U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

Clean. Reliable. Nuclear.

High Burnup Spent Fuel Data Project & Thermal Modeling and Analysis

Brady Hanson

PNNL-SA-13859

NWTRB Meeting

Albuquerque, NM

October 24, 2018

Outline

- Loading of the TN-32B "Demo Cask"
- Thermal modeling
- Temperature measurements and comparison to models
- Gas samples
- Future plans
  - Demo cask and sister rods
  - Thermal modeling
  - Drying studies

Low Burnup Demonstration

- CASTOR V/21 thermal tests[1]
  - Cask loaded Sept. 1985
  - Fuel burnups 29.8 – 35.7 GWd/MTU
  - Cooling times 26-46 months
  - Cask heat load **28.4 kW**
  - Assembly heat load **1.00-1.83 kW**
  - Estimated Peak Clad Temperature (PCT) under vacuum **424°C**
- Low burnup "Demo"[2]
  - Cask opened Sept 1999
  - 14 year storage period
  - 12 rods pulled for examination
  - 3 rods sent to ANL for detailed examination and testing

Photo courtesy of Idaho National Laboratory

1 *The Castor-V/21 PWR Spent-Fuel Storage Cask: Testing and* Analysis, EPRI NP-4887, November 1986.

2 *Dry Cask Storage Characterization Project,* EPRI 1002882, September 2002

- "Based on the 1999 examination and testing results, there was no evidence of cask, shielding, or fuel rod degradation during long-term (14 years) storage that would affect cask performance or fuel integrity."[2]

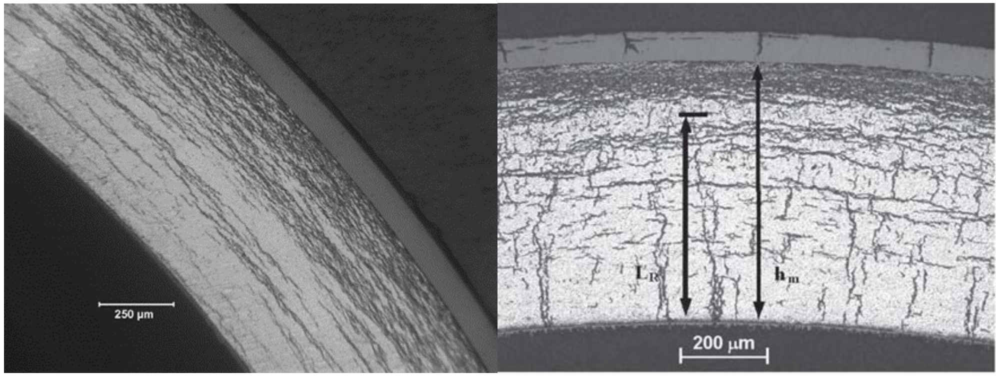
High Burnup Demonstration

- High burnup ≥ 45 GWd/MTU
- Typical characteristics
  - Increased fission gas release
  - Increased cladding oxidation
  - Increased hydrogen content
    - Hydrides
- NRC limits burnup to 62 GWd/MTU peak rod-average burnup
- Practical limits
  - 5 w/o ^{235}U enrichment
  - US cycle lengths of 18 or 24 months
- Potential for hydride reorientation and cladding creep if hoop stress and temperatures are large enough
- Confirm technical basis with high burnup fuel under real dry storage conditions

GC-859 Reported Average Assembly-Average Discharge Burnup

	Number of Assemblies		Average burnup (GWd/MTU)	
Year	BWR	PWR	BWR	PWR
2000	4603	3122	**38.3**	**44.9**
2001	3617	2896	**40.1**	**45.5**
2002	4148	3765	**40.2**	**46.0**
2003	4584	3585	**39.5**	**46.4**
2004	4431	2669	**42.8**	**46.9**
2005	4075	3704	**42.8**	**46.6**
2006	3995	3516	**43.1**	**46.9**
2007	4574	2782	**43.3**	**46.9**
2008	4480	3550	**43.1**	**47.2**
2009	4395	3677	**45.1**	**46.5**
2010	4617	2856	**44.3**	**46.8**
2011	4105	3663	**45.1**	**46.6**
2012	4476	3759	**45.0**	**44.5**
2013	3246	1534	**44.1**	**45.4**

U.S. Energy Information Administration, Form GC-859, "Nuclear Fuel Data Survey" (2013). https://www.eia.gov/nuclear/spent_fuel/ussnftab3.cfm



Micrographs courtesy of Mike Billone, ANL. They are illustrative only, not from sister rods.

Final Fuel Selection – Loading Pattern

- DOE contract with EPRI awarded April 2013
- Dominion Energy
  - 4 cladding types
- TN-32 B cask
  - Loaded November 2017
  - Burnups 50 – 55.5 GWd/MTU
  - Cooling time 5 – 30 yr
  - Assembly heat load 0.574 – 1.142 kW
- Iterations on fuel assemblies to be loaded
  - Maximize decay heat
  - Attempt to approach 400°C PCT
  - Can't exceed thermal limits on other materials

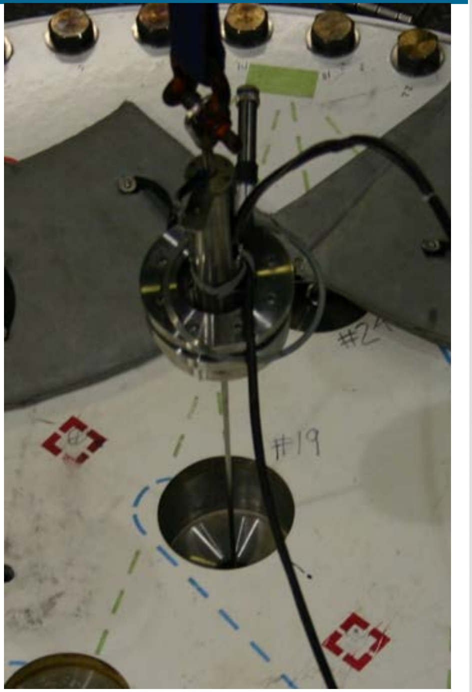
	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 912.2 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 978.2 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 914.4 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 799.5 W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 800.9 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1008.6 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1142.4 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1121.2 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 975.1 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 814.5 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 802.6 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.0 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 573.8 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1037.0 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1124.8 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 941.3 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 961.7 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1131.1 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 920.2 W	20 0A4* Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 646.2 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1135.8 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 941.2 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 934.7 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 914.2 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1133.7 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1136.3 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 988.2 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 916.9 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 914.2 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 968.0 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 927.7 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 804.3 W	High Priority Assys

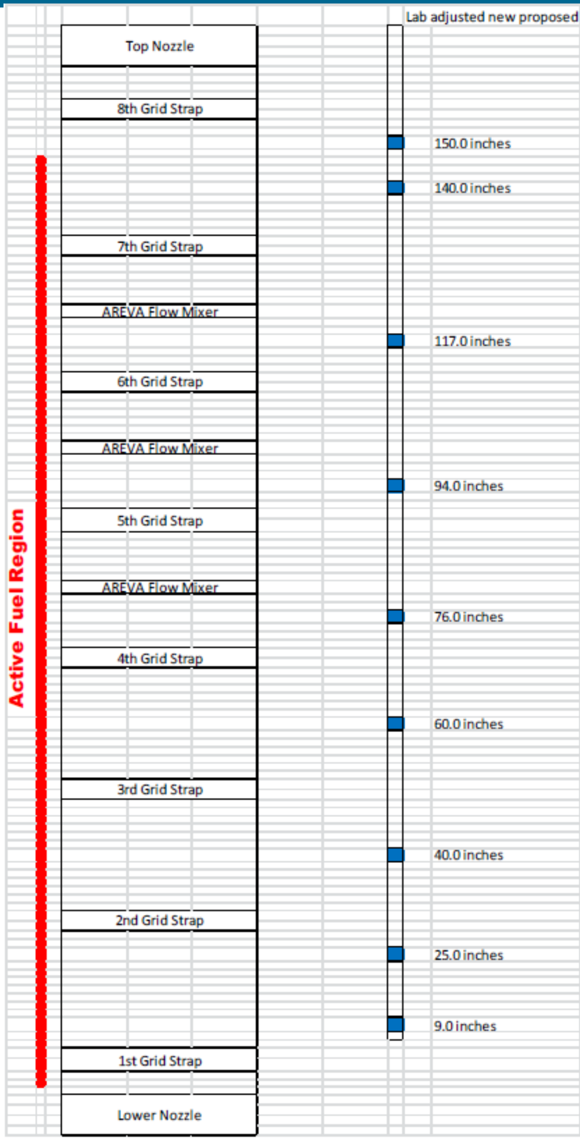
KEY
Location (Thermocouple)
Assy ID (high priority)
Cladding , BU
Enr, #cycles, Yrs cooled
Decay Heatloading

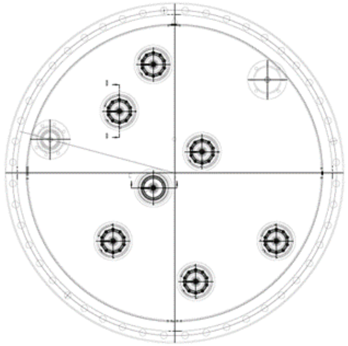
Clad Type	Qty	Burnup Range
Zr-4	1	50.6
low tin Zr-4	1	50
Zirlo	12	51.9 - 55.5
M5	18	50.5 - 53.5

Thermocouple Lances

- 63 thermocouples
  - 7 lances each with 9 axially spaced thermocouples
  - Gives both radial and axial profiles within the cask
- Lances installed into assembly guide tube locations
- Jacking plate and double metallic o-ring for confinement







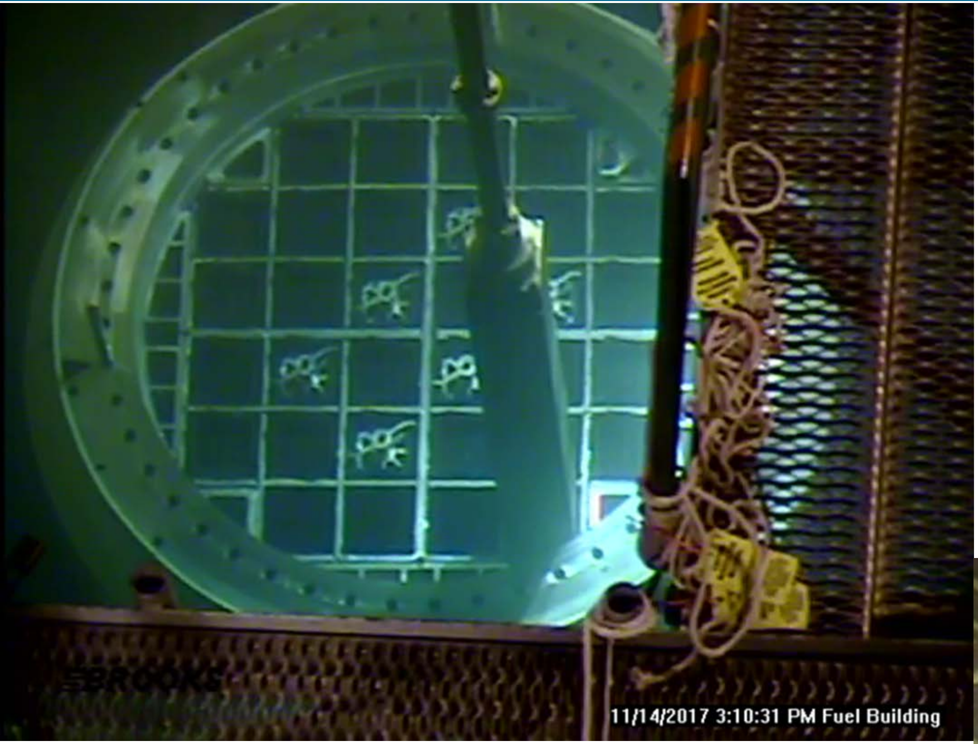
Thermocouple radial locations

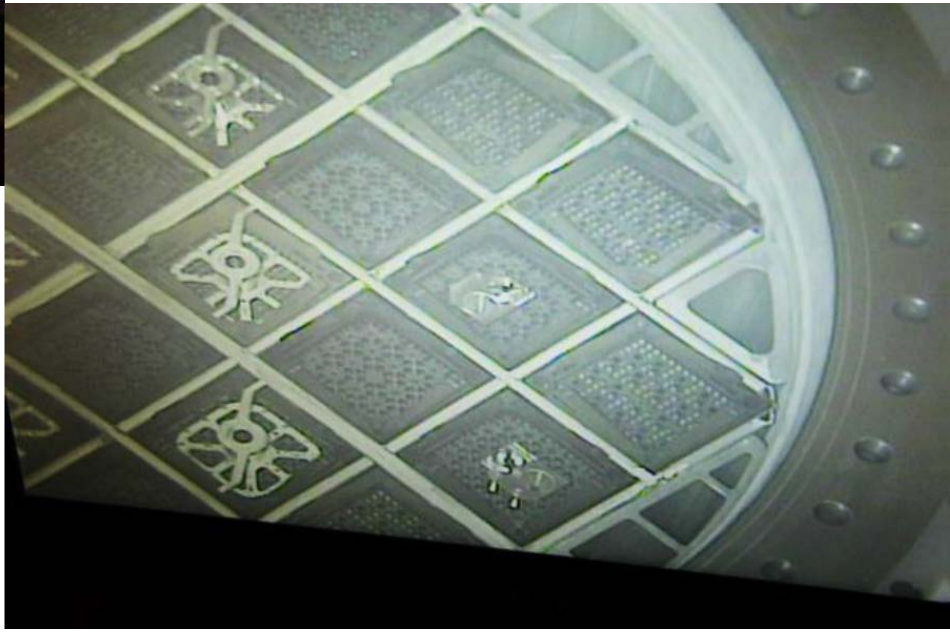
TC lance photo courtesy of Dominion Energy

Cask Receipt

Photos courtesy of Dominion Energy

Cask Loading and Funnel Guide Installation





Photos courtesy of Dominion Energy

Cask Removal from Spent Fuel Pool

Photos courtesy of Dominion Energy

Placement in Decontamination Bay

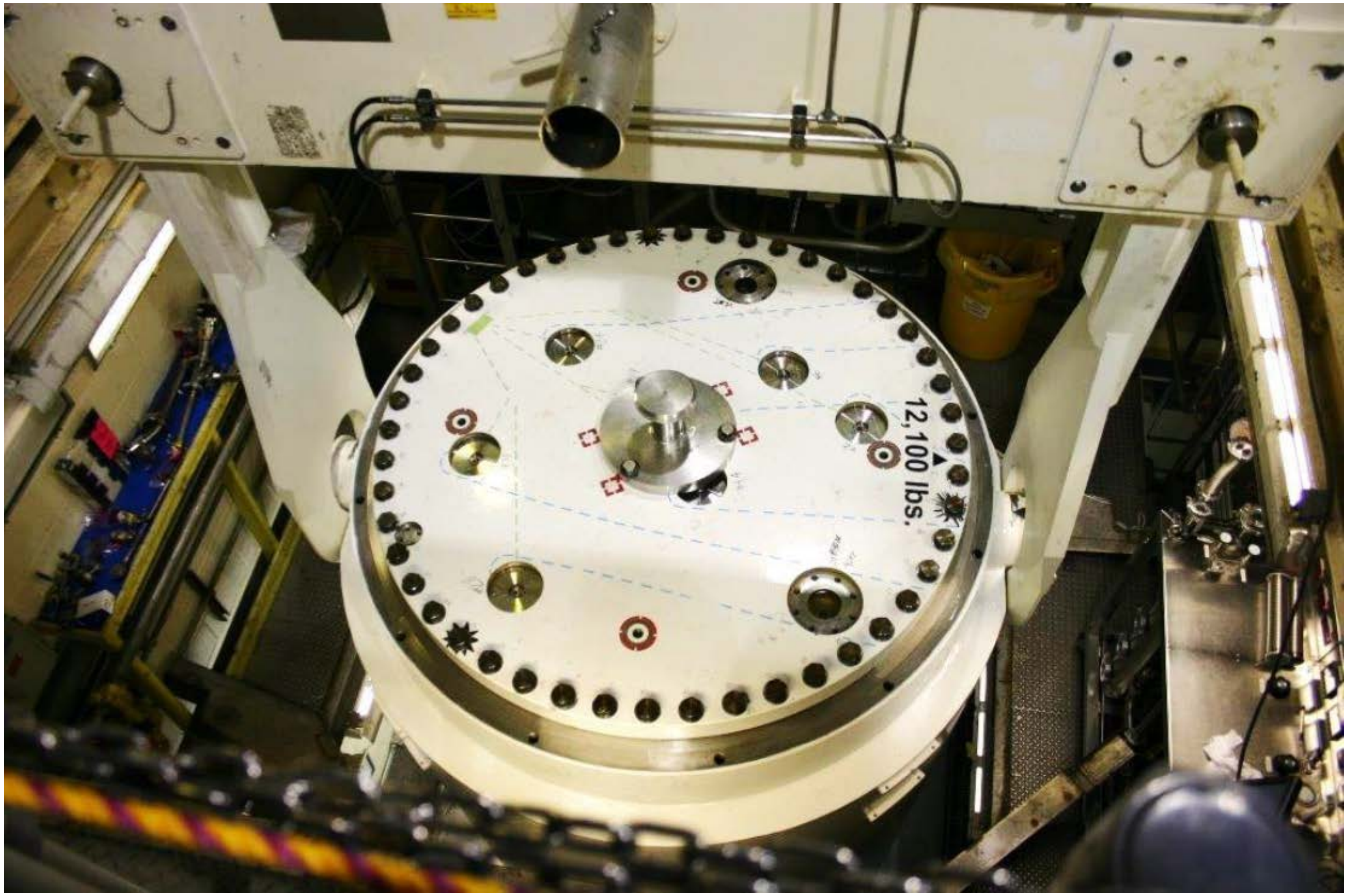


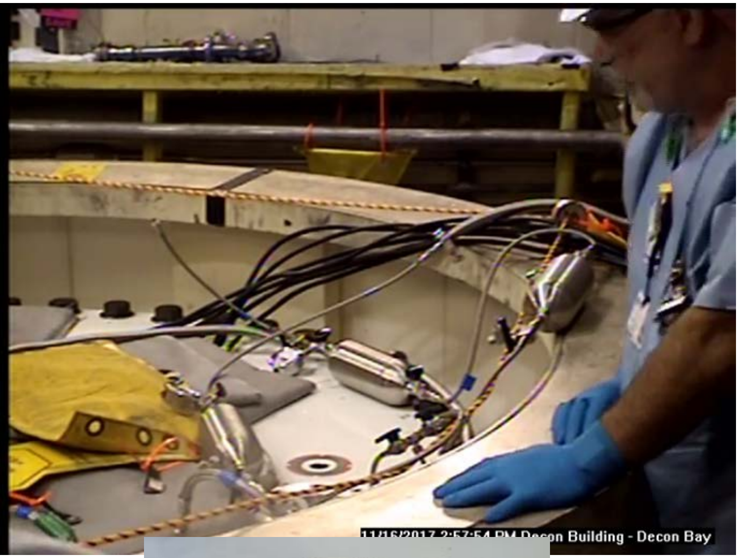
Photo courtesy of Dominion Energy

Loading Timeline

Activity	Date	Time	Duration
Load 1st assembly	11/14	1122	
Load last assembly	11/14	1530	4.1 hrs
Remove cask from spent fuel pool	11/14	2040	
Begin draining	11/15	1722	
Complete draining	11/15	1805	0.7 hrs
Water in cask			22.7 hrs
Blowdowns to remove residual water			4.5 hrs
Begin drying	11/16	0035	
Drying duration			8.4 hrs
Begin 1st He backfill	11/16	0900	
Complete He backfill	11/16	1024	1.4 hrs
Final pressure check	11/28	1155	
Thermal soak			12.2 days
Leave decon bay	11/30	909	
Set cask on pad	11/30	1124	

Table courtesy of Keith Waldrop, EPRI project manager

Gas Sampling



Vent port with quick-connect

- 3 Samples taken
  - 1st ~5 hours after He backfill
  - 2nd ~5 days after sample 1
  - 3rd ~7 days after sample 2

- 3 containers each time
- First vessel was a purge to capture air contamination from coupling joint
- Second vessel analyzed at North Anna for ^{85}Kr, O_2, H_2, and H_2O
- Third vessel sent to SNL for same analyses plus CH_4

Photos courtesy of Dominion Energy

Cask External Surface Temperature

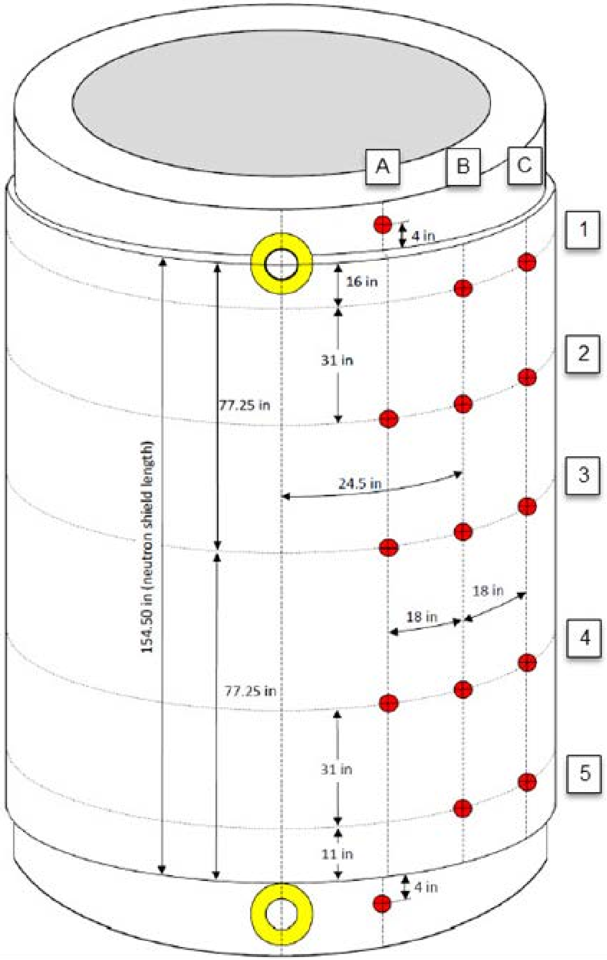


Photo courtesy of Dominion Energy

Cask Transferred to North Anna ISFSI Pad

Temperature is recorded hourly

Data will be retrieved quarterly

Photos courtesy of Dominion Energy

Evolution of Thermal Modeling Results

Peak Cladding Temperature

	270	284	279	267	
267	297	312	312	295	268
275	311	300	315	312	283
283	311	307	301	313	284
271	291	312	312	296	272
	273	284	281	268	

Minimum Cladding Temperature

	156	156	156	156	
156	156	157	157	157	156
156	157	158	157	156	156
156	157	156	157	156	156
156	157	157	157	157	156
	158	156	155	156	

FSAR dimensions and properties; T_{amb} = 100°F; Decay heat=36.8 kW

Peak Cladding Temperature

	238	247	244	234	
234	257	269	268	256	235
241	268	255	271	269	246
247	268	268	260	269	247
238	255	269	269	257	238
	239	248	246	235	

Minimum Cladding Temperature

	138	138	138	138	
138	138	138	138	138	138
138	138	139	138	138	138
138	138	139	139	138	138
138	139	138	138	138	138
	139	138	138	138	

FSAR dimensions and properties; T_{amb} = 100°F; Decay heat=30.6 kW

COBRA-SFS

Peak Cladding Temperature

	226	235	232	222	
222	244	255	255	243	222
229	255	245	258	255	234
234	255	255	247	255	234
226	242	256	255	244	226
	226	235	233	223	

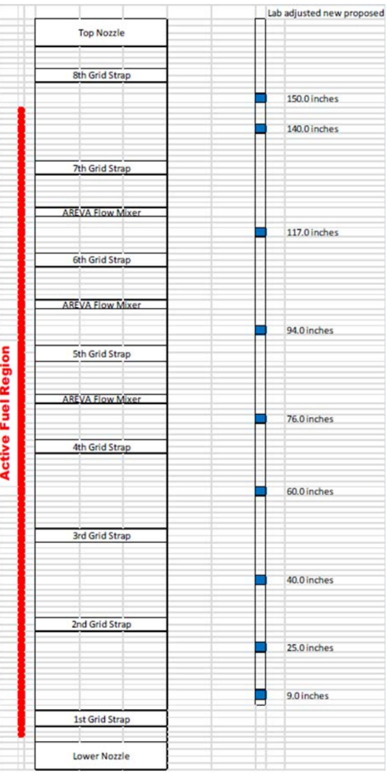
STAR-CCM+

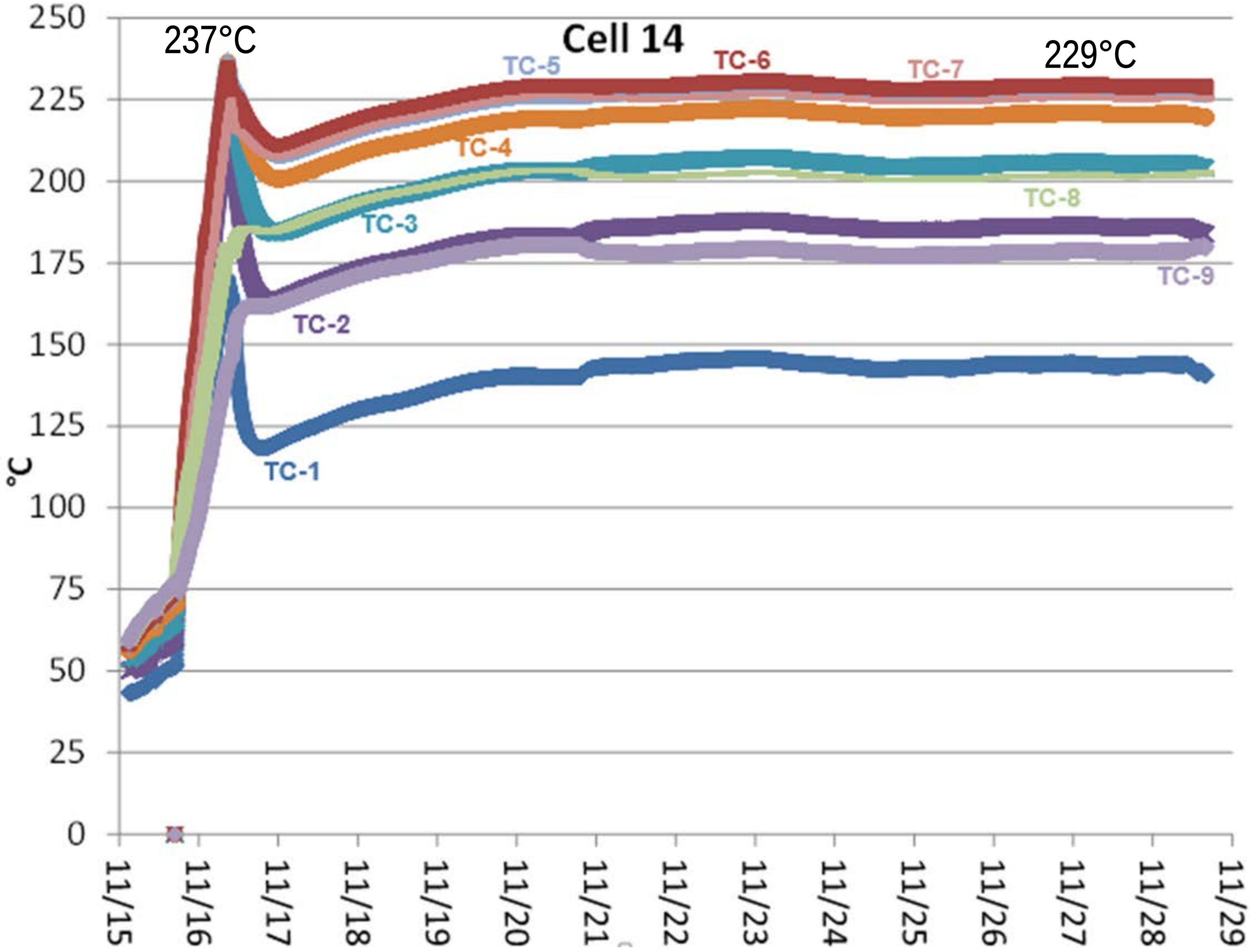
Peak Cladding Temperature

	211	234	231	206	
214	241	258	257	240	215
230	261	245	263	262	237
237	262	260	248	262	237
221	238	258	258	241	220
	212	234	232	206	

FSAR dimensions and properties; T_{amb} = 75°F; Decay heat=30.5 kW

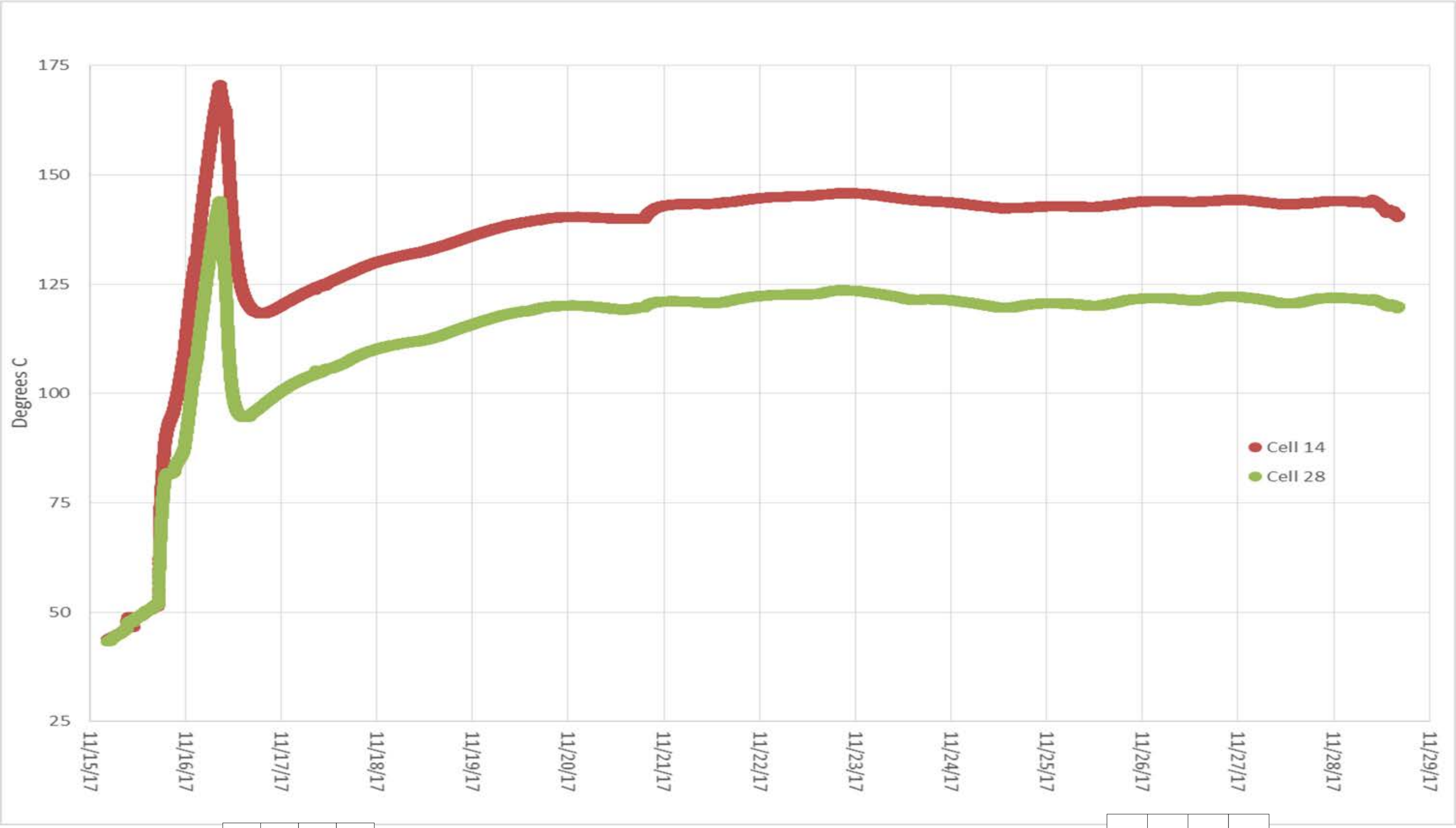
Measured Temperatures in Hottest Assembly



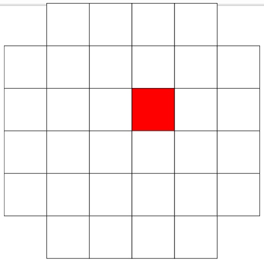


TC-1 is thermocouple near bottom TC-9 is thermocouple near top

Measured Temperatures at 9” Above Cask Bottom



Cell 14



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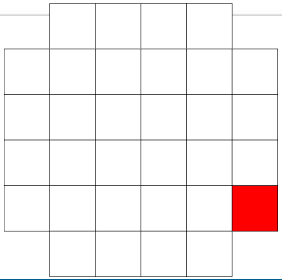
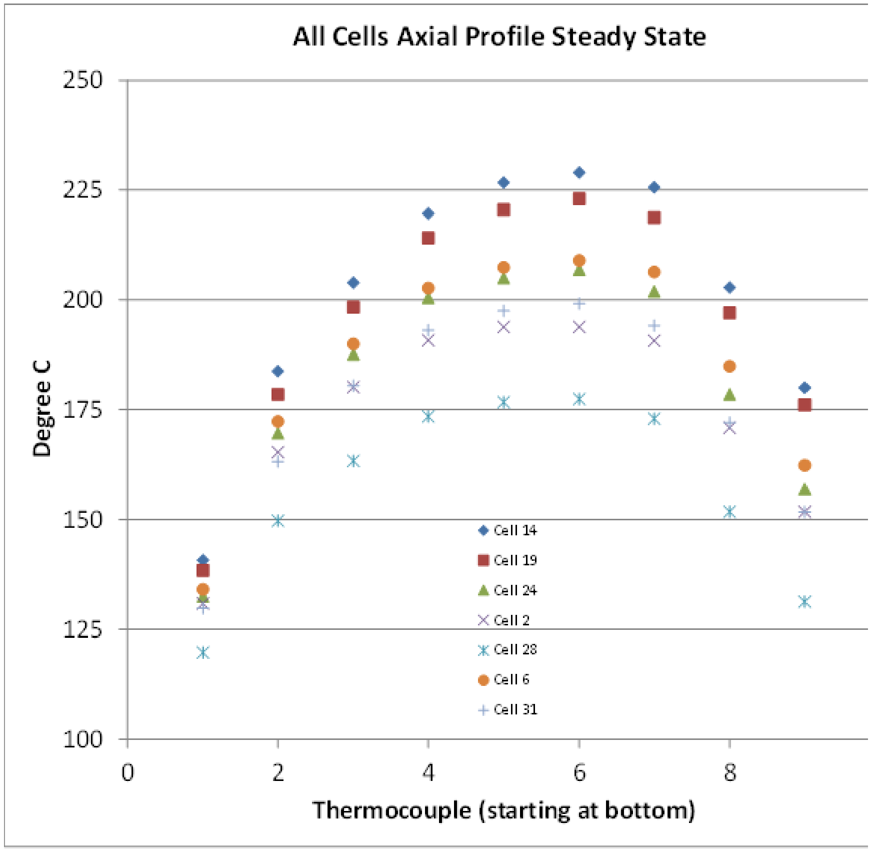
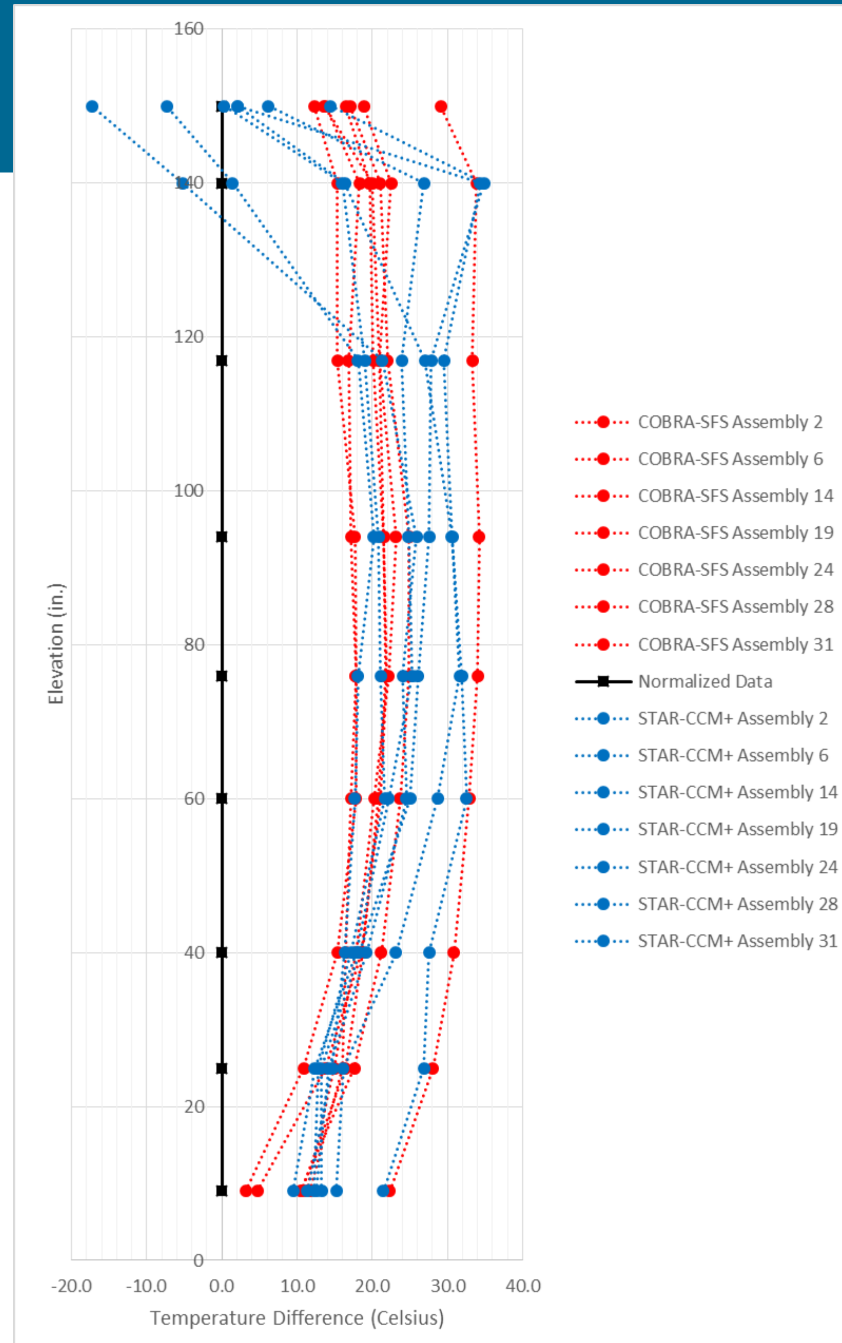


Comparison of Models to Measured at Steady Sate



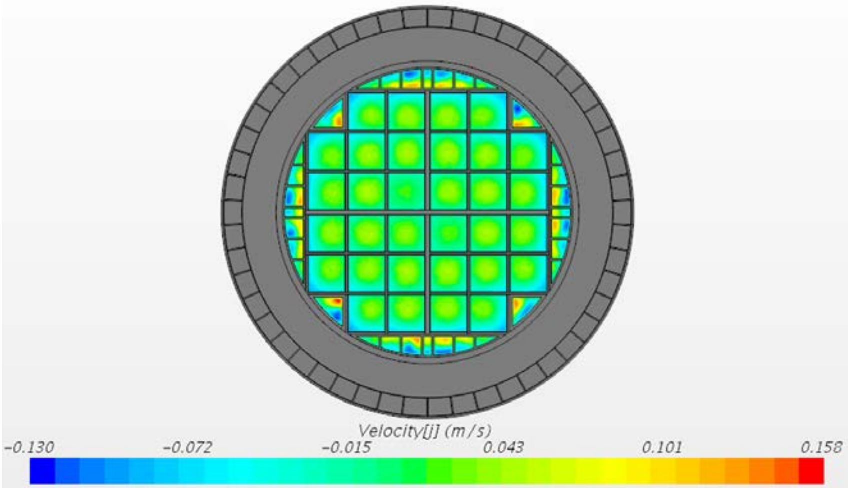


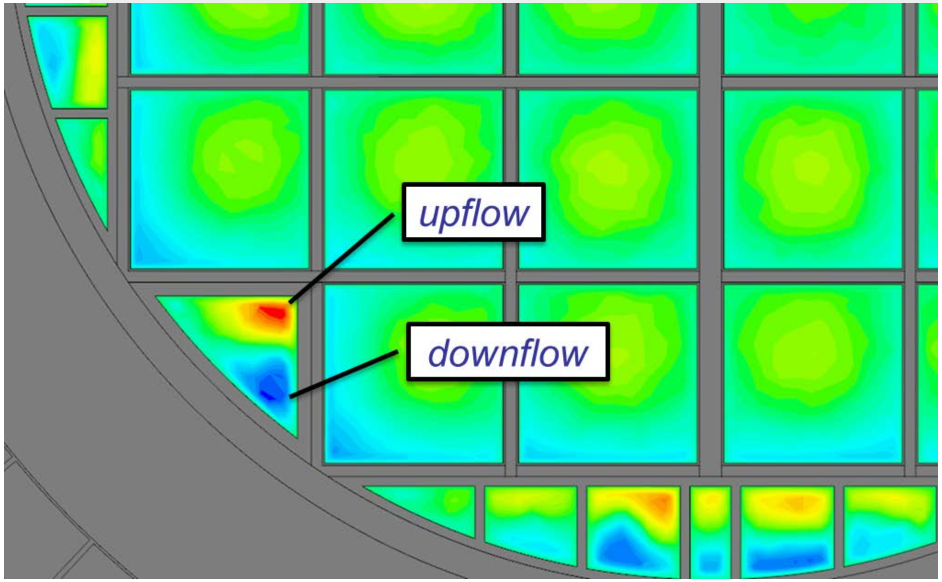
Thermal Modeling of TN-32B CASK for High Burnup Spent Fuel Data Project,
JA Fort, DJ Richmond, JM Cuta, and SR Suffield. PNNL-24549 Rev 2. 9/2018

Surface temperature boundary condition

Model Sensitivity Runs

Condition	PCT Difference from Baseline (˚C)
Increase Basket Emissivity to 0.8	-2
Closed rail-shell gaps	-2
99% Decay Heat	-2
98% Decay Heat	-3
95% Decay Heat	-8
90% Decay Heat	-16
Basket-Rail Gap 0.15 in.	-5
Basket-Rail Gap 0.10 in.	-12
Basket-Rail Gap 0.05 in.	-20



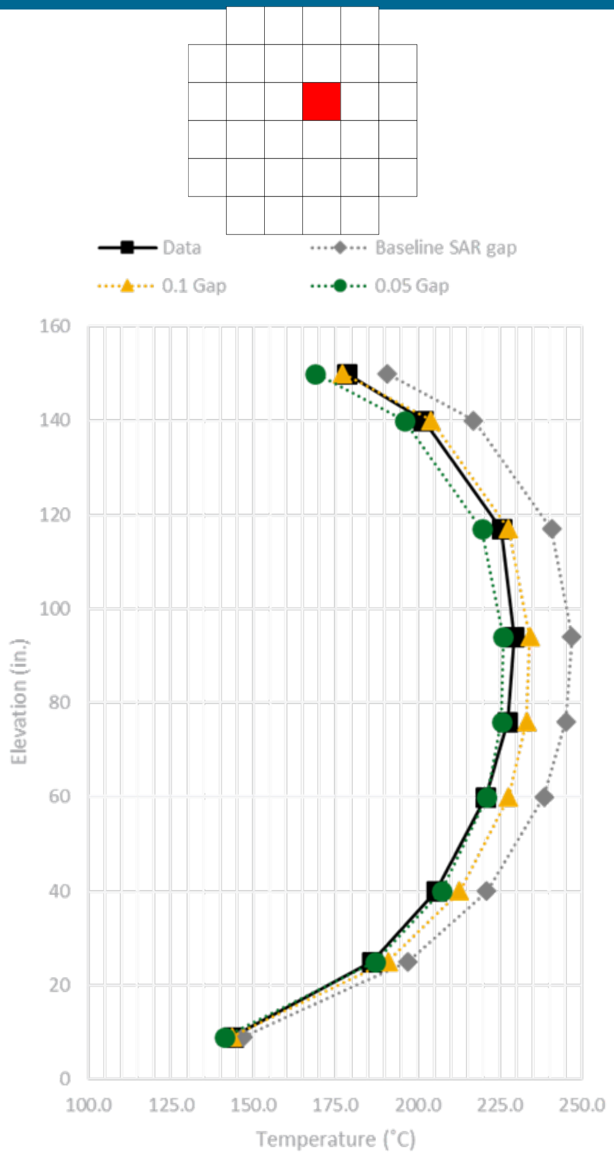


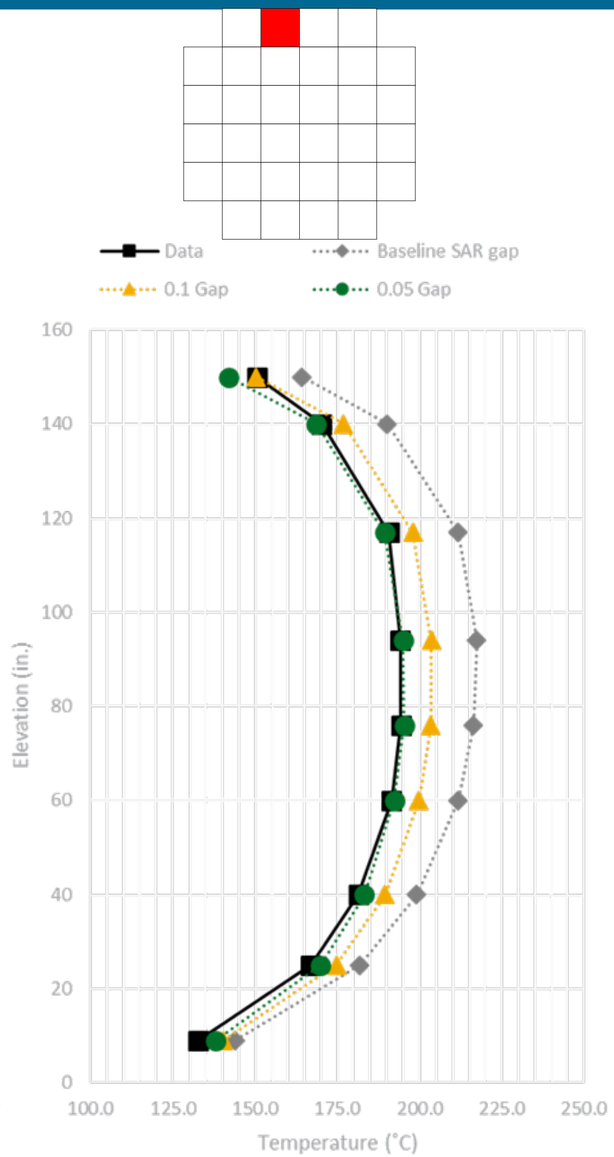
Temperatures are biased high because of the basket-rail gap provided by the FSAR or conservative decay heat calculations

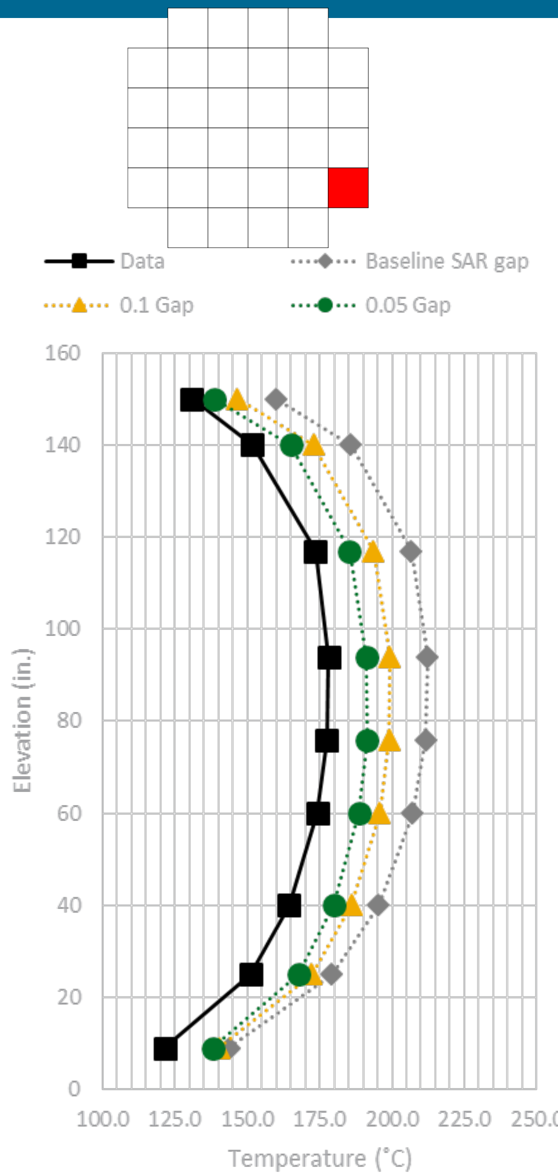
Temperatures are uncertain because of the unknown axial and circumferential gap variability

Thermal Modeling of TN-32B CASK for High Burnup Spent Fuel Data Project, JA Fort, DJ Richmond, JM Cuta, and SR Suffield. PNNL-24549 Rev 2. 9/2018

Adjusting Basket-Rail Gap Size





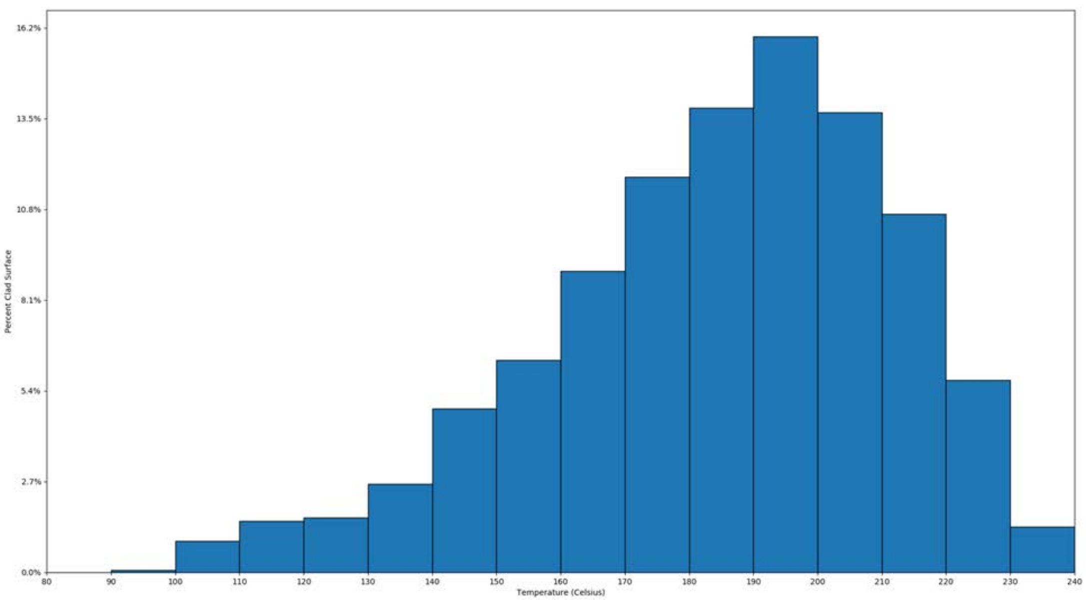


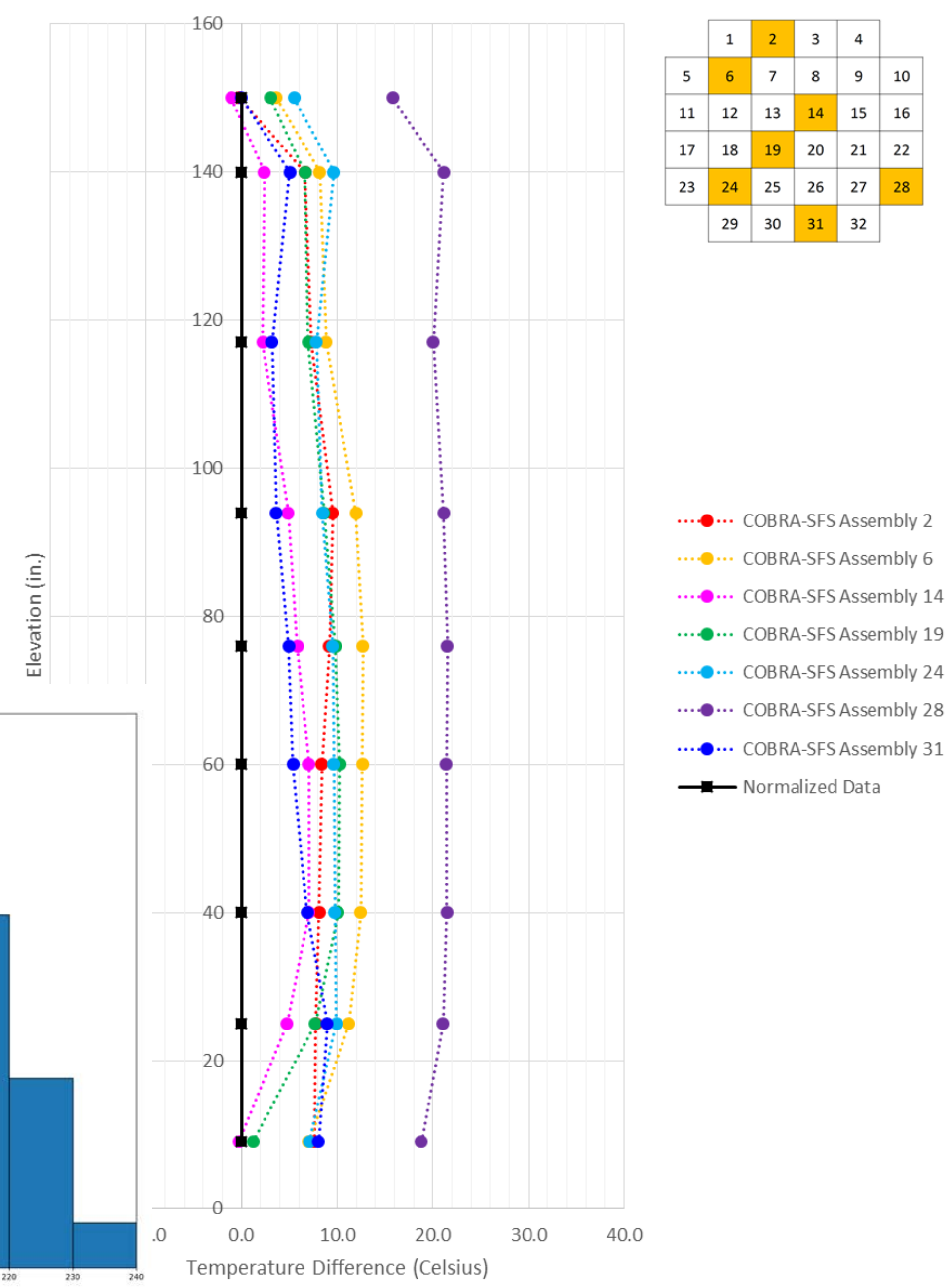
Courtesy David Richmond and Jim Fort, PNNL

Adjusted Best Estimate

PCT

	205	214	211	201	
201	224	235	235	223	202
208	235	224	238	235	213
213	235	235	227	235	213
206	222	236	235	224	206
	206	215	213	202	





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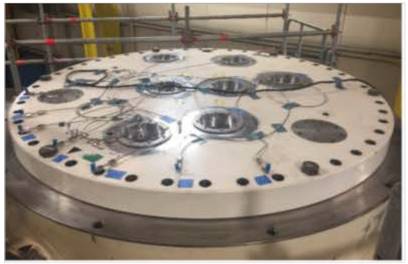
Phase II Round Robin Summary



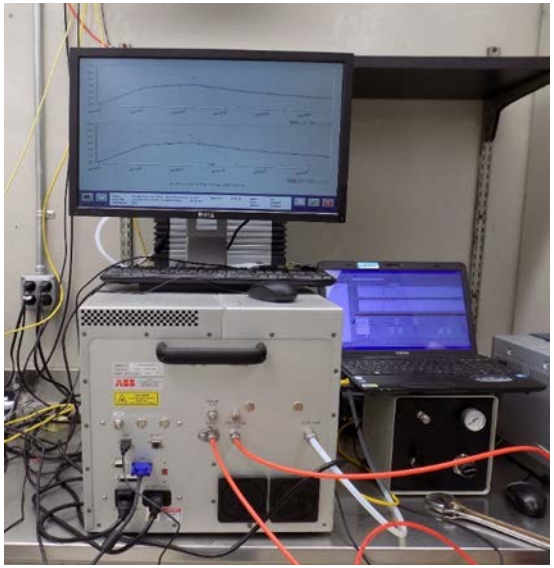
- Steady state PCTs from all models and measurements significantly lower than the design licensing basis:

Parameter	FSAR	LAR	Best-Estimate	HBU Cask Measurements
PCT (model vs data)	348°C	318°C	254-288°C	229°C
Heat Loadouts	36.96kW	32.934kW	30.456kW	30.456kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?

Slide courtesy of Al Csontos, Co-chair of EPRI ESCP Thermal Subcommittee

Gas Sampling

- IRP study at University of South Carolina showed no detectable water after vacuum drying
  - Except “failed” rod had ~5 mL
- Moisture content still being evaluated
  - Not easy to relate measurement from sample container (ppm) to cask conditions (grams)
  - North Anna equipment uses Los Gatos Water Vapor Isotope Analyzer (WVIA)
    - Based on laser absorption technology
    - Recently completed a calibration run using known moisture content gases
  - Sandia has used different techniques
    - Calibration run to be performed soon



Moisture analysis equipment

Summary

- Models can accurately predict cask and component temperatures when accurate inputs are provided
- Bias for high predicted temperatures comes from using known conservatisms
  - Decay heat
  - Ambient temperature
  - Conduction gaps in FSAR/CoC (e.g., basket/rail gaps)
- "Gaps" important for conductive systems, including horizontal
  - Gravity and mass will close gaps at the bottom of the canister
- DOE, EPRI, NRC, and International groups under ESCP Thermal Subcommittee working to understand conservatisms/bias and address uncertainties
- More accurate temperatures become important when close to a thermal limit or threshold where degradation may occur
  - Hoop stress appears to be much more important than temperatures for the range expected in the U.S.
- Quantification of residual water after drying still to be determined

Future Work

- Complete Phase 1 Round Robin thermal analysis (Sam Durbin)
- EPRI to release Phase 2 Round Robin report
- Model Demo cask on the ISFSI pad and compare to data-
- Perform transient analyses and compare to demo drying data
- Perform Phase 3 testing for horizontal configuration (Sam Durbin)
- Determine need for testing of other configurations, fuel types, and scale
- SNL to perform calibrations and quantify water in gas samples
- SFWST is supporting a comprehensive analysis being led by ASTM International C26.13 to determine consequences of residual water after drying
- SFWST has issued a call for a follow-on IRP to examine effects of temperature gradients, scale, and other variables
- SFWST is conducting small scale tests to relate the results of gas moisture analyses to internal conditions

Continuation of the "Demo"

- Cask remains on the North Anna ISFSI and data is being recorded hourly and collected quarterly
- No additional gas sampling of the Demo cask is planned until end of the storage period prior to transportation
- SFWST and EPRI looking into sampling of other systems
- DOE is exploring options for where to ship the Demo cask after ~10 years
- Sister rod testing is expected to bound behavior of rods in the Demo cask

Questions?

Clean. **Reliable.** **Nuclear.**