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Spent Fuel and Waste Science and Technology (SFWST)

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Integrated Approach to Closing Cladding Data Gaps; Thermal Analysis, and Hoop Stress

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PNNL-SA-139950

NRC Division of Spent Fuel Management Regulatory Conference

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Outline

- Cladding data gaps
- Integrated approach to closing cladding data gaps
- Loading of the TN-32B "Demo Cask"
- Thermal analysis
- Hoop stress

Technical Data Gaps Associated with Cladding - 2012

- Thermal profiles
- Stress profiles
- H_2 effects: hydride reorientation and embrittlement
- H_2 effects: delayed hydride cracking
- Annealing of radiation damage
- Oxidation
- Creep

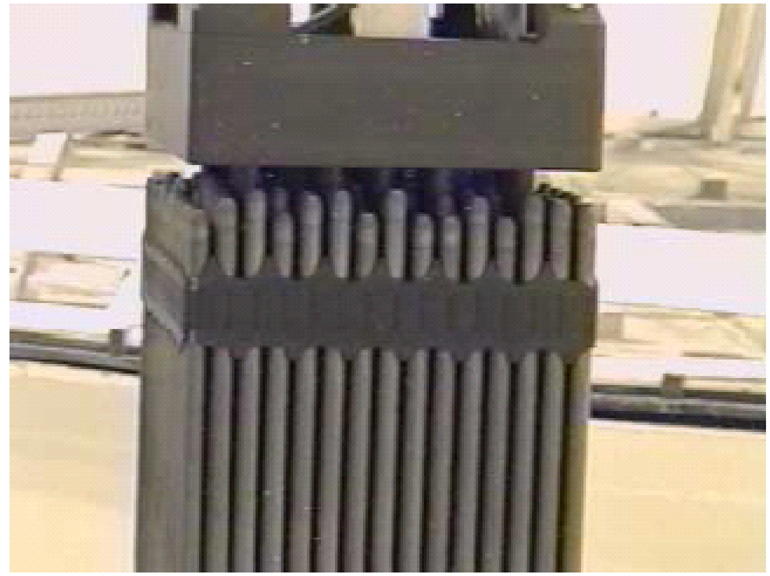


Photo courtesy of Idaho National Laboratory

High Burnup Spent Fuel

- High burnup ≥ 45 GWd/MTU
- Typical characteristics
  - Increasing fission gas release
  - Increasing cladding oxidation
  - Increasing 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

Integrated Approach to Closing Cladding Data Gaps

- Thermal Analysis (this presentation)
  - What are the ***realistic*** temperatures that cladding experiences during drying and extended storage?
- Hoop Stress (this presentation/Mike Billone)
  - 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 (Mike Billone)
  - Identify the ductile transition temperatures for cladding under ***realistic*** temperatures and hoop stress
- Cyclic Integrated Reversible Bending Fatigue Test (NUREG/CR-7198)
  - Identify the role of fuel/clad and pellet/pellet bonding, the number of cycles as a function of applied stress to failure
- External Stresses (Brady Hanson presentation this afternoon)
  - Identify ***realistic*** stresses to cladding during extended storage and normal conditions of transport
- Confirm post-drying material properties (Rose Montgomery)

Licensing Changes for TN-32B Research Project Cask

	TN-32 Safety Evaluation Report	TN-32B Research Project Cask
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
Peak cladding temperature	328°C	348°C

Photo courtesy of Dominion Energy

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**

Peak Cladding Temperature

COBRA-SFS

	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	

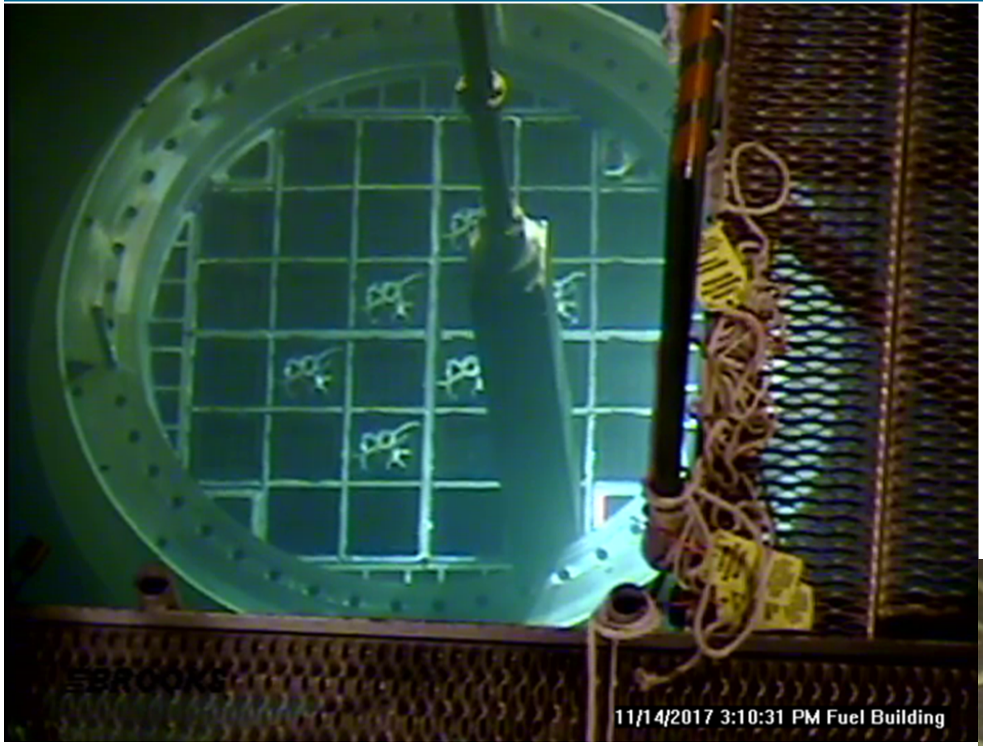
Peak Cladding Temperature

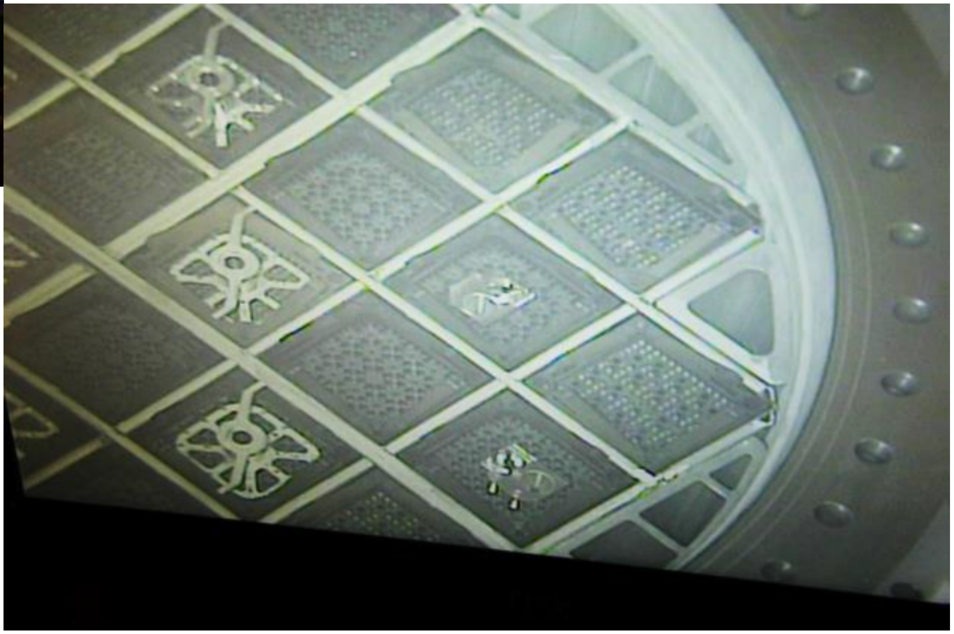
STAR-CCM+

	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

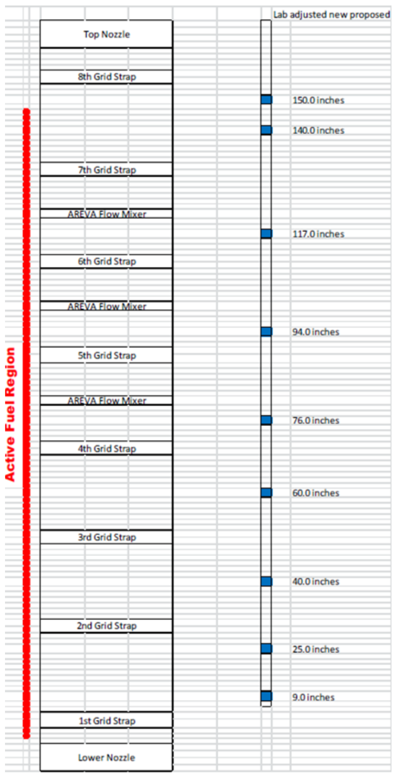
Cask Loading and Funnel Guide Installation

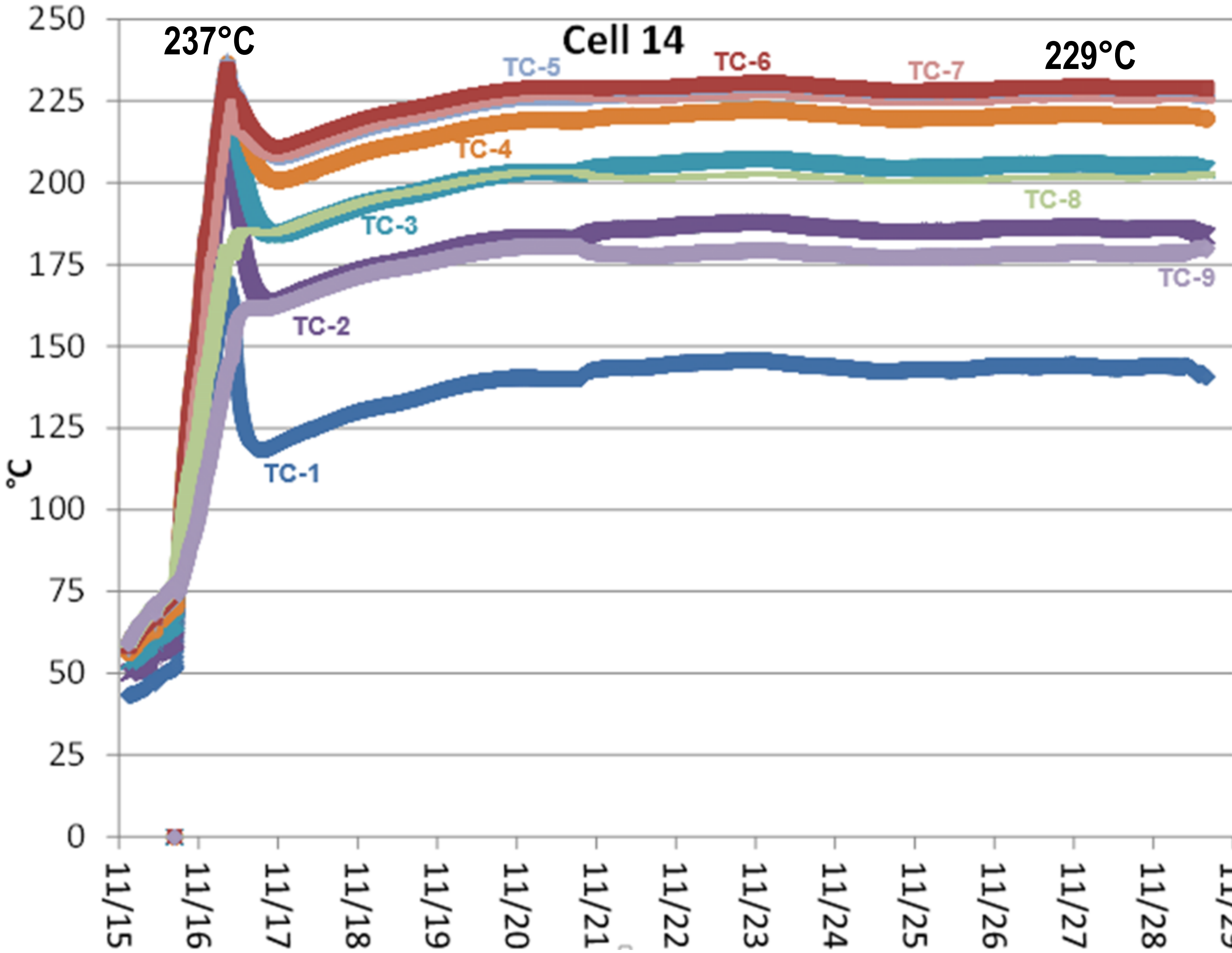




Photos courtesy of Dominion Energy

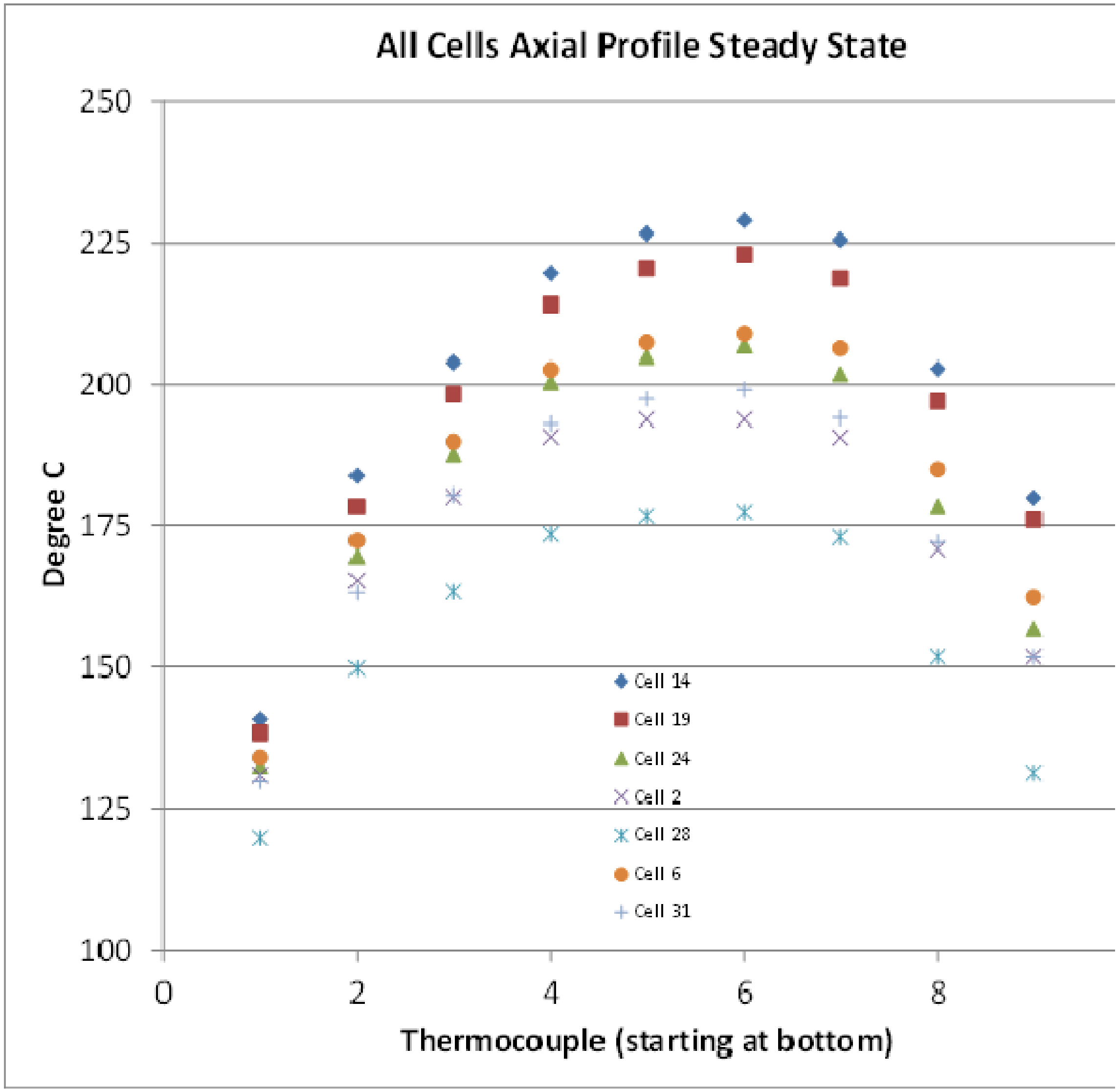
Measured Temperatures in Hottest Assembly

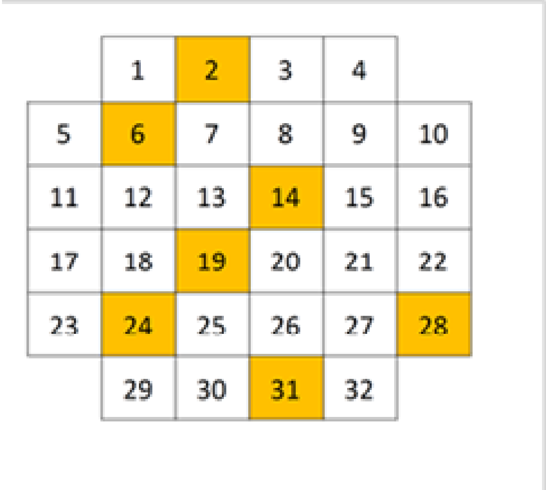




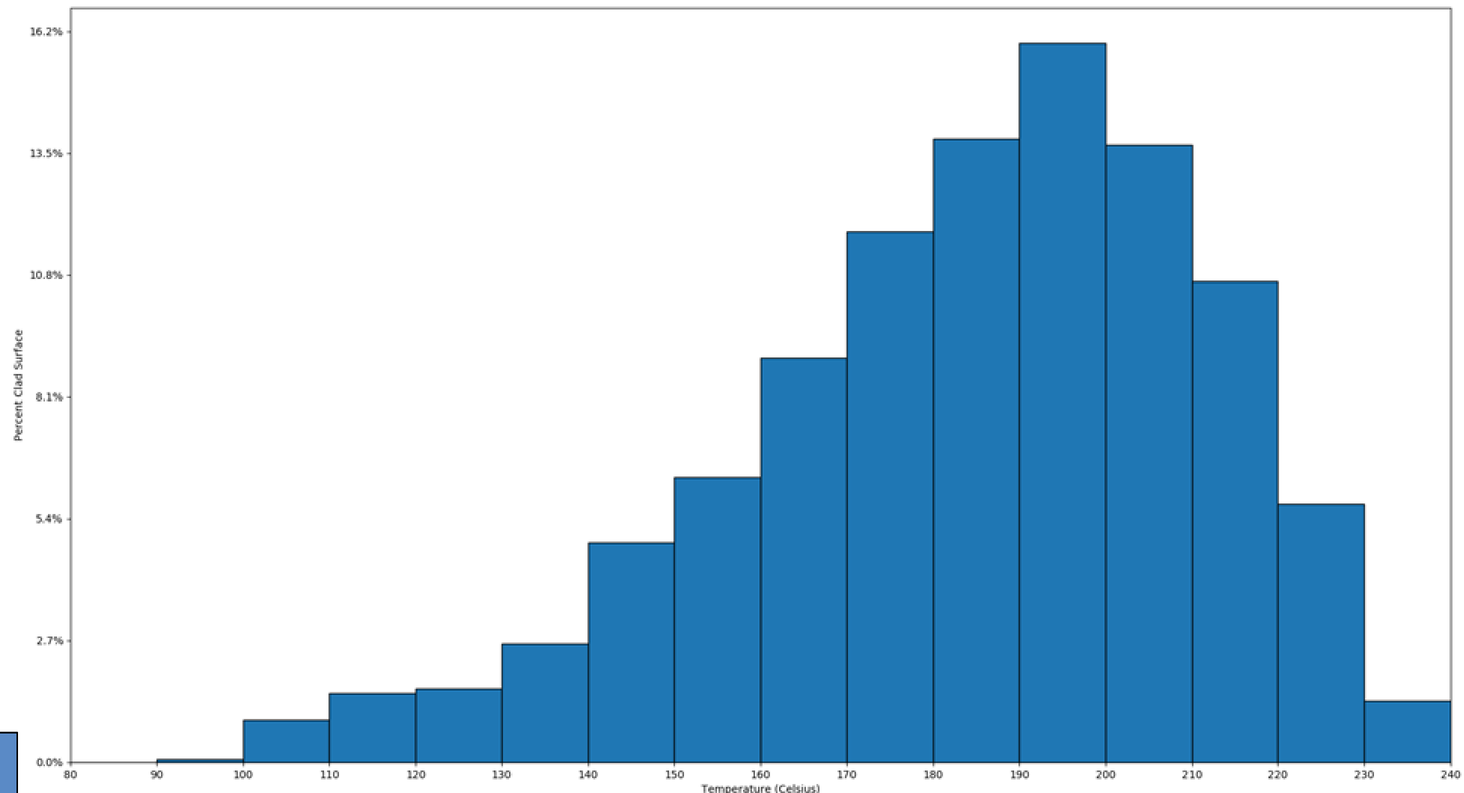
TC-1 is thermocouple near bottom TC-9 is thermocouple near top

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





Adjusted FSAR Basket/Rail Gap Input to Model



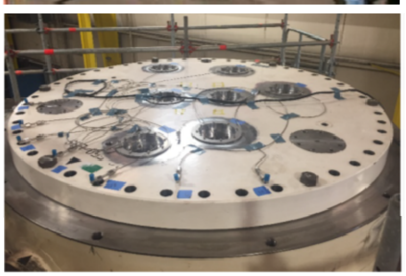
PCT

	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 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

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

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

Modeled Hoop Stress from Rod Internal Pressure

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.

Conclusions

- 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)
- DOE, EPRI, NRC, and International groups under ESCP Thermal Subcommittee working to understand conservatisms/bias and address uncertainties

- Realistic temperatures and hoop stresses are significantly lower than the conservative values previously modeled
- With the data that is currently available and using the integrated approach, cladding integrity will not be challenged during extended storage and normal conditions of transport

Questions?

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