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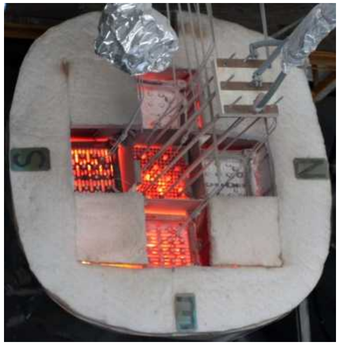

Dry Cask Simulator for a Boiling Water Reactor Fuel Assembly

Sam Durbin, Eric Lindgren, and Ken Sorenson

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

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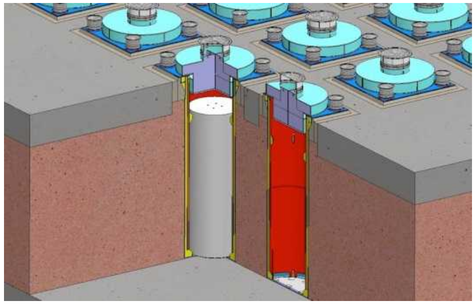
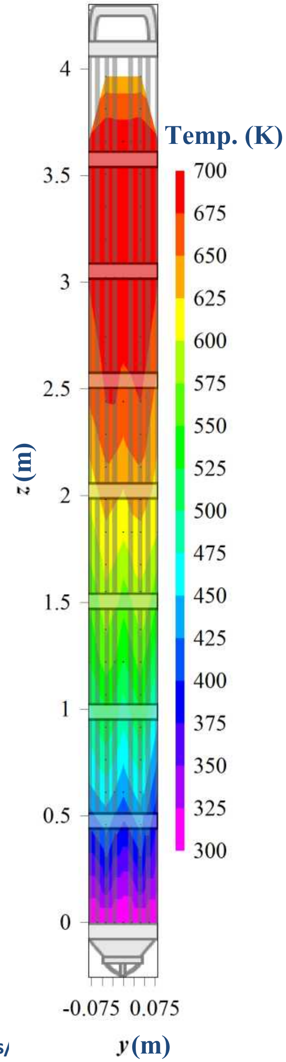
Aboveground Storage

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 belowground 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 Cask Simulator (BCS)
- 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)
    - Possible to examine krypton settling issues

Past Validation Efforts

Unconsolidated Fuel

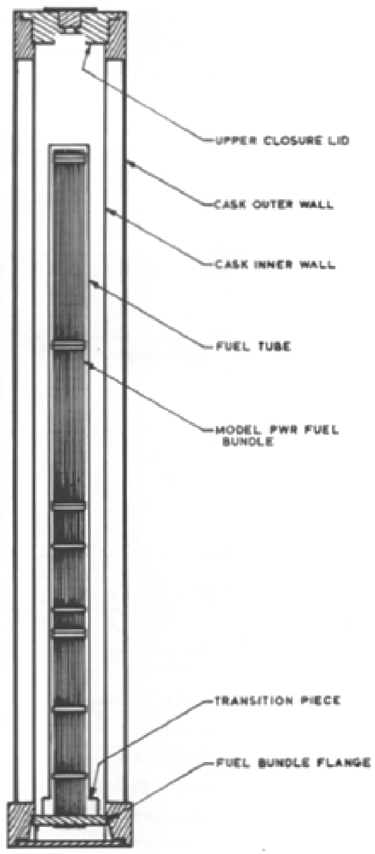
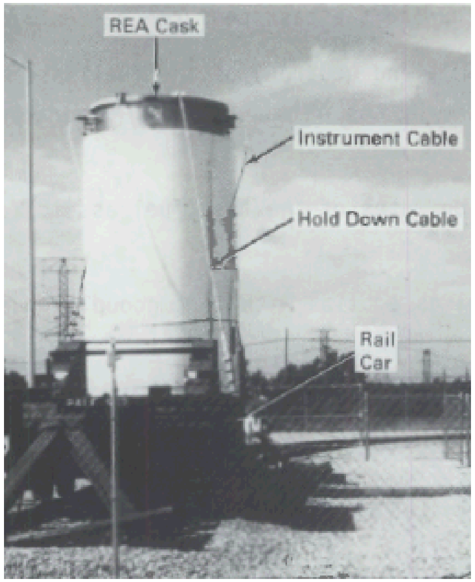
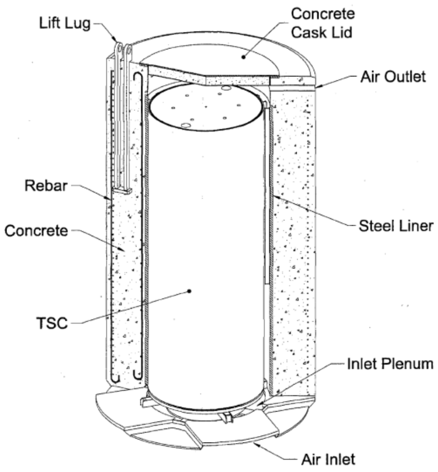


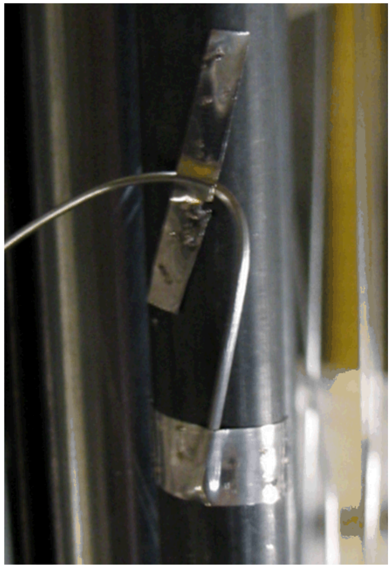
FIGURE 4-1. SAHTT Assembly

- Full scale, multi-assembly
  - Castor-V/21 [1986: EPRI NP-4887, PNL-5917]
  - REA 2023 [1986: PNL-5777 Vol. 1]
    - Both unventilated
    - Both unpressurized
- 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:
    - BC: Controlled outer wall temperature (unventilated)
    - Atmospheric (air & He) and vacuum
- <u>None</u> appropriate for elevated helium pressures or ventilated configurations



Current Approach

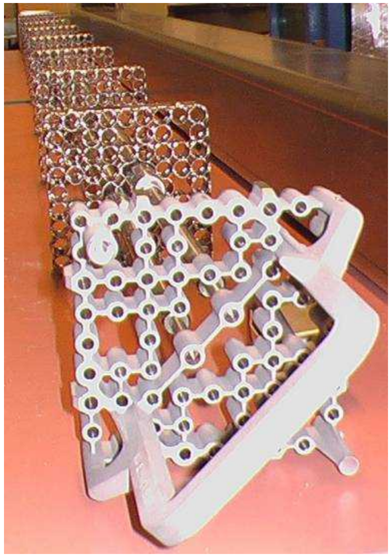


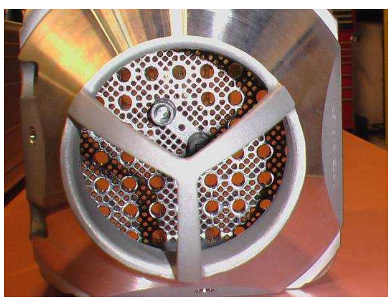


- Focus on pressurized canister systems
  - BCS capable of 24 bar internal pressure @ 400 °C
    - Current commercial designs up to ~8 bar
- Ventilated designs
  - Aboveground configuration
  - Belowground configuration
    - With crosswind conditions
- Thermocouple (TC) attachment allows better peak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

Prototypic Hardware

Upper tie plate



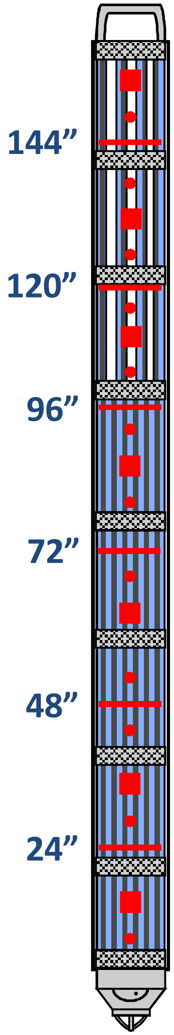


Nose piece and debris catcher

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

Thermocouple Layout



Internal Thermocouples

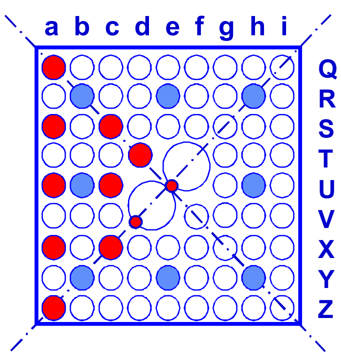
Radial Array
24” spacing
11 TC’s each level
66 TC’s total (details below)

Axial array A1
6” spacing
20 TCs

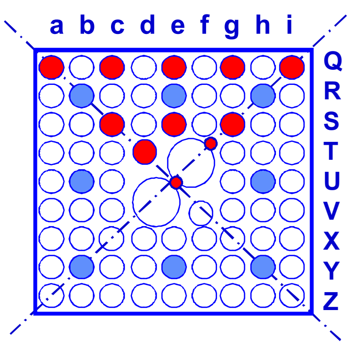
Axial array A2
12” spacing – 7 TC’s
Water rods inlet and exit – 4 TC’s
Total of 97 TCs

- 97 total TC’s internal to assembly
- 10 TC’s mounted to channel box
  - 7 External wall
    - 24 in. spacing starting at 24 in. level
  - 3 Internal wall
    - 96, 120, and 144 in. levels

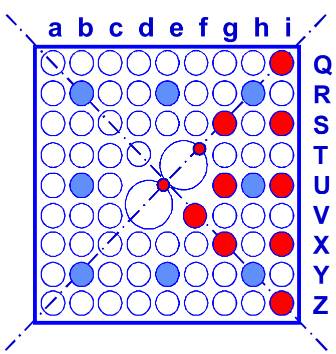
24” & 96” levels



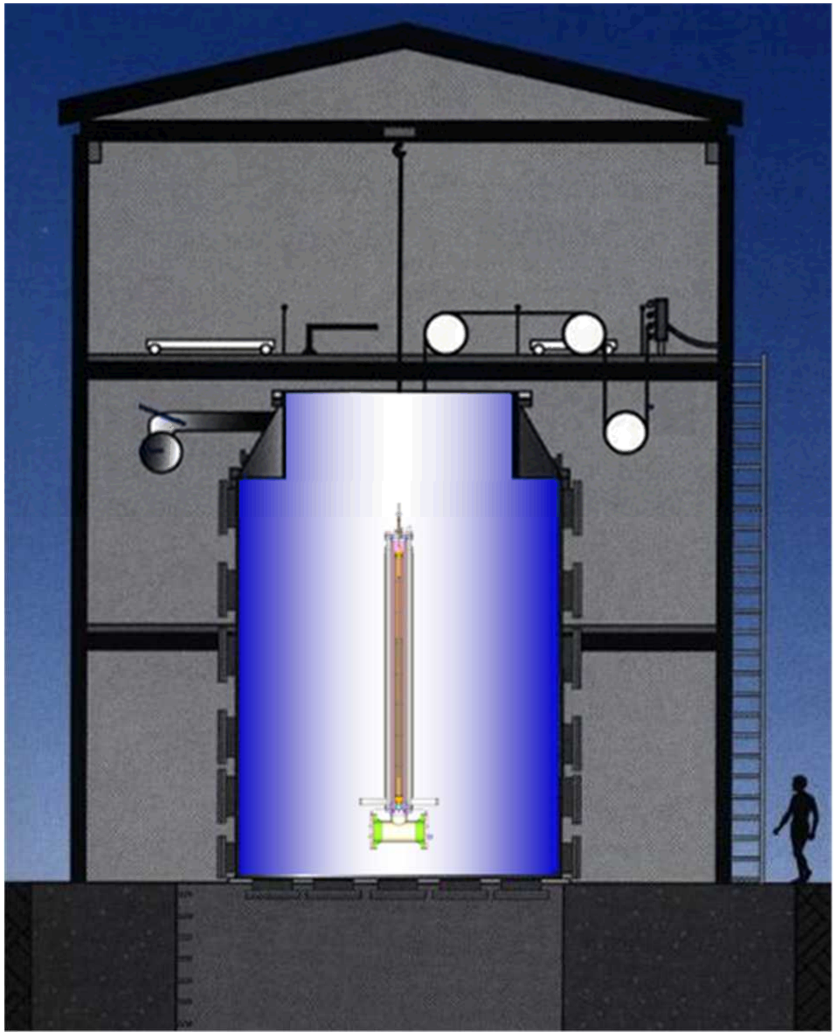
48” & 120” levels



72” & 144” levels

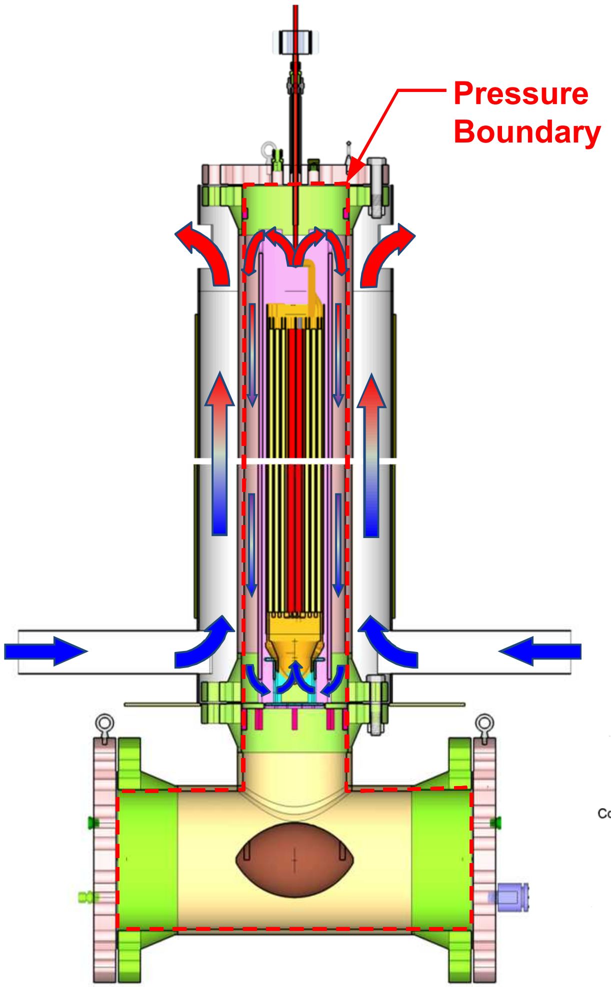


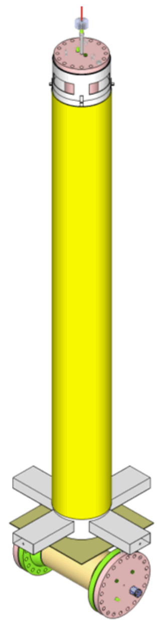
CYBL Test Facility

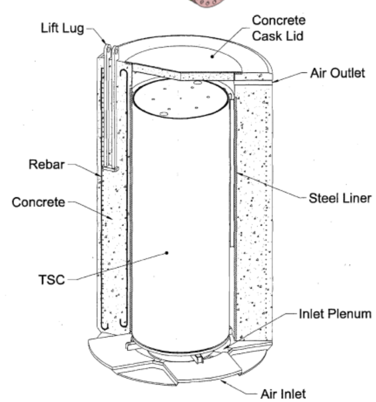


- Large stainless steel containment
  - Repurposed from earlier CYLINDRICAL BOILING Testing sponsored by DOE
  - Excellent general-use engineered barrier for isolation of high-energy tests
    - 3/8 in. stainless steel
    - 17 ft diam. by 28 ft cylindrical workspace
- Part of the Nuclear Energy Work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

Aboveground Configuration

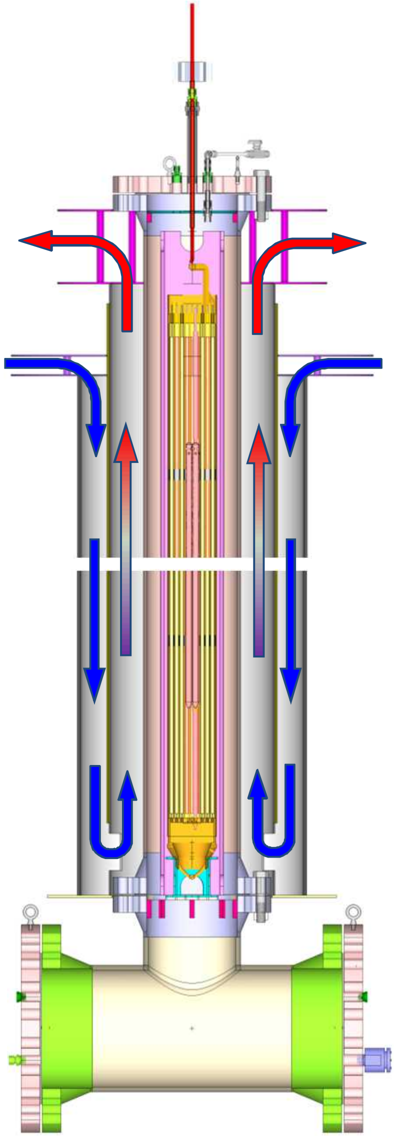


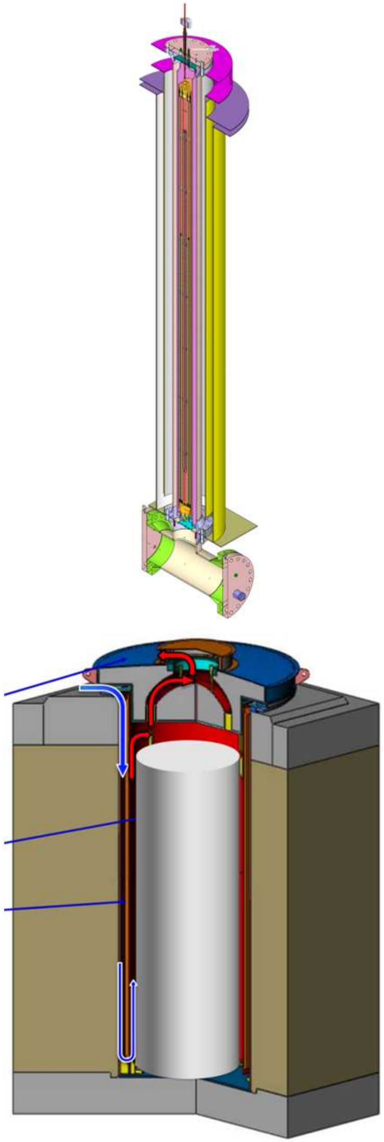




- BWR Cask Simulator (BCS) system capabilities
  - Power: 0 – 2.5 kW (anticipated)
  - Pressure vessel
    - Vessel temperatures up to 400 °C
    - Pressures up to 24 bar
    - ~200 thermocouples throughout system
  - Air velocity measurements at inlets
    - Calculate external mass flow rate
    - Estimate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

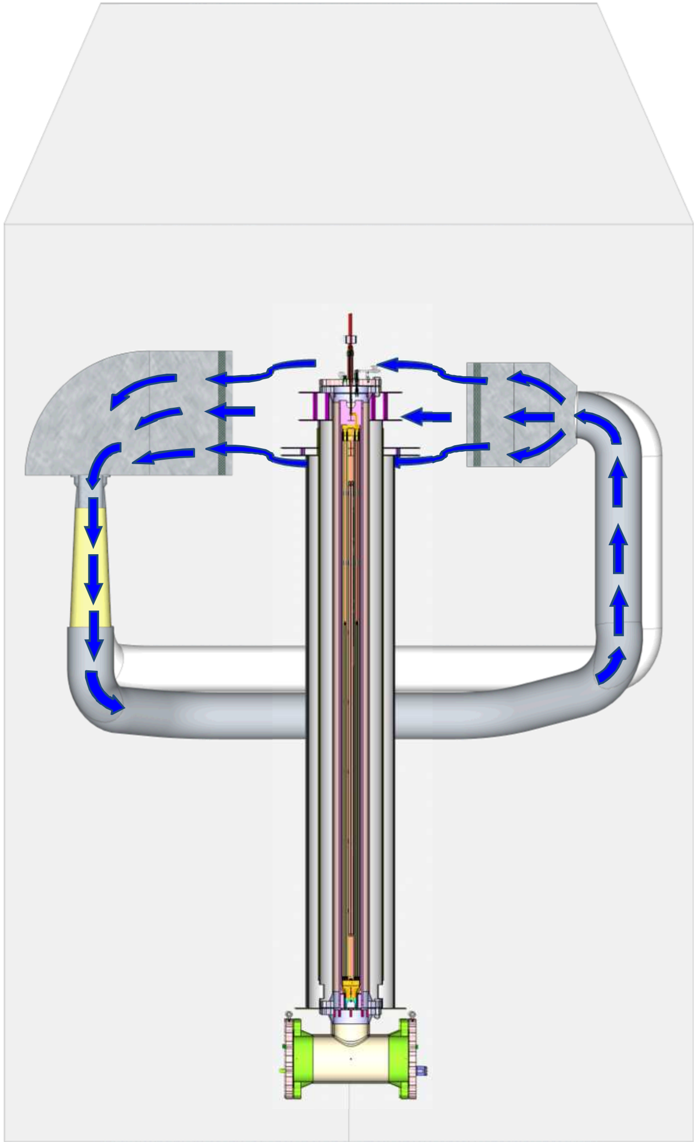
Belowground Configuration





- 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

Crosswind Conditions



- Crosswind conditions imposed on belowground configuration
  - Speeds of 0 to 12 mph
- Air forced across inlet and outlet ducts
  - Push/Pull system currently considered for use in CYBL
    - Vessel size limitations / Minimization of vorticity
- CFD modeling indicates reduction in cooling air flow rate at sustained crosswinds of 5 mph
  - NUREG -2174

Commercial Equipment

High-Density TC Feedthroughs

Electrode Feedthroughs

Air Velocity Transducers

- Commercial off-the-shelf solutions when possible
  - Thermocouple feedthroughs
  - Electrode feedthroughs
  - Air velocity transducers
- Decreased cost and construction time

BCS Pressure Vessel Hardware

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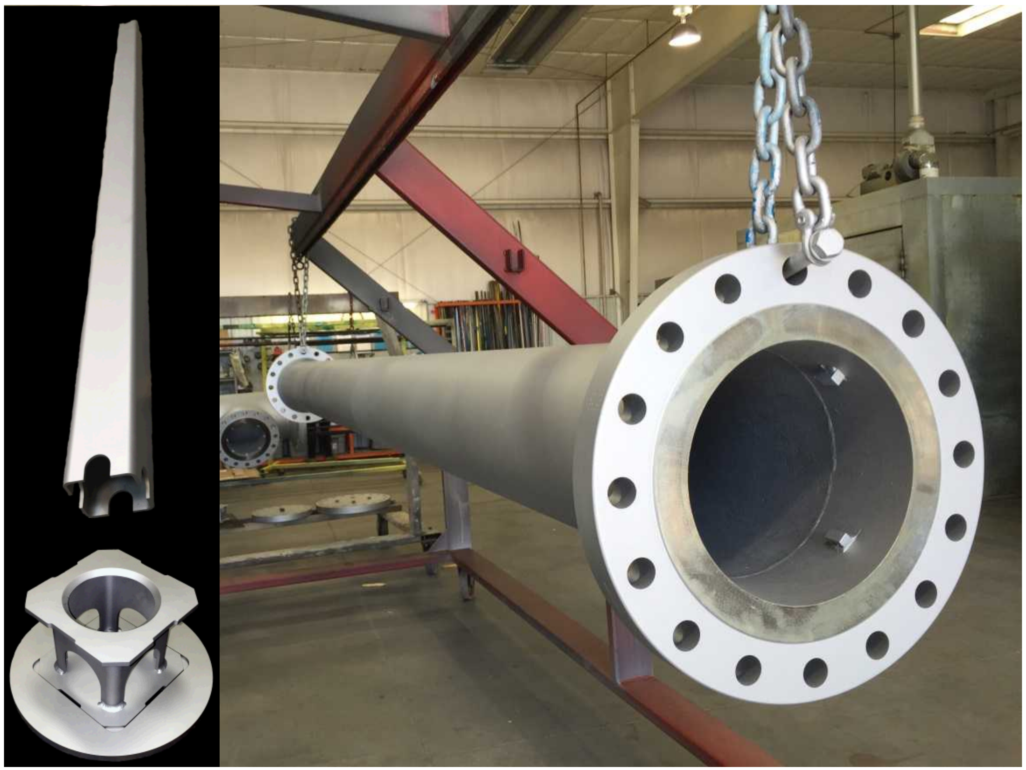
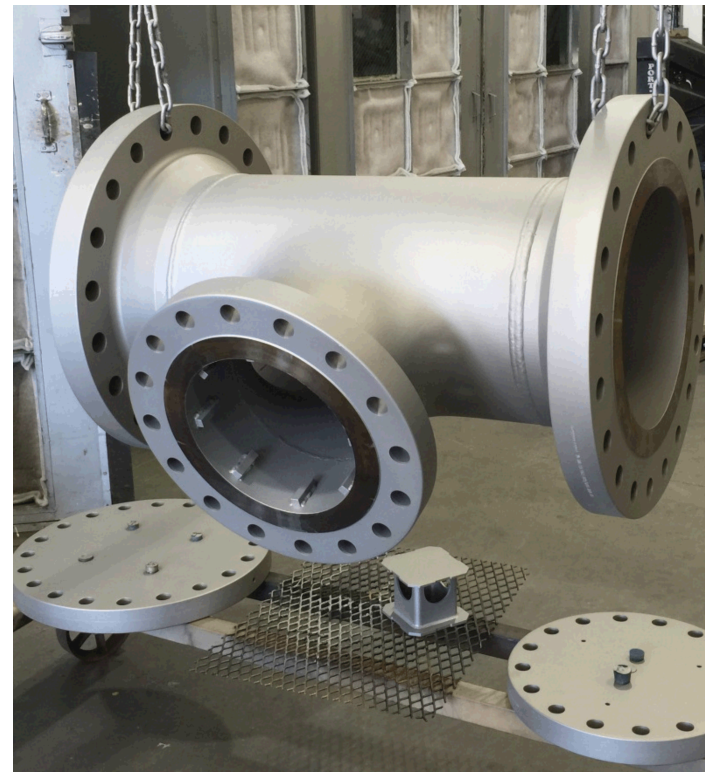
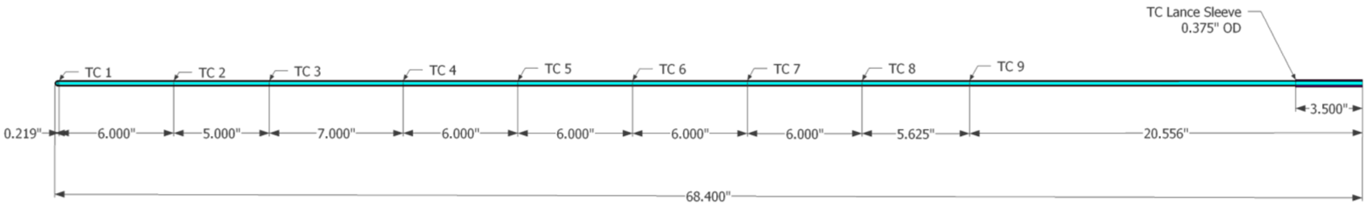
- Fabricated and pressure tested
- Coated with ultra high temperature paint

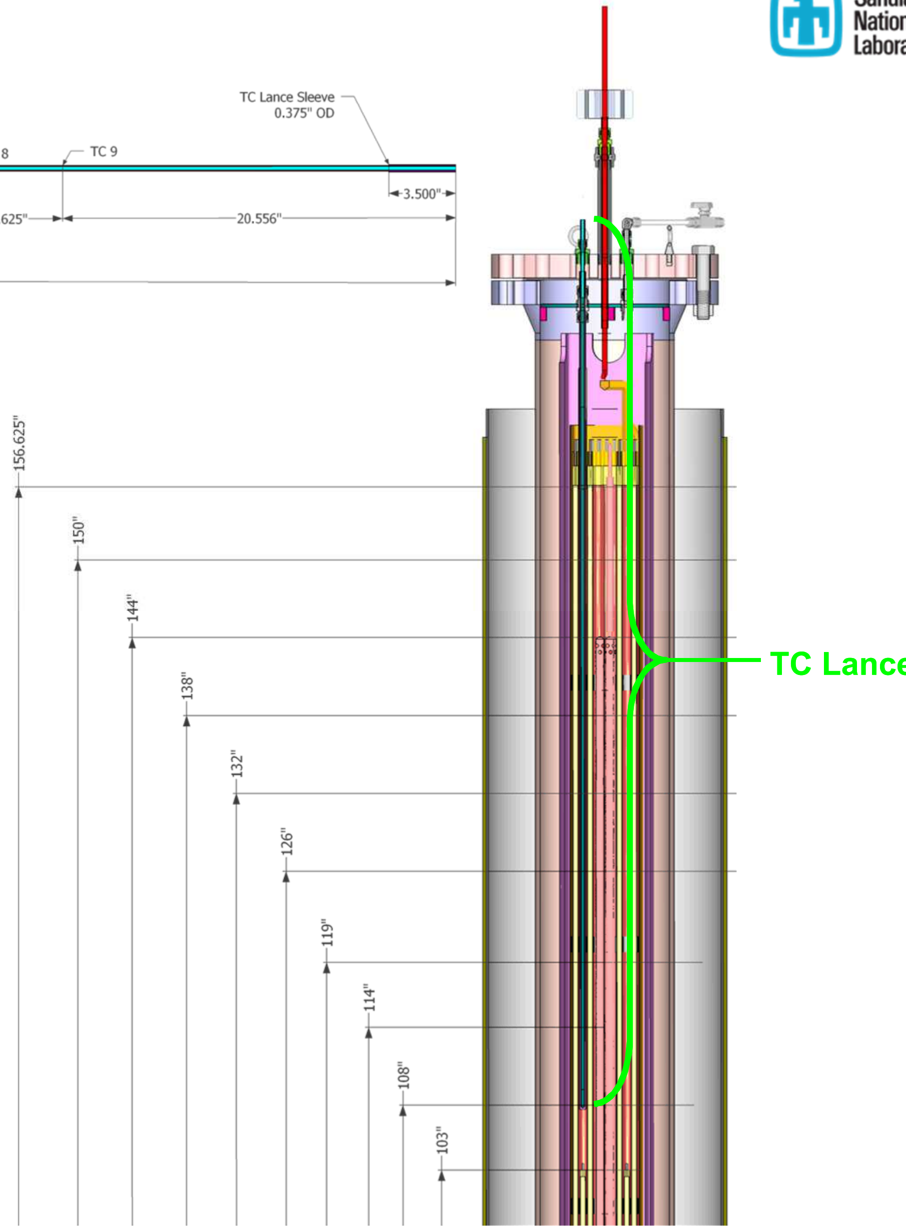




Custom TC Lance



- Compliments the TC lance in the Cask Demo Project
  - Same fabricator (AREVA)
    - Same materials and fabrication process
- TC elevations match BWR assembly TCs
  - Provides direct comparison between lance TCs and clad TCs



Gantt Chart

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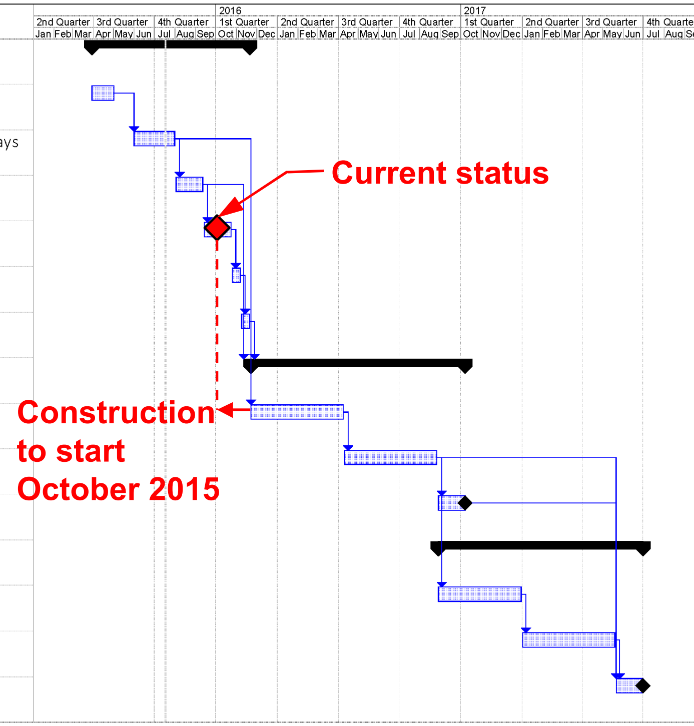
- 27 month total project duration
  - Aboveground configuration testing starts April 2016
  - Belowground configuration testing starts January 2017

ID	Task Name	Duration	Start	Finish	Predecessors
1	**Project Setup Activities**	**170 days**	**Mon 3/30/15**	**Fri 11/20/15**	
2	Design Pressure Vessel	25 days	Mon 3/30/15	Fri 5/1/15	
3	Fabricate Pressure Vessel	45 days	Mon 6/1/15	Fri 7/31/15	2FS+20 days
4	ES&H	30 days	Mon 8/3/15	Fri 9/11/15	3
5	Draft Test Plan	30 days	Mon 9/14/15	Fri 10/23/15	4
6	COR Test Plan Review	10 days	Mon 10/26/15	Fri 11/6/15	5
7	Final Test Plan	10 days	Mon 11/9/15	Fri 11/20/15	6
8	**Aboveground Test Configuration**	**230 days**	**Mon 11/23/15**	**Fri 10/7/16**	**4,7**
9	Fabrication and Setup	100 days	Mon 11/23/15	Fri 4/8/16	3
10	Testing and Analysis	100 days	Mon 4/11/16	Fri 8/26/16	9
11	Preliminary Report	30 days	Mon 8/29/16	Fri 10/7/16	10
12	**Belowground Test Configuration**	**220 days**	**Mon 8/29/16**	**Fri 6/30/17**	
13	Fabrication and Setup	90 days	Mon 8/29/16	Fri 12/30/16	10
14	Testing and Analysis	100 days	Mon 1/2/17	Fri 5/19/17	13
15	Final Report	30 days	Mon 5/22/17	Fri 6/30/17	14,11,10



Project: BWR_Cask_Simulator_Sched
Date: Fri 7/17/15

Task | Milestone | Rolled Up Task | Rolled Up Progress | External Tasks | Group By Summary
Progress | Summary | Rolled Up Milestone | Split | Project Summary | Deadline

Page 1

BCS Status

- Project is on schedule and budget
  - Initial safety analysis conducted May
- Pressure vessel hydrostatic test complete
  - Final pressure rating of 24 bar at 400 °C
- Overpack and inlet channel dimensions were optimized to match Ra_S^* and Re
- Refinements of design ongoing with NRC staff
  - Current configurations are final
  - Remaining tasks include finalization of instrumentation layout
- Update report completed SAND 2015-7846

BACKUP SLIDES

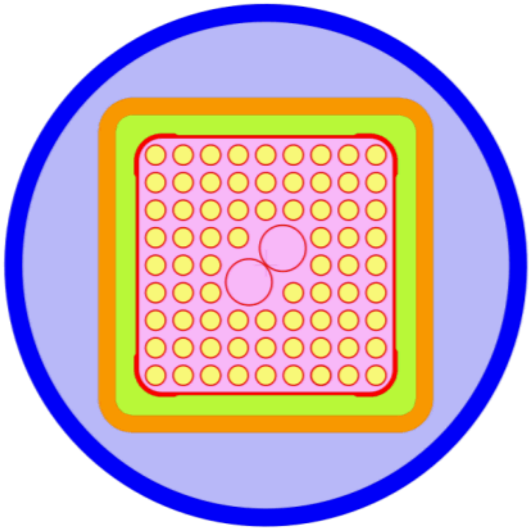
Test Matrix

		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						
	1000		2500		2500		2500
	1500						
	2500						

Step through powers

Step through wind speeds

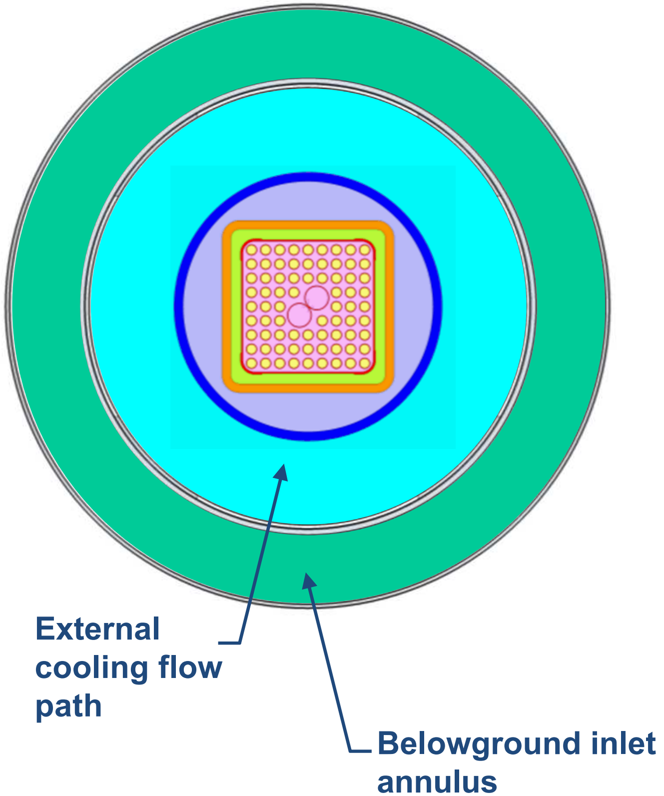
Internal Dimensional Analyses



- Internal flow and convection prototypic
  - Near prototypic geometry for fuel and basket
- Downcomer and external cooling flows matched using elevated decay heat (5 kW)
  - Downcomer dimensionless groups

	BCS High Power	NAC TSC-87	Holtec 100U
Re_{Down}	290	220	220
Ra_H^*	4.7E+11	4.7E+11	5.6E+11
Nu_H	220	210	220

External Dimensional Analyses

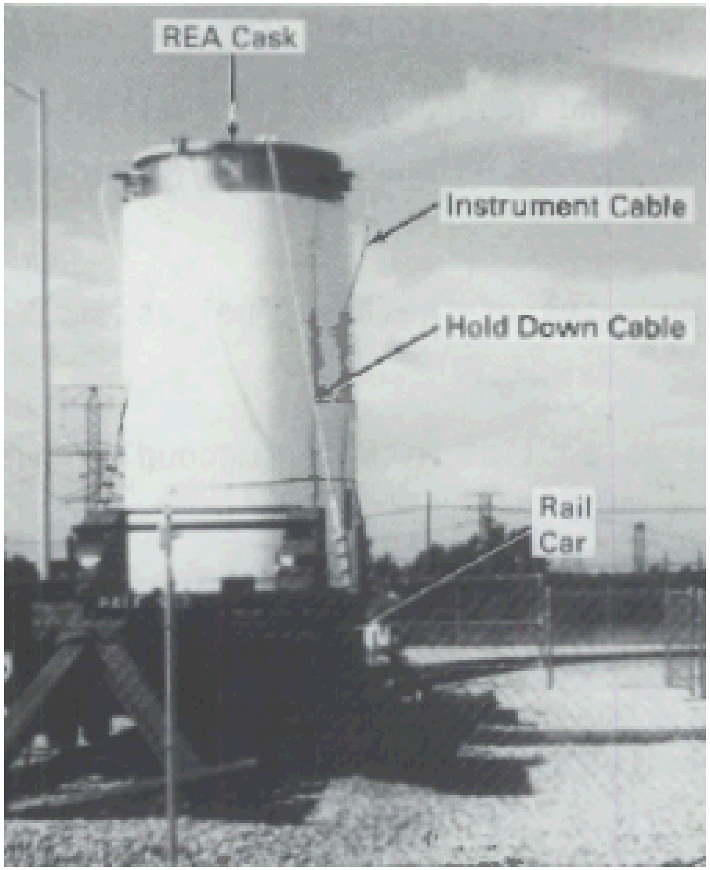


- External cooling flows matched using elevated decay heat (5 kW)
  - External dimensionless groups

	BCS High Power	NAC TSC-87	Holtec 100U
External Cooling			
Re_{Ex}	11200	7300	7700
Ra_{DH}^{*}	4.7E+09	3.0E+09	2.0E+09
$(D_{H, Cooling} / H_{PV}) \times Ra_{DH}^{*}$	1.9E+08	1.2E+08	6.9E+07
Nu_{DH}	29	26	23
Aboveground Inlet Duct			
$Re_{Above, Inlet}$	10700	11200	--
Belowground Inlet Annulus			
$Re_{Below, Inlet}$	8300	--	8600

Past Validation Efforts

Full Scale with Unconsolidated Fuel



- Full scale, multi-assembly
  - Castor-V/21 cast iron/graphite with polyethylene rod shielding
    - 1986: EPRI NP-4887, PNL-5917
    - 21 PWRs
    - 95 Thermocouples (TC's) total
      - 60 TC's on 10 lances deployed in 8 guide tubes and 2 basket void spaces
      - 35 TC's on outer surface of cask
    - 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
      - 38 TC's at 8 axial levels in the basket and 7 assemblies
      - 32 TC's on outer cask surface
    - Unventilated
    - Sub-atmospheric (air & He) and vacuum

Past Validation Efforts (cont.)

Unconsolidated Fuel

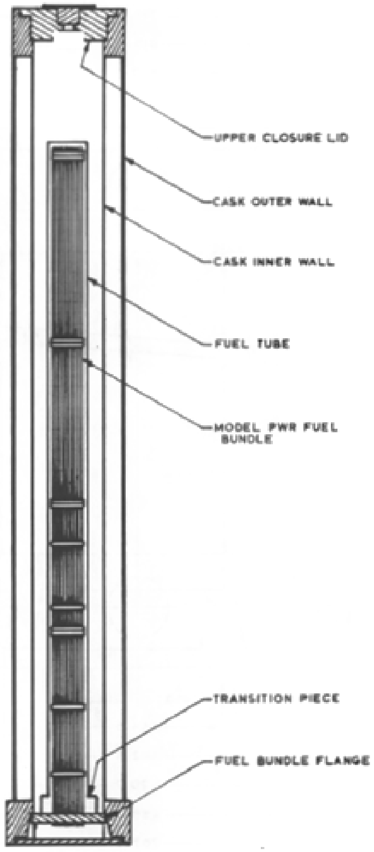


FIGURE 4-1. SAHTT Assembly

- 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