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

Spent Fuel and Waste Science and Technology (SFWST)

Clean. Reliable. Nuclear.

SFWST Perspectives on Thermal Modeling for Storage and Transportation of Commercial Spent Fuel

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Summary of SFWST Perspective

- DOE prefers no additional cladding failures (through-wall penetration) resulting from drying, extended storage, or normal conditions of transport
  - To facilitate either repackaging, if necessary, or for cladding credit in a deep geologic repository
- Thermal modeling is mature and the physics and phenomena well understood
- Inputs to the models are typically conservative and biased, such that predicted temperatures are higher than actual temperatures
- Temperatures are important because they drive degradation phenomena
  - The closer the temperature is to a limit causing degradation, the better the inputs should be unless it is shown the inputs are conservative and biased towards higher temperatures
- Peak Cladding Temperature represents a very small fraction of total cladding
- From a cladding perspective, degradation effects operate on a continuum and there is no “cliff edge” at 400˚C
  - Flexibility to a strict 400˚C limit is available while still meeting the DOE preference of no additional cladding failure

Background – Where Did 400°C Come From?

- CASTOR V/21 thermal tests
  - **15 × 15** assemblies
  - Assembly burnups **29.8-35.7 GWd/MTU**
  - Cask heat load **28.4 kW**
  - Assembly heat load **1.00-1.83 kW**
  - Decay times
    - 8 assemblies @ **26 months**
    - 13 assemblies @ 46 months
  - Estimated Peak Cladding Temperature (PCT) under vacuum **424°C**

Photo Courtesy of Idaho National Laboratory

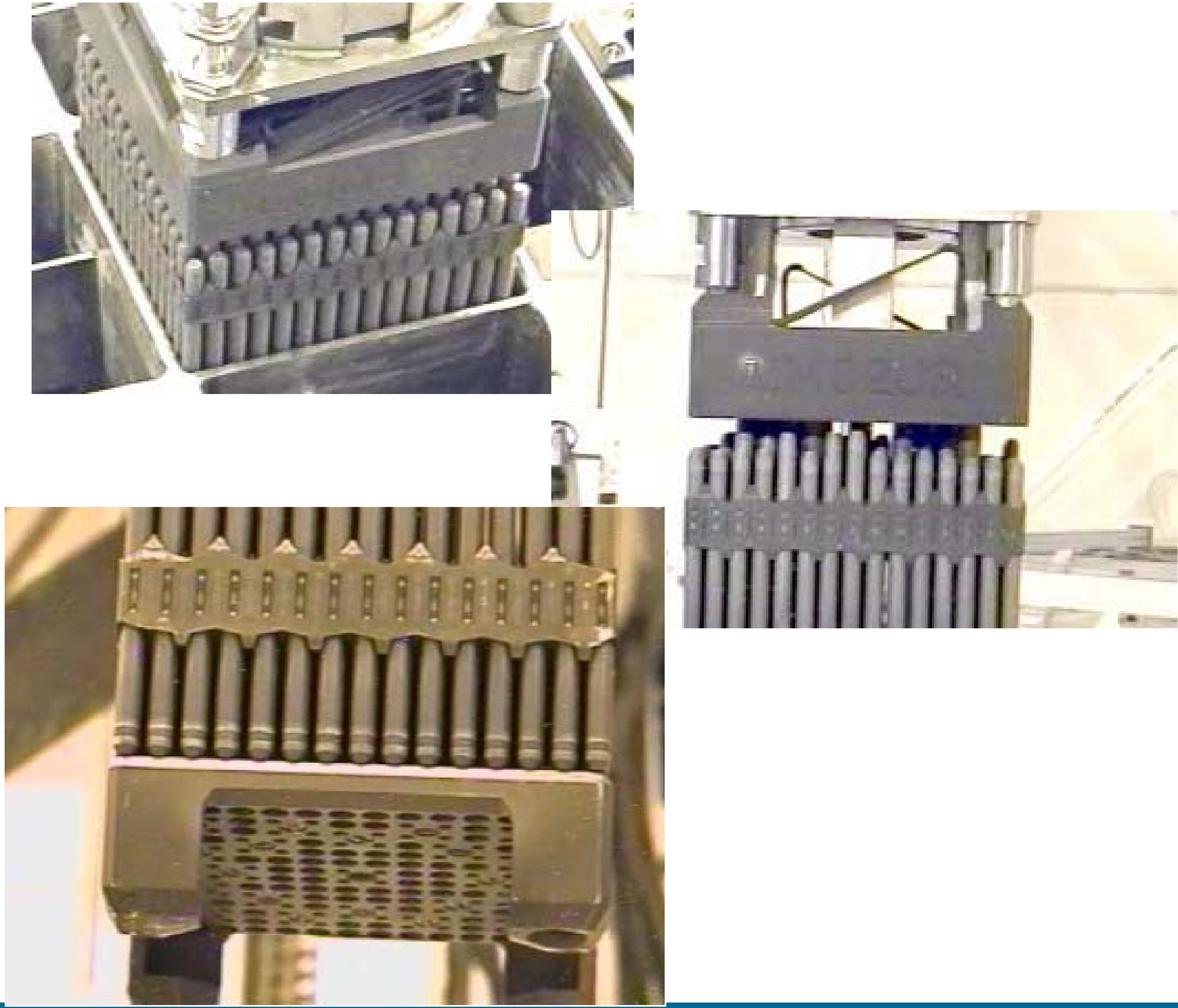
Run No	Loading	Orientation	Backfill	Cask Heat Load, kW	Ambient Temp, °C	Measured Guide Tube Temp, °C	Estimated Peak Clad. Temp, °C
1	Full	Vertical	Helium	28.4	27	347	352
2	Full	Vertical	Nitrogen	28.4	24	358	368
3	Full	Vertical	Vacuum	28.4	25	414	424
4	Full	Horizontal	Helium	28.4	24	360	365
5	Full	Horizontal	Nitrogen	28.4	24	395	405

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

Dry Cask Storage Characterization Project

EPRI 1002882, September 2002

- Thermal tests conducted Sep. 1985
- CASTOR V/21 opened Sep. 1999
- No fission product gas detected → no rod failure
- All 21 assemblies lifted from the cask
  - Little sticking
  - No significant assembly bowing or development of corrosion products
- Visual examination
- 12 rods from assembly T11 removed
  - Profilometry (creep)
  - End of life rod internal pressure (EOL RIP) on 4 rods (3.43 – 3.61 MPa)
  - Metallography (hydrides), hydrogen content, microhardness on 3 rods
  - Laboratory creep tests (on 2 rods)



Conclusions About Low Burnup Fuel Rod Performance After 14 Years of Storage (EPRI 1002882, September 2002)

- Gas analysis showed ~0.5% air after the 1994 He backfill
  - Presence of the residual air appears to have no detrimental effect on the fuel or cask components
- Very little thermal creep
  - Best estimate model suggests <0.1%
- Within experimental uncertainty, no additional fission gas release
- No evidence of hydrogen pickup or hydride reorientation
  - Very few, if any, radial hydrides (hoop stress <62 MPa @ 415℃)
  - Possible migration of hydrogen from fuel midplane to cooler upper plenum
- Little, if any, cladding annealing based on microhardness
- Residual creep strain >1% for thermal creep temperatures of 380˚C (hoop stress of 220 MPa) and 400˚C (190 MPa) with no failure (laboratory creep tests)

Background – Other Thermal Demonstrations

- TN-24P with consolidated fuel
  - Cask heat load **~23 kW**
  - Canister heat load **0.7-1.18 kW**
    - Average **0.97 kW**
  - Decay times **6.2- 12.2 years**
  - Post-test COBRA-SFS predictions using a more detailed fuel model were within
    - -13˚C for the vertical/nitrogen case
    - Mean difference of 6˚C
    - Standard deviation ±5˚C

Run No.	Orientation	Backfill	Cask Heat Load, kW	Ambient Temp, °C	Side Surface Temp, °C	Measured Peak Basket Temp, °C	Measured Guide Tube Temp, °C	Estimated Peak Clad. Temp, °C
1	Vertical	Helium	23.3	22	71	203	211	211
2	Vertical	Nitrogen	23.3	16	71	240	267	268
3	Vertical	Vacuum	23.2	22	70	262	291	293
4	Horizontal	Helium	23.2	17	71	198	205	205
5	Horizontal	Nitrogen	23.2	22	69	229	251	252
6	Horizontal	Vacuum	23.1	23	73	252	280	282
7[a]	Horizontal	Vacuum	23.1	24	85	255	280	282

[a]The top and bottom of the cask were insulated during this run. This run was sponsored by Transnucleaire.

Testing and Analyses of the TN-24P PWR Spent-Fuel Dry Storage Cask Loaded with Consolidated Fuel, EPRI NP-6191, February 1989

ISG-11, Rev 2

- ISG-11, Rev 2 (7/30/2002)
  - Removed the 1% creep strain limit
    - Deformation caused by creep will proceed slowly over time and will decrease the rod pressure
    - Decreasing cladding temperature decreases the hoop stress, will slow the creep rate
    - In the unlikely event that breaching of the cladding due to creep occurs, it will not result in gross rupture
  - Maximum cladding temperature should not exceed 400˚C (570˚C for accidents based on creep)
  - Criteria to limit hydride reorientation, also a limit of 400˚C for normal conditions

“It should be noted that, in any one storage cask, there will be a distribution of cladding temperatures less than 400˚C resulting in distributions in the rod internal pressures and cladding hoop stresses. It is expected that due to these distributions a small fraction of the rods will experience the temperature and stress conditions that could lead to the formation of radial hydrides.”

ISG-11, Rev 3

- ISG-11, Rev 3 (11/17/2003)
  - Maximum calculated fuel cladding temperature should not exceed 400˚C for normal conditions of storage and short-term loading operations
  - Higher short-term temperature allowed for low burnup fuel is the best estimate cladding hoop stress is ≤ 90 MPa
  - Thermal cycling should be limited to <10 cycles with variations <65˚C
  - For off-normal and accident conditions, the maximum cladding temperature should not exceed 570˚C
- References “indicate that stresses greater than 120 MPa are required to initiate the formation of radial hydrides. Other data obtained from unirradiated zirconium-based cladding materials indicate that radial hydrides can form at stresses as low as 90 MPa.”
- “The maximum allowable temperature should be based upon the **peak** rod temperature, not the average rod temperature.”

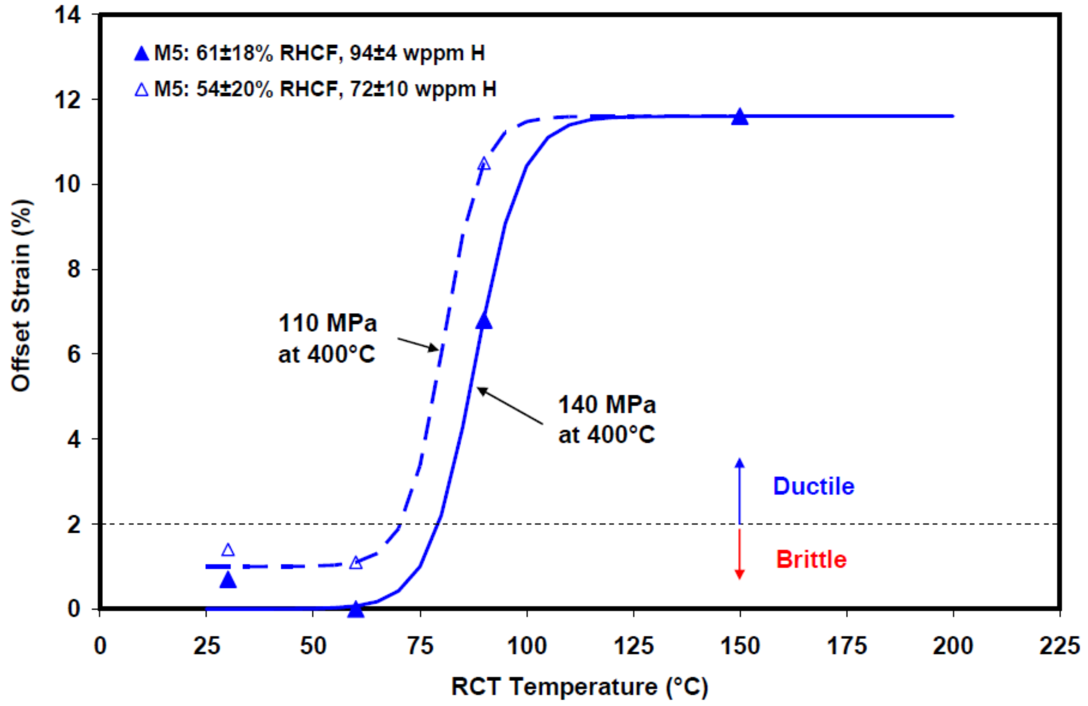
Cask Loading Perspective

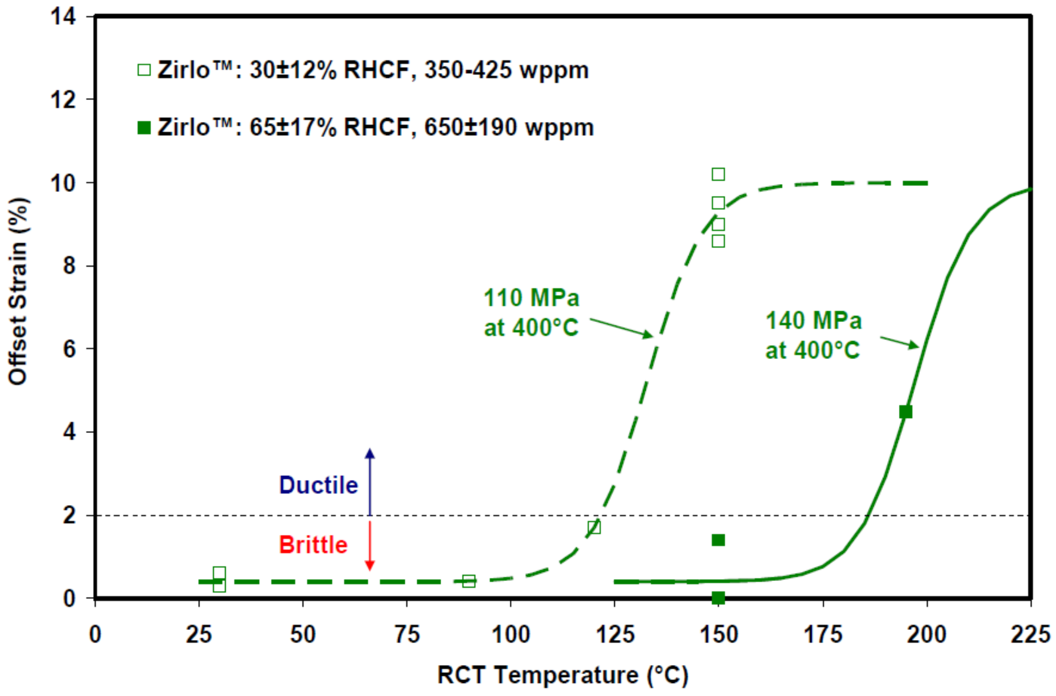
- In September 2004, ~654 systems in service
- As of 3/1/2020, 3,219 casks have been loaded

End of Year	Assemblies	Casks	# Deployed
2019	135,949	3,203	222
2018	126,521	2,981	261
2017	113,797	2,720	249
2016	102,416	2,471	194
2015	93,426	2,277	190
2014	85,166	2,087	195
2013	76,097	1,892	182
2012	67,831	1,710	168
2011	60,304	1,542	155
2010	54,046	1,387	147
2009	47,455	1,240	129
2008	41,856	1,111	152
2007	34,690	959	NA

Data from UxC StoreFuel

Hydride Reorientation – Hoop Stress (Early Studies)





Cladding Alloy	TMT	Burnup, GWd/MTU	Hydrogen Content, wppm	Peak RHT T, °C	Peak RHT Stress, MPa	References
M5®	RXA	63	94±4	400	140	7
		68	72±10	400	110	7
ZIRLO™	CWSRA	70	650±190	400	140	4-6
		70	425±63	400	110	4-6
		70	350±80	400	110	5-6
Zry-4	CWSRA	67	615±82	400	140	5-6
		67	520±90	400	110	5-6
Zry-4	CWSRA	40–55	Not Reported	250–340	85–130	8
Zry-2	RXA	30–59	Not Reported	250–400	16–100	8

Baseline Studies for Ring Compression Testing of High-Burnup Fuel Cladding, Billone, Burtseva, and Liu, *FCRD-USED-2013-000040, Nov 2012.*

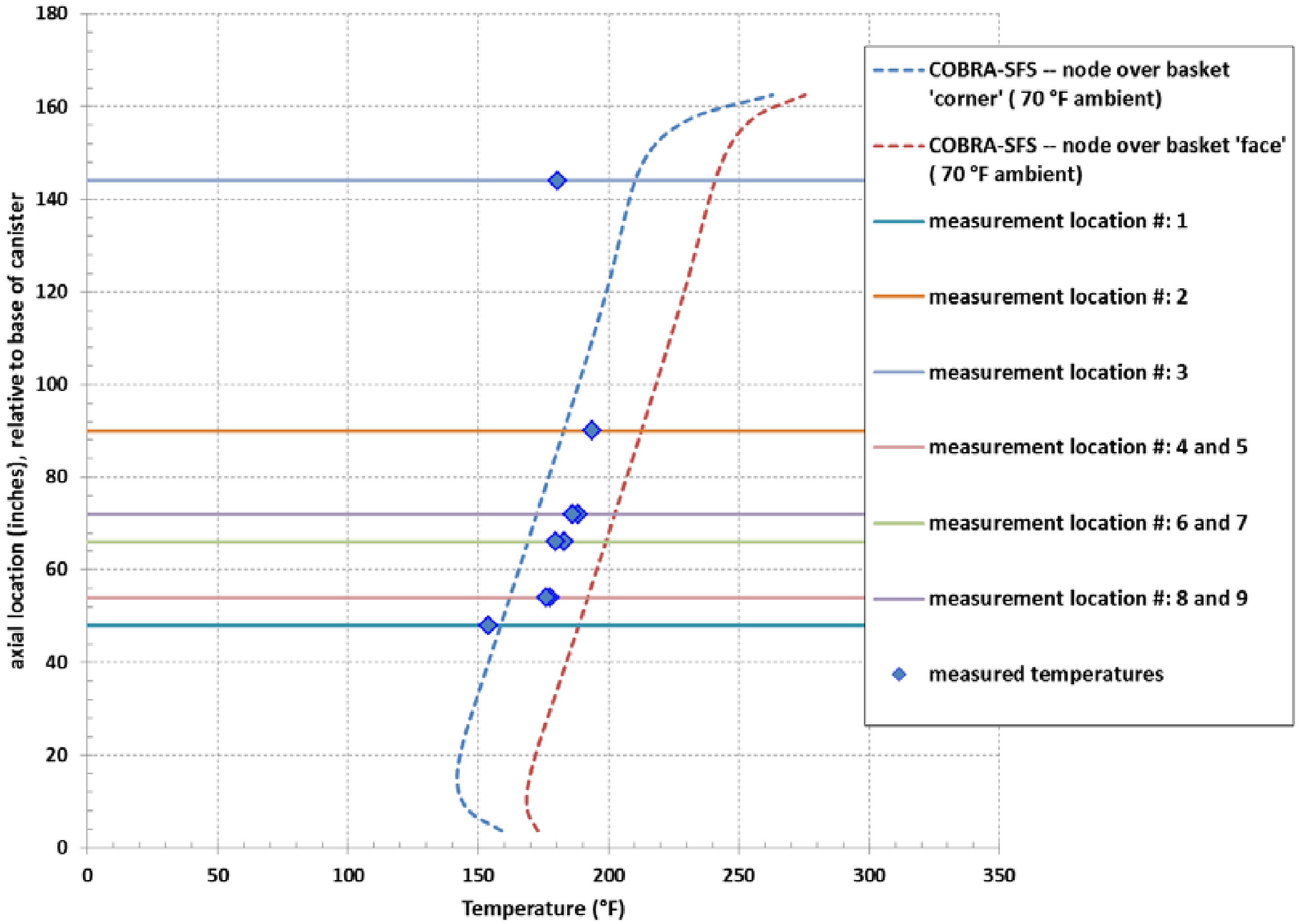
Are these hoop stresses realistic?

Integrated Approach

- Thermal Analysis
  - What are the ***realistic*** temperatures that cladding experiences during drying and extended storage?
- Hoop Stress
  - What is the range and distribution of end of life rod internal pressures, accounting for He and pellet swelling/bonding, and clad thicknesses and diameters?
- Ring Compression Tests
  - Identify the ductile transition temperatures for cladding under ***realistic*** temperatures and hoop stress
- Cyclic Integrated Reversible Bending Fatigue Test
  - Identify the role of fuel/clad and pellet/pellet bonding, the number of cycles as a function of applied stress to failure
- External Stresses
  - Identify ***realistic*** stresses to cladding during extended storage and normal conditions of transport
- Confirm post-drying material properties (Sibling Pin Testing)

Early Thermal Benchmarking

- Measure canister surface temperatures at Diablo Canyon, Hope Creek, and Calvert Cliffs
- Thermocouple deployment was difficult and could not maintain good contact
- Variable ambient conditions (T, wind) significantly impacted comparison with models
- Unknown location on canisters (e.g., basket "corner" or "face")



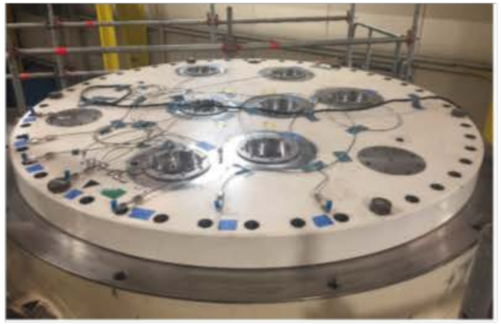
Post-Inspection Thermal Modeling of HI-STORM Storage Modules at Diablo Canyon Power Plant ISFSI, Cuta and Adkins, FCRD-UFD-2015-000492, PNNL-24771, September 2015.

High Burnup Spent Fuel Data Project

	TN-32 Safety Evaluation Report (generic)	TN-32B Research Project Cask License Amendment
Maximum burnup (GWd/MTU)	≤45	≤60
Maximum decay heat per assembly	1.02 kW	1.5 kW
Total decay heat	32.7 kW	36.96 kW
Minimum decay time	7-10 years	4.81 years
Est. Peak cladding temperature (PCT)	328°C	348°C

Photo courtesy of Dominion Energy

Phase II Round Robin Summary



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

Parameter	LAR	Updated 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?

Research Project Cask Cladding Storage Temperatures COBRA-SFS (36.8 kW)

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 1013/818W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 1167/837W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 1015/820W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 909/756W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 914/761W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1276/832W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1503/841W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1477/827W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 1163/834W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 906/796W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 885/778W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1496/837W	13 F40 Zirc-4, 50.6 GWd 3.59%, ?cy, 30yr 696W/not reported	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1281/834W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1482/830W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 1120/803W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 1165/835W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1492/835W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 1037/805W	20 0A4* Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 725/664W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1496/837W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 1121/804W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 1036/837W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 1031/801W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1495/837W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1511/846W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 1178/843W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 1035/803W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 1073/787W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 1155/828W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 1031/832W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 918/764W	High Priority Assys

	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	

Peak Cladding Temperature (°C)

	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	

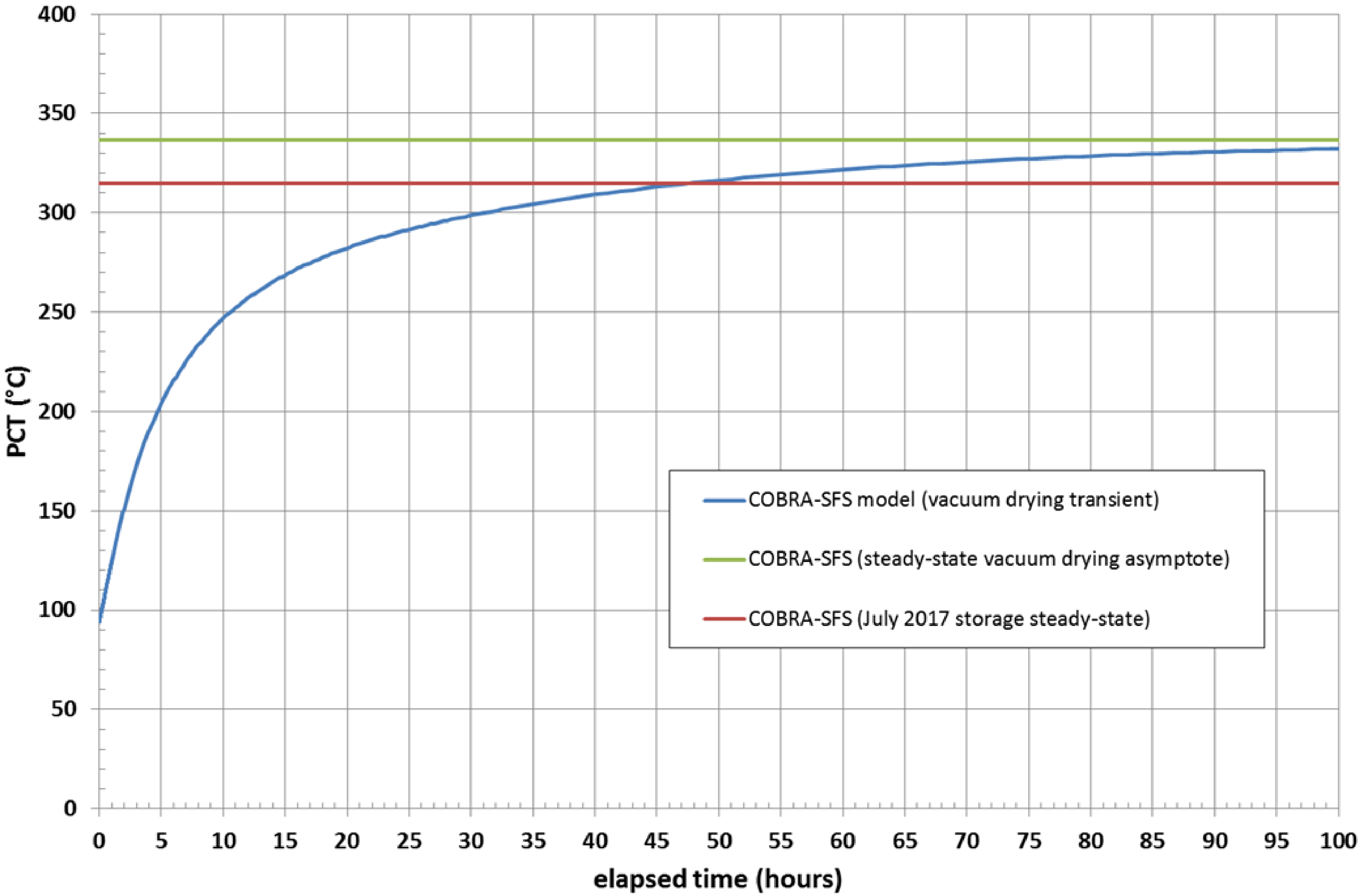
Minimum Cladding Temperature (°C)

One assembly changed from LAR resulting in slight decrease in total decay heat

17×17 assemblies; Assembly burnup 50.6 – 55.5 Gwd/MTU

JA Fort et. al, *Thermal Modeling of Proposed TN-32B Cask for High Burnup Fuel Storage Demonstration Project,* December, 2016. FCRD-UFD-2015-000119, PNNL-24549, Rev. 1

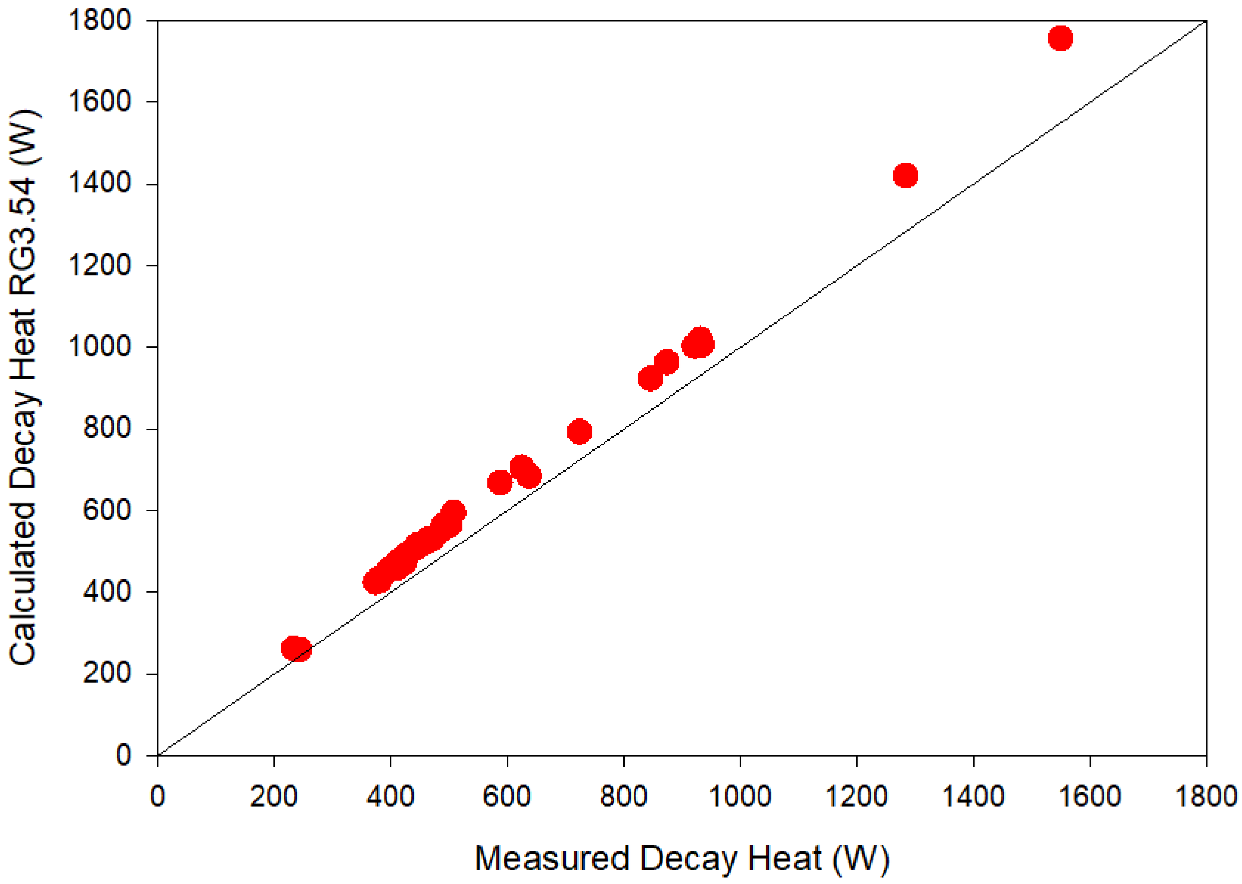
Research Project Cask PCT Under Transient Drying COBRA-SFS (36.8 kW)



JA Fort et. al, *Thermal Modeling of Proposed TN-32B Cask for High Burnup Fuel Storage Demonstration Project,* December, 2016. FCRD-UFD-2015-000119, PNNL-24549, Rev. 1

- **337°C PCT (drying steady state) compares to 348°C calculated in LAR**

Conservatisms in Assembly Decay Heat Calculations



- Reg Guide 3.54 methodology
  - Is always conservative (higher decay heat than actual/measured)
  - PWR Range 6.8% - 17.2%
  - PWR average 12.5%
  - PWR median 12.9%
  - BWR Range 3.7% - 55.3%
  - BWR average 22.6%
  - BWR median 19.9%

Gauld IC and BD Murphy. 2010. Technical Basis for a Proposed Expansion of Regulatory Guide 3.54-Decay Heat Generation in an Independent Spent Fuel Storage Installation. NUREG/CR-6999. ORNL/TM-2007/231. Prepared for the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, Washington, D.C.

Research Project Cask Pre-Loading Best Estimate Cladding Storage Temperatures (30.6 kW)

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 907 / 727 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 983 / 749 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 909 / 729 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 793 / 653 W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 795 / 653 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1039 / 746 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1170 / 754 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1149 / 741 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 977 / 745 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 806 / 668 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 795 / 660 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1162 / 750 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 463 / 397 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1047 / 752 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1152 / 744 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 944 / 718 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 979 / 746 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1159 / 747 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 918 / 724 W	20 0A4 Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 641 / 541 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1163 / 750 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 944 / 717 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 929 / 744 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 912 / 719 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1161 / 749 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1162 / 759 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 989 / 756 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 915 / 721 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 915 / 709 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 970 / 740 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 922 / 738 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 798 / 656 W	

COBRA-SFS

	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	

STAR-CCM+

	227	250	247	222	
230	258	274	274	256	231
246	278	256	280	279	253
254	279	276	264	279	254
237	255	275	275	257	236
	254	250	248	223	

Peak Cladding Temperature (°C)

	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	

Minimum Cladding Temperature (°C)

Modifications:

ORIGEN vs conservative/regulator practice decay heats.

~17% total reduction in decay heat at loading.

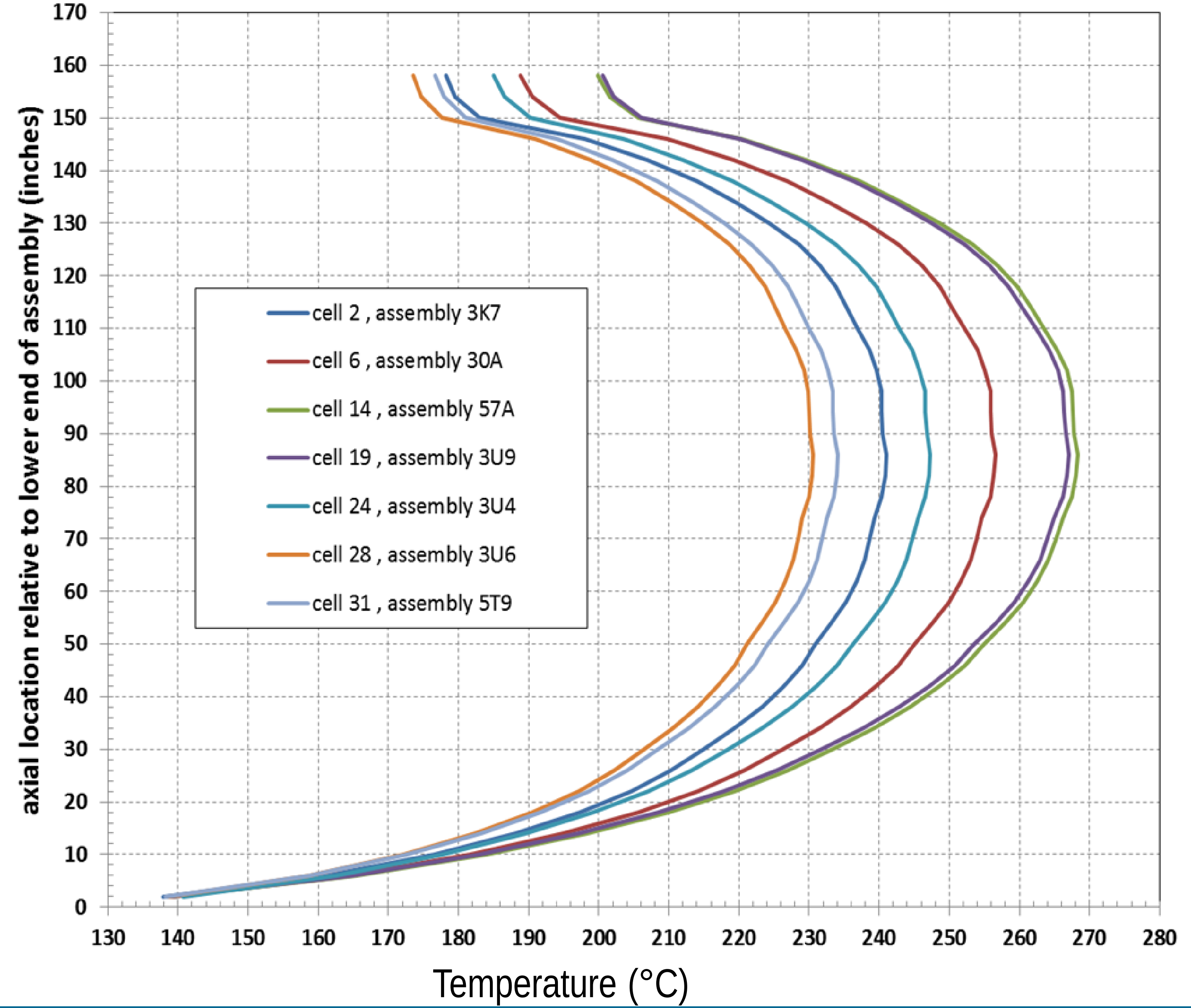
Actual decay heat profiles

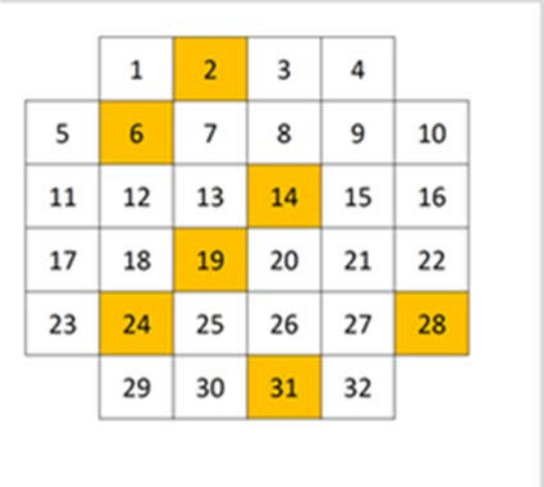
Proper assembly design parameters

Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project

Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

Temperature Variability in Instrumented Assemblies Modeled with COBRA-SFS

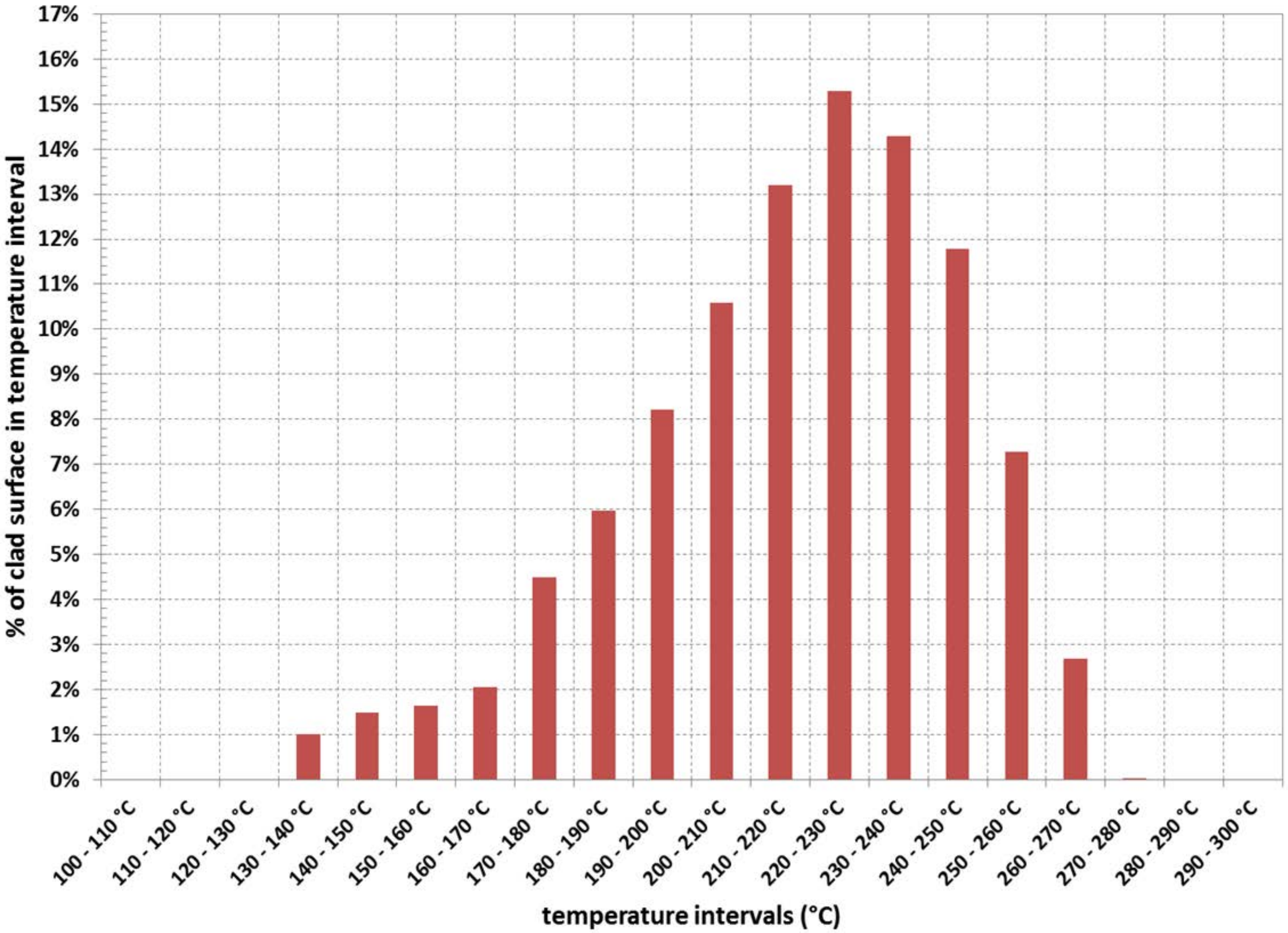




Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project

Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

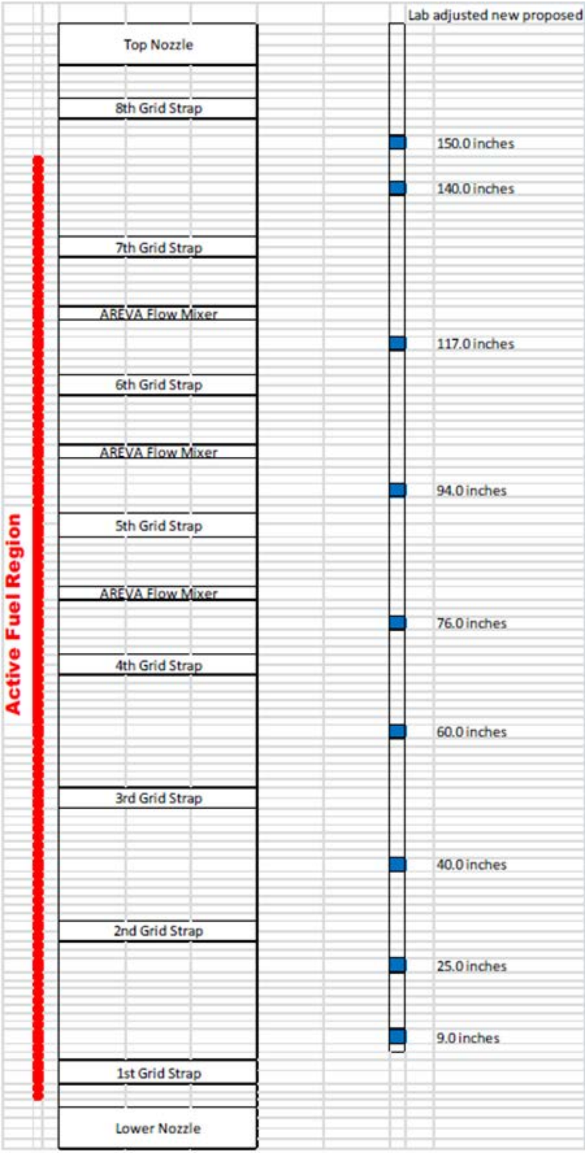
Cladding Temperature Distribution COBRA-SFS (30.6 kW)

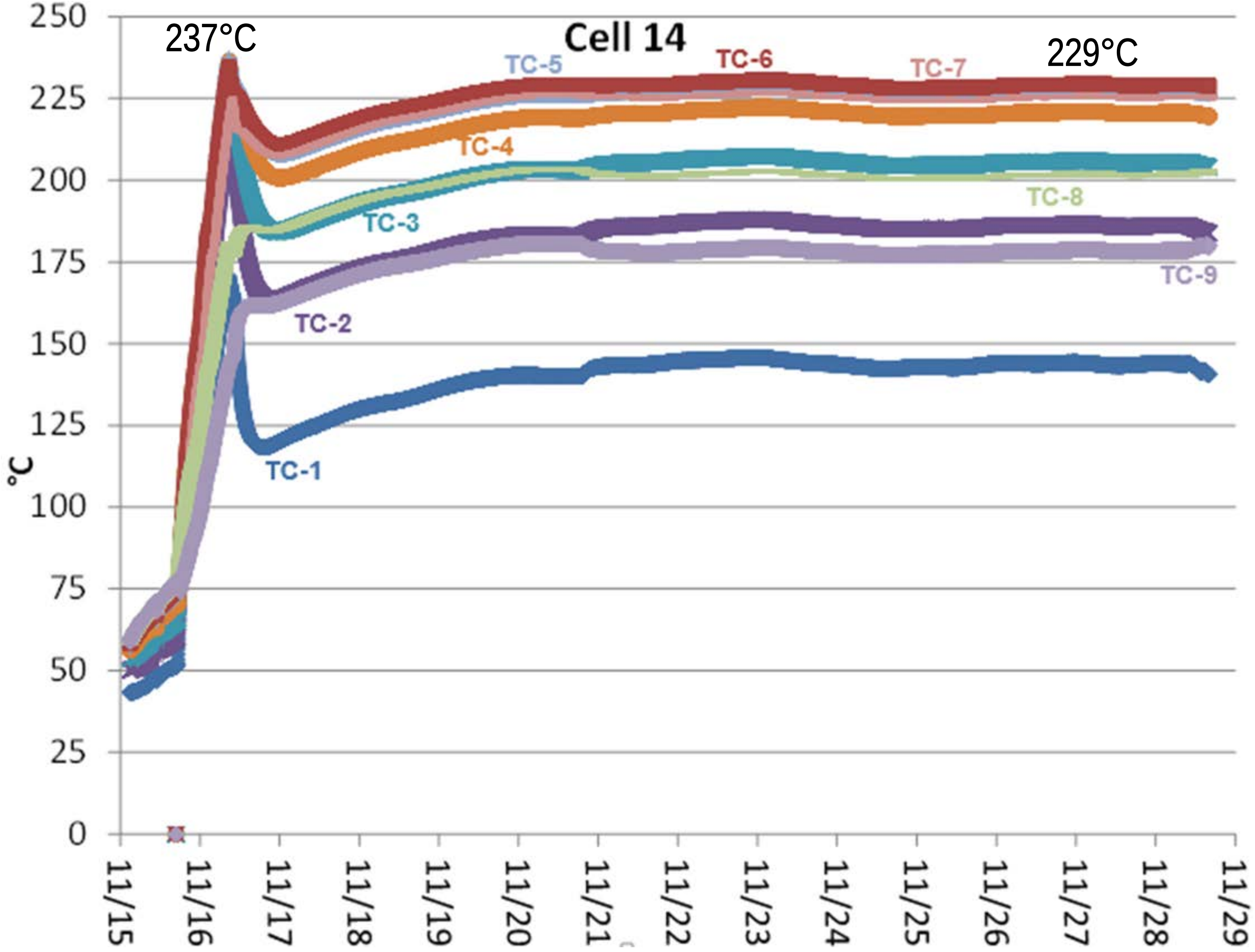


Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project

Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

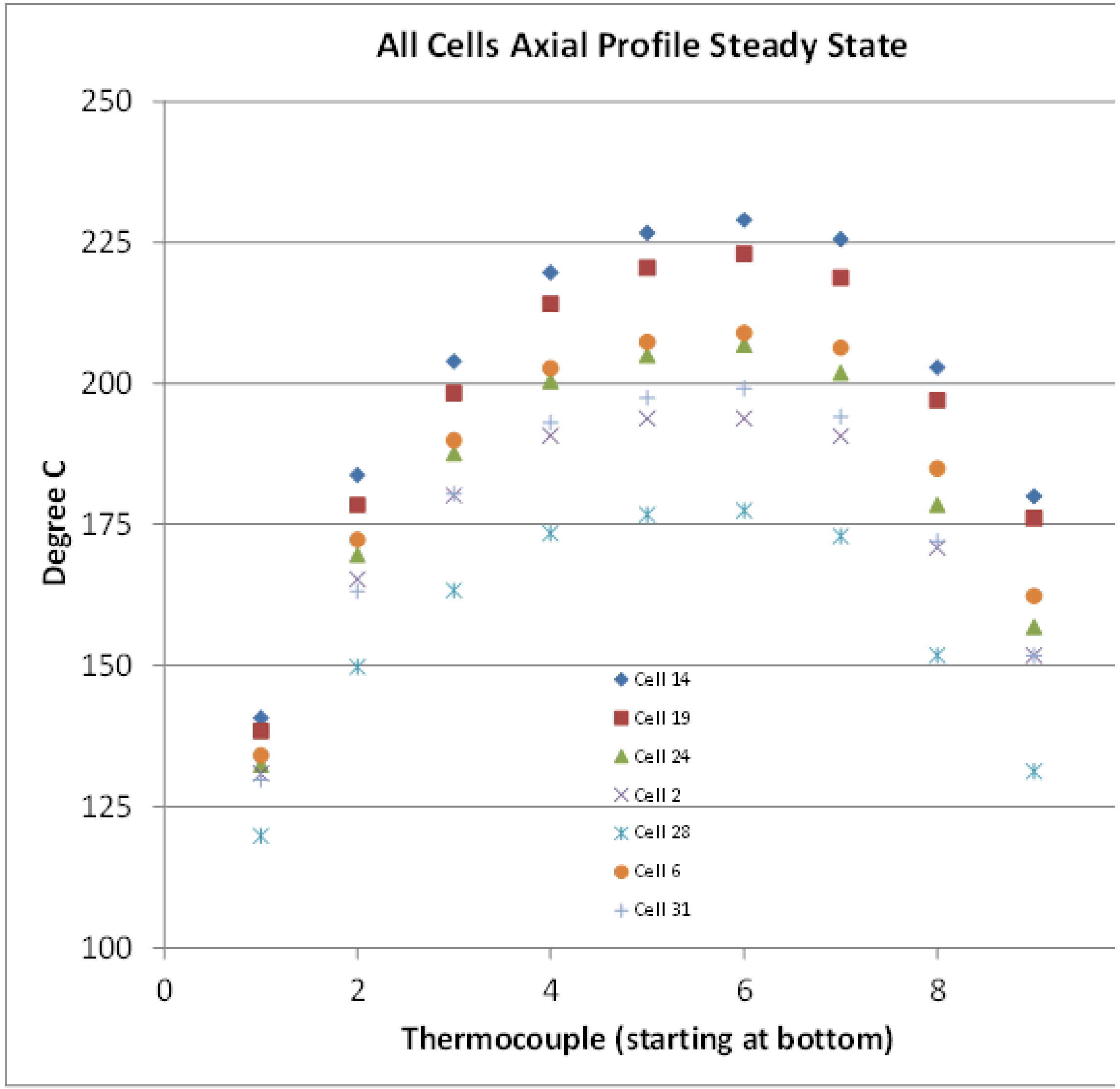
Measured Temperatures in Hottest Assembly

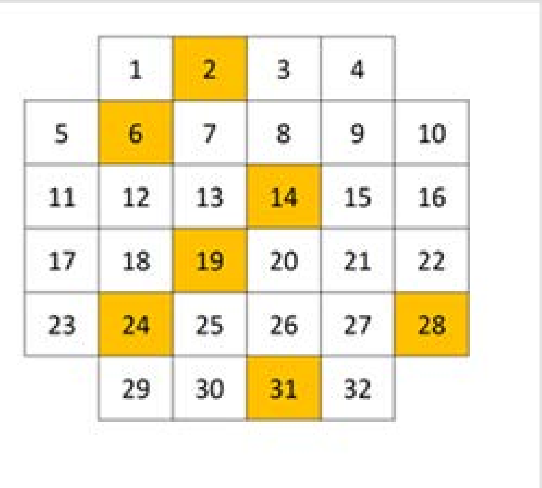




TC-1 is thermocouple near bottom   TC-9 is thermocouple near top

Measured Temperatures at Steady Sate (after 2 week thermal soak)





Evolution of Thermal Modeling Results:

Effect of Realistic Decay Heat and Ambient Temperature Inputs

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

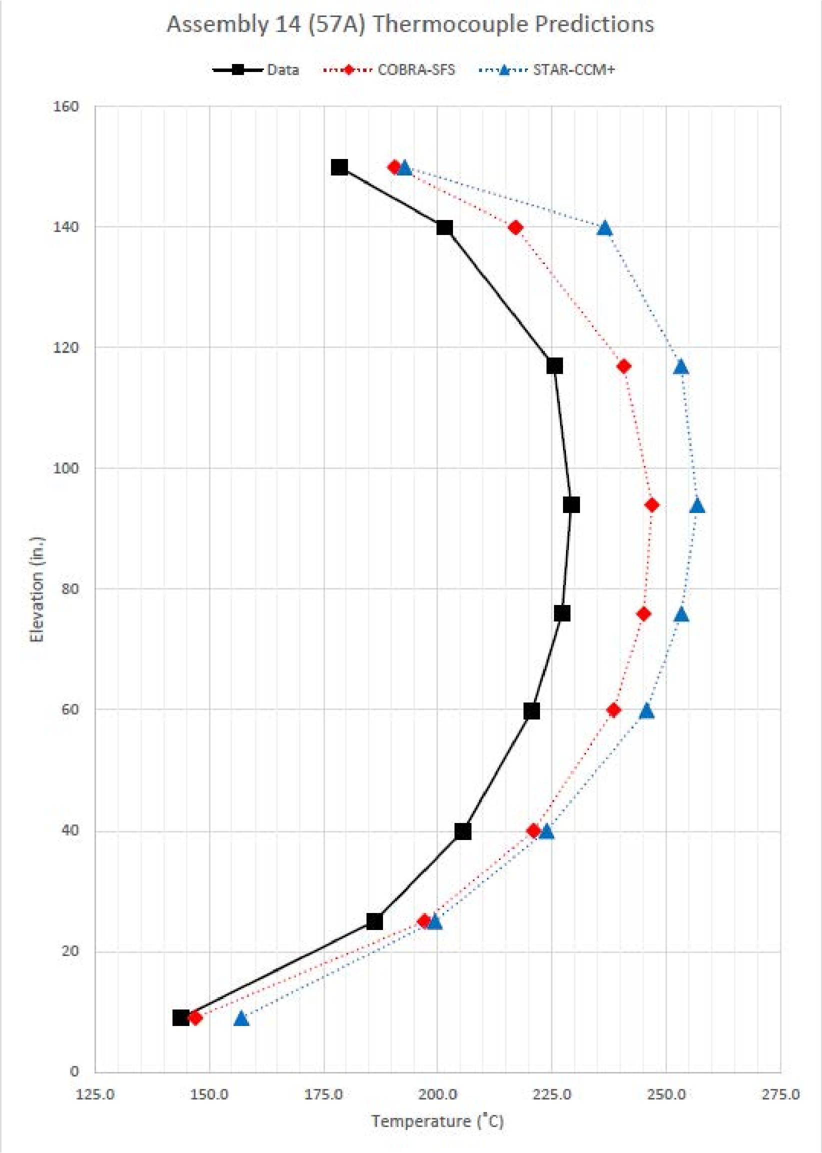
	211	234	231	206	
214	241	258	257	240	215
230	261	245	263	262	237
237	262	260	248	262	237
221	238	258	258	241	220
	212	234	232	206	

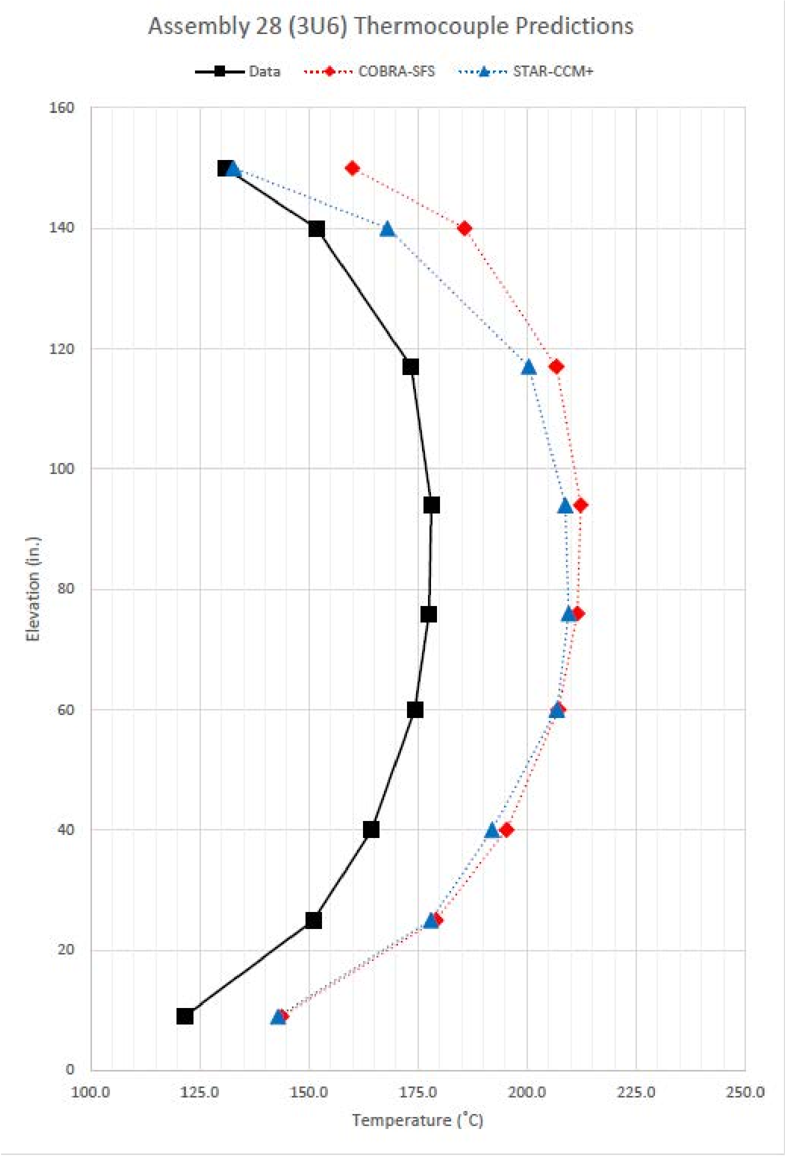
FSAR dimensions and properties; **T_{amb} = 75°F**; Decay heat=30.5 kW

Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project

Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

Model to Data Comparison

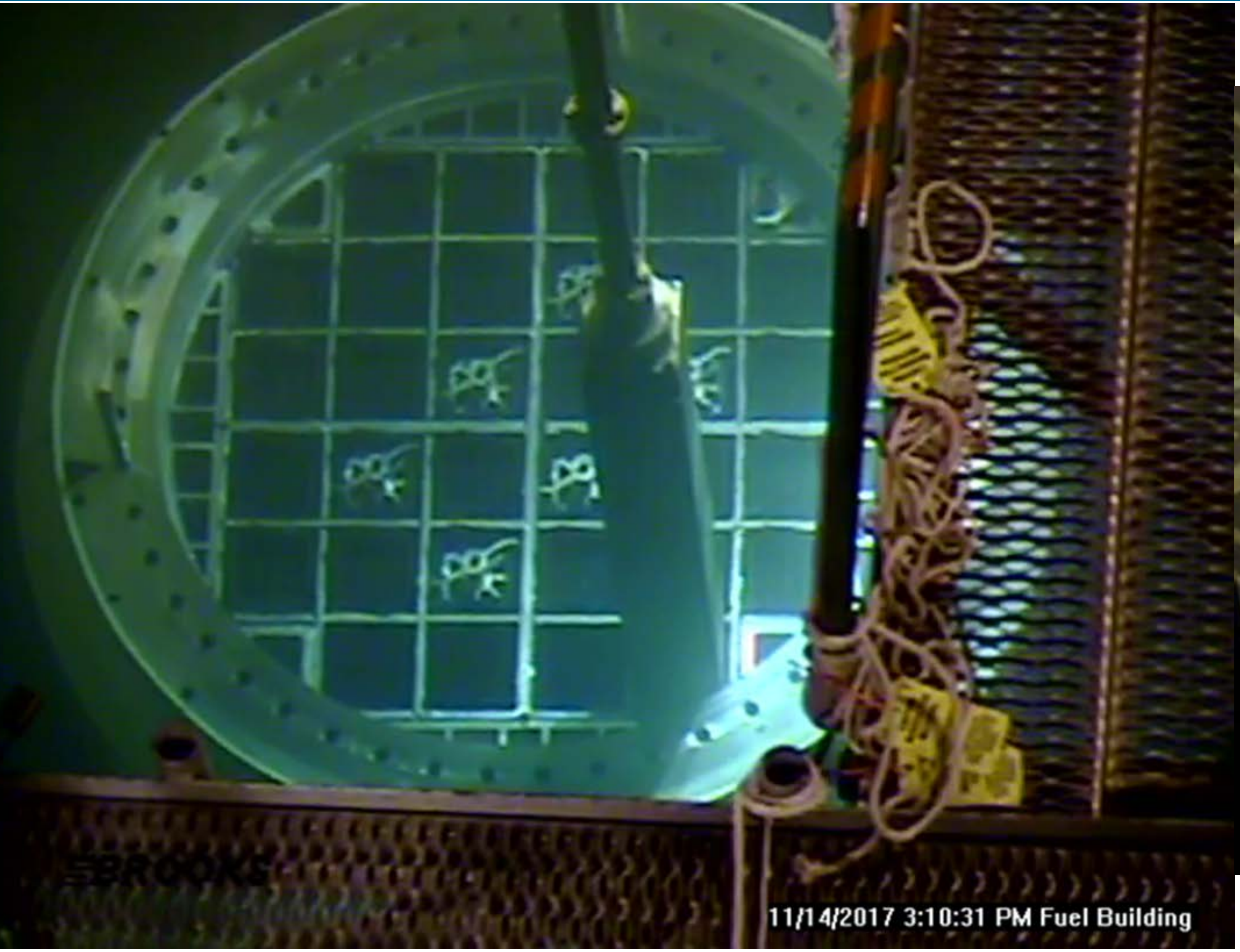


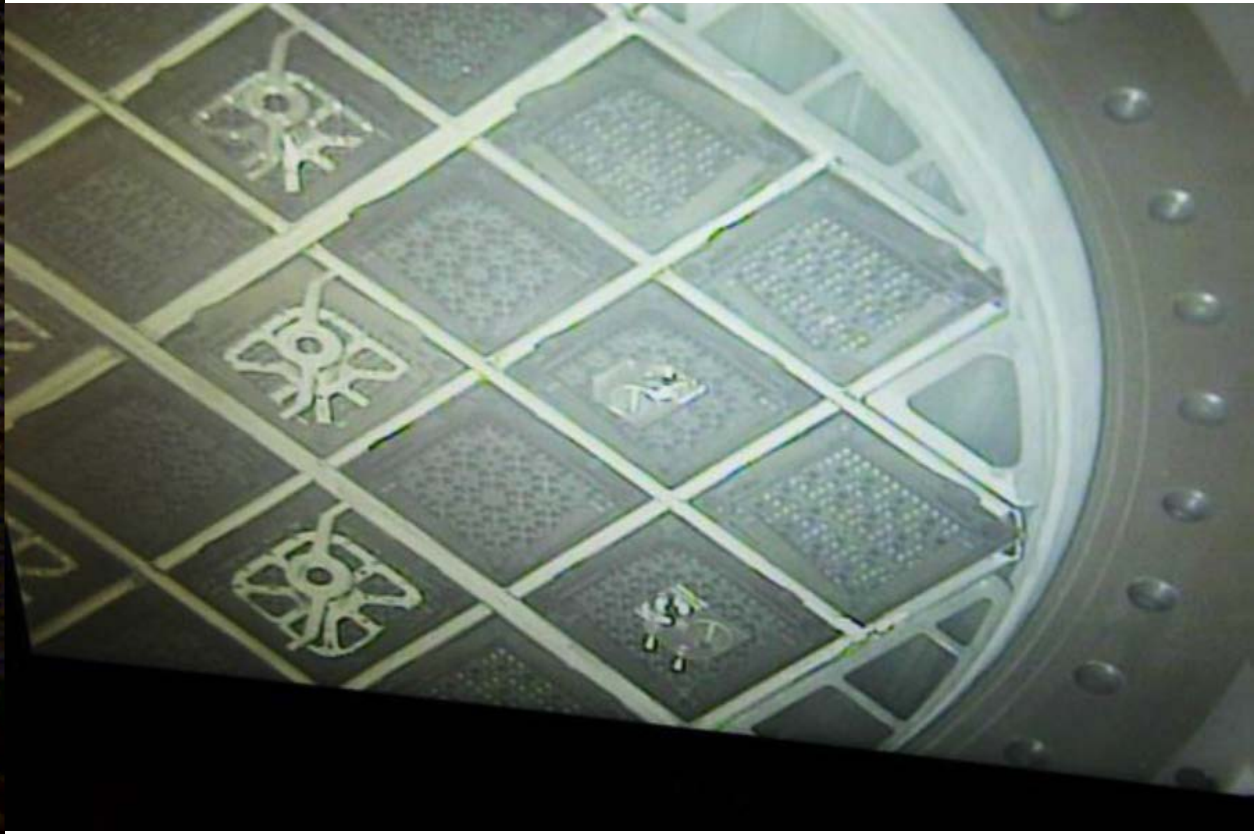


	6T0	3K7	3T6	6F2	
3F6	30A	22B	20B	5K6	5D5
5D9	28B	F40	57A	30B	3K4
5K7	50B	3U9	0A4	15B	6K4
3T2	3U4	56B	54B	6V0	3U6
	4V4	5K1	5T9	4F1	

Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project. Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

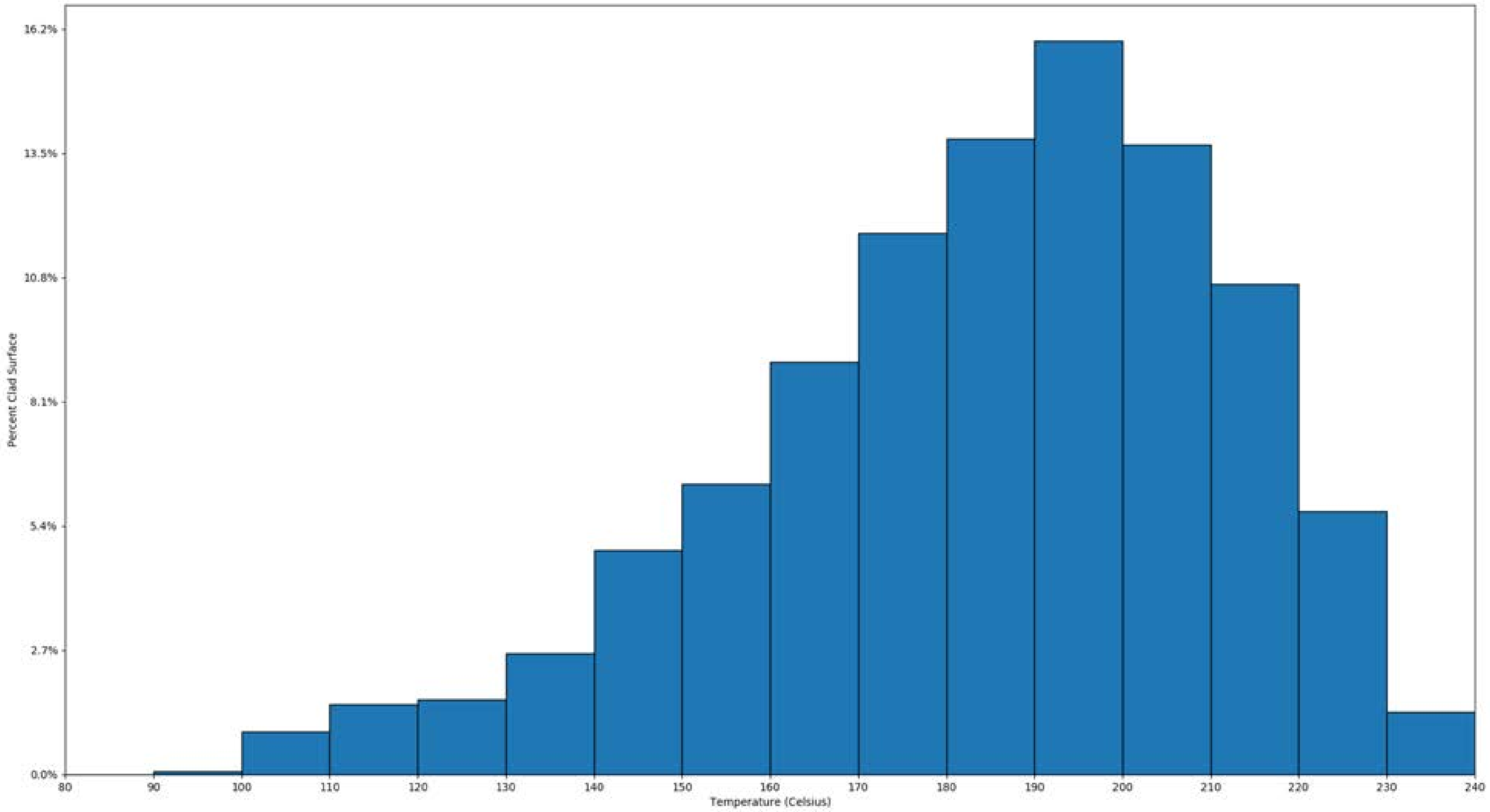
Cask Loading and Funnel Guide Installation





Photos courtesy of Dominion Energy

Adjusted FSAR Basket/Rail Gap Input to Model



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	

Given the large axial and radial temperature gradients, <2% of all cladding in the Demo cask is modeled to have temperatures >230°C

Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project. Fort, Richmond, Cuta, Suffield, PNNL-28915, July 2019.

ISFSI Transient

- Data sets from EPRI HBU Demo website[1]
- Applying storage models used for planning HBU Demo
- Update with adjusted best estimate inputs
- Use these to model transient response of fuel to ambient changes

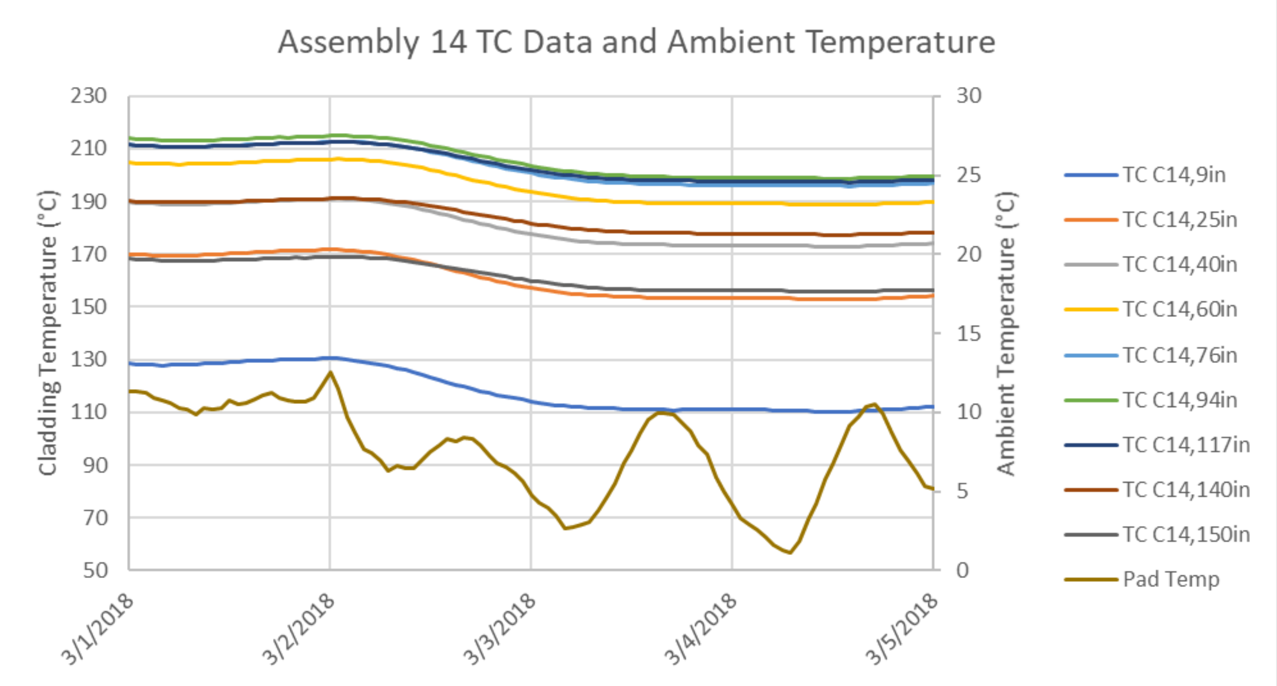
Photo courtesy of Dominion Energy

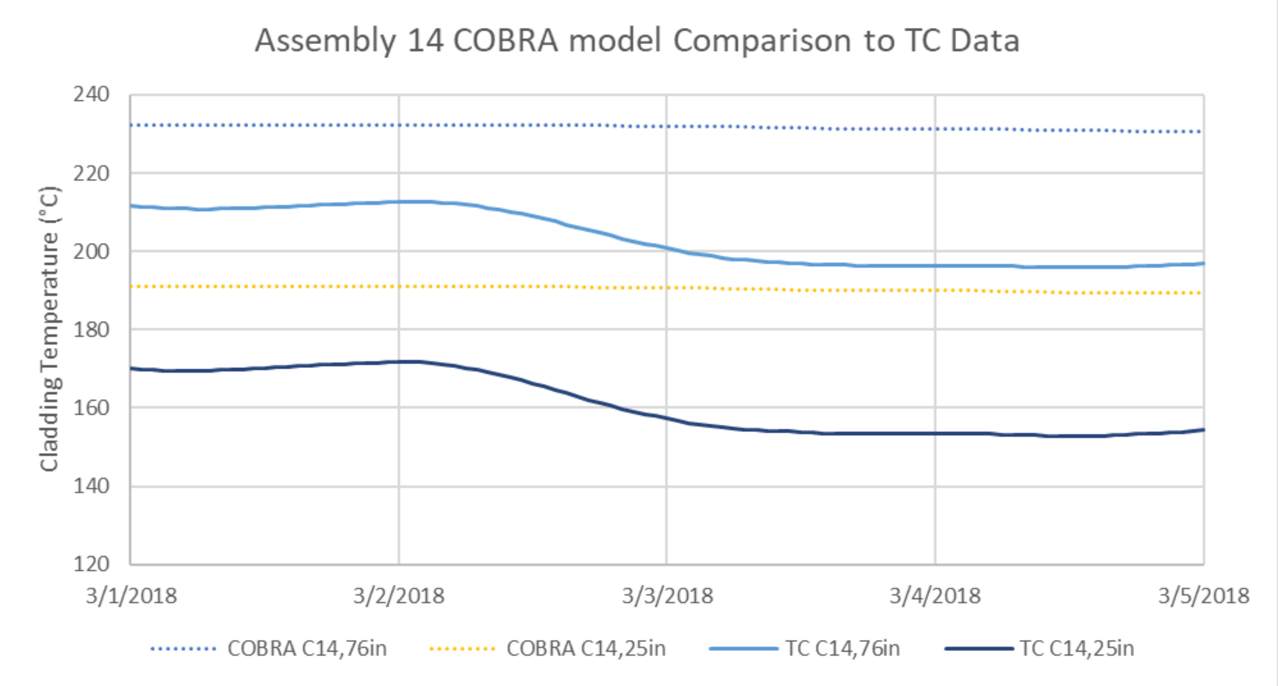
[1] https://www.epri.com/#/portfolio/2020/research_areas/2/061149?lang=en-US.

Example Case

Measured Data
- Small ambient temperature change
- Larger change in fuel

Model Compared to TC Measurements
- Ambient temperature change as BC
- Barely discernable change in fuel





Ambient temperature data courtesy Dominion Energy.

High-Burnup Demonstration: Thermal Modeling of TN-32B Vacuum Drying and ISFSI Transients.
Fort, Richmond, Jensen, and Suffield. PNNL-29058. September 2019.

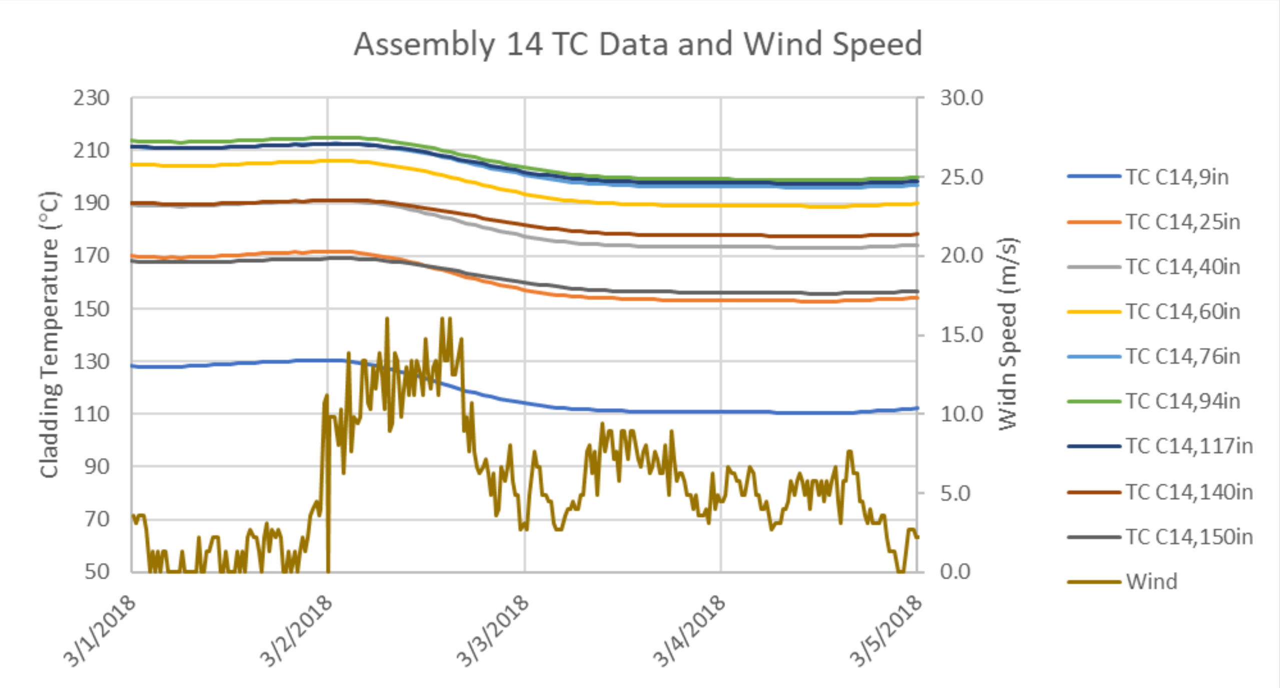
Example Case – Including Wind

Measured Data

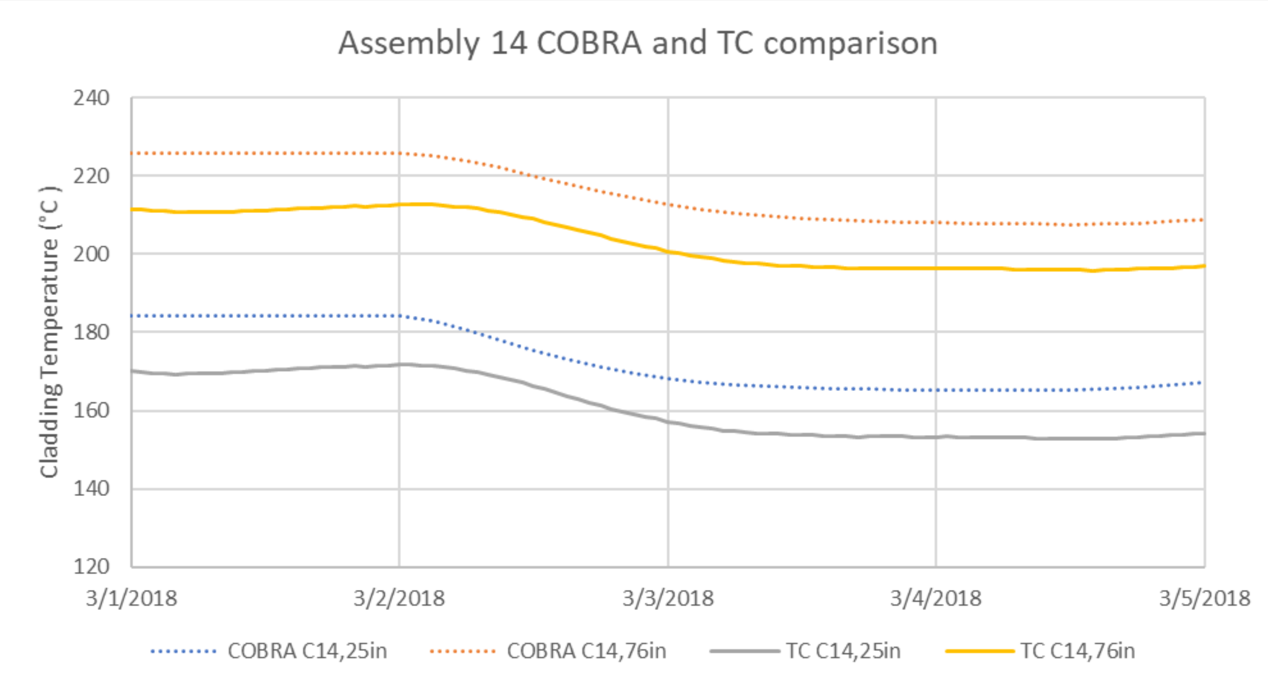
- Wind data from local airport
- Shows significant increase in wind

Model Compared to TC Measurements

- BC modified to include wind speed
- Model gives good agreement



Wind data from NOAA Local Climatological Data set, Louisa County's Freeman Field Airport (WBAN:03715).



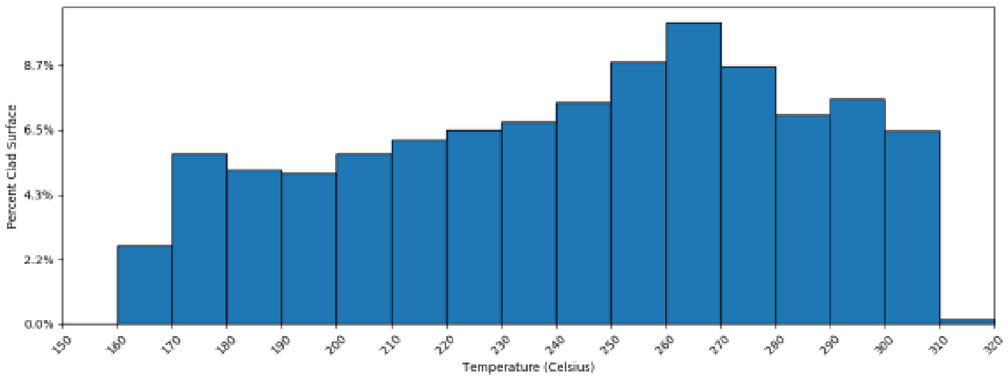
High-Burnup Demonstration: Thermal Modeling of TN-32B Vacuum Drying and ISFSI Transients.
Fort, Richmond, Jensen, and Suffield. PNNL-29058. September 2019.

MAGNASTOR Sensitivity Analyses – For R&D Purposes Only

Thermal Analysis of High Decay Heat Loading Strategies in the MAGNASTOR System, Jensen and Richmond, PNNL-28864, July 2019.

		753	753	731		
	753	939	936	937	463	
730	969	850	849	849	913	492
731	935	849	848	848	913	731
475	913	848	848	847	913	711
	475	913	913	913	709	
		752	730	730		

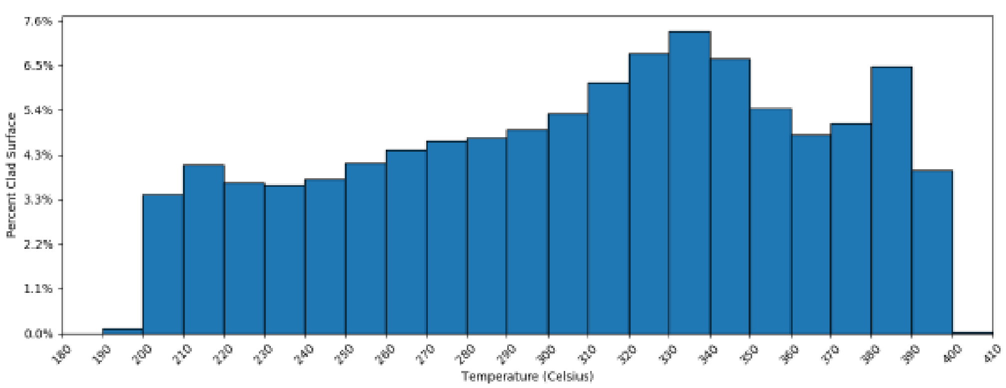
		282.8	286.4	281.5		
	290.0	304.2	310.0	303.0	283.5	
282.0	304.7	312.1	311.1	311.3	301.6	276.4
284.8	309.5	311.0	314.0	310.8	308.6	284.3
276.3	301.7	311.2	310.8	311.6	302.8	280.9
	283.5	302.3	309.0	303.0	288.3	
		281.6	285.5	281.6		



Total decay heat = 29.5 kW
Max Assembly heat load = 969 W
0% Cladding above 350°C

		944	944	944		
	944	1416	1416	1416	944	
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
	944	1416	1416	1416	944	
		944	944	944		

		357.7	363.8	357.7		
	367.9	390.7	400.1	390.7	367.9	
357.7	390.7	399.9	399.5	399.9	390.7	357.7
363.8	400.1	399.5	403.0	399.5	400.1	363.8
357.7	390.7	399.9	399.5	399.9	390.7	357.7
	367.9	390.7	400.1	390.7	367.9	
		357.7	363.8	357.7		

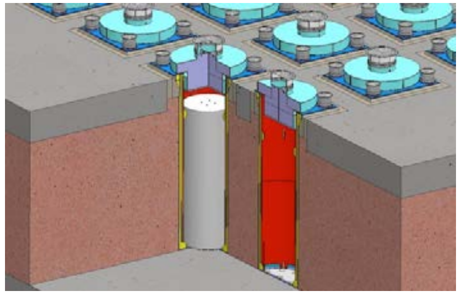


Total decay heat = 41.9 kW
Max Assembly heat load = 1416 W
26% Cladding above 350°C

BWR Dry Cask Simulator Overview

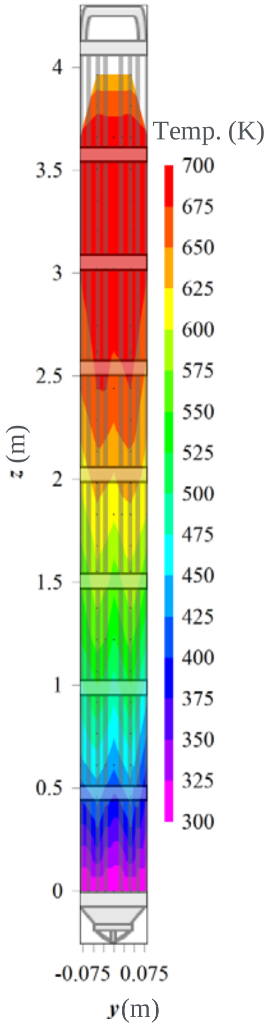
Aboveground Storage

Source: www.nrc.gov/reading-rm/doc-collections/fact-sheets/storage-spent-fuel-fs.html



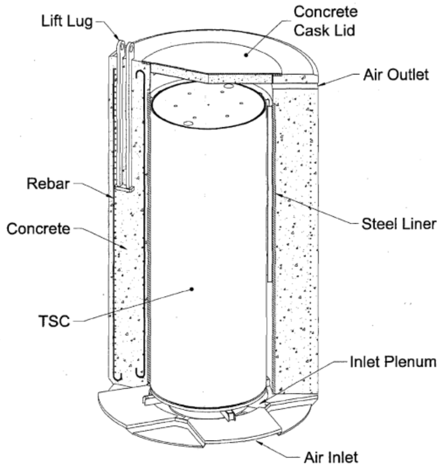
Belowground Storage

Source: www.holtecinternational.com/productsandservices/wasteandfuelmanagement/hi-storm/



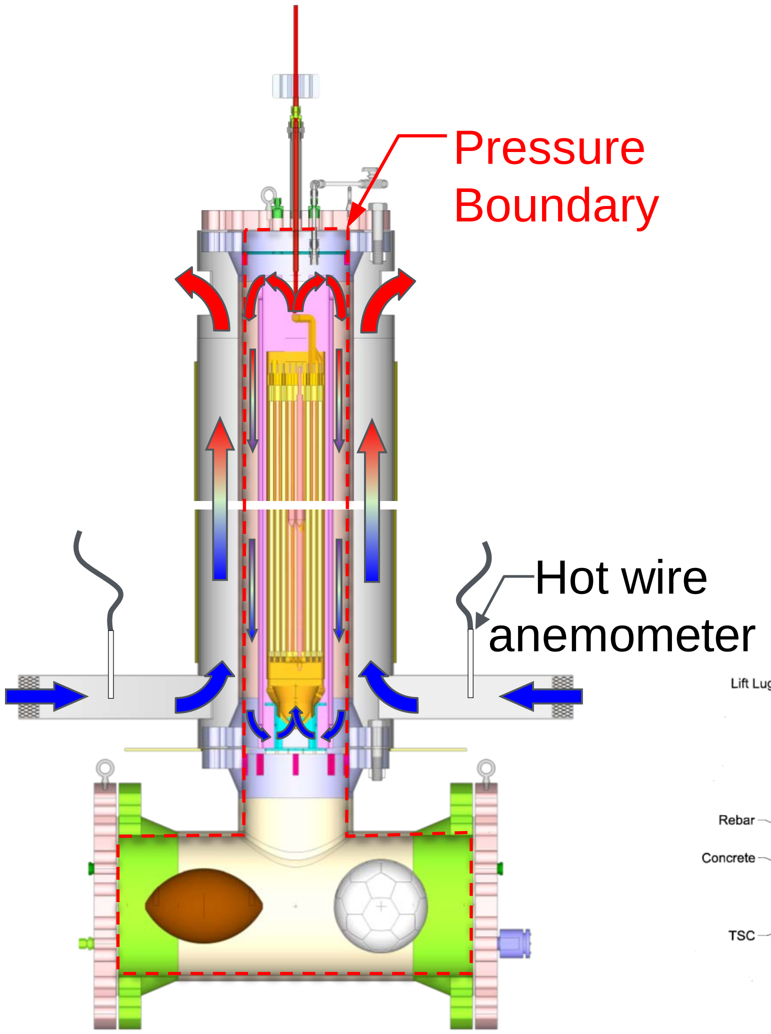
- Purpose: Validate assumptions in CFD calculations for spent fuel cask thermal design analyses
  - Used to determine steady-state cladding temperatures in dry casks
  - Needed to evaluate cladding integrity throughout storage cycle
- Measure temperature profiles for a wide range of decay power and helium cask pressures
  - Mimic conditions for above and belowground configurations of vertical, dry cask systems with canisters
  - Simplified geometry with well-controlled boundary conditions
  - Provide measure of mass flow rates and temperatures throughout system
- Use existing prototypic BWR Incoloy-clad test assembly

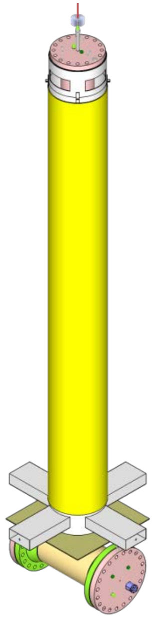
Current Approach

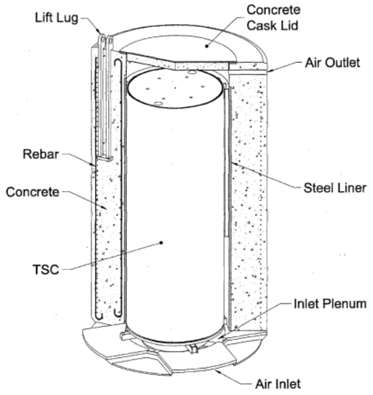


- Focus on pressurized canister systems
  - DCS capable of 2,400 kPa internal pressure @ 400 °C
    - Current commercial designs up to ~800 kPa
- Ventilated designs
  - Aboveground configuration
  - Belowground configuration
    - With crosswind conditions
- Thermocouple (TC) attachment allows better 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

Aboveground Configuration

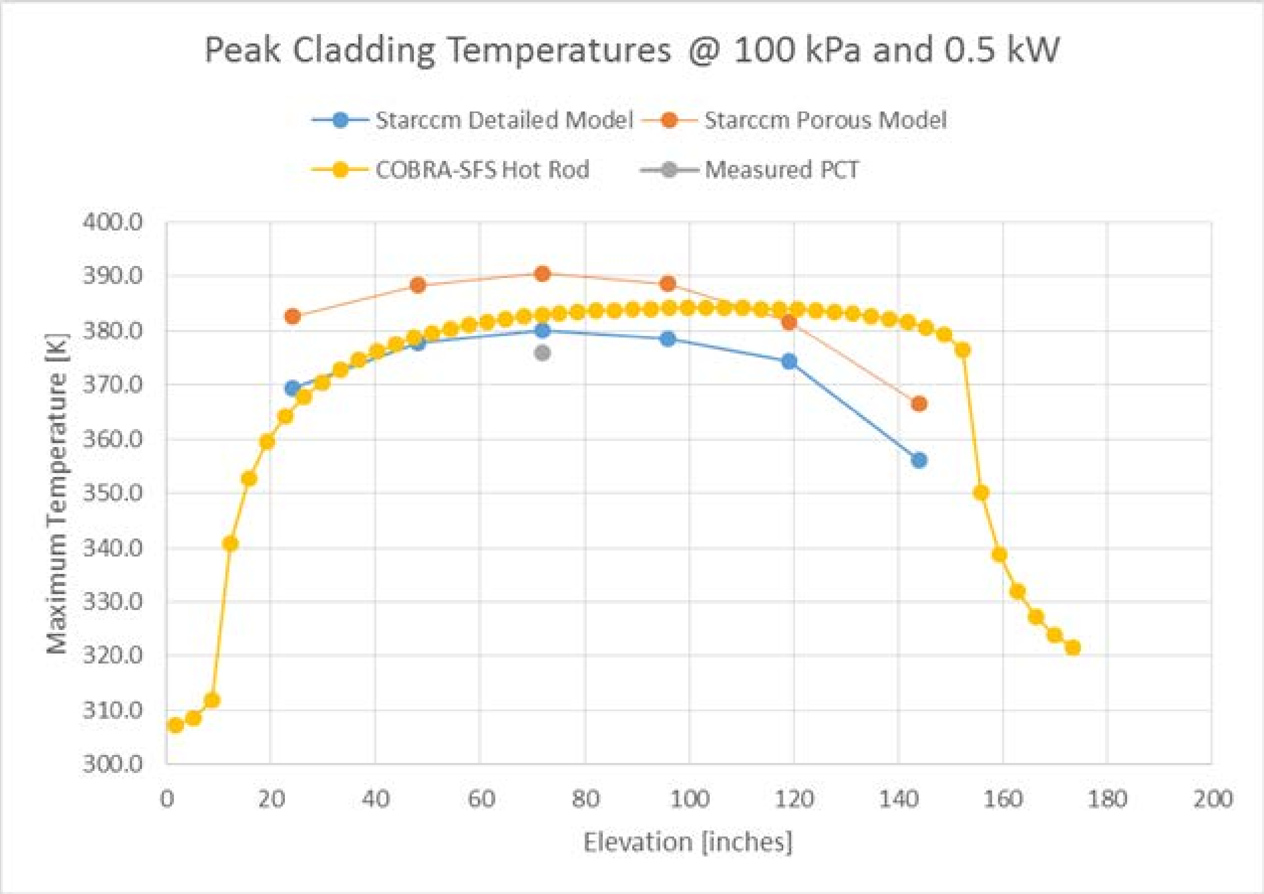


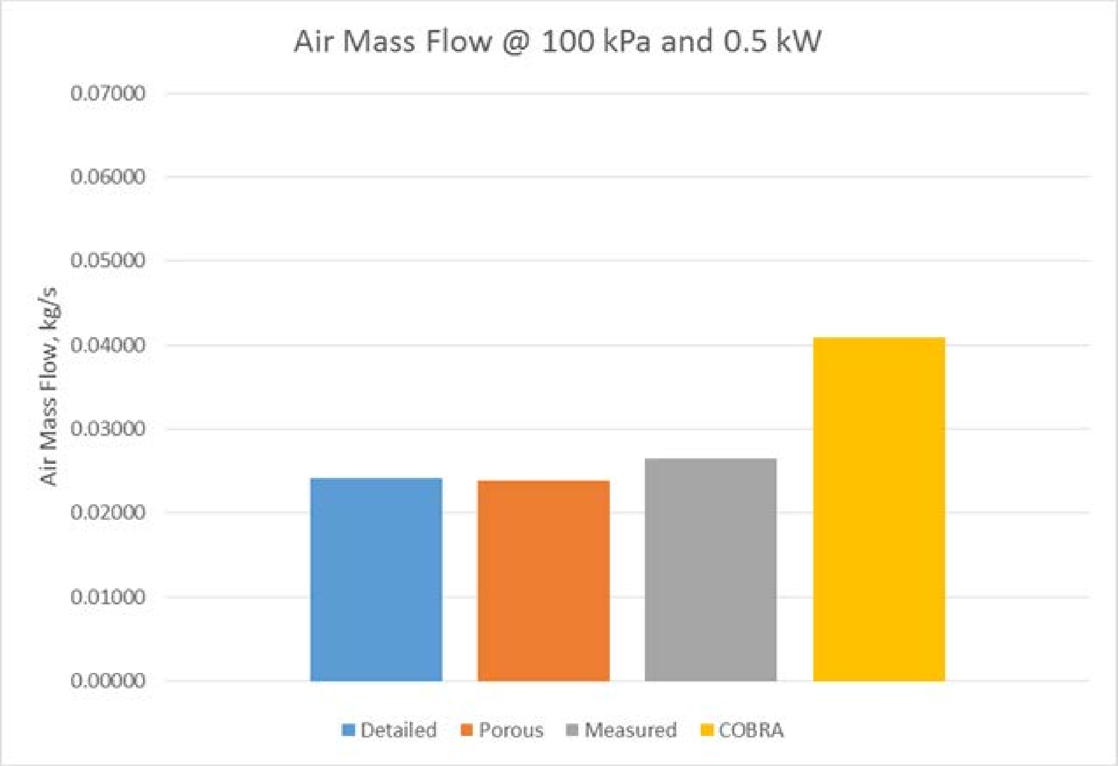




- BWR Dry Cask Simulator (DCS) system capabilities
  - Power: 0.1 – 20 kW
  - Pressure vessel
    - Vessel temperatures up to 400 °C
    - Pressures up to 2,400 kPa
    - ~200 thermocouples throughout system (internal and external)
  - Air velocity measurements at inlets
    - Calculate external mass flow rate
- *Testing Completed August 2016*
  - 14 data sets collected
    - Transient and steady state
  - Ongoing validation exercises

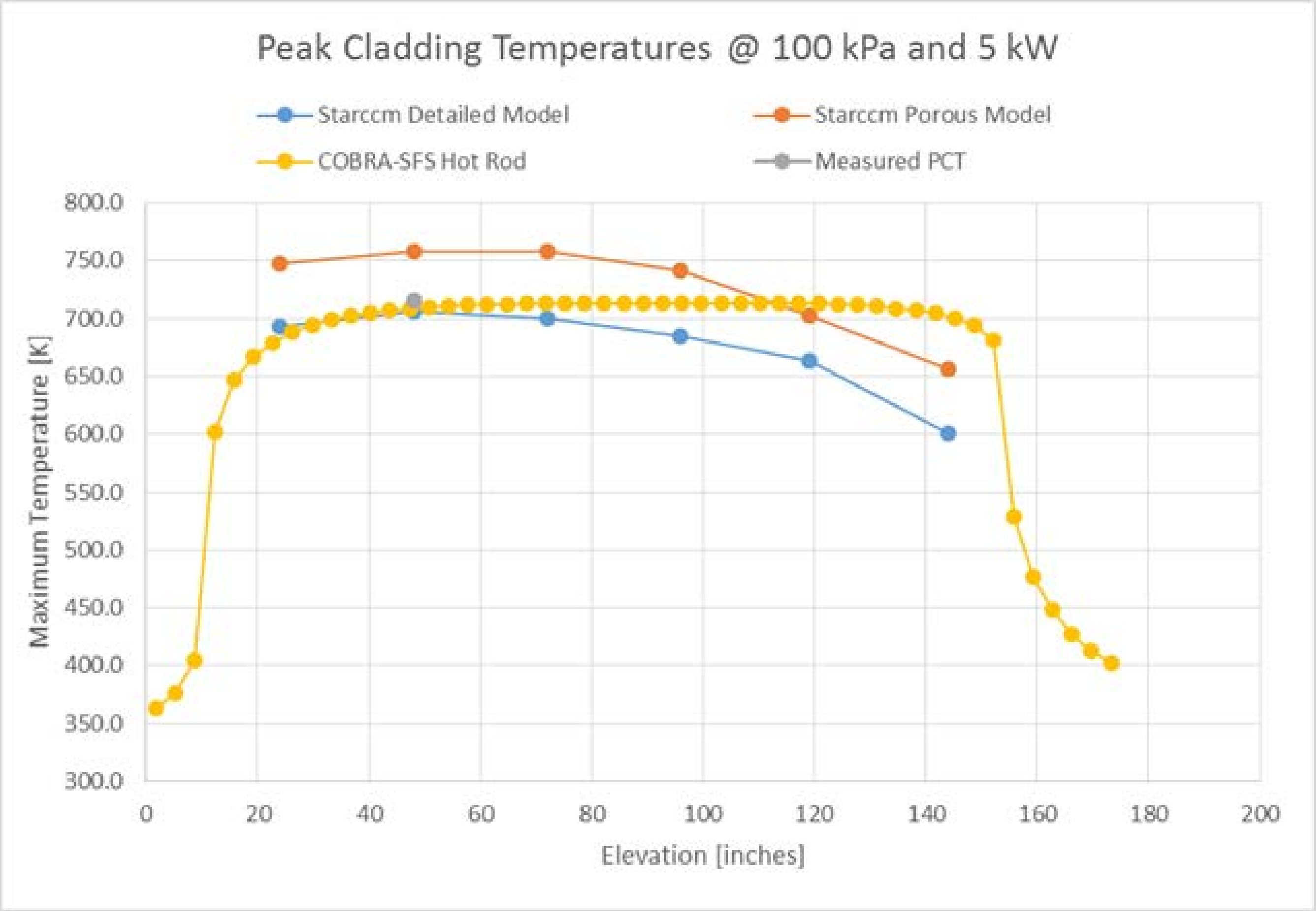
Comparison of Models with Data (100 kPa, 0.5 kW)

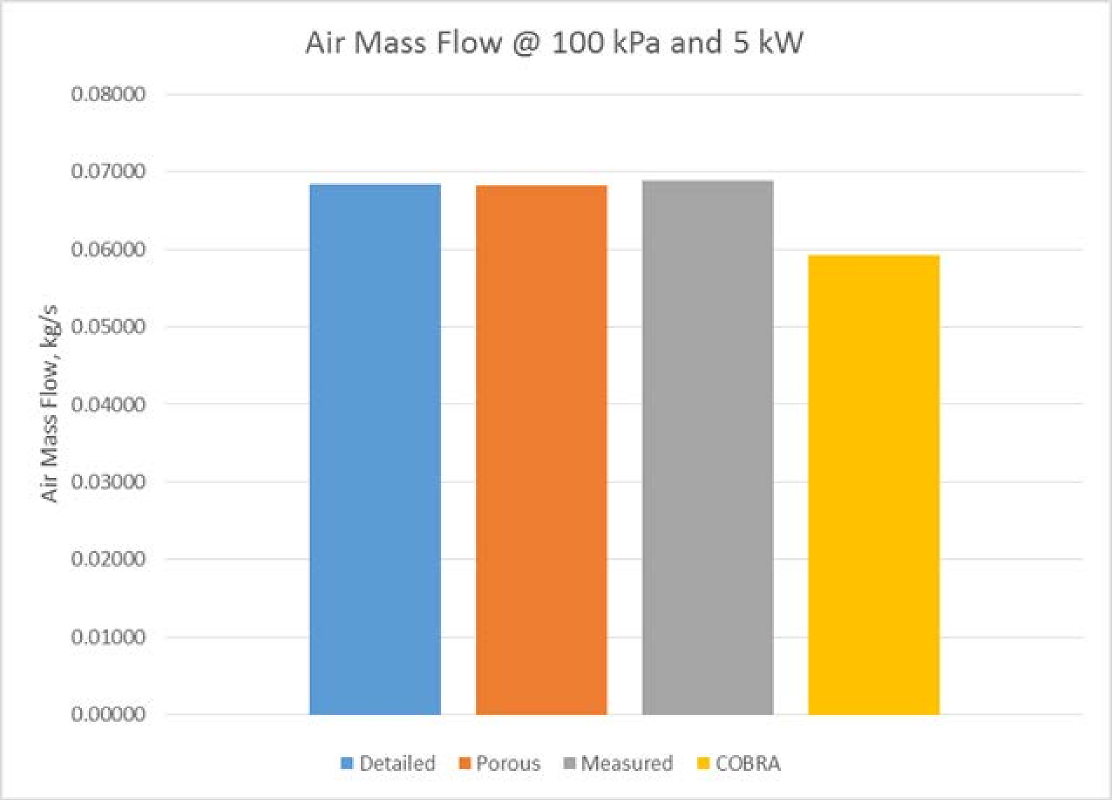




Modeling of the Boiling Water Reactor Dry Cask Simulator. Suffield, Richmond, and Fort. PNNL-28424 May 2019.

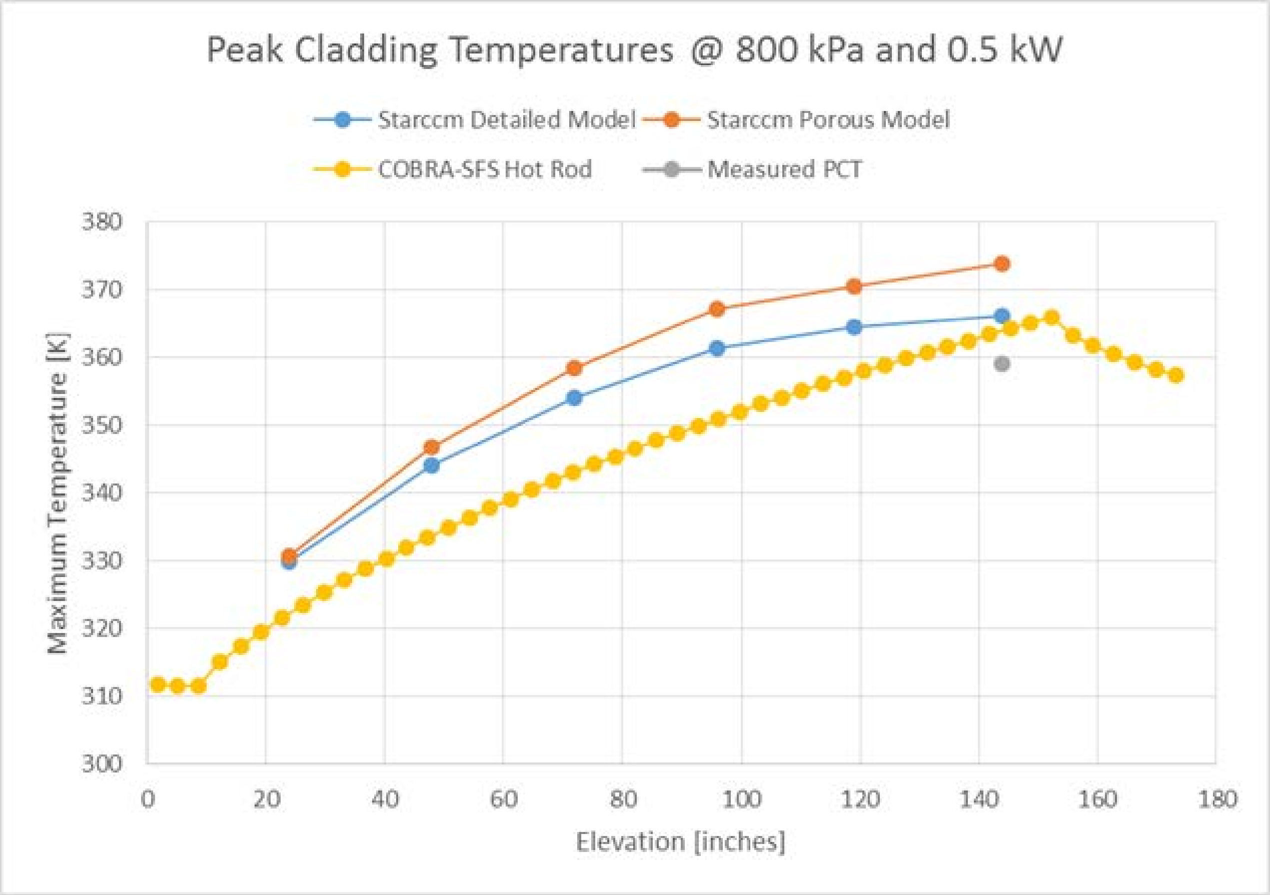
Comparison of Models with Data (100 kPa, 5 kW)

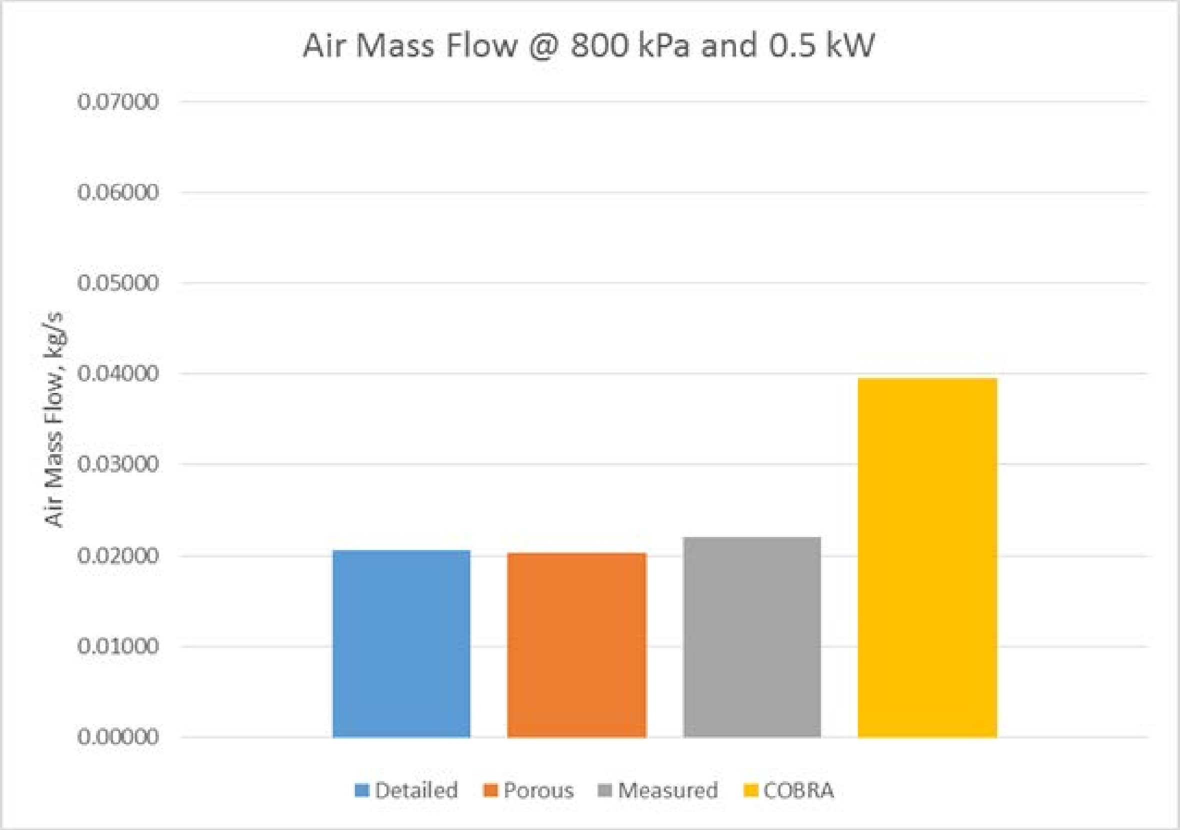




Modeling of the Boiling Water Reactor Dry Cask Simulator. Suffield, Richmond, and Fort. PNNL-28424 May 2019.

Comparison of Models with Data (800 kPa, 0.5 kW)





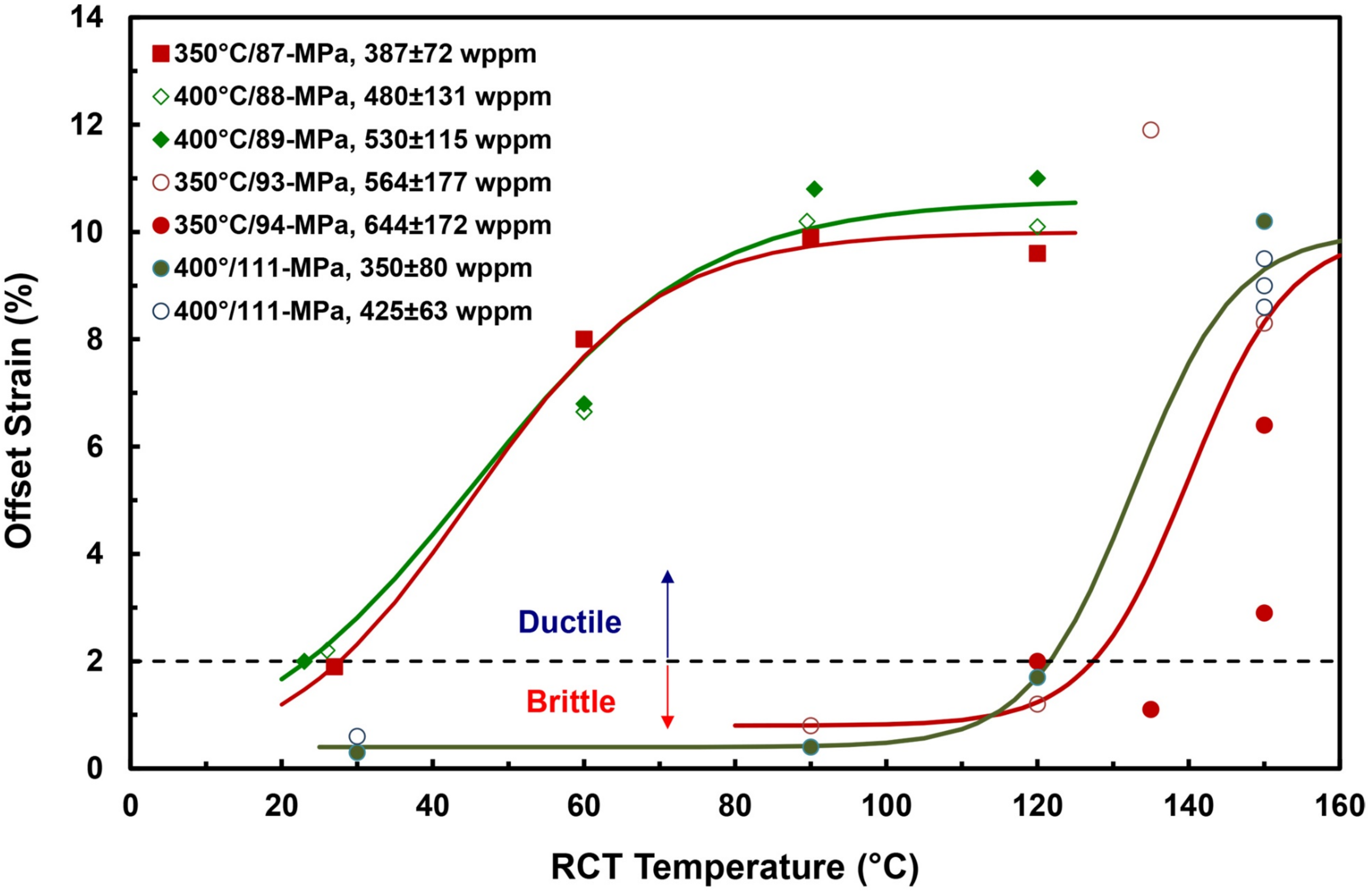
Modeling of the Boiling Water Reactor Dry Cask Simulator. Suffield, Richmond, and Fort. PNNL-28424 May 2019.

Temperature Sensitivities and Summary

- Conservative decay heat calculations → 20°C - 50°C+ margin
- Actual loading (50%-90%) vs. design basis heat load → 20°C - 50°C+
- Actual drying times vs. vacuum steady state asymptote → 0°C - 50°C+
- Ambient temperature assumption → 0°C - 20°C+
- “Best Estimate” thermal models removing known conservatisms → 10°C - 20°C+

- Modeling of high burnup dry cask storage systems loaded to date:
  - Peak Cladding Temperatures << 400°C
  - All cladding temperatures < 325°C
  - Most < 300°C
  - Many 250°C - 275°C
  - Fraction of cladding near PCT is very small

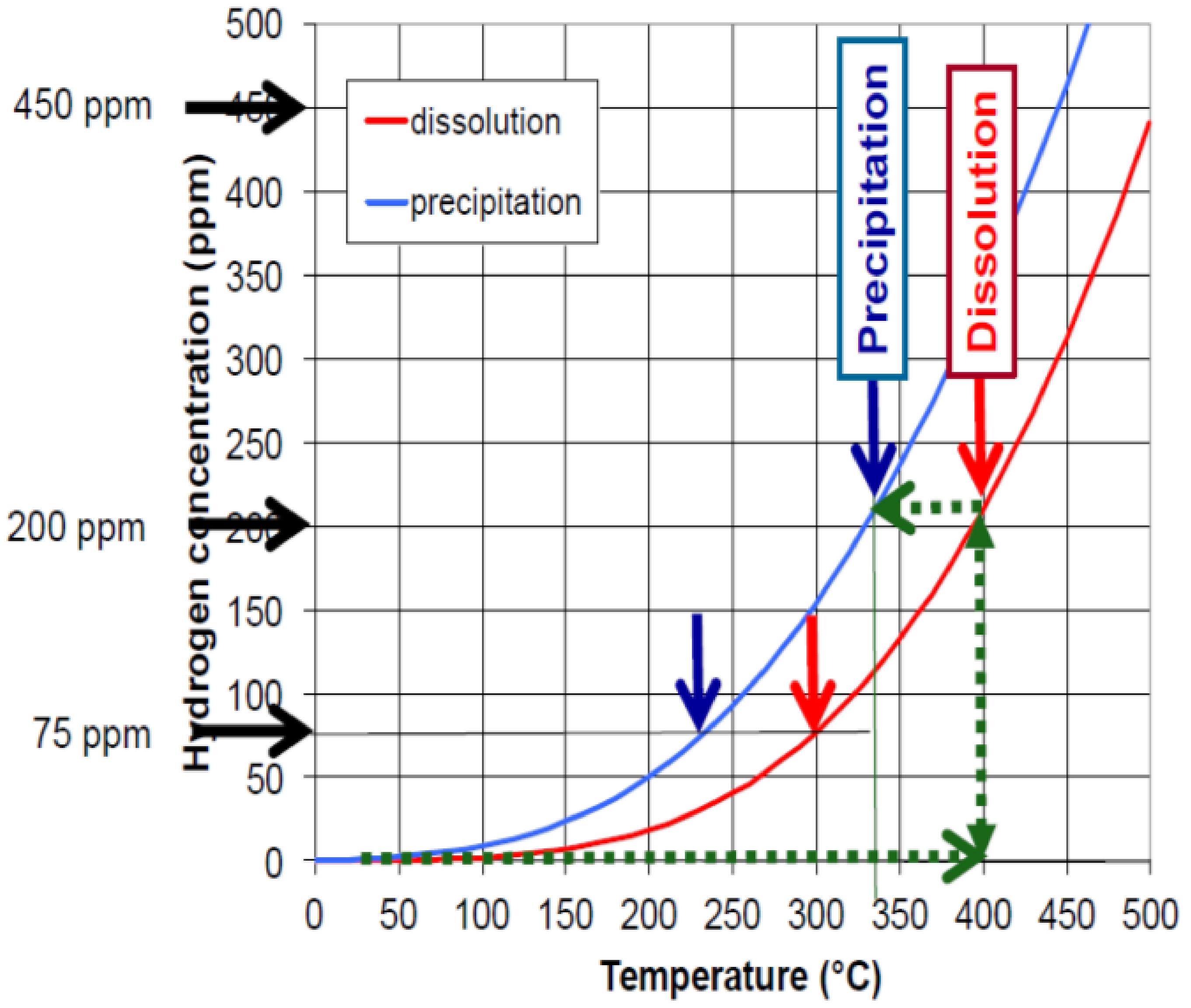
Ductility (Offset Strain) for ZIRLO® vs. Test Temperature – DTT Determination



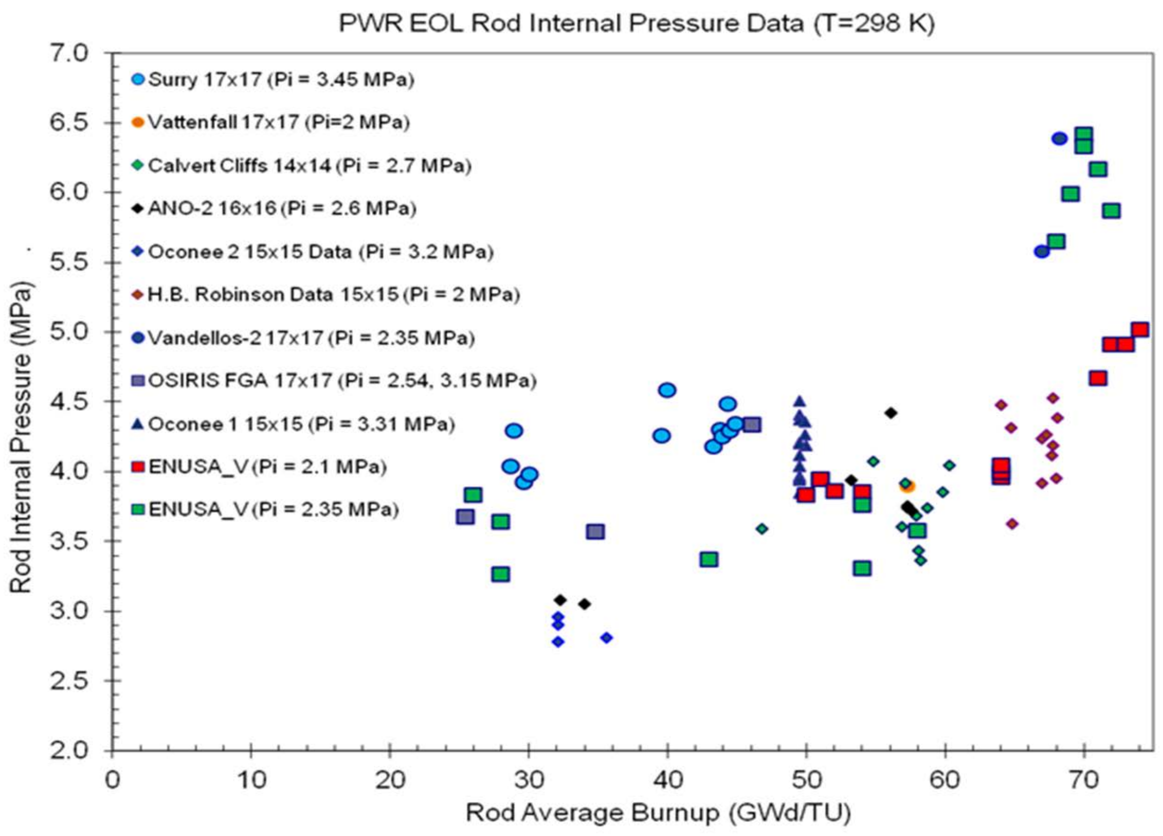
Review of Hydride-Induced Ductility Degradation

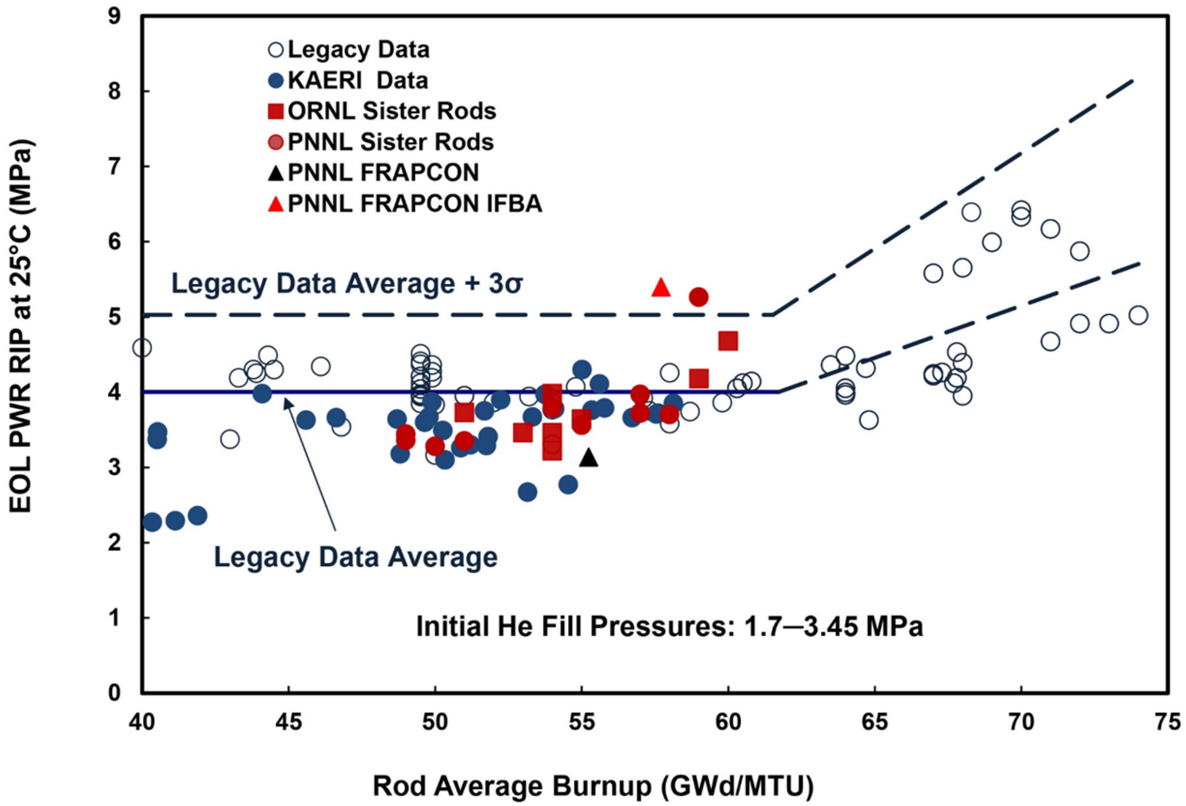
- As-Irradiated Cladding
  - Hydrides are primarily oriented in circumferential direction
  - Distribution of circumferential hydrides across cladding wall has a significant effect on ductility & radial-hydride precipitation
  - Short isolated radial hydrides have been observed in cladding (ZIRLO® and M5 ®) from PWR fuel rods irradiated to high burnup
- Conditions for ***Significant*** Radial Hydride Precipitation
  - High enough (>60 wppm) hydrogen content and peak cladding temperature (PCT >285^{o}C)
  - High enough (>10 MPa) internal pressure at PCT
  - High enough (>80 MPa: ZIRLO® and Zry-4) hoop stress @ PCT
  - Cladding microstructure (RXA more susceptible than CW-SRA)
  - Distribution of circumferential hydrides @ PCT
- ANL Results for 400^{o}C & 350^{o}C PCT

Hydride Reorientation - Temperature



EOL RIP





Billone, M., Burtseva, T., “Results of Ring Compression Tests”, SFWD-SFWST-2018-000510, ANL-18/36. September 2018.

End-of-Life Rod Internal Pressure in Spent Pressurized Water Reactor Fuel, EPRI 3002001949, December 2013.

Initial fill pressure of Sibling Pins: 1.7 MPa, 2.0 MPa, 2.5 MPa

Modeled Hoop Stress

Table 1. Maximum Hoop Stress (MPa) 400˚C Peak Temperature

Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	40.0	43.8	41.7
17x17	49.9	53.4	50.5
17x17 IFBA	84.4	88.1	86.3

Table 2. End of Life Rod Internal Pressure (MPa) 400˚C Peak Temperature

Profile	Vacuum (0.004 atm)	Medium Flow (1 atm)	High Flow (6.8 atm)
Fuel			
10x10	5.4	6.1	6.4
17x17	6.2	6.8	7.0
17x17 IFBA	10.6	11.1	11.5

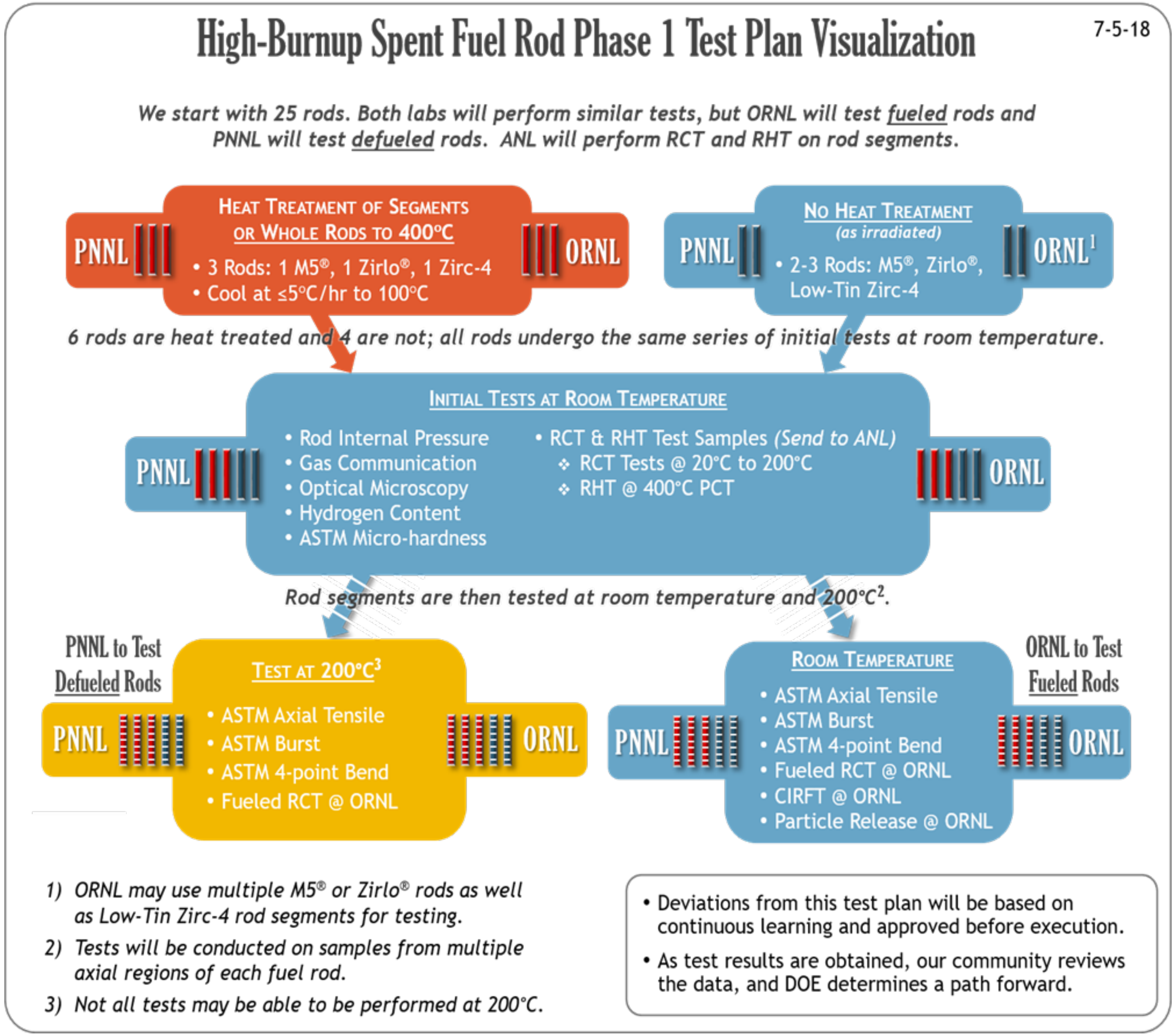
Table 3. Maximum Plenum Temperature (all fuel types)

Profile	Temperature (˚C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

Richmond, DJ and KJ Geelhood, *FRAPCON Analysis of Cladding Performance during Dry Storage Operations,* PNNL-27418, April 2018.

- Sibling Pin initial fill pressures
  - 1.7, 2.0, and 2.5 MPa
- EOL RIP (Room Temp)
  - 22 out of 25 <4.0 MPa
  - 3.22 to 5.26 MPa
- Assume uniform cladding temperature of 400˚C
  - EOL RIP 7.3 to 11.9 MPa
- For 4.0 MPa @ RT, 9.0 MPa
  - Hoop stress <72 MPa

Sibling Pin Phase 1 Test Plan



Three sibling pins (M5, Zirc-4, ZIRLO) were heat treated to simulate temperatures during dry storage vacuum drying [4]

- Each rod was heat treated using a flat axial profile at 400ºC with a ≤ 5ºC/h cooldown rate
- Each rod heat treatment included approximately 38 h heat up + 8 h at temperature + 100 h cooldown
- The metallographic and mechanical test results from the heat-treated rods are compared with the data from baseline rods to determine if vacuum drying results in any changes to the cladding

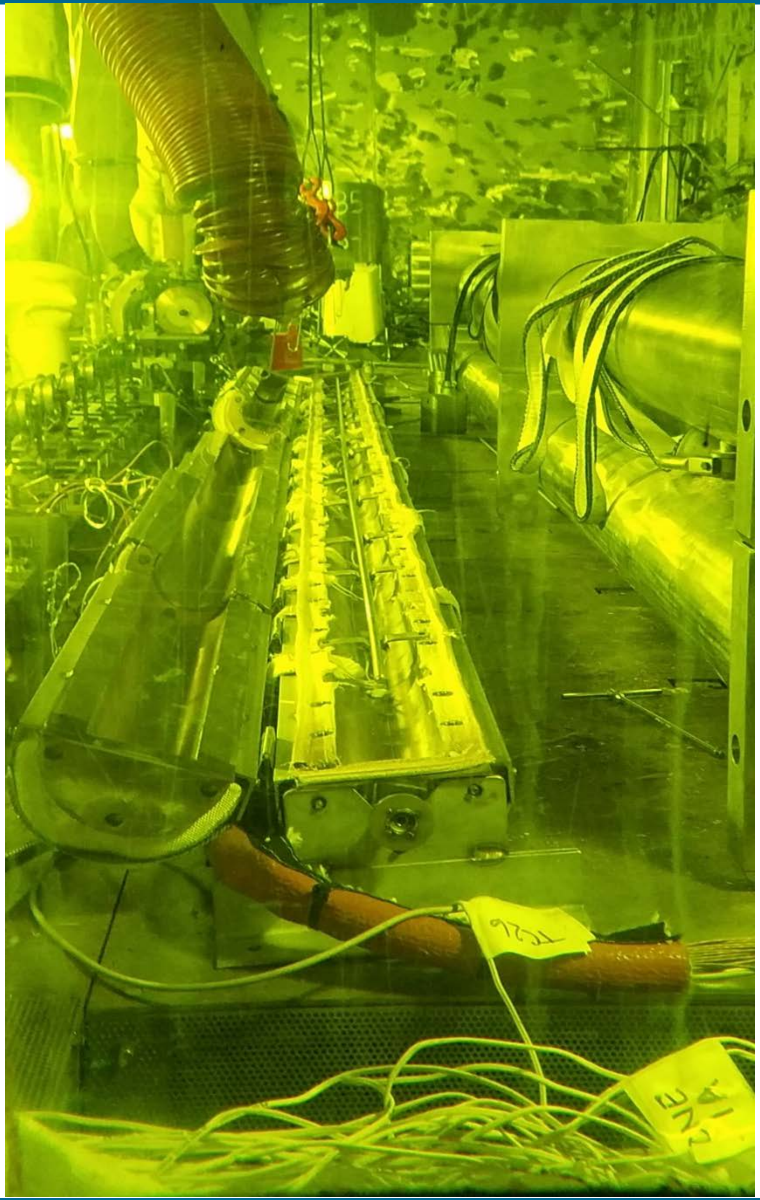


Photo Courtesy of ORNL

Metallographic images (METs) of M5-clad sibling pins 30AD05 and 30AE14

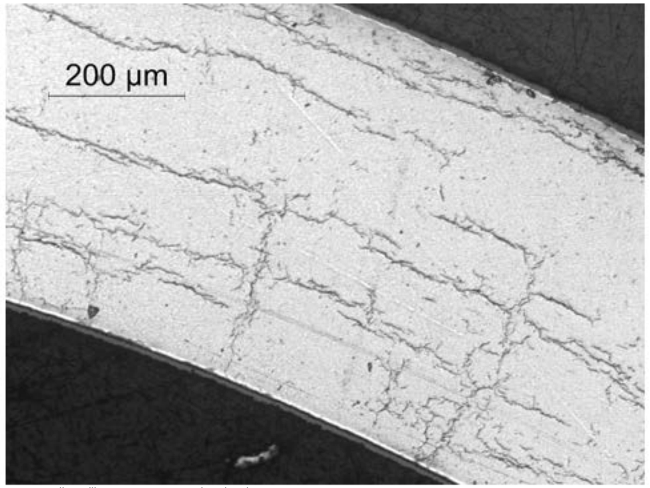
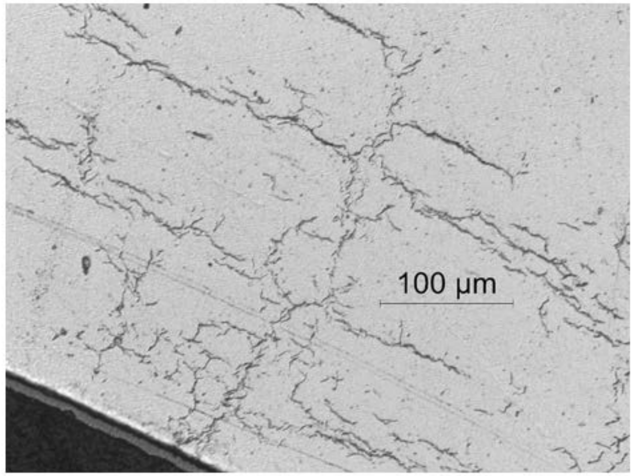


Image: Mike Billone, Argonne National Laboratory

(a) 100X image



(b) 200X image

Image: Mike Billone, Argonne National Laboratory

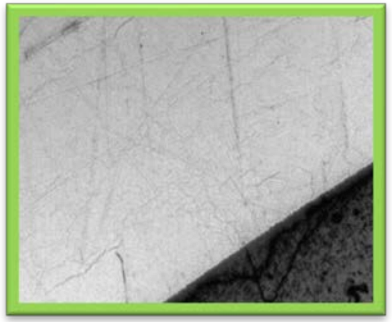


Image: ORNL

Heat-treated rod (400°C) 30AE14, elevation ~3,350 mm, local burnup estimated 50 GWd/MTU

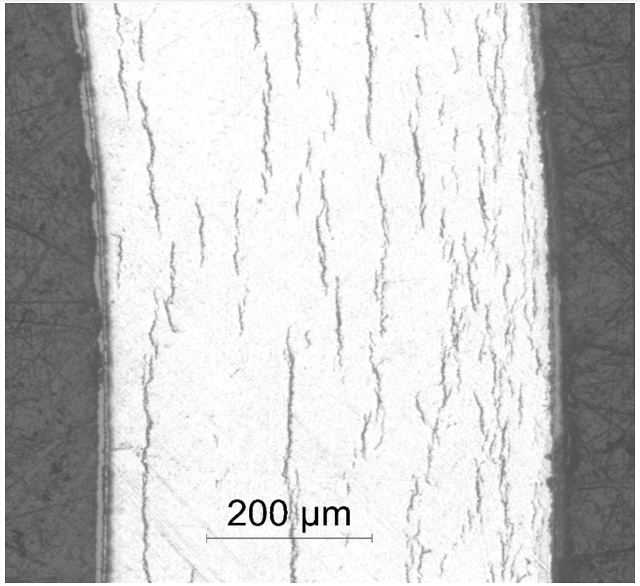
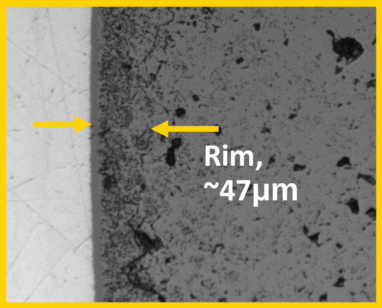


Image: Mike Billone, Argonne National Laboratory

Baseline rod 30AD05, elevation ~3,300 mm, , local burnup estimated 52 GWd/MTU

Image: ORNL



- Long radial hydrides were observed on the heat-treated rod
- The baseline rod cladding has circumferentially oriented hydrides
- Hoop Stress at PCT was 52 MPa
- Radial hydrides appear to lack the continuity for degradation – to be confirmed by ring compression tests

Potential for Hydride Reorientation

- Radial-Hydride-Induced-Degradation
  - DEMO Cask fuel rods
    - Peak cladding temperature (PCT) < 250°C; <44 wppm H in solution
    - Rod internal pressure (RIP) < 9 MPa → peak hoop stress <68 MPa
    - Do not anticipate to observe radial-hydride-induced degradation
  - Sister Rods
    - PCT = 400°C; ≤ 200 wppm H; pressure < 11.3 MPa → hoop stress <87 MPa
    - Expect to observe radial hydrides
    - Do not expect to observe radial-hydride-induced degradation

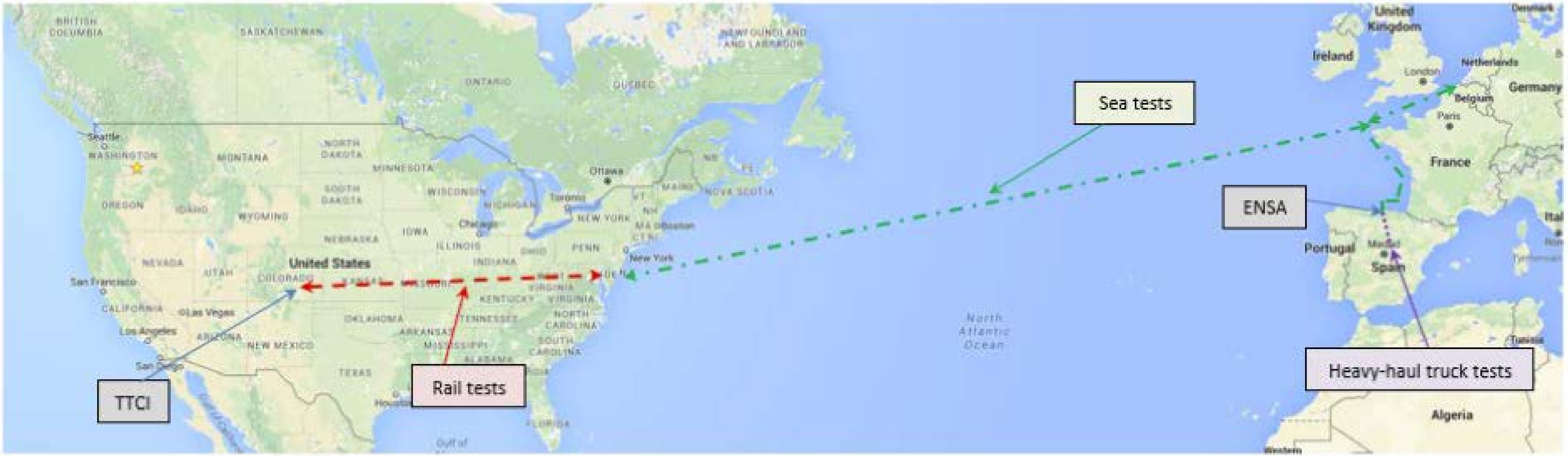
- Hoop stress and hydride reorientation degradation should be bounding for current US standard high burnup PWR cladding

Slide courtesy of M Billone presented at NRC DSFM REGCON, December 11, 2018

Ring Compression Test Summary

- At peak hoop stress <90 MPa, hydride reorientation may occur, but it is not expected to result in loss of ductility
  - Expect no failure from pinch loading
- Argonne National Laboratory will continue to perform RCT on defueled cladding samples that have undergone radial hydride treatment at 400°C
- Oak Ridge National Laboratory will perform RCT on fueled cladding segments both on as-received (no heat treatment) and from rods subjected to whole rod heating at 400°C
  - Determine how the presence of fuel affects pinch load response, limits displacement, load bearing?

Transportation Triathlon collected Strain and Acceleration Data on Surrogate Fuel over Rail, Truck, and Ship.

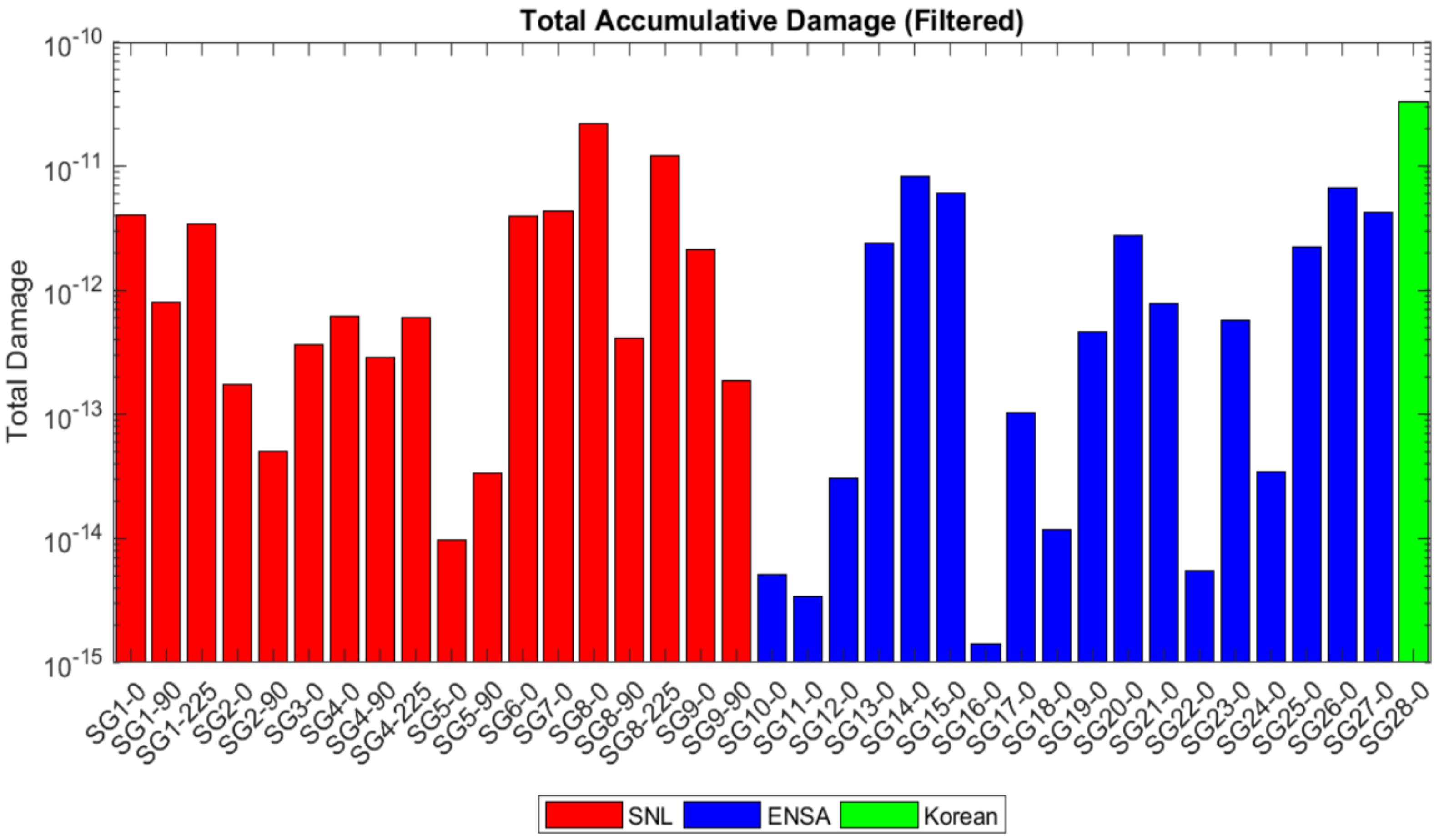


- Cask handling tests at ENSA, Santander/Spain
- Heavy-haul truck tests in Northern Spain (245 mi/394 km)
- Barge transport from Spain to Belgium (929 mi/1,495 km)
- Ocean ship transport from Belgium to Baltimore (4,290 mi/6,904 km)
- Rail shipment from Baltimore to TTCI (Rail 1, 1,950 mi/3,138 km)
- Testing at TTCI
- Rail shipment from TTCI to Baltimore (Rail 2, 1,125 mi/1,811 km)
- Return ocean transport from Baltimore to Spain (not recorded)

Total distance traveled with data acquisition: 8,539 mi (13,742 km)

Data Shows that Fatigue is Not a Concern

1.0 = Fatigue Failure; Data is all below 1E-10



Strain data collected during the multi-modal transportation test were used to perform fatigue analysis on the fuel cladding. The ASTM Standard E1049 rainflow counting method was used to count the number of strain cycles in the data. Accumulated fatigue damage was calculated according to Miner's Rule.

Klymyshyn et al, Structural Dynamic Analysis of Spent Nuclear Fuel, SWFD-SFWST-M2SF-19PN01202014; PNNL-29150

- Damage fraction of 1.0 indicates fatigue failure. Accumulated damage in all cases is below 1E-10
- This calculation estimates ***it would take 10 billion cross-country (2,000-mile) trips to challenge the fatigue strength*** of irradiated fuel cladding.

Ongoing Work

- International Round Robin on Demo Cask
  - Will show variability of models
  - Compare use of proprietary data (e.g., dimensions) with generic values
- Horizontal BWR Dry Cask Simulator
  - Testing
  - Round Robin blind modeling
- Sibling Pin testing
- Support to PIRT
- Continued model improvement (e.g., modify COBRA-SFS to better model BWR assemblies, especially with partial length rods)

Summary of SFWST Perspective

- DOE prefers no additional cladding failures (through-wall penetration) resulting from drying, extended storage, or normal conditions of transport
  - To facilitate either repackaging, if necessary, or for cladding credit in a deep geologic repository
- Thermal modeling is mature and the physics and phenomena well understood
- Inputs to the models are typically conservative and biased, such that predicted temperatures are higher than actual temperatures
- Temperatures are important because they drive degradation phenomena
  - The closer the temperature is to a limit causing degradation, the better the inputs should be unless it is shown the inputs are conservative and biased towards higher temperatures
- Peak Cladding Temperature represents a very small fraction of total cladding
- From a cladding perspective, degradation effects operate on a continuum and there is no “cliff edge” at 400˚C
  - Flexibility to a strict 400˚C limit is available while still meeting the DOE preference of no additional cladding failure