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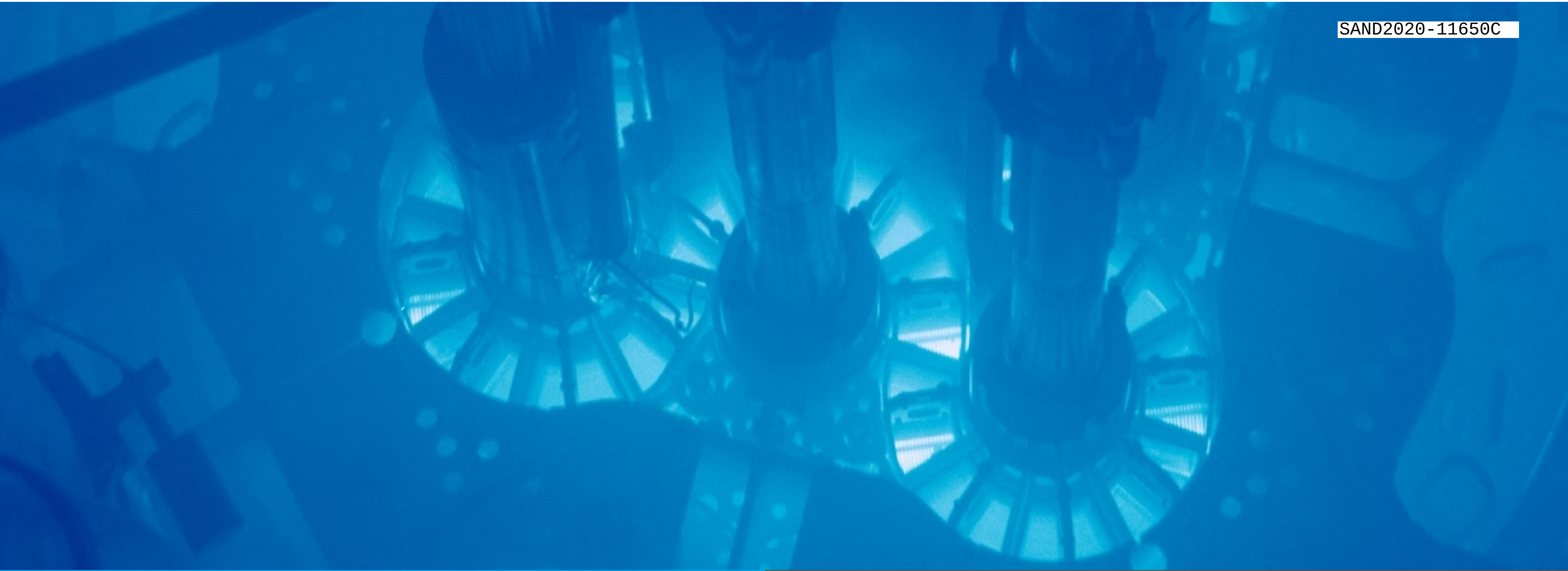

Blind Modeling Validation Exercises Using a Horizontal Dry Cask Simulator

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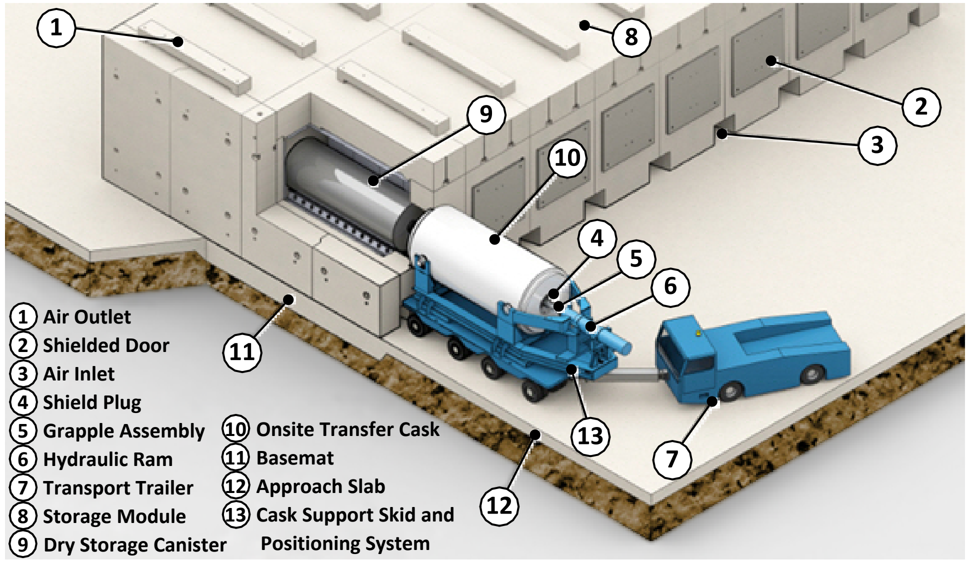
Horizontal Dry Cask Simulator (HDCS) Overview

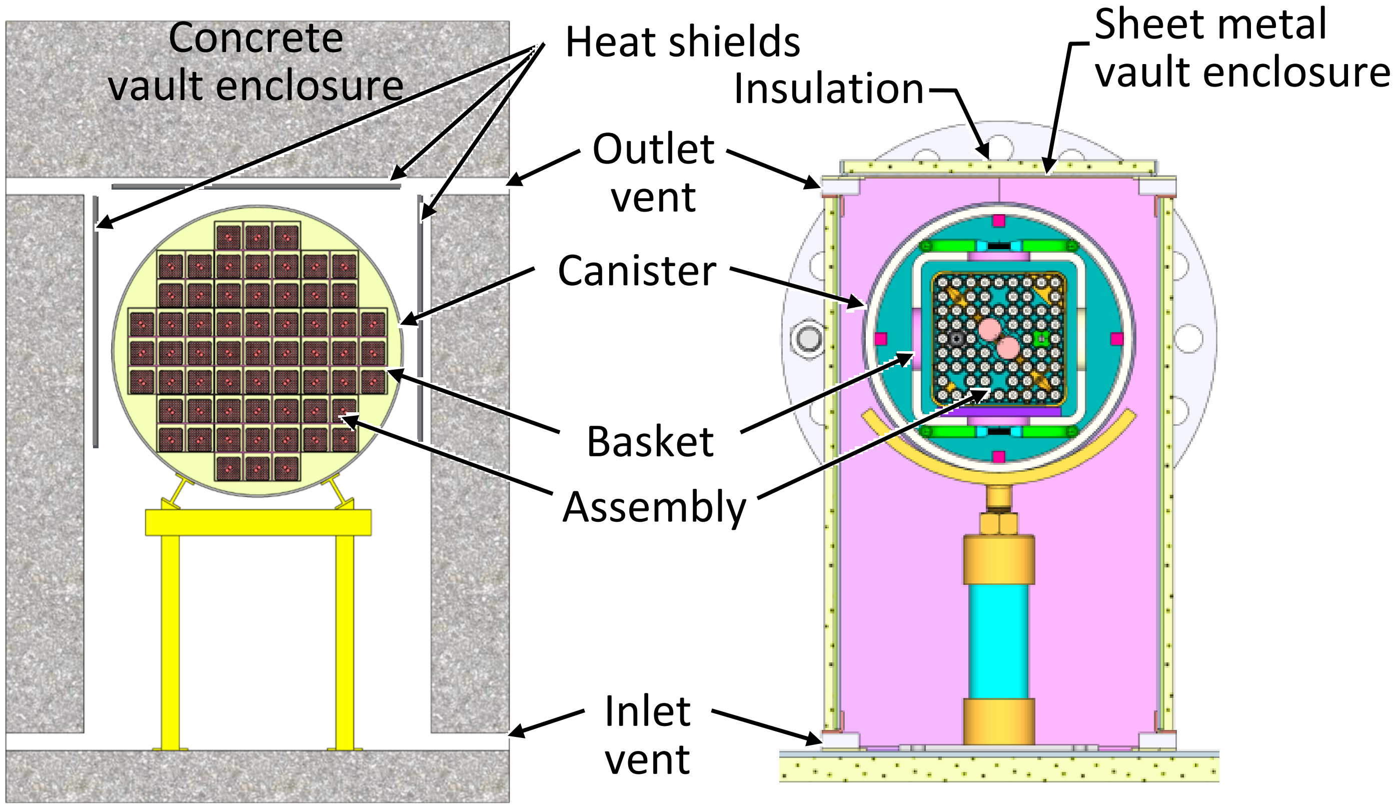


Source: http://us.areva.com/EN/home-3138/areva-nuclear-materials-tn-americas--nuhoms-used-fuel-storage-system.html#tab=tab6

- Purpose: Validate thermal-hydraulic modeling codes used for spent fuel cask thermal design analyses
  - Used to determine peak cladding temperatures in dry casks
  - Needed to evaluate cladding integrity throughout storage cycle
- Measure temperature profiles for a wide range of decay power and backfill gas pressures
  - Mimic conditions for horizontal dry cask systems with canisters
  - Simplified geometry with well-controlled boundary conditions
  - Provide measure of mass flow rates and temperatures throughout system
- Use existing geometrically-prototypic BWR Incoloy-clad test assembly
  - Electrically-heated fuel simulators

Goal of Investigation

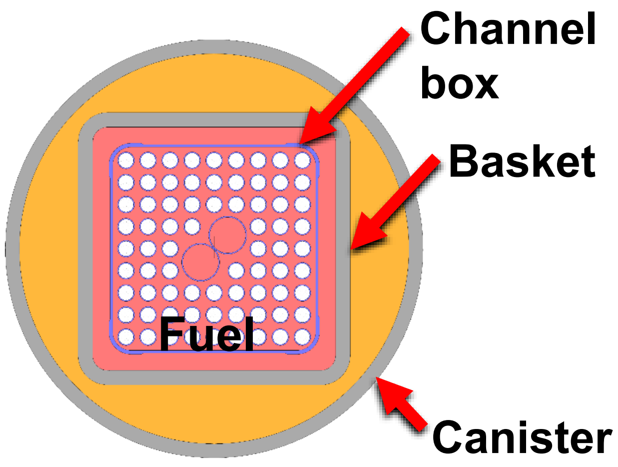
- Goal: Simulate commercial horizontal dry cask storage system
  - Response to a need for modern model validation
    - Determine effectiveness of modern codes in predicting dry cask storage system peak cladding temperatures
  - Wide range of test parameters
    - Decay heats, gas backfills, and internal pressures
  - Collect validation-quality data
    - Temperatures and external air mass flow rates



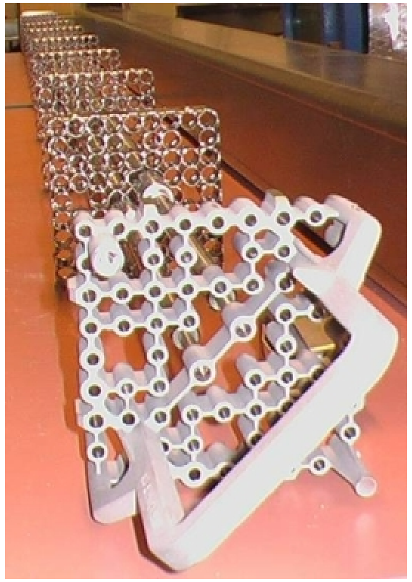
NUHOMS HSM Model 80 with 61BT canister
BR = 0.84

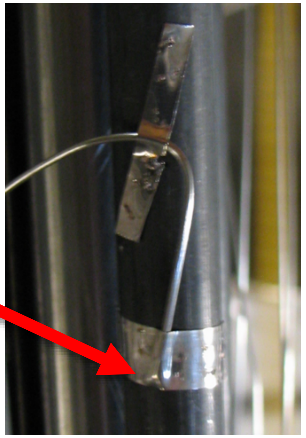
HDCS
BR = 0.84

Prototypic Assembly Hardware

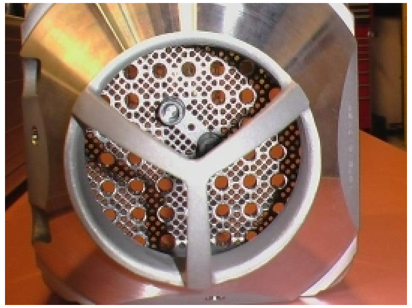


Upper tie plate

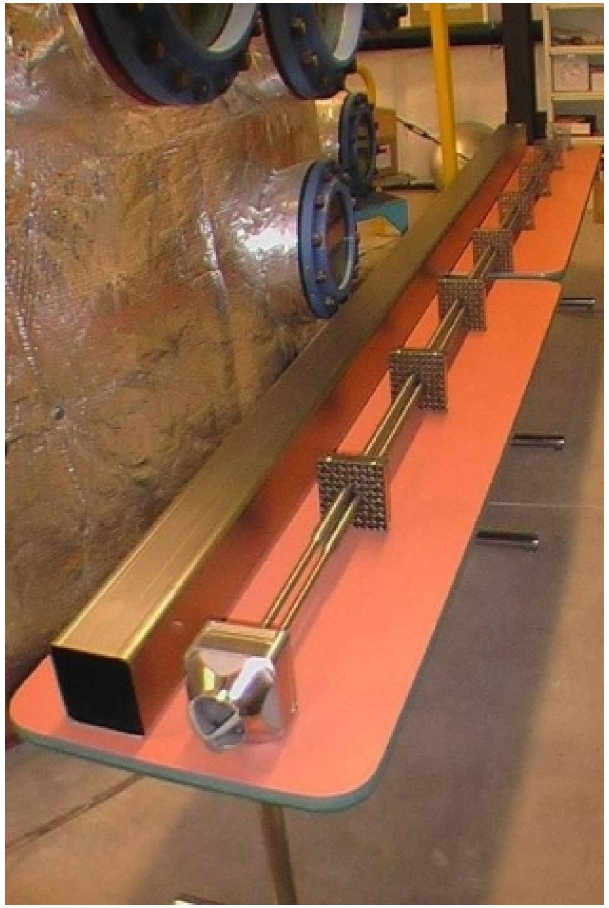




Thermocouple (TC) attached directly to cladding



Nose piece and debris catcher

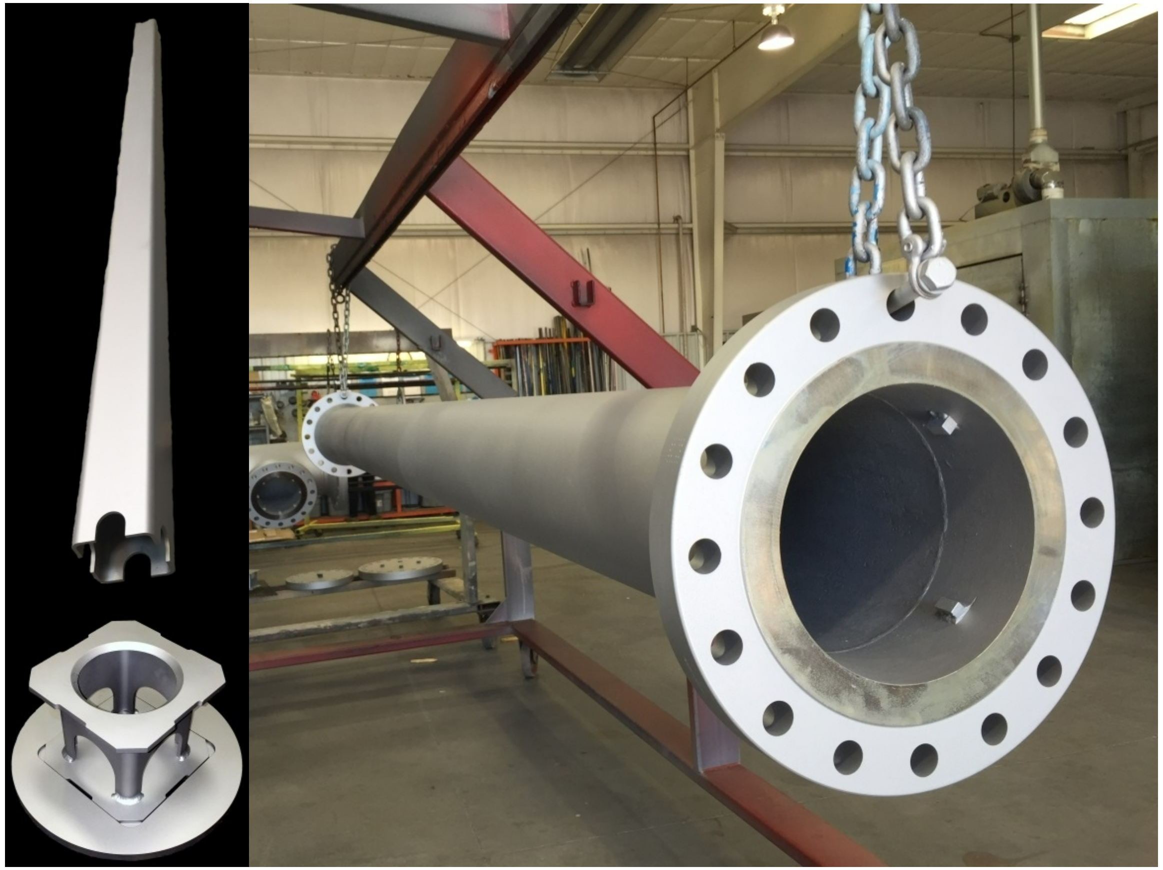


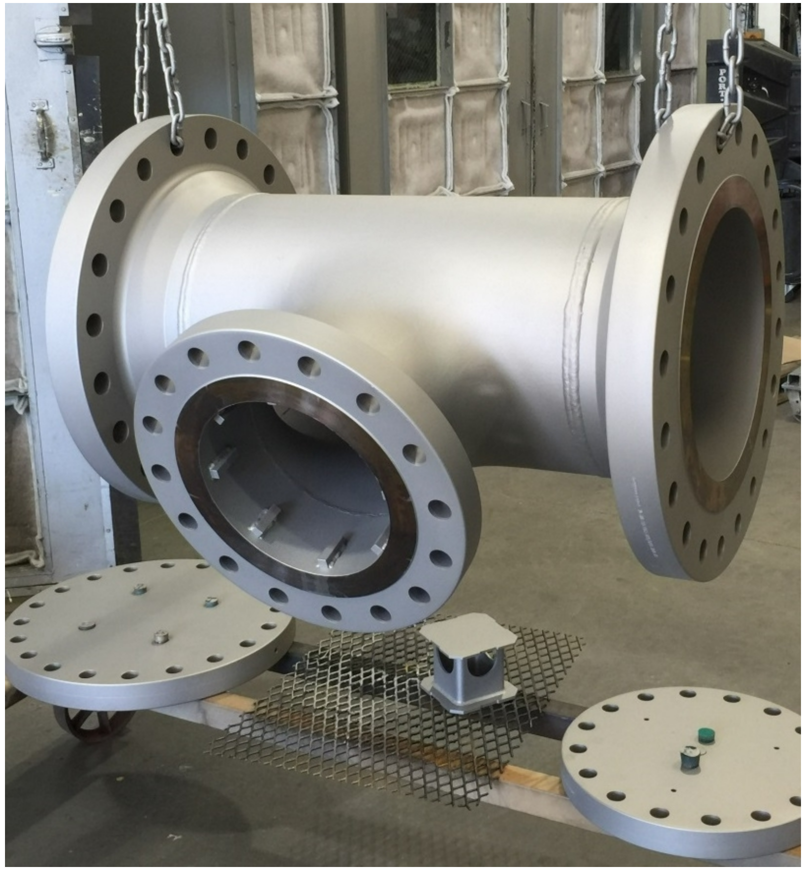
BWR channel box, water rods, and spacers

- Most common 9×9 BWR fuel 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 run 2/3 the length of assembly
  - 2 water rods
  - 7 spacers

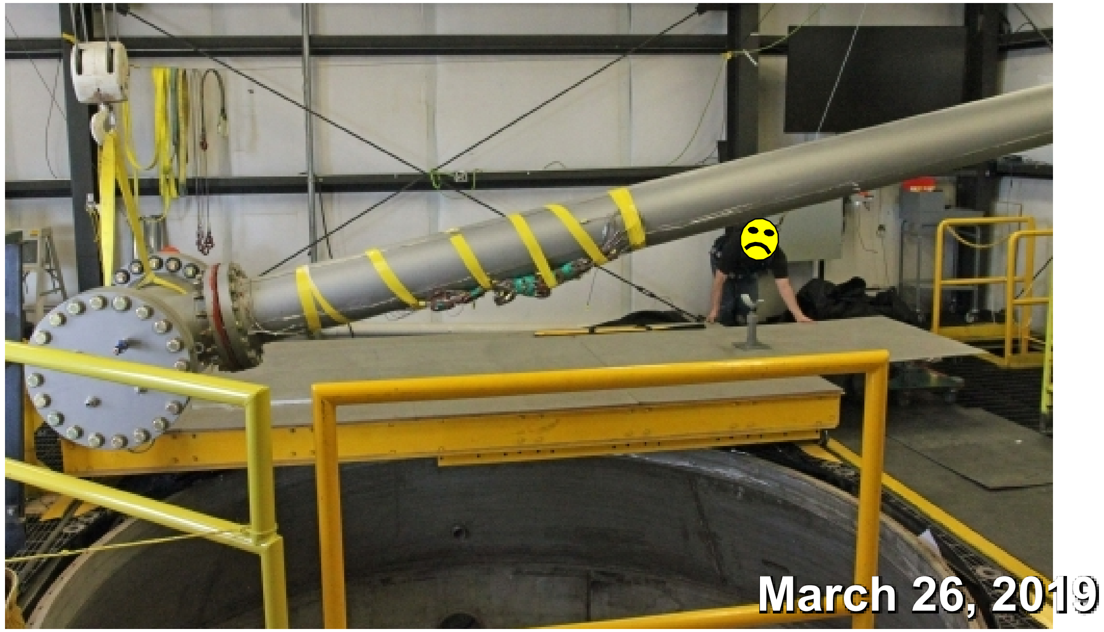
Pressure Vessel Hardware

- Scaled components with instrumentation well
- Coated with ultra-high-temperature paint



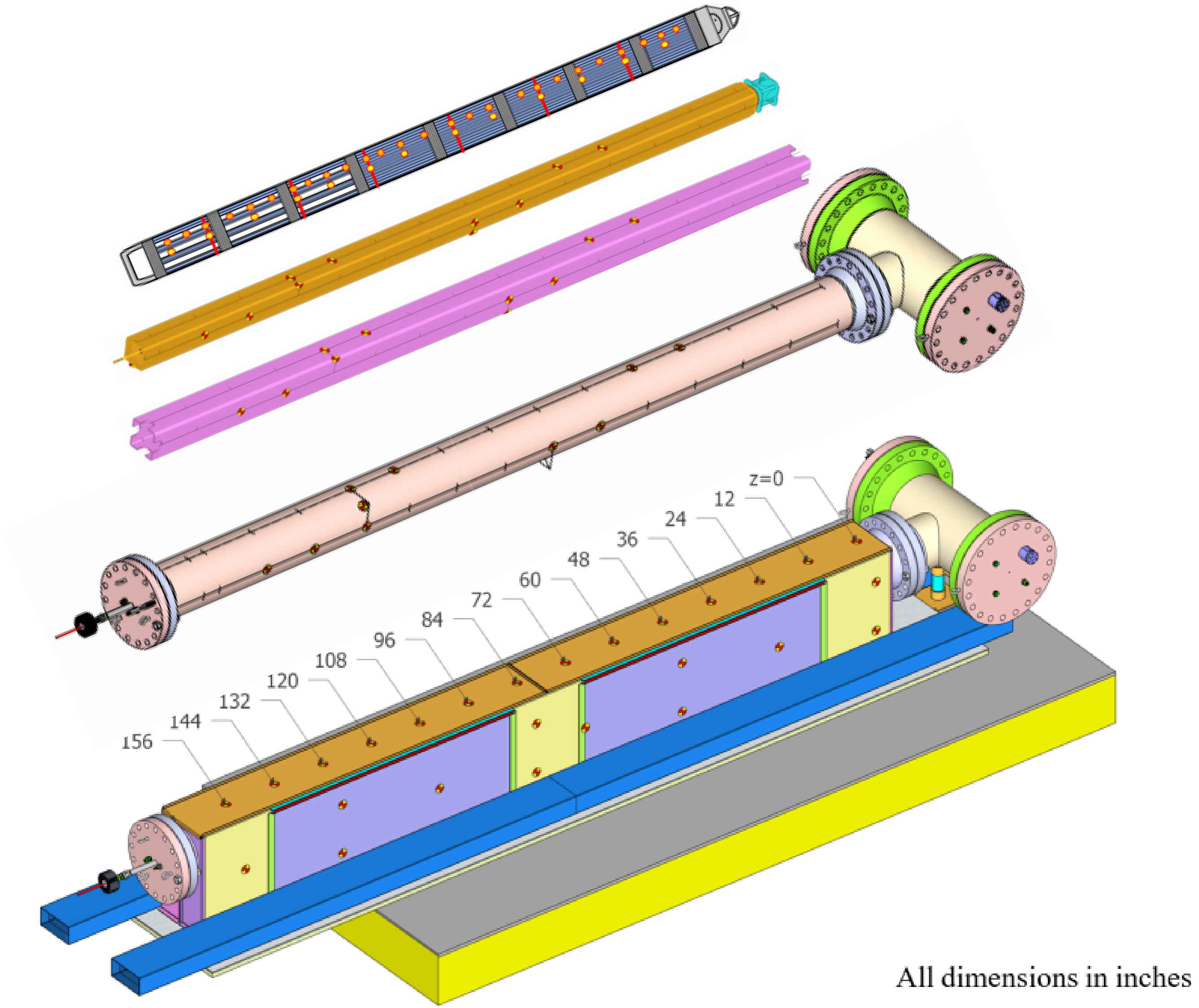


HDCS Construction



- Gently rotated assembly from vertical to horizontal configuration
- Constructed vault enclosure
  - Inlets and outlets
- Installed additional instrumentation
- Conducted testing

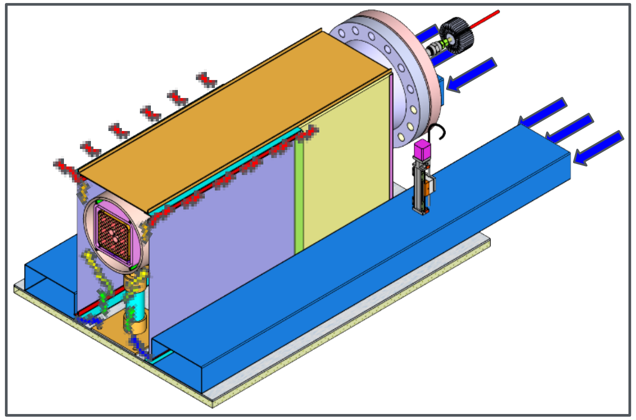
Temperature Measurements

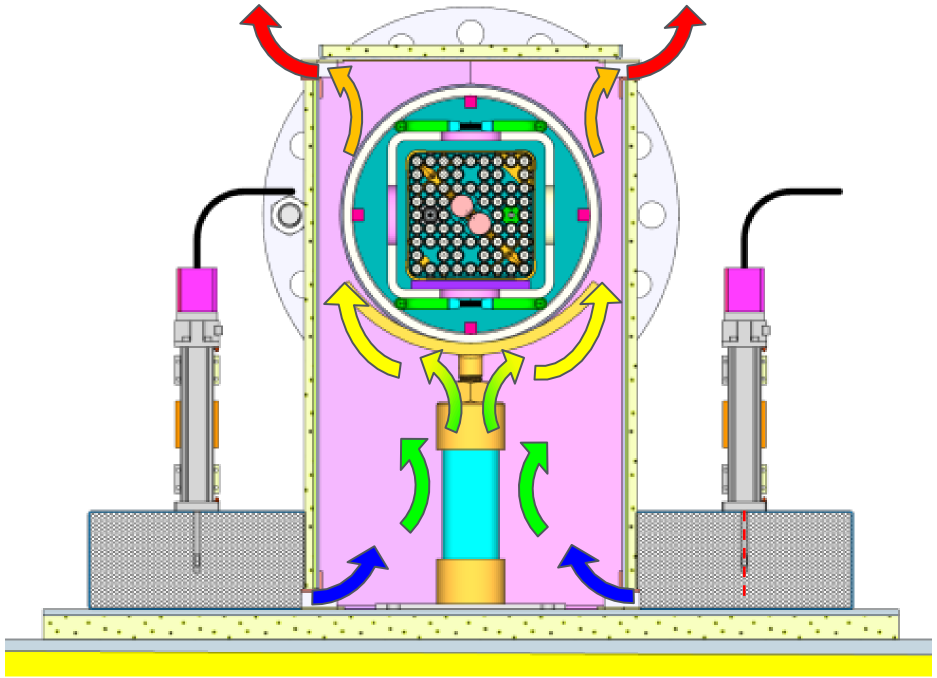


- Thermocouples used to make temperature measurements
  - 281 total TCs
  - TCs attached directly to surfaces
  - 95% confidence interval measurement uncertainty: U_{T_E} = ±1% of maximum temperature measurement*

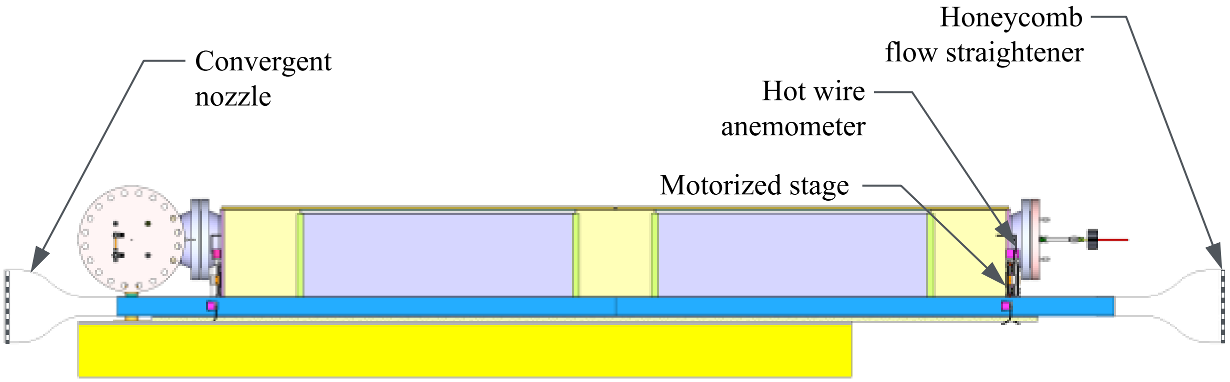
*Nakos, J.T., "Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant Heat Facility and Lurance Canyon Burn Site," SAND2004-1023, Sandia National Laboratories, Albuquerque, New Mexico, April 2004.

Air Mass Flow Measurements





- Hot wire anemometers used to make air mass flow measurements
  - Flow facilitated into duct via convergent nozzles
  - Anemometers traversed ducts via motorized stages
  - Measurement uncertainty across all 4 ducts: $U_{\dot{m}_{E},\ Total} = \pm 3.0 \times 10^{-4}$ kg/s



HDCS Modeling Validation Exercise

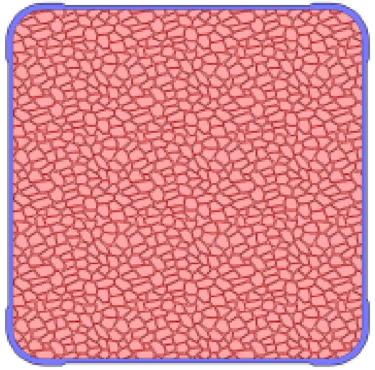
- Results provided for two cases of the overall test matrix
  - 2.5 kW power, 100 kPa pressure, helium backfill
  - 2.5 kW power, 100 kPa pressure, air backfill
- Limited data set provided to calibrate models for blind model validation exercise

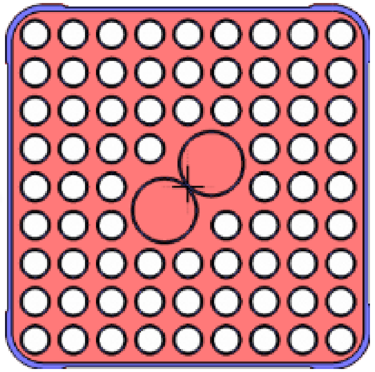
Fill Gas	Pressure (kPa)	Power (kW)
Helium	100	0.5
	100	1.0
	100	2.5
	100	5.0
	800	0.5
	800	5.0
Air	100	0.5
	100	1.0
	100	2.5
	100	5.0

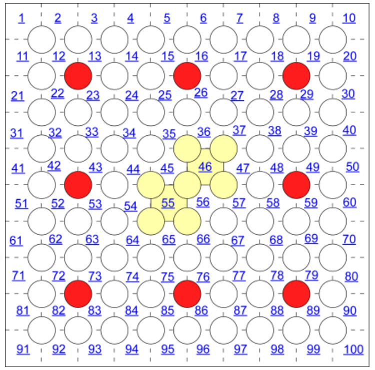
Model Descriptions

- The 5 models can be categorized by:
  - Code type
  - Fuel representation
  - Cross-sectional symmetry
- Results from 4 models are presented

Modeling Contributor	Code Type	Fuel Representation	Cross-Sectional Symmetry
NRC	CFD	Porous Media	1/2
PNNL	CFD	Porous Media	1/2
PNNL	CFD	Explicit	Full
PNNL	Subchannel	Quasi-3D Rods	Full
ENUSA	Subchannel	Quasi-3D Rods	Full

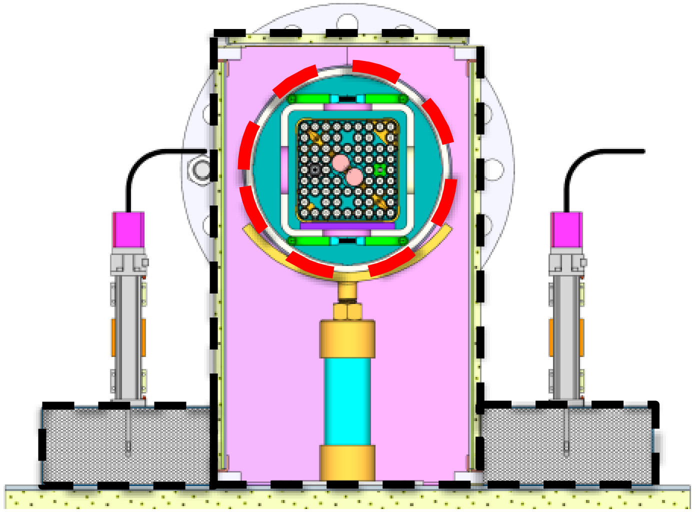






Comparison Metrics

Metric	Notes
Peak cladding temperature	PCT
Air mass flow rate	$\dot{m}_{Air}$
Axial temperature profile	T(*z*) at assembly center (5 locations)
Transverse *x*-axis temp. profile	T(*x*) at *z* = 1.219 m (11 locations)*
Transverse *y*-axis temp. profile	T(*y*) at *z* = 1.829 m (7 locations)**

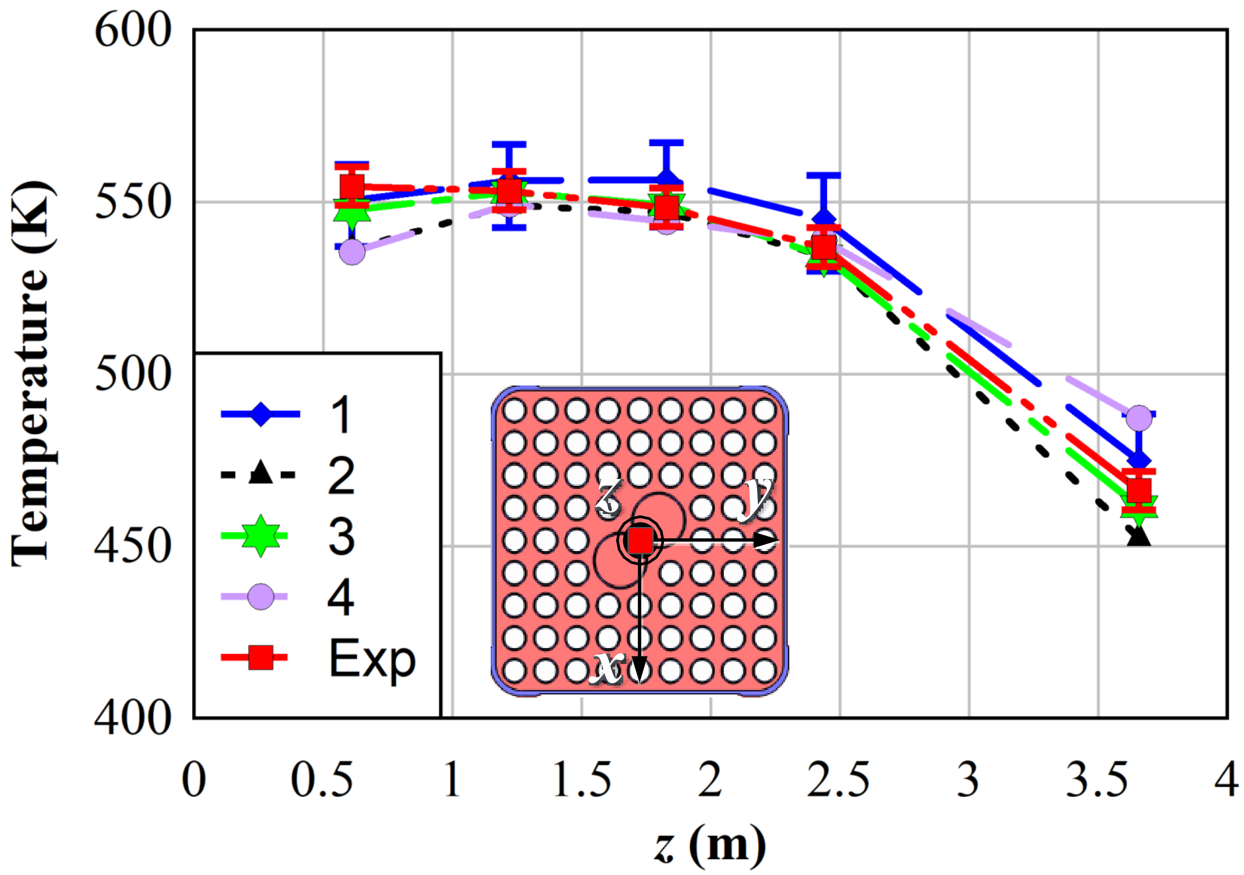


* 9 locations for model with boundary condition set at pressure vessel

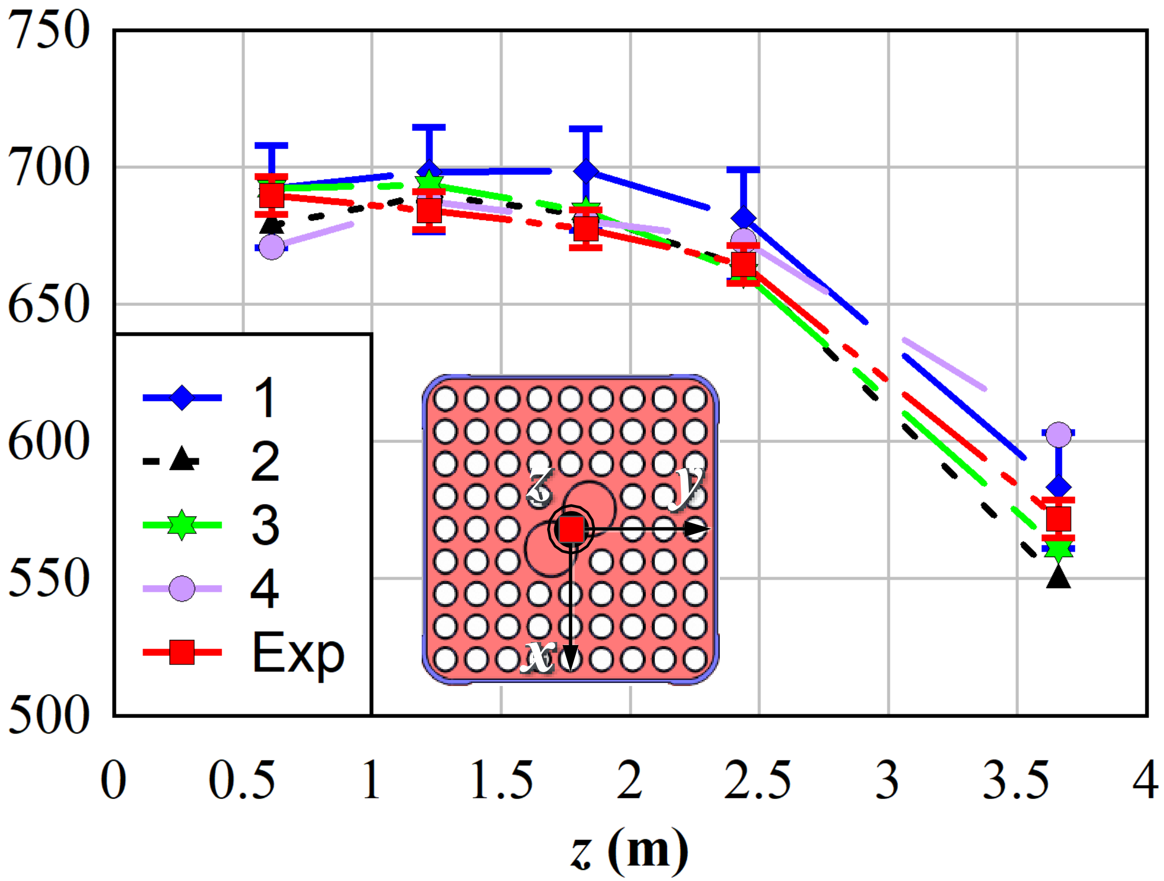
** 6 locations for model with boundary condition set at pressure vessel

Axial Temperature Profile T(z) Data Comparison

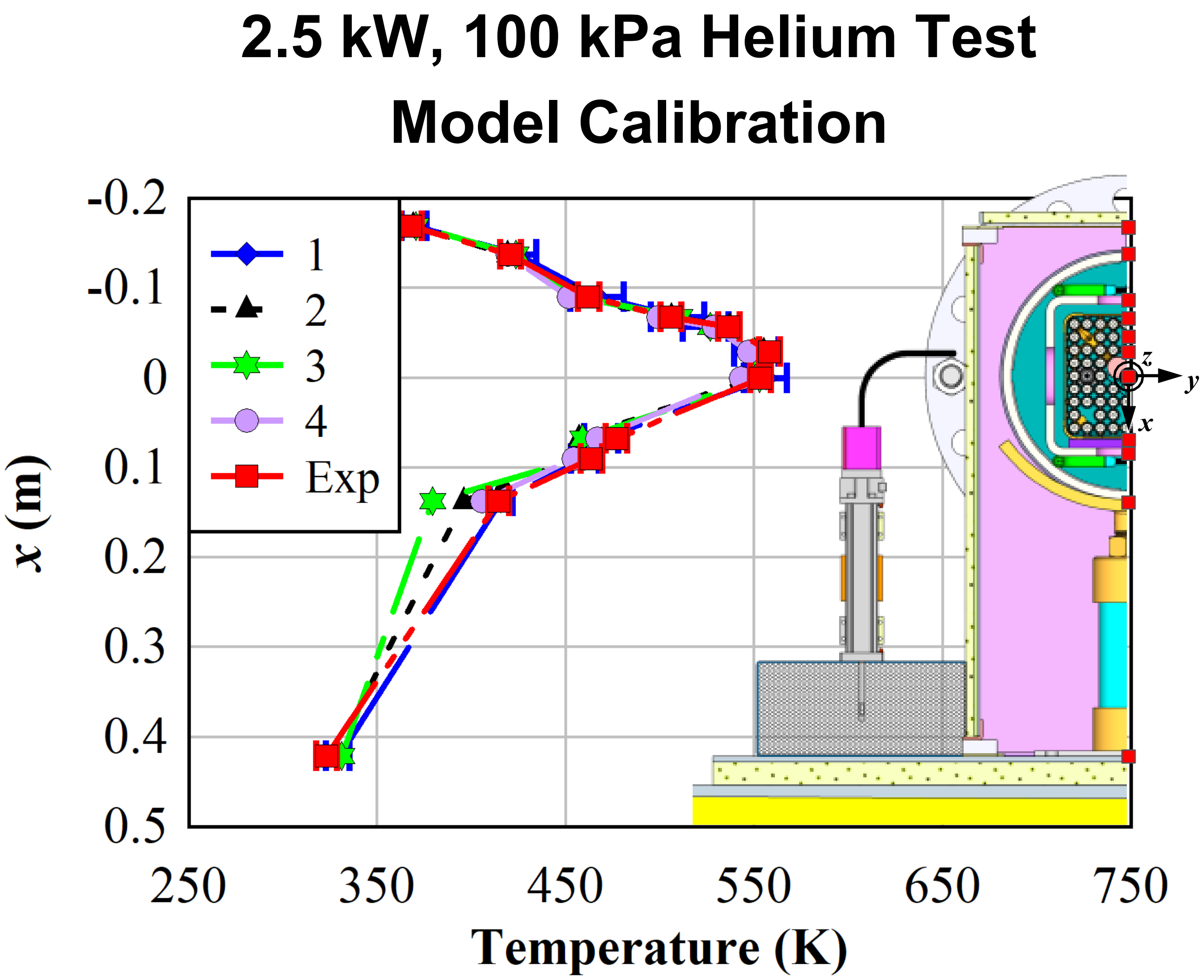
2.5 kW, 100 kPa Helium Test
Model Calibration

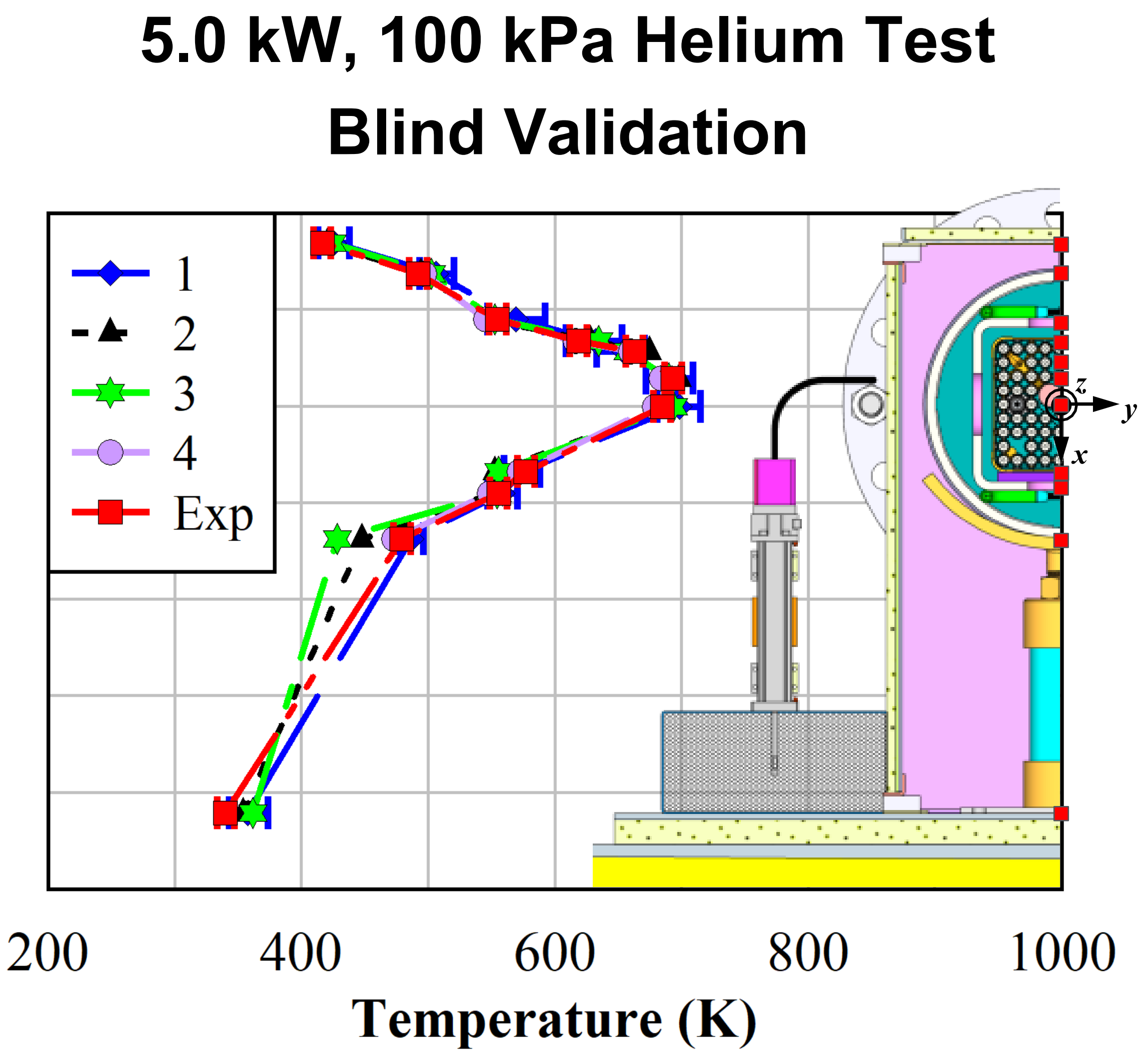


5.0 kW, 100 kPa Helium Test
Blind Validation



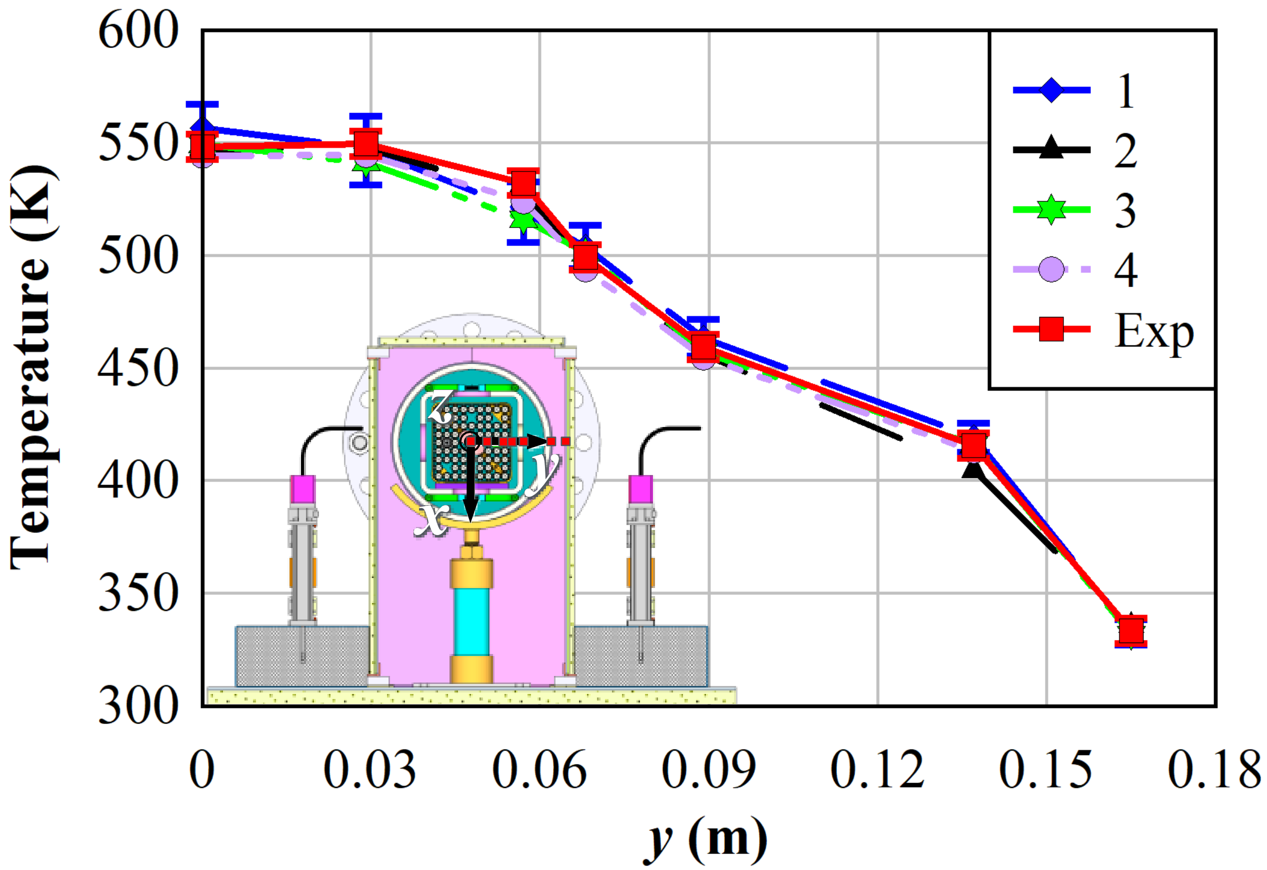
Vertical Temperature Profile T(*x*) Data Comparison



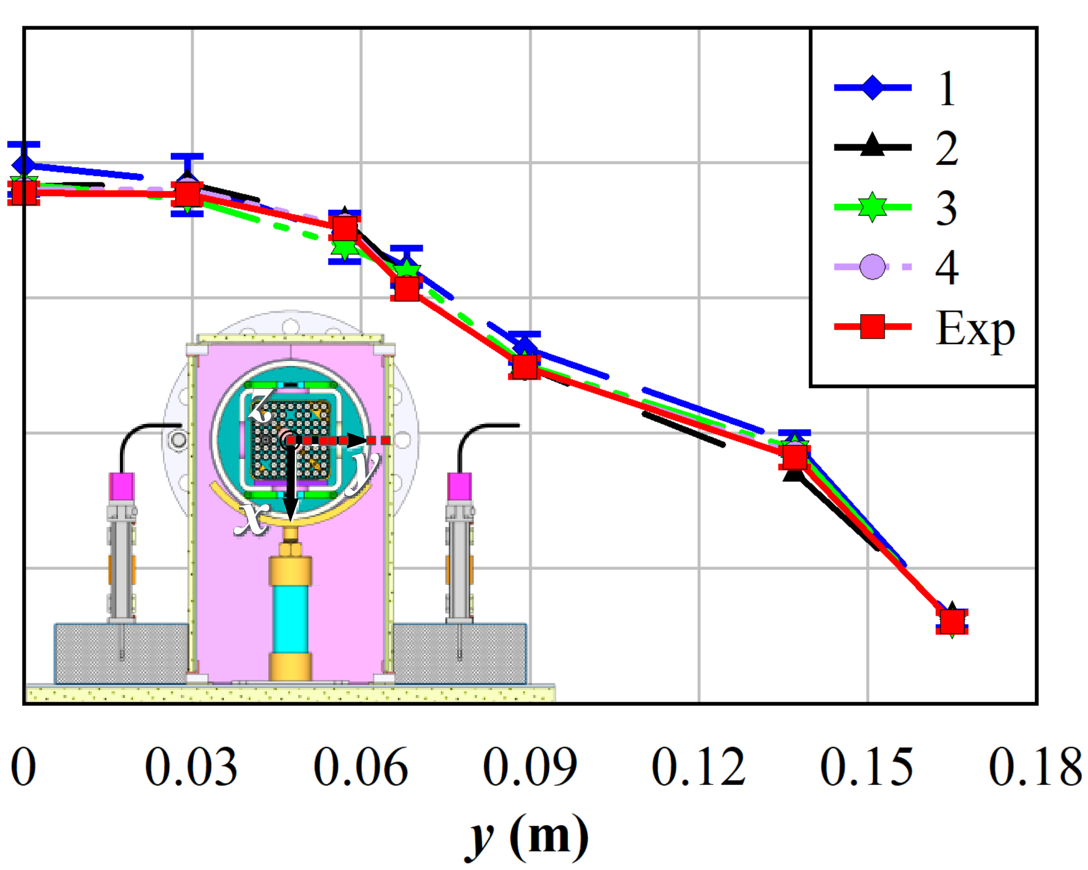


Horizontal Temperature Profile T(*y*) Data Comparison

2.5 kW, 100 kPa Helium Test
Model Calibration



5.0 kW, 100 kPa Helium Test
Blind Validation



Root Mean Squares of the Normalized Errors

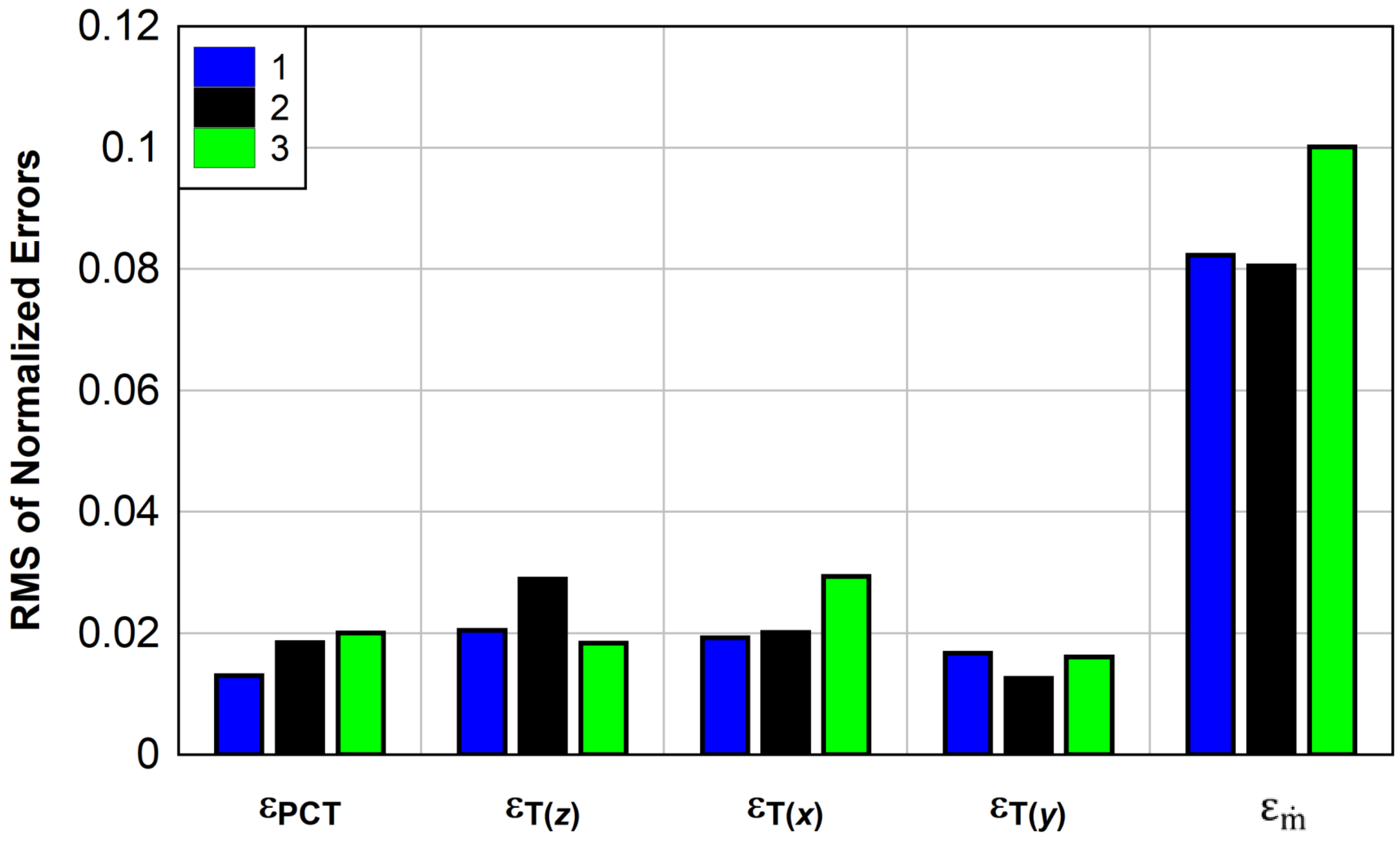
Root Mean Squares (RMSs) of the errors in comparison metrics, normalized by the experimental result, were calculated for all models

- Normalized error equation for parameter x:

$$\varepsilon_x = \frac{X_M - X_E}{X_E}$$

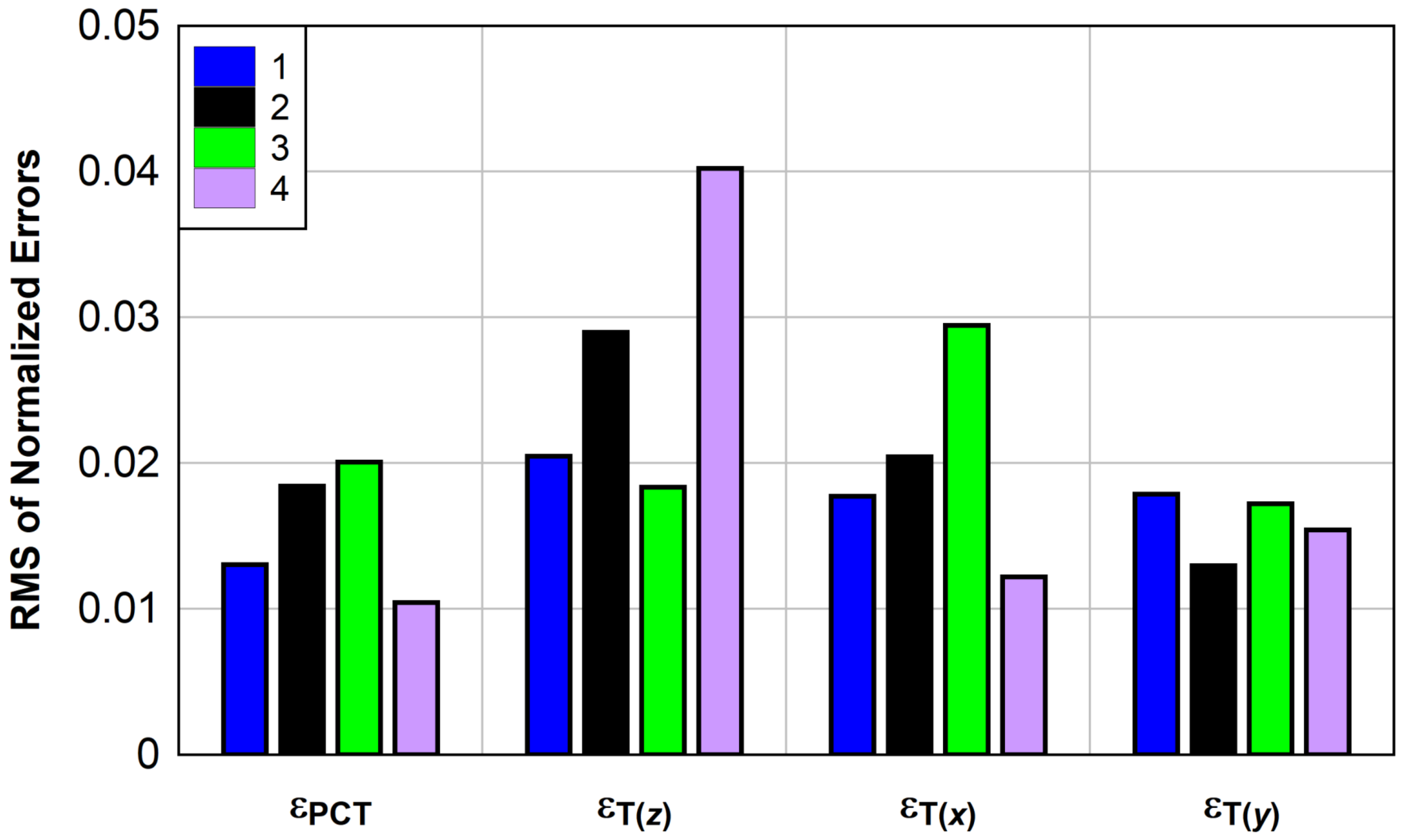
- Comparison metrics: PCT, air mass flow rate, T(*x*), T(*y*), T(*z*)
- Combined RMS of the normalized errors across all parameters gives direct comparison of model goodness of fit
- Does not take uncertainties into account

Comparisons Including Vault Data



Model	**1**	**2**	**3**
Combined RMS of Normalized Errors	0.040	0.041	0.049

Comparisons Excluding Vault Data



Model	1	2	3	4
Combined RMS of the Normalized Errors	0.017	0.021	0.022	0.023

Validation Uncertainty Quantification

Validation Uncertainty Quantification approach derived from ASME V&V 20 (2009)*

- Validation uncertainty in the error**: $U_{\varepsilon_x} = \sqrt{\left(\frac{\partial \varepsilon_x}{\partial x_E}\right)^2 \cdot U_{x_E}^2 + \left(\frac{\partial \varepsilon_x}{\partial x_M}\right)^2 \cdot U_{x_M}^2}$
- Normalized error divided by validation uncertainty: $\frac{\varepsilon_x}{U_{\varepsilon_x}}$
- Validation uncertainties used to define a model validation criterion
  - Pass condition: $\frac{\varepsilon_x}{U_{\varepsilon_x}} \leq 1$
  - Fail condition: $\frac{\varepsilon_x}{U_{\varepsilon_x}} > 1$

*American Society of Mechanical Engineers, “ASME V&V 20-2009 – Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer,” New York, NY, November 2009.

**Taylor, J.R., An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, University Science Books, 2nd Ed., August 1996

Ifan, H. and T. Hughes, Measurements And Their Uncertainties: A Practical Guide To Modern Error Analysis, Oxford University Press, 1st Ed., October 2010.

Validation Criterion

Pass Condition: $\frac{\varepsilon_x}{U_{\varepsilon_x}} \leq 1$

Fail Condition: $\frac{\varepsilon_x}{U_{\varepsilon_x}} > 1$

Metric	Units	RMS of Normalized Errors/ U_{ε_x}
PCT	K	0.57
PCT Axial Location	m	0.36
T(*z*)	K	0.74
T(*x*)	K	0.64
T(*y*)	K	0.66
$\dot{m}$	kg/s	1.25
Combined RMS of Normalized Errors Divided by Validation Uncertainty		**0.75**

Overall, **model 1 passes the validation criterion**

– Combined RMS of the normalized errors, divided by the validation uncertainty, for this model is less than 1

Summary

Horizontal Dry Cask Simulator Blind Modeling Validation Exercise

- HDCS tests completed April 2020
- Final model results from modeling institutions submitted June 2020
- Validation exercise results reported in “Blind Modeling Validation Exercises Using a Horizontal Dry Cask Simulator” – SAND2020-10344 R
  - https://www.osti.gov/servlets/purl/1669198
- Key takeaways
  - All models agreed with experiment to within 5%
    - Based on most significant comparison metrics
  - Additional uncertainty quantification for Model 1 shown to satisfy validation criterion
    - Criterion derived from ASME V&V 20