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

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Nuclear Waste Technical Review Board
Albuquerque, NM
October 24, 2018
Overview

- **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

- **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

- **None** 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

- 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

Upper tie plate

Nose piece and debris catcher

BWR channel, water tubes and spacers
Thermocouple Layout

- 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

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

- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DCS Low Power</th>
<th>DCS High Power</th>
<th>Cask</th>
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<tr>
<td>Power (kW)</td>
<td>0.5</td>
<td>5.0</td>
<td>36.9</td>
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<tr>
<td>Re_{Down}</td>
<td>170</td>
<td>190</td>
<td>250</td>
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<tr>
<td>Ra_{H}</td>
<td>3.1E+11</td>
<td>5.9E+11</td>
<td>4.6E+11</td>
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<tr>
<td>Nu_{H}</td>
<td>200</td>
<td>230</td>
<td>200</td>
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External Dimensional Analyses

• External cooling flows evaluated against prototypic
  – External dimensionless groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aboveground</th>
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<tbody>
<tr>
<td></td>
<td>DCS Low Power</td>
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<tr>
<td>Power (kW)</td>
<td>0.5</td>
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<tr>
<td>Re_{Ex}</td>
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<td>Ra_{DH}^{*}</td>
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<tr>
<td>(D_{H, Cooling}/H_{PV}) × Ra_{DH}^{*}</td>
<td>1.1E+07</td>
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<tr>
<td>Nu_{DH}</td>
<td>16</td>
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</table>
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
    - \( U_{\text{PCT, max}} = 7 \text{ K} \)
  - 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 \( U_{\dot{m}} = 1.5E-3 \text{ kg/s} \)
  - 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 $\dot{m}$
Graphical Steady State Comparisons
Belowground Configuration

- PCT average difference of 6 K across all conditions
  - 95% exp. uncertainty of $U_{PCT, \text{max}} = 7$ K
  - Max. observed difference = 16 K
    - (5 kW and 100 kPa)
- Air flow rate lower for experiment
  - 95% exp. uncertainty of $U_{\text{m}} = 7 \times 10^{-4}$ kg/s
  - Max. observed difference = 5E-3 kg/s
    - (5 kW and 450 bar)

Non-uniformities at flow straightener seams
Cross Wind Testing

- 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)

CFD simulations
by A. Zigh (USNRC)
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**
  - 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

- **Phase II: HBU Demonstration Cask**
  - Multiple activities as outlined previously

- **Phase III: Ongoing and Future Thermal-Hydraulic Studies**
  - Horizontal Dry Cask Simulator
  - Advanced simulators
  - Potential collaboration with South Korea under the High Level Bilateral Commission studies

Previous SNL slides

Ongoing Work

Previous PNNL Presentation

These slides
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