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Modeling Used Fuel Storage Temperatures

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Thermal Model Development and Evaluation in Support of UFD Campaign

- **Why is it of concern to the campaign?**
  - Gap Analysis identified thermal profiles as a High Priority, NRC gap analysis in agreement
  - Ranked #1 in Gap Prioritization because almost all degradation mechanisms are dependent on temperature
- **Realistic, not overly conservative, temperature profiles are needed**
  - Industry typically uses conservative models (limited conduction and convection, and simplifying assumptions) to assure that peak cladding temperature is within technical specifications
- **Over estimated temperatures will (to name a few):**
  - Over predict amount of hydride reorientation and radiation damage annealing
  - Under predict the onset of potential deliquescence on the canister surface

Thermal Model Development and Evaluation in Support of UFD Campaign

- **Need accurate past, present, and future temperatures for clad and system components**
  - Especially critical for transportation, to know if we are at or below the ductile to brittle transition temperature during movement
  - Hottest fuel that could facilitate hydride reorientation will be the last to cool to the DBTT
  - Understanding temperature distribution throughout UF payload important to characterizing potential overall behavior characteristics

COBRA-SFS Development, Validation, and Application History

Code Development:

- **Early 1980's – DOE/OCRWM initiated a search for an analysis tool for accurate thermal prediction of spent fuel storage systems, to determine**
  - Peak fuel cladding temperature and assembly temperature distributions
  - Temperatures of system components related to safety (e.g., seals) to determine that they remained within design limits
- **Capability requirements were essentially "grand challenge" equivalent for CFD codes of the time, including**
  - Flow modeling within the fuel rod array
  - Steady-state natural convection cooling within the package and on the external boundary
  - Thermal radiation, which typically contributes over 20% of heat transfer within the package

COBRA-SFS Development, Validation, and Application History

- **COBRA-SFS and HYDRA-II selected from a survey of existing codes, as best available starting point for a multi-phase effort to**
  - Calibrate the codes for flow and heat transfer with inert gas (including thermal radiation) within rod arrays
  - Verify the implementation of the conservation equations (mass, energy, & momentum)
  - Validate against data from full-scale systems
- **Initial verification performed by comparison to single-assembly experiments, including**
  - Single PWR Spent Fuel Assembly tests at PNNL (PNL-5571, 1986)
  - Mitsubishi 15x15 PWR test assembly (Irino et al., 1986)
  - BNFL 16x16 PWR test assembly (Fry et al., 1983)
- **OCRWM Validation of COBRA-SFS at INL (cycle 3 of COBRA-SFS released)**

COBRA-SFS Development, Validation, and Application History

- **Validation consisted of performing "blind" pre-test predictions and post-test analysis of experiments at the Idaho National Laboratory's Test Area North (TAN) facility**
- **Over 78 "blind" test analyses were performed, including**
  - Transnuclear TN24P (EPRI NP-5128 and PNL-5777 (Vol. I)), loaded with 24 spent fuel assemblies
  - Pacific Sierra Nuclear Associates' Ventilated Concrete Cask (VCC) with Multi-Assembly Sealed Basket (MSB), loaded with 17 canisters containing consolidated spent fuel rods from 15x15 assemblies
  - Ridihalgh, Eggers, and Associates' REA 2023 storage cask for BWR spent fuel

COBRA-SFS Development, Validation, and Application History

COBRA-SFS Validation:

- **Summary of COBRA-SFS V&V Analyses**
  - Single assembly (electrically heated) tests
    - EMAD Single Assembly (15x15) tests – Unterzuber, 1981
    - SAHTT (15x15 PWR assembly tests at PNNL) – PNL-5571, 1986
    - Mitsubishi 15x15 PWR test assembly – Irino et al., 1986
    - BNFL 16x16 PWR test assembly – Fry et al., 1983
  - Multi-Assembly tests (with spent fuel)
    - CASTOR-V/21 (loaded with 21 PWR spent fuel assemblies from Surry) – EPRI NP-4887, 1980
    - REA 2023 cask (52 BWR spent fuel assemblies) – PNL-5777 (Vol. I), 1986
    - Transnuclear TN24P loaded with 24 spent fuel assemblies (from Turkey Point) – EPRI NP-5128, 1987 and EPRI NP-6191, 1987
    - Pacific Sierra Nuclear Associates Ventilated Concrete Cask (VCC) with Multi-assembly Sealed Basket (MSB), loaded with 17 canisters of consolidated rods from 15x15 assemblies – TR-100305 (EPRI), 1992.

COBRA-SFS Development, Validation, and Application History

- **Sample Results of COBRA-SFS V&V for Multi-Assembly Storage Cask (TN24P)**

Image from EPRI NP-5128, 1987

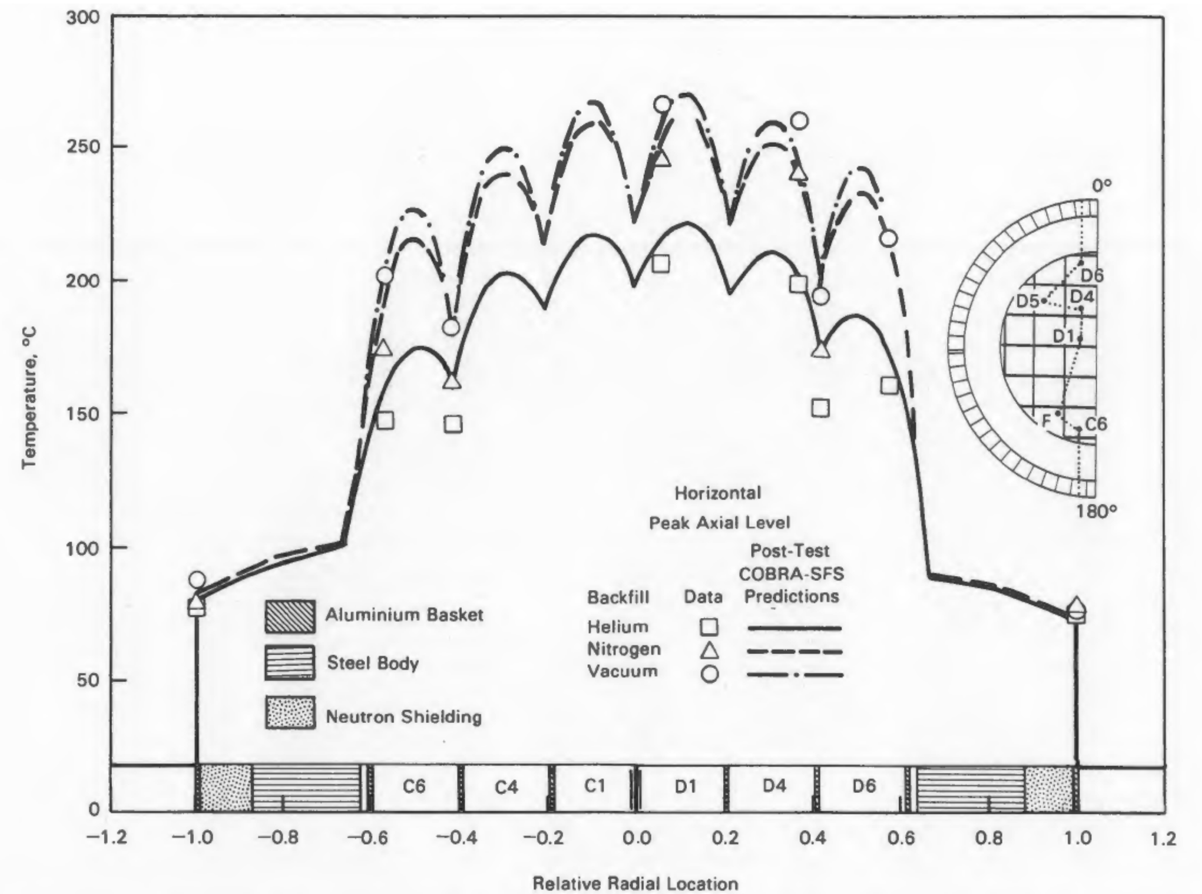


Figure 5-29. Post-Test Horizontal, Helium, Nitrogen, and Vacuum Radial Temperature Profile Predictions Compared to Test Data at Peak Temperature Axial Locations

COBRA-SFS Development, Validation, and Application History

- **Sample Results of COBRA-SFS V&V for Multi-Assembly Storage Cask (TN24P)**

Image from EPRI NP-5128, 1987

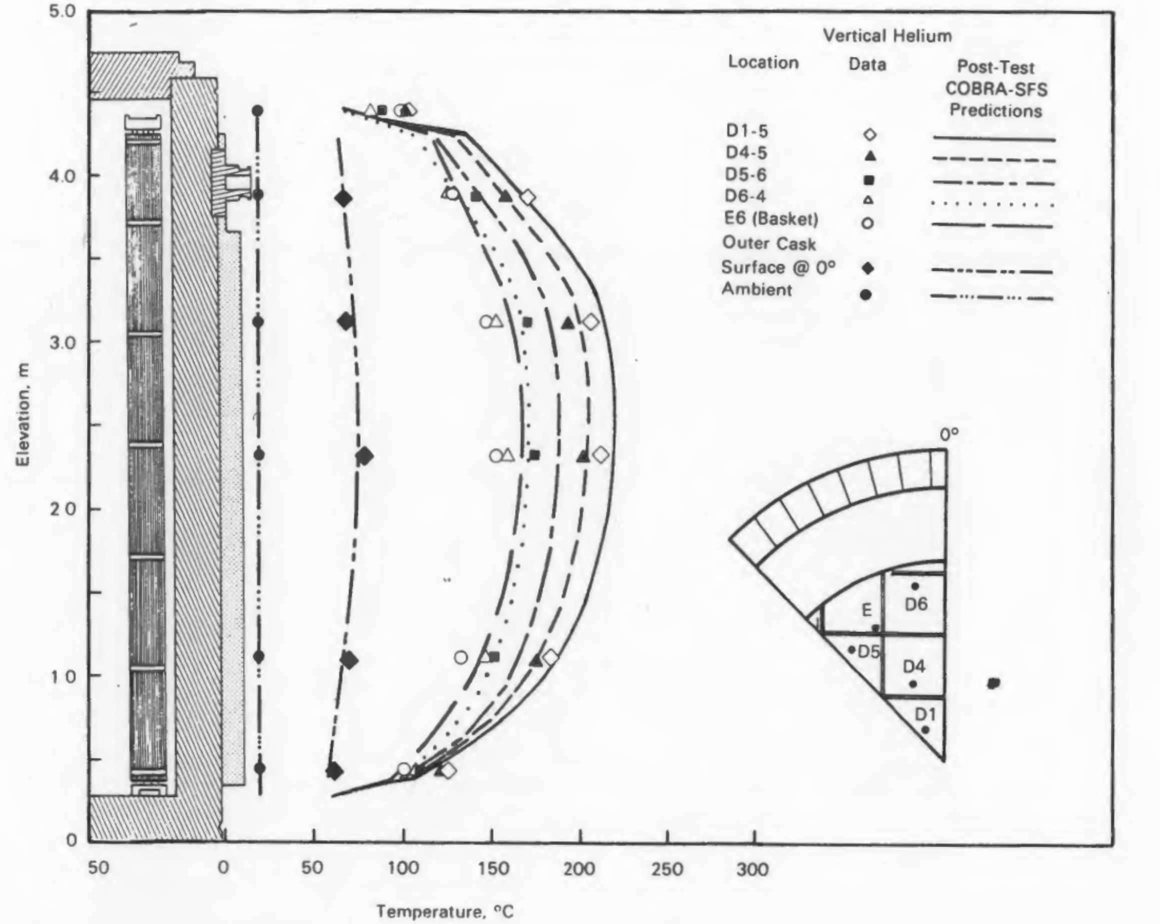


Figure 5-20. Post-Test Vertical, Helium Axial Temperature Profile Predictions Compared to Test Data

COBRA-SFS Development, Validation, and Application History

From Validation to Application:

- **DOE funded review by NRC of the COBRA-SFS code**
  - NRC subcontracted a team of national experts to review the code for use in predicting thermal performance of spent fuel storage/transportation systems
- **NRC establishes contract with PNNL to perform confirmatory analyses and review of applicant submittals (case work)**
- **PNNL applies many other analytical codes, methodologies, correlation developments, however, all are verified via direct comparison back COBRA-SFS validation work**
  - Application of codes such as FLUENT, STAR-CD, STAR-CCM+, ANSYS, etc.
  - Calibration of effective thermal conductivity (Keff) correlations for UF
  - Correlations for enhanced Keff via pressurization of He in UF payload region
- **Additional codes beyond COBRA-SFS necessary as:**
  - Existing general purpose commercial codes are already in use by trained users
  - COBRA-SFS requires seasoned operator and lacks pre- and post- GUI

COBRA-SFS Development, Validation, and Application History

Previous Applications:

- Duke power NUHOMS module relicensing support initiative
- EPRI funded dual purpose NAC cask performance evaluation
- Wire-wrap fuel feasibility evaluation for FFTF core
- Hanford Canister Storage Building
- Spent Fuel Pool analyses with postulated Zr fire
- Skull Valley Contention “H” rebuttal - model of field of Ventilated Vertical Concrete Storage Casks

COBRA-SFS Development, Validation, and Application History

Recent and Current Applications:

- **Numerous confirmatory analyses of Applicant's proposed Storage, Transfer, and Transport systems performed for NRC**
  - Normal and Hypothetical Accident Conditions
- **Extra regulatory fire evaluations**
  - Baltimore Tunnel Fire
  - Caldecott Tunnel Fire
  - MacArthur Maze Fire/Collapse
  - Newhall Pass Fire

Our Present UFD Campaign Goals and Objectives

- Need to validate predictive tools for high burnup fuel and newer, higher capacity Dry Cask Storage Systems
- NRC asking Industry for inspections to support license renewal
- DOE teaming with EPRI (including supplying funding for future inspections)
- Pre-test and post-test thermal predictions performed on Calvert Cliffs Nuclear Power Station

Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

Objectives:

- **Determine Storage System (Module, Canister, and Fuel Assembly) Component Temperatures**
- **Demonstrate "State of the Art" Evaluation Capability & Analytical Practices**
- **Perform Partial Verification (via comparison to measured canister temperature data to be gathered by Calvert Cliffs)**

Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

Calvert Cliffs Nuclear Power Station

Independent Spent Fuel Storage Installation (ISFSI)

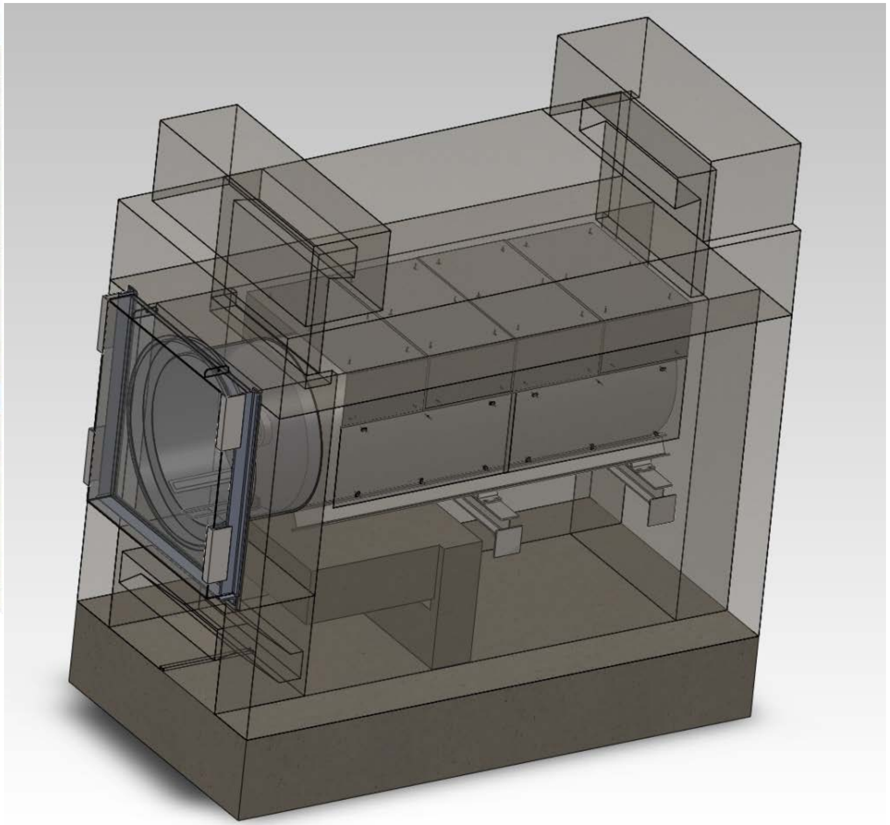
Ref. Google Maps

Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

Calvert Cliffs Site Specific NUHOMS Storage Module

SolidWorks® Model[2]

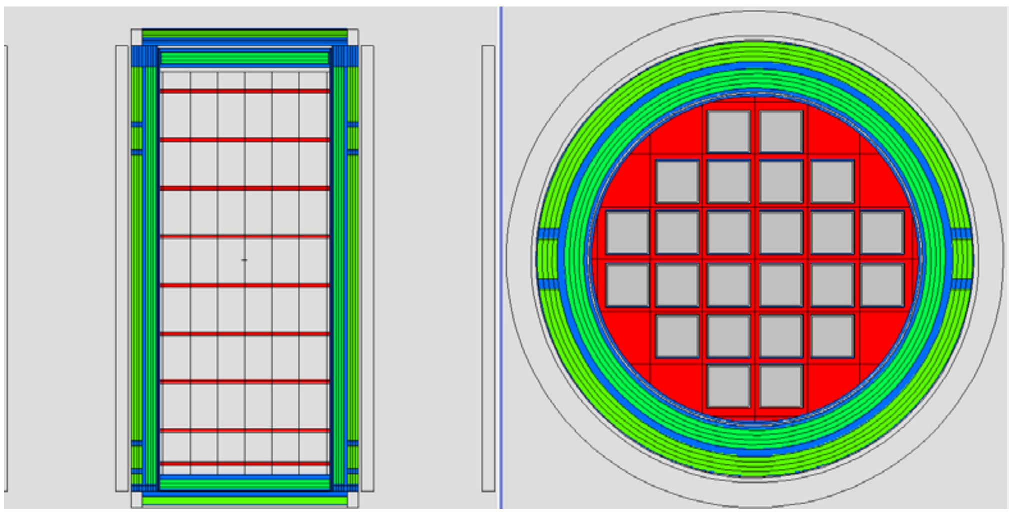
Module front vent and doorway[1]



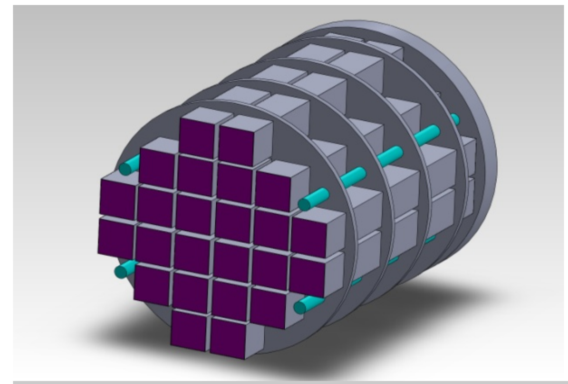
[1]Ref. 'Jones 2010.ppt', Calvert Cliffs Dry Fuel Storage and Industry Lessons Learned
[2]SolidWorks® model provided by EPRI

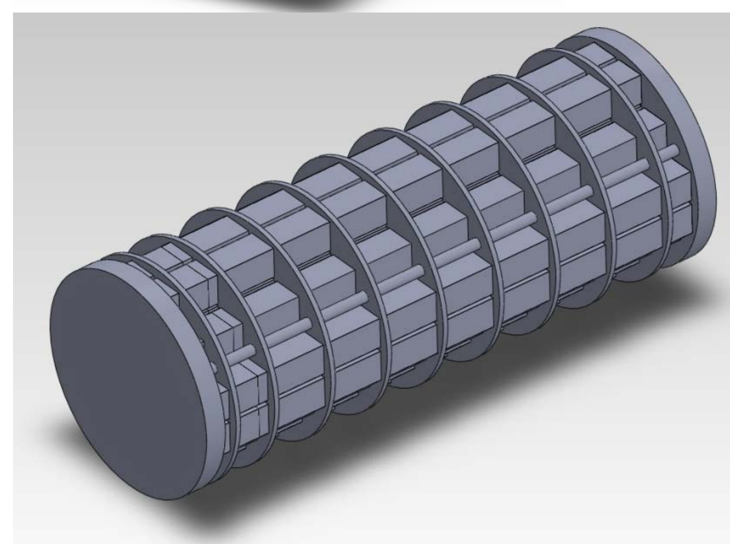
Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

DSC Details Extracted from MCNP Model and SolidWorks®



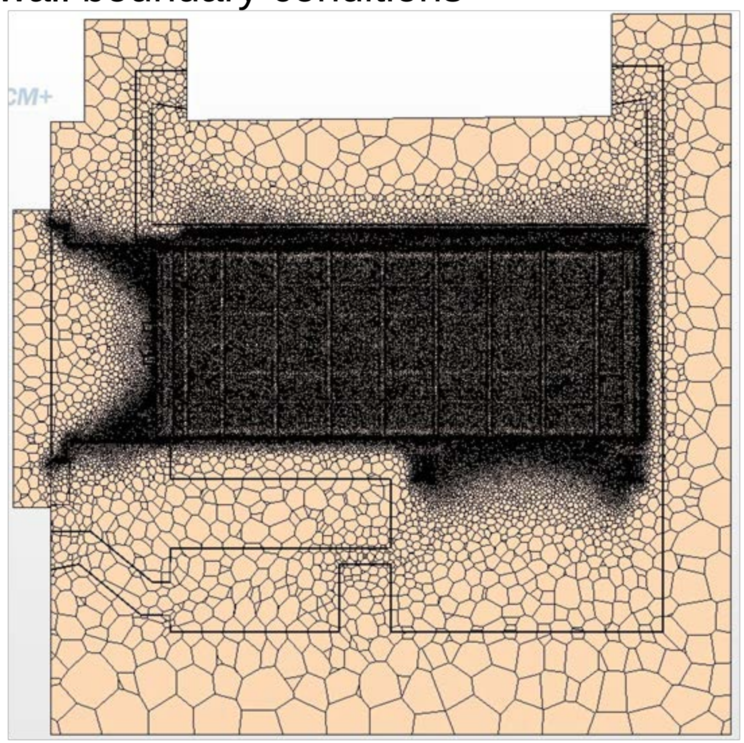
Ref. MCNP input model for DSC and transfer cask provided by John Massari, Calvert Cliffs



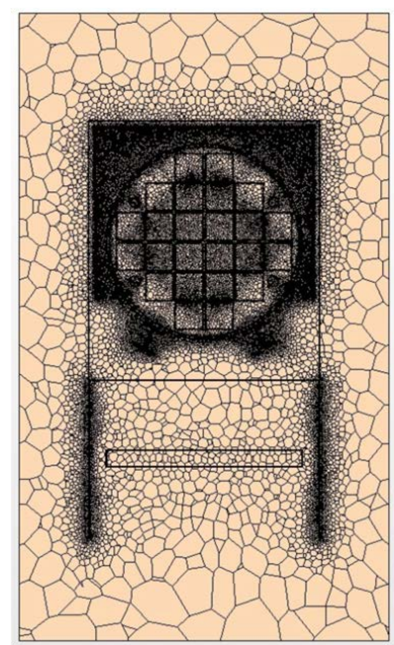


Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

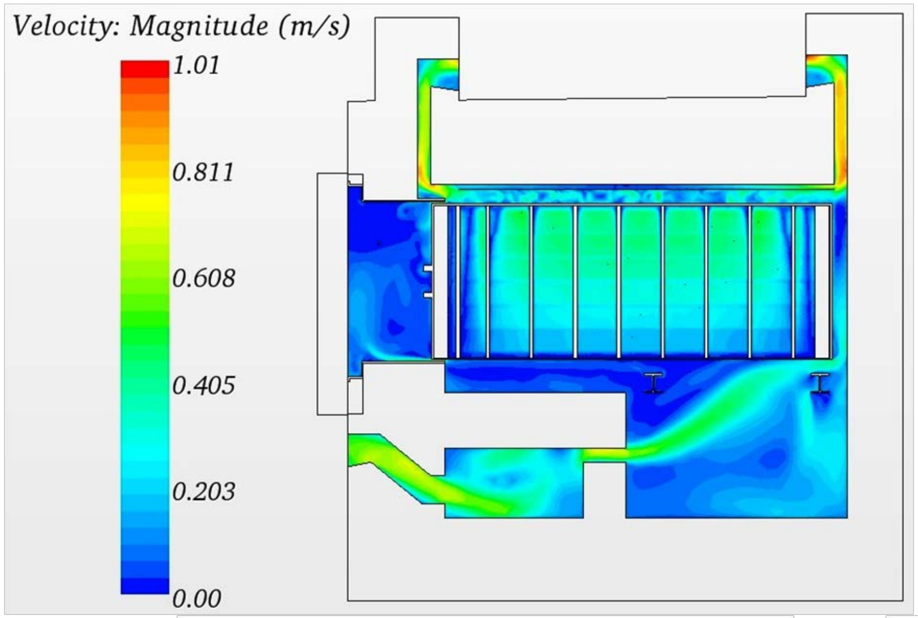
- **Solid Model Primitives Transformed into STAR-CCM+® CFD Model and solved for HSM1 & HSM15 Temperature Distributions**
  - 43 separate regions connected by 117 interface boundaries
  - SST (Menter) K-Omega Turbulence Model
  - Flexible (all-y+) treatment for wall boundary conditions
  - Default turbulent Prandtl #
  - Default parameters in general
  - 21,536,624 cells
  - 127,598,563 faces
  - 106,295,728 vertices

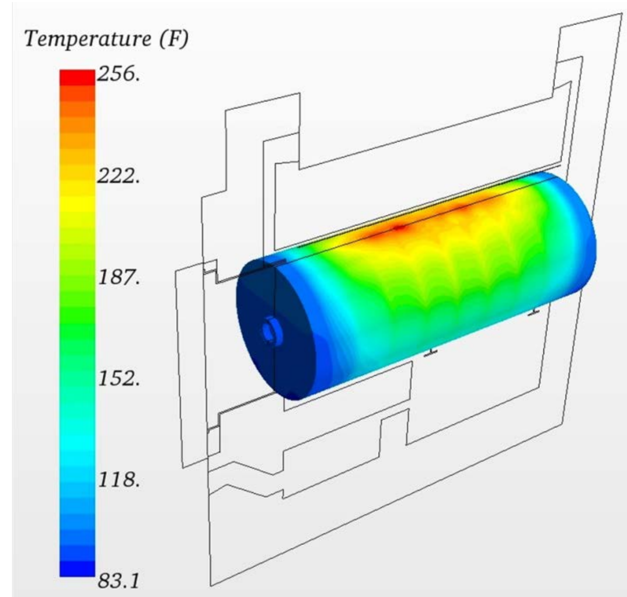


HSM15 Model Shown (Lead Canister)

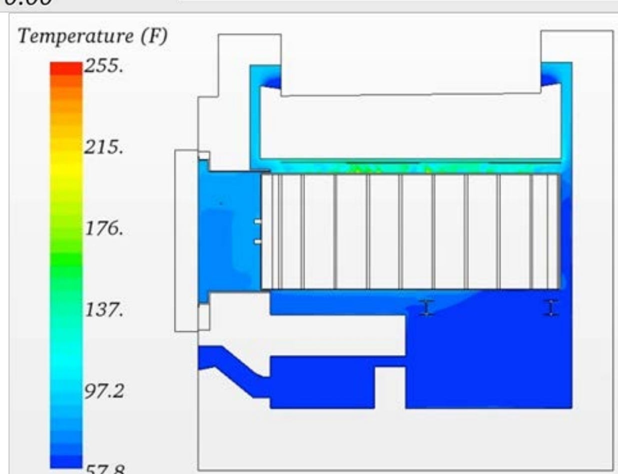


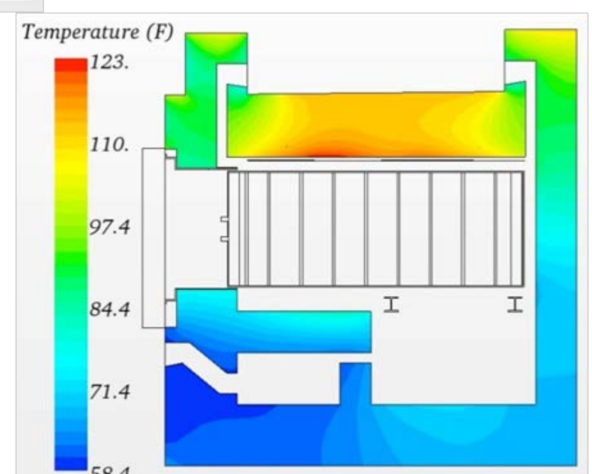
Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS





Pre-test HSM15 Thermal Predictions 58°F (14°C) Ambient





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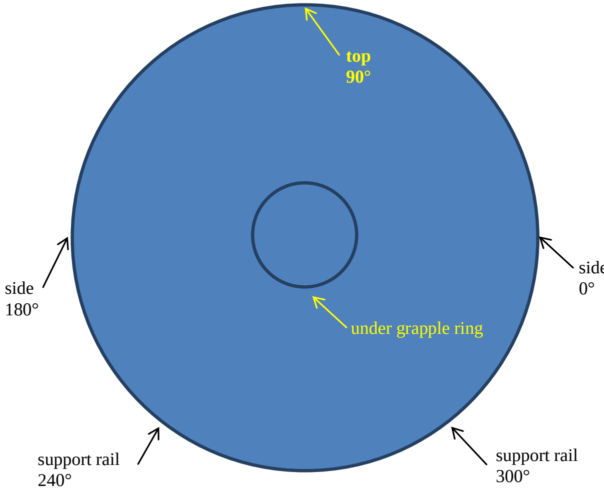
Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

How did pre-test predictions compare with collected data?

Temperature Location	Temperature (°F (°C))			
	TC measurement HSM-1	TC measurement HSM-15	CFD Model HSM-1	CFD Model HSM-15
Under Grapple Ring	112 (44)	124 (51)	100 (38)	110 (43)
Side (0°) – 0.0 in. (0.0 m)	108 (42)	n/a	100 (38)	110 (43)
Side (0°) – 20 in. (0.51 m)	109 (43)	n/a	116 (47)	133 (56)
Side (0°) – 40 in. (1.02 m)	108 (42)	n/a	136 (58)	164 (73)
Top (90°) – 0.0 in. (0.0 m)	115 (46)	n/a	103 (39)	114 (46)
Top (90°) – 20 in. (0.51 m)	117 (47)	n/a	142 (61)	180 (82)
Top (90°) – 40 in. (1.02 m)	119 (48)	n/a	178 (81)	242 (117)
Side (180°) – 0.0 in. (0.0 m)	104 (40)	n/a	100 (38)	110 (43)
Side (180°) – 20 in. (0.51 m)	105 (41)	n/a	115 (46)	135 (57)
Side (180°) – 40 in. (1.02 m)	108 (42)	n/a	134 (57)	167 (75)
Rail (240°) – 0.0 in. (0.0 m)	106 (41)	n/a	97 (36)	104 (40)
Rail (240°) – 20 in. (0.51 m)	107 (42)	n/a	101 (38)	112 (44)
Rail (240°) – 40 in. (1.02 m)	108 (42)	n/a	109 (43)	123 (51)
Rail (300°) – 0.0 in. (0.0 m)	105 (41)	n/a	97 (36)	104 (40)
Rail (300°) – 20 in. (0.51 m)	106 (41)	n/a	101 (38)	111 (44)
Rail (300°) – 40 in. (1.02 m)	106 (41)	n/a	109 (43)	122 (50)



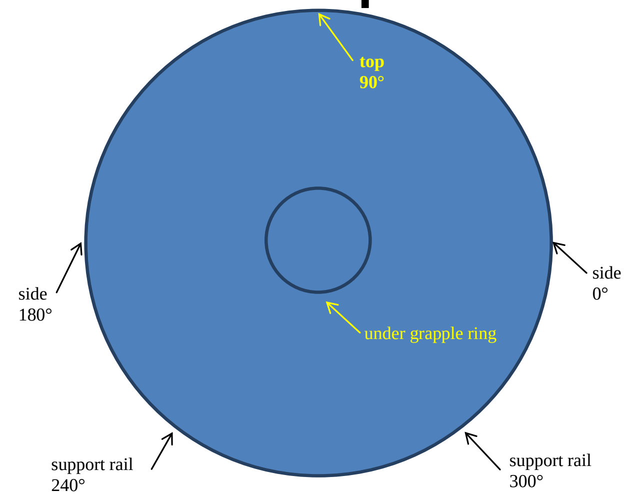
Reasons for differences:

- Ambient 82°F (28°C) instead of seasonal average of 58°F (14°C)
- Canister end temperatures highly sensitive to fuel location and degree of contact
- Anomalous temperature data collected past 0.0 m insertion (measurement difficulties)
- Protective vent screens with smaller grids than modeled (larger pressure drop)

Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS

Taking these things into account, how do we compare?

Temperature Location	Temperature (°F (°C))			
	TC measurement HSM-1	TC measurement HSM-15	**HSM-1 Model (post-test)**	HSM-15 Model (post-test)
Under Grapple Ring	**112 (44)**	124 (51)	**113 (45)**	127 (53)
Side (0°) – 0.0 inches	**108 (42)**	n/a	**113 (45)**	127 (53)
Top (90°) – 0.0 inches	**115 (46)**	n/a	**116 (47)**	133 (56)
Side (180°) – 0.0 inches	**104 (40)**	n/a	**113 (45)**	128 (53)
Rail (240°) – 0.0 inches	**106 (41)**	n/a	**107 (42)**	118 (48)
Rail (300°) – 0.0 inches	**105 (41)**	n/a	**107 (42)**	118 (48)



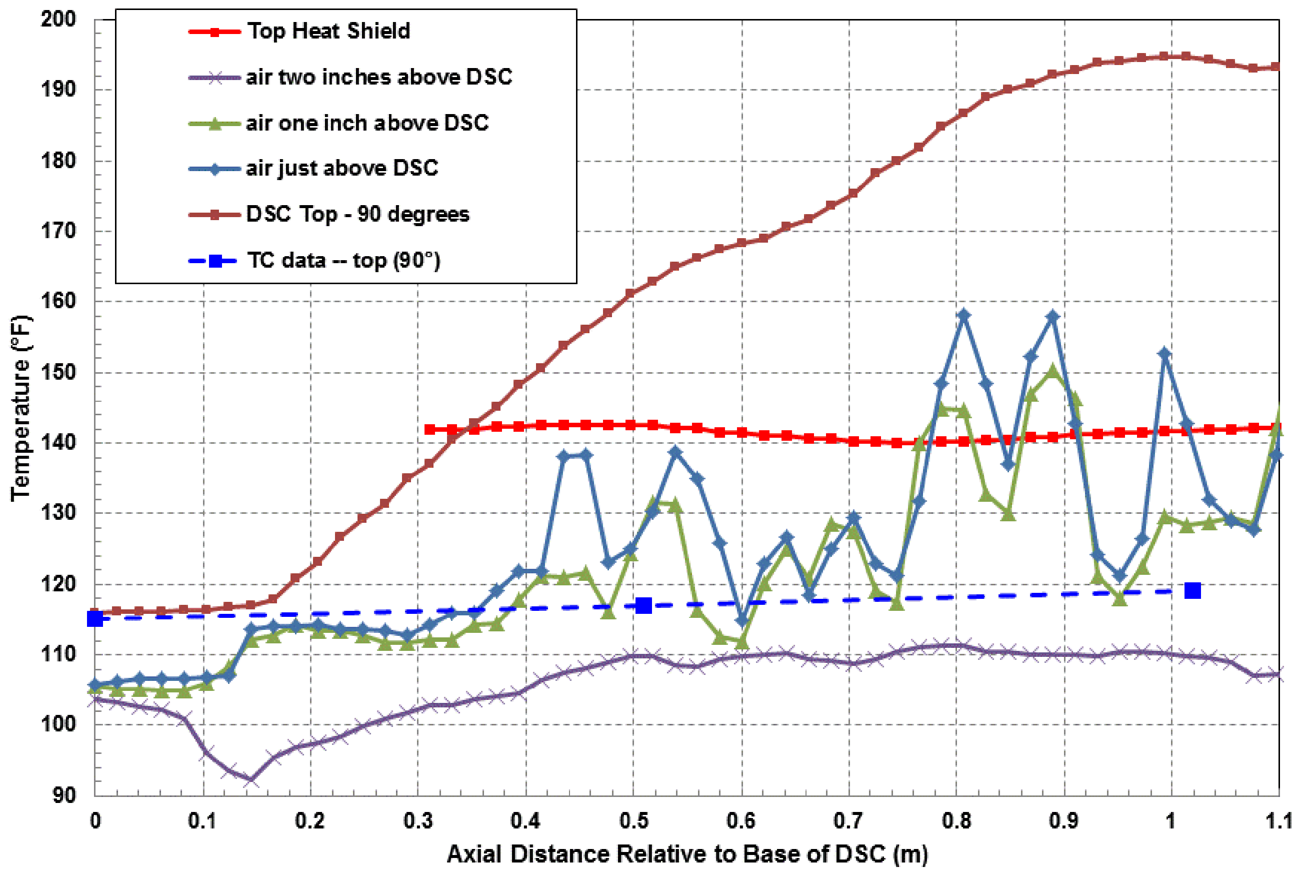
Remaining reason for differences:

- Module door removed 40 minutes prior to taking outside measurements

Maximum component temperatures from CFD Models:

	Concrete temperature (°F (°C))	DSC temperature (°F (°C))	Fuel temperature (°F (°C))	Heat Shield temperature (°F (°C))
HSM-1 (Pre-test)	128 (53)	197 (92)	265 (129)	134 (57)
HSM-1 (Post-test)	133 (56)	208 (98)	279 (137)	143 (62)
HSM-15 (Pre-test)	145 (63)	278 (137)	402 (206)	166 (74)
HSM-15 (Post-test)	158 (70)	290 (143)	422 (217)	187 (86)

Thermal Predictions of HSM1 & HSM15 at Calvert Cliffs NPS



Axial Temperature Comparison for Top Heat Shield, Air Above DSC, and DSC Top Surface in HSM-1

Planned UFD Work

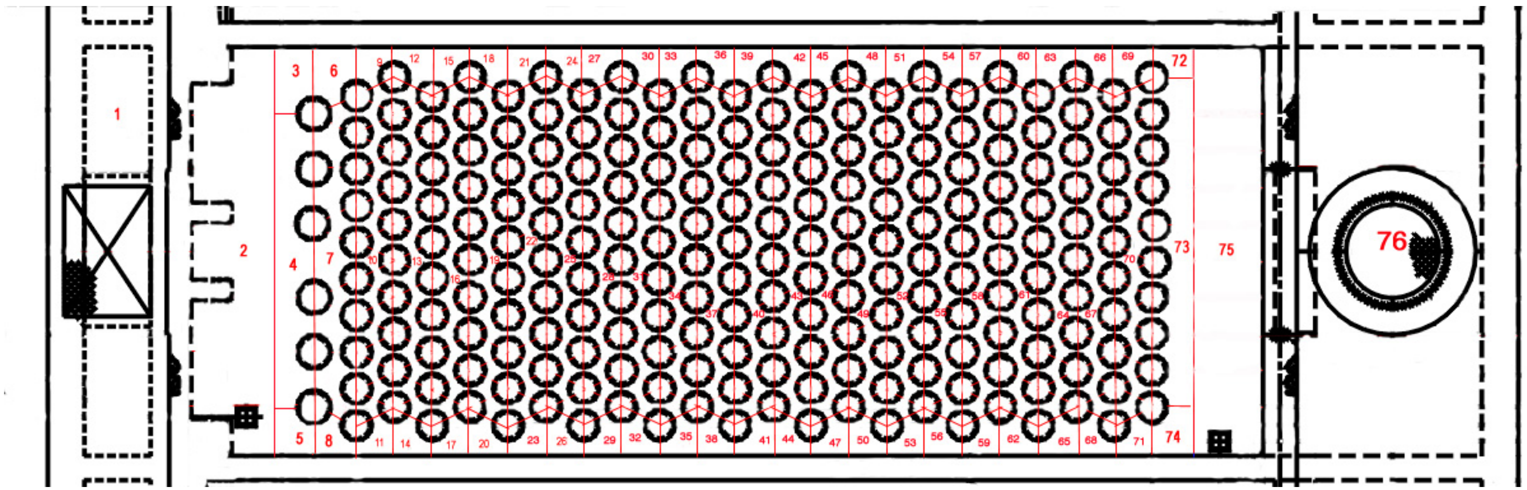
- **Two EPRI inspections planned during FY13**
- **Sensitivity/Uncertainty analyses will be performed to identify important parameters to focus research efforts**
- **Extend CFD code validation**
- **Work with industry (demo) to validate codes during vacuum drying of HBU fuel under prototypic conditions**
- **Current codes can be extended from storage and transportation to disposal**
  - Hanford CSB as an example

Questions?

COBRA-SFS modeling of Canister Storage Building

- **Project W-464, IHLW Interim Storage Detailed Design (client: MacTec / CH2M Hill Hanford Group)**
- **Design-basis calculations for 150 kW heat load in Vault #2 of Canister Storage Building (CSB)**
- **Objective was to determine temperature distributions and magnitude and location of peak temperatures in**
  - IHLW glass,
  - stainless steel canisters,
  - steel storage tubes,
  - concrete walls of vault, and
  - circulating air within vault
- **Evaluated maximum heat load (150 kW) and low-heat load startup conditions**

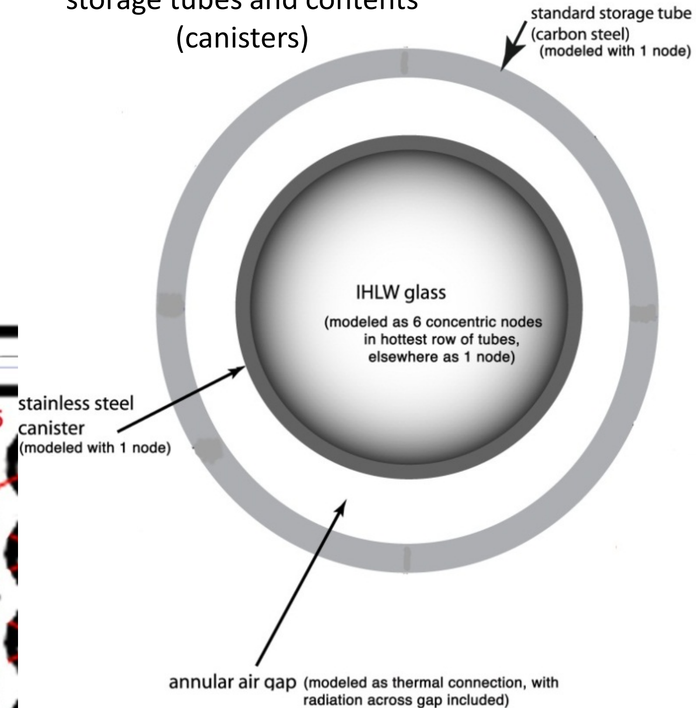
Canister Storage Building Model



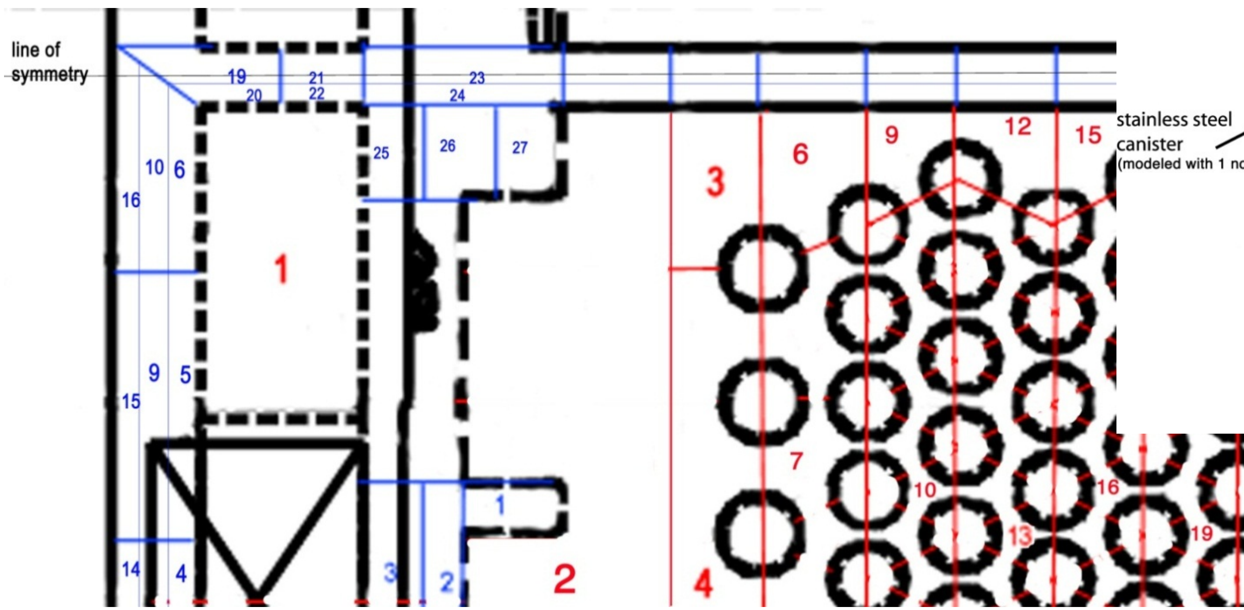
- **Vault #2 description:**
  - Triangular array of storage tubes, with up to 2 stacked canisters containing high-level waste glass per tube (up to 0.6 kW/canister)
  - Cooled by natural circulation of air through underground concrete vault
- **COBRA-SFS model:**
  - Detailed representation of canisters and flow paths through ‘forest’ of storage tubes
  - Detailed representation of vault walls, storage tubes, canisters, and canister contents (glass)

CSB Model Details

Example of noding detail for storage tubes and contents (canisters)



Note: conceptual diagrams; not to scale.



Example of noding detail for solid conduction nodes (blue) and flow paths (red)

COBRA-SFS V&V References

- Bates, JM, 1986. *Single PWR Spent Fuel Assembly Heat Transfer Data for Computer Code Evaluations*, PNL-5571, Pacific Northwest Laboratory, Richland, Washington.
- Irino, M., M. Oohashi, T. Irie, and T. Nishikawa, 1986. *Study on Surface Temperatures of Fuel Pins in Spent Fuel Dry Shipping/Storage Casks*, IAEA-SM-286/139P. pp/ 585-598.
- Fry, CJ, E. Livesey, and GT Spiller, 1983. *Heat Transfer in a Dry, Horizontal LWR Spent Fuel Assembly*, New Orleans, Louisiana. Oak Ridge National Laboratory, Oak Ridge, Tennessee. Packaging and Transportation of Radioactive Materials Symposium (PATRAM83), in *Proceedings of Seventh International Symposium*.
- Creer, J.M., R.A. McCann, M.A. McKinnon, J.E. Tanner, E.R. Gilbert, R.L. Goodman, C. Dziadosz, E.V. Moore, D.H. Schoonan, M. Jensen, and C. Mullen. 1986. *The CASTOR-V/21 PWR Spent Fuel Storage Cask: Testing and Analysis.* EPRI NP-4887, Electric Power Research Institute, Palo Alto, CA.
- Creer, J.M., T.E. Michener, M.A. McKinnon, J.E. Tanner, E.R. Gilbert, and R.L. Goodman, 1987. *The TN-24P PWR Spent Fuel Storage Cask: Testing and Analyses*, EPRI-NP-5128/PNL-6054, Electric Power Research Institute, Palo Alto, CA.
- McKinnon, M.A., J.W. Doman, J.E. Tanner, R.J. Guenther, J.M. Creer, and C.E. King, 1986. *BWR Spent Fuel Storage Cask Performance Test; Volume I: Cask Handling Experience and Decay Heat, Heat Transfer, and Shielding Data.* PNL-5577, Vol. I, Pacific Northwest Laboratory, Richland, WA. (Note: cask is REA 2023)
- McKinnon, M.A., L.E. Wiles, N.J. Lombardo, C.M. Heeb, U.P. Jenquin, T.E. Michener, C.L. Wheeler, J.M. Creer, and R.A. McCann, 1986. *BWR Spent Fuel Storage Cask Performance Test; Volume II: Pre- and Post-Test Decay Heat, Heat Transfer, and Shielding Analyses.* PNL-5577, Vol. II, Pacific Northwest Laboratory, Richland, WA. (Note: cask is REA 2023)
- McKinnon, M.A., T.E. Michener, M.F. Jensen, and G.R. Goodman, 1989. *The 24P PWR Spent Fuel Dry Storage Cask Loaded with Consolidated Fuel*. EPRI-NP-6191/PNL-6631/UC-85, Electric Power Research Institute, Palo Alto, CA.

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COBRA-SFS V&V References

- McKinnon, M.A., R.E. Dodge, R.C. Schmitt, L.E. Eslinger, and G. Dineen, 1992. Performance Testing and Analyses of the VSC-17 Ventilated Concrete Cask. EPRI-TR-100305/PNL-7839, Electric Power Research Institute, Palo Alto, CA.
- Rector, D.R., R.A. McCann, U.P. Jenquin, C.M. Heeb, J.M. Creer, and C.L. Wheeler, 1986. *CASTOR-1C Spent Fuel Storage Cask Decay Heat, Heat Transfer, and Shielding Analyses*. PNL-5974, Pacific Northwest Laboratory, Richland, WA.
- Lombardo, N.J., T.E. Michener, C.L. Wheeler, and D.R. Rector, 1986. *COBRA-SFS Predictions of Single-Assembly Spent Fuel Heat Transfer Data*. PNL-5781, Pacific Northwest National Laboratory, Richland, WA.
- Cuta, J.M., D.R. Rector, and J.M. Creer, 1984. *Comparisons of COBRA-SFS Calculations with Data from Simulated Sections of Unconsolidated and Consolidated BWR Spent Fuel*. EPRI-NP-3764, Electric Power Research Institute, Palo Alto, CA.
- Lombardo, N.J., J.M. Cuta, T.E. Michener, D.R. Rector, and C.L. Wheeler, 1986. *COBRA-SFS: A Thermal-Hydraulic Analysis Computer Code: Volume III: Validation Assessments*. PNL-6049, Vol. 3, Pacific Northwest National Laboratory, Richland, WA.
- Rector, D.R., J.M. Cuta, and N.J. Lombardo, 1986. *COBRA-SFS Thermal-Hydraulic Analyses of the CASTOR-1C and REA 2023 BWR Storage Casks Containing Consolidated Spent Fuel*. PNL-5802, Pacific Northwest National Laboratory, Richland, WA.
- Rector, D.R., T.E. Michener, and J.M. Cuta, 1998. *Verification and Validation of COBRA-SFS Transient Analysis Capability.* PNNL-11883, Pacific Northwest National Laboratory, Richland, WA.
- Rector, D.R., T.E. Michener, 1989. COBRA-SFS Modifications and Cask Model Optimization. PNL-6706, Pacific Northwest Laboratory, Richland, WA.
- Wheeler, C.L., R.A. McCann, N.J. Lombardo, D.R. Rector, and T.E. Michener, 1986. *HYDRA and COBRA-SFS Temperature Calculations for CASTOR-1C, REA-2023, CASTOR-V/21, and TN-24P Casks*. In *Proceedings, Third International Spent Fuel Storage Technology Symposium and Workshop*, Vol. 1, S77-S98, CONF-960417, National Technical Information Service, Springfield, Virginia.