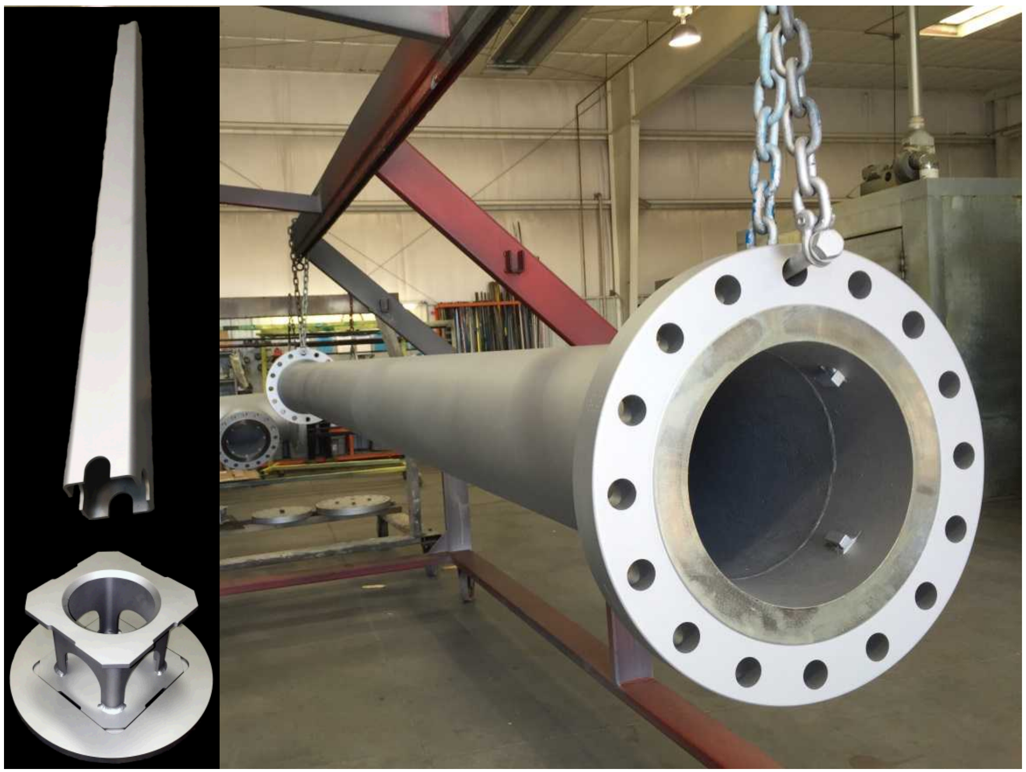


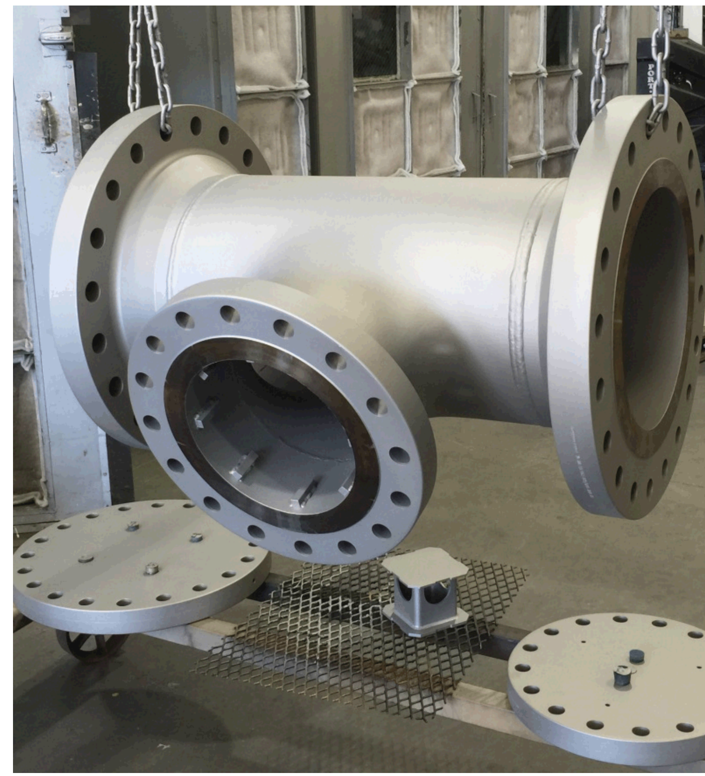
- Focus on pressurized canister systems
  - BCS capable of 24 bar internal pressure @ 400 °C
    - Current commercial designs up to ~8 bar
- Ventilated designs
  - Aboveground configuration
  - Belowground configuration
    - With crosswind conditions
- Thermocouple (TC) attachment allows better peak cladding temperature measurement
  - 0.030” diameter sheath
    - Tip in direct contact with cladding
- Provide validation quality data for CFD
- Complimentary to Cask Demo Project

BCS Pressure Vessel Hardware

- Fabricated and pressure tested
- Coated with ultra high temperature paint

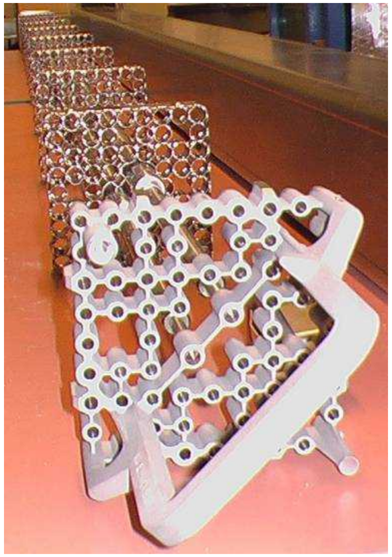


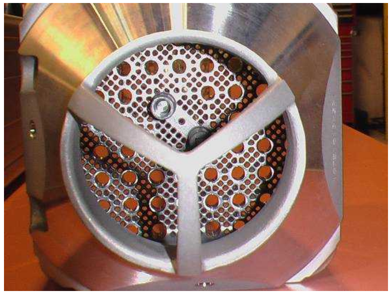




Prototypic Hardware

Upper tie plate

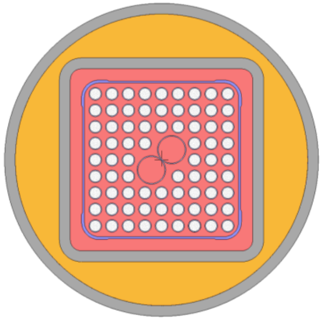




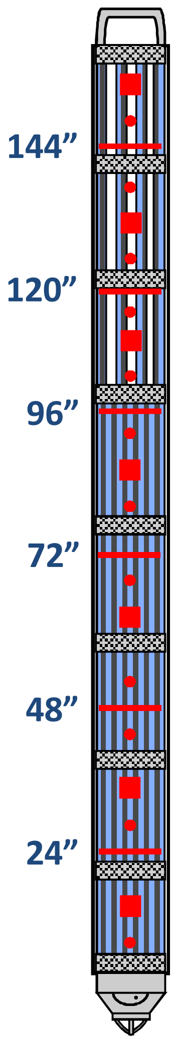
Nose piece and debris catcher

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 end 2/3 the length up assembly
  - 2 water rods
  - 7 spacers



Internal Thermocouple Layout



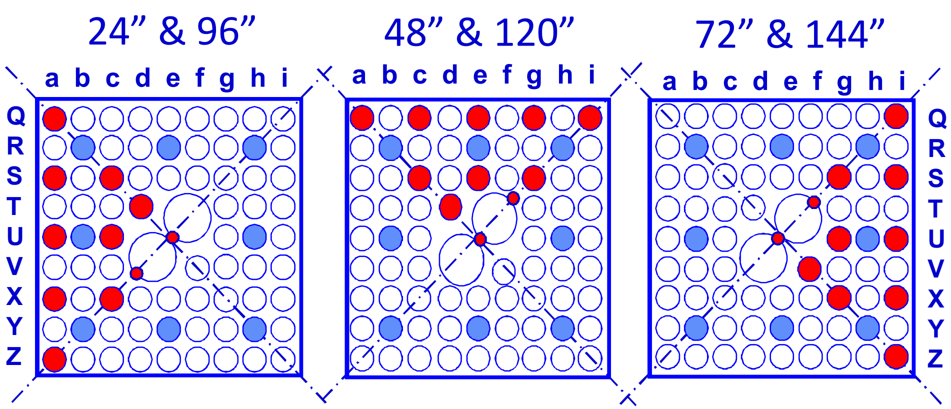
Internal Thermocouples

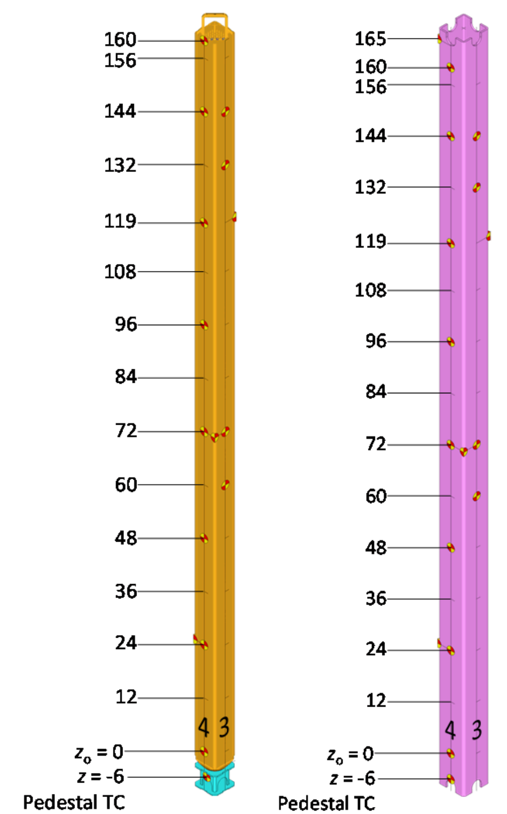
Radial Array
24” spacing
11 TC’s each level
66 TC’s total (details below)

Axial array A1
6” spacing
20 TCs

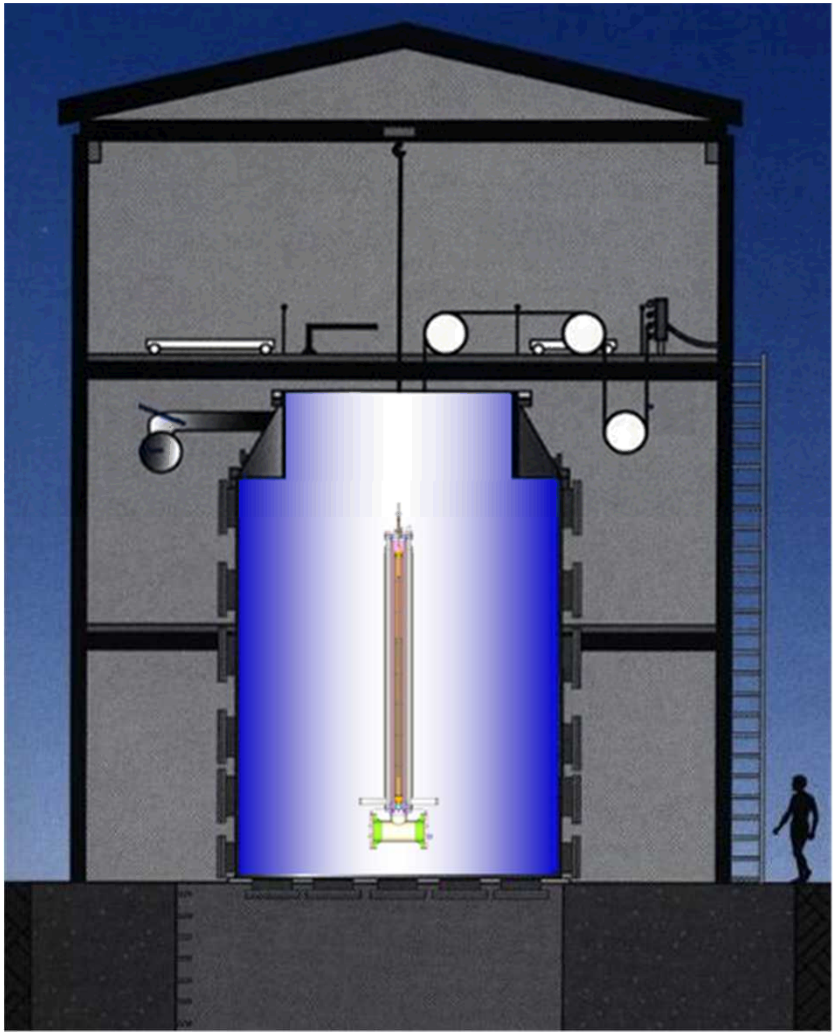
Axial array A2
12” spacing – 7 TC’s
Water rods inlet and exit – 4 TC’s
Total of 97 TCs

- 97 total TC’s internal to assembly
- 25 TC’s mounted to channel box
- 28 TC’s mounted to basket



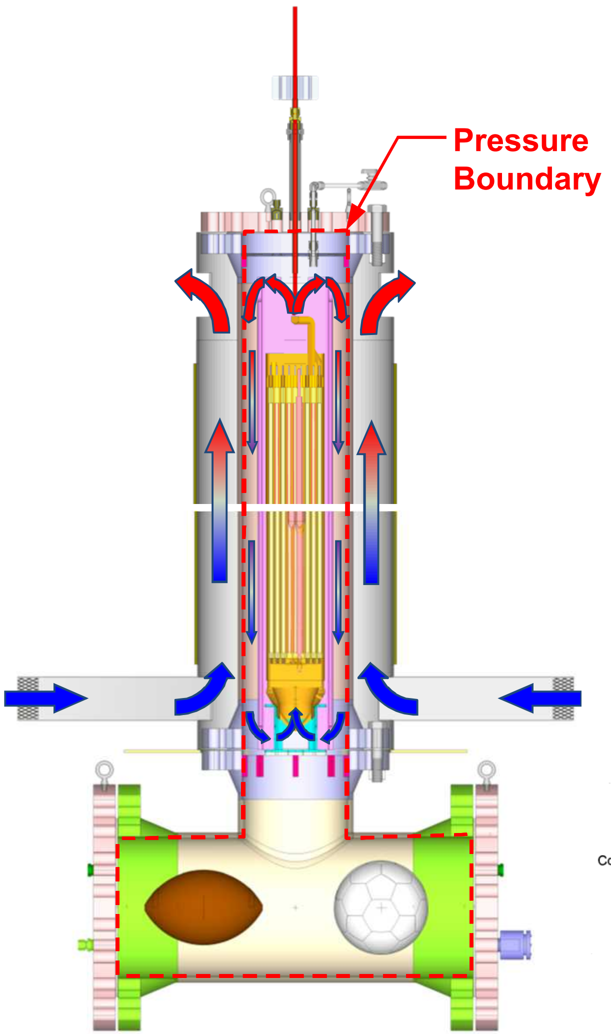


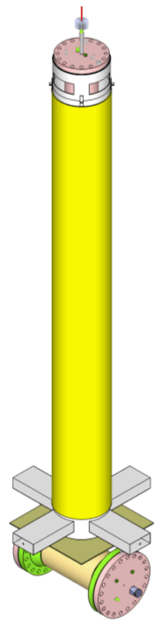
CYBL Test Facility

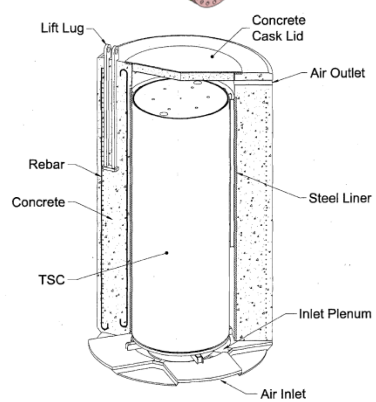


- Large stainless steel containment
  - Repurposed from earlier CYLINDRICAL BOILING Testing sponsored by DOE
  - Excellent general-use engineered barrier for isolation of high-energy tests
    - 3/8 in. stainless steel
    - 17 ft diam. by 28 ft cylindrical workspace
- Part of the Nuclear Energy Work Complex (NEWC)

Aboveground Configuration

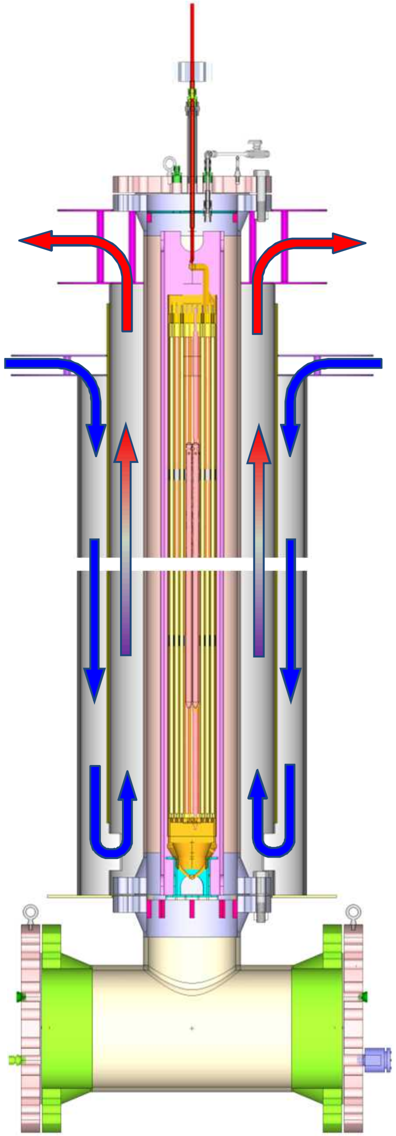


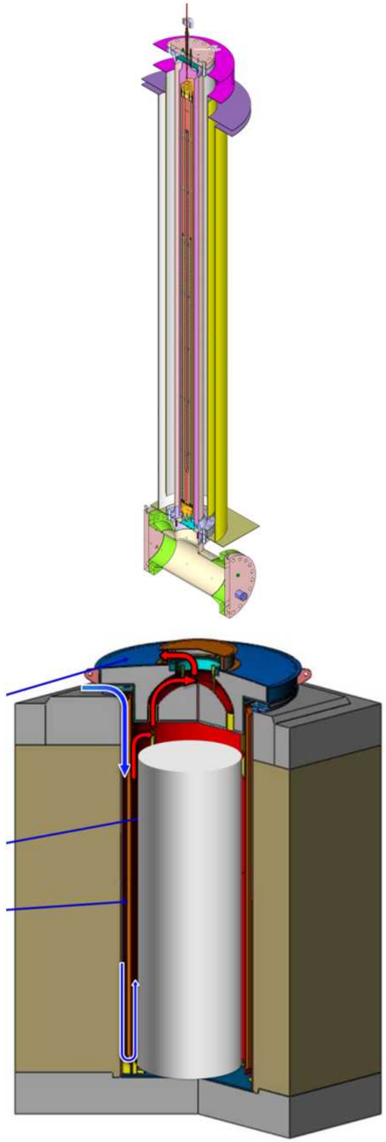




- BWR Cask Simulator (BCS) system capabilities
  - Power: 0 – 2.5 kW (anticipated)
  - Pressure vessel
    - Vessel temperatures up to 400 °C
    - Pressures up to 24 bar
    - ~200 thermocouples throughout system (internal and external)
  - Air velocity measurements at inlets
    - Calculate external mass flow rate
    - Estimate external convection coefficient

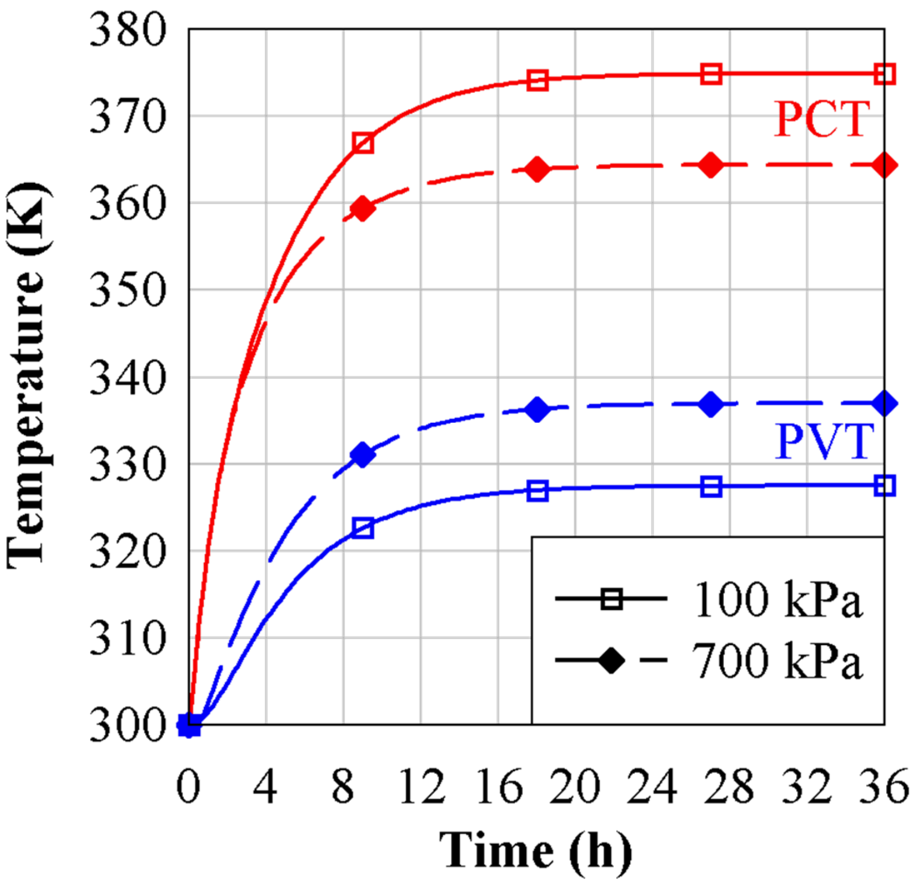
Belowground Configuration





- Modification to aboveground ventilation configuration
  - Additional annular flow path
- Final design complete
  - Inlet and outlet based on prototypic configuration
  - Reviewed by NRC staff
- Scaling analysis completed
  - Favorable comparisons
    - Modified, channel Rayleigh number (Ra_S^*)
    - Reynolds (Re) number

CFD Transient



- Aboveground configuration at 500 W
  - Axisymmetric with fuel represented as porous media
  - Internal laminar flow
  - External Low-Re k-ε
- Peak cladding temp. (PCT) and peak vessel temp. (PVT)
  - 100 and 700 kPa
- Increased helium pressure ⇒ increased internal convection
  - Decreased internal thermal gradient

CFD Summary

Aboveground

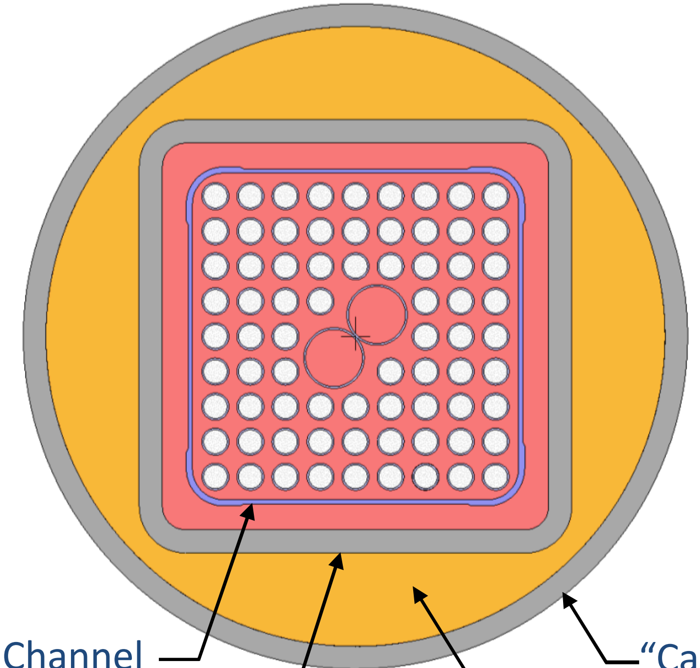
Parameter	DCS Low Power	DCS High Power	Cask
Power (W)	500	5,000	36,900
$\dot{m}_{Air}$ (kg/s)	0.039	0.083	0.350
$\dot{m}_{He}$ (kg/s)	1.3E-3	1.8E-3	2.1E-2
PCT (K)	364	647	663
PVT (K)	337	495	531
$T_{Air,\ out}$ (K)	306	332	371

Belowground

Parameter	DCS Low Power	DCS High Power	Cask
Power (W)	500	5,000	36,900
$\dot{m}_{Air}$ (kg/s)	0.038	0.083	0.452
$\dot{m}_{He}$ (kg/s)	1.3E-3	1.7E-3	2.2E-2
PCT (K)	365	653	646
PVT (K)	333	475	518
$T_{Air,\ out}$ (K)	309	349	350

- All results for 700 kPa
- PCT, PVT, and $T_{Air,\ out}$ compare best with Cask at DCS power of 5,000 W
- Dimensional analysis shows similarity for relevant dimensionless groups

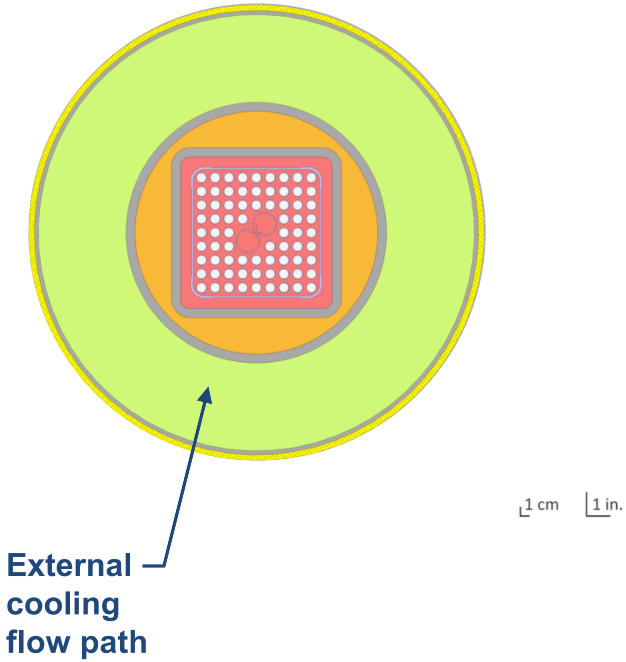
Internal Dimensional Analyses



- 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	500	5,000	36,900
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	500	5,000	36,900
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

Summary

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- Dry cask simulator capable of wide range of helium fill pressures and decay heats in final construction
  - Mimic aboveground and belowground configurations
  - Provide validation-quality data for CFD modeling
- Pre-test predictions show favorable scaling with prototypic cask designs
  - PCT, PVT, and exit air temps. closely reproduced
  - Suitable matching of dimensionless groups demonstrated