High Burnup Fuel, Associated Data Gaps, and Integrated Approach for Addressing the Gaps

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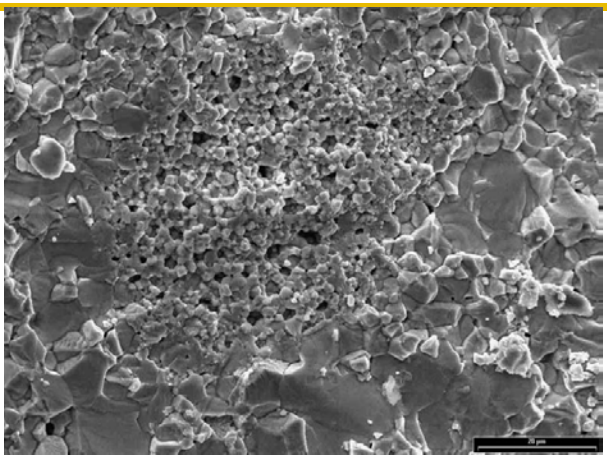
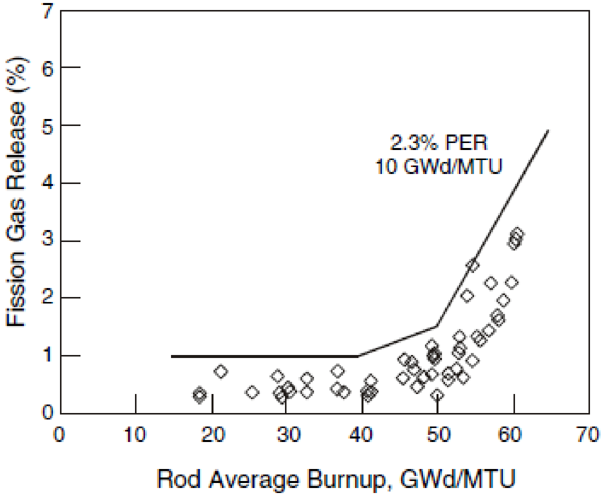
What is High Burnup Fuel?

- **By definition, burnup ≥ 45 GWd/MTU**
  - Longer time in reactor or higher power
    - More fissions, higher radionuclide content, higher decay heat
  - Based on changes to the fuel and cladding
    - Continuum, not step changes
- **High Burnup Structure (HBS)**
  - Initiates with pellet-average burnup ~35-40 GWd/MTU
    - Increases with burnup from 0 to ~200µm
  - Grains subdivide ~10µm → 0.1-0.3µm
  - Up to 20% closed porosity
- **Increased fission gas release**



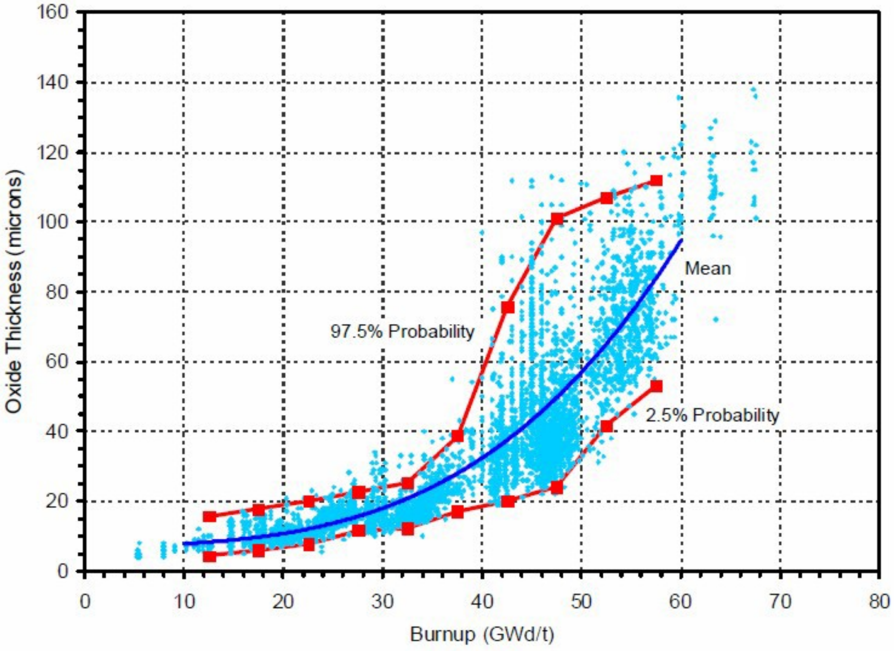
Example of HBS in MOX fuel(1)



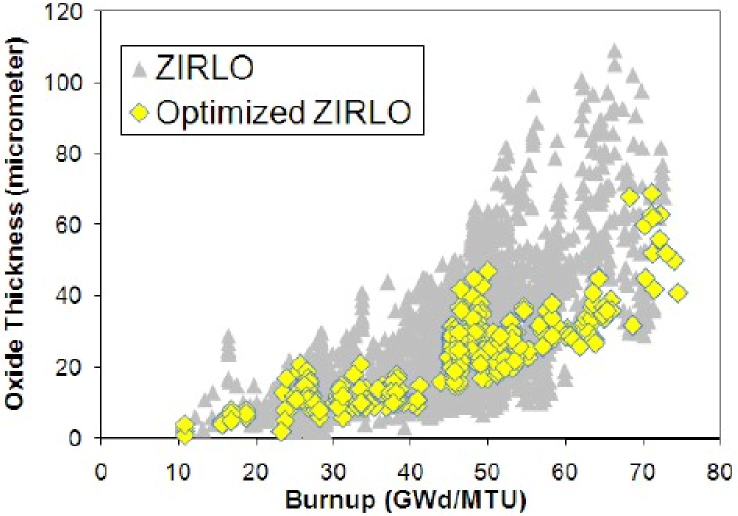
Fission Gas Release in US PWRs(2)

Cladding Oxidation

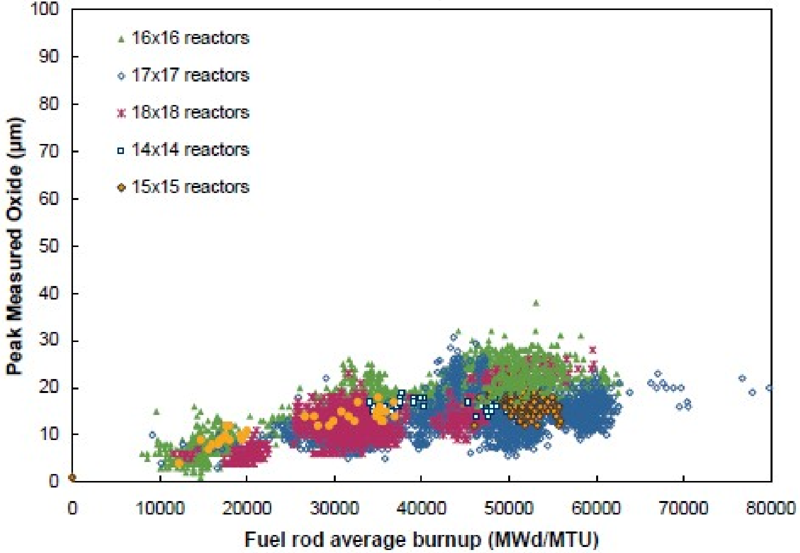
- NRC limits oxide thickness to <100µm
- Newer alloys oxidize less



Low-tin Zircaloy-4(3)

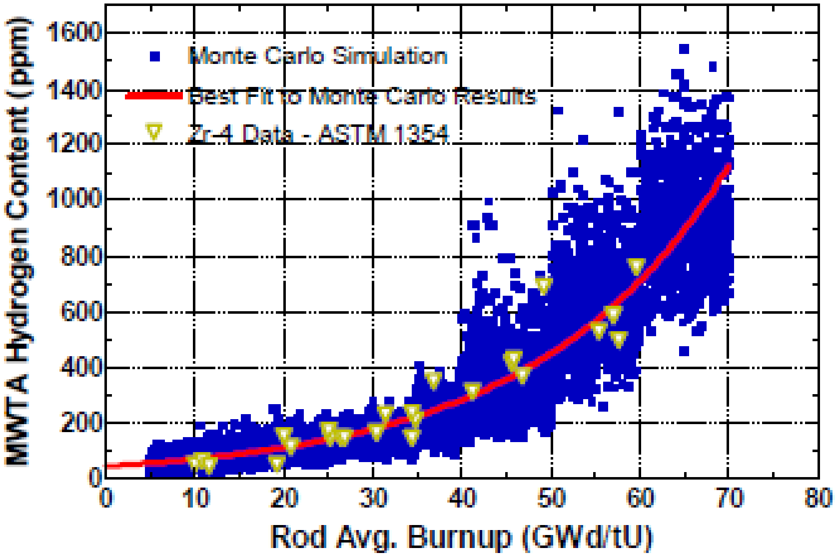


ZIRLO™(4)

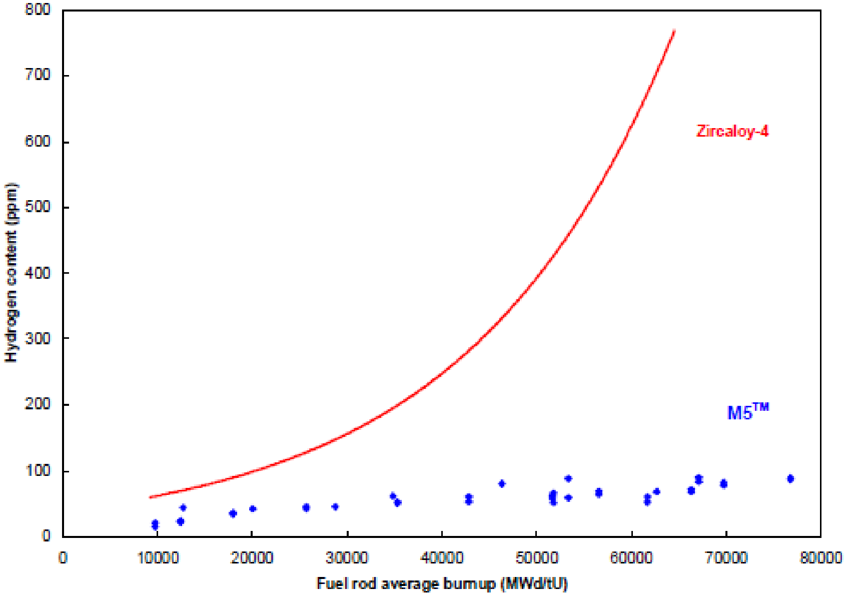


M5®(5)

Hydrogen Content



Low-tin Zircaloy-4(3)



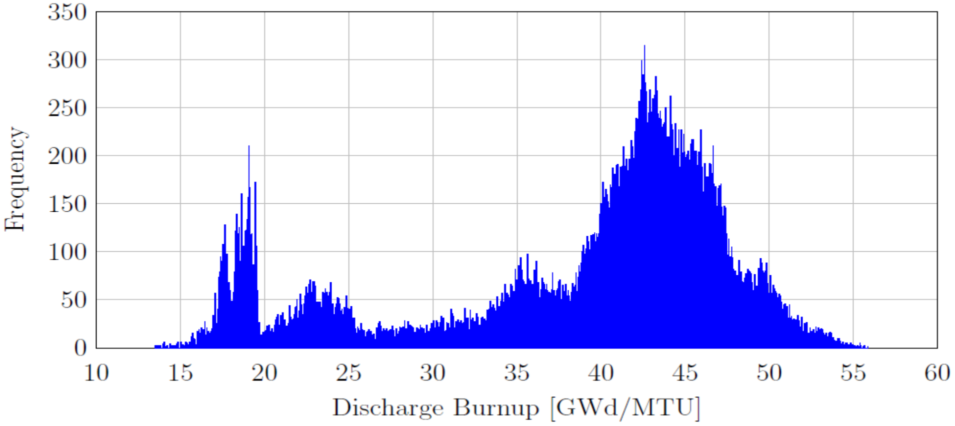
M5®(5)

High Burnup Fuel Inventory

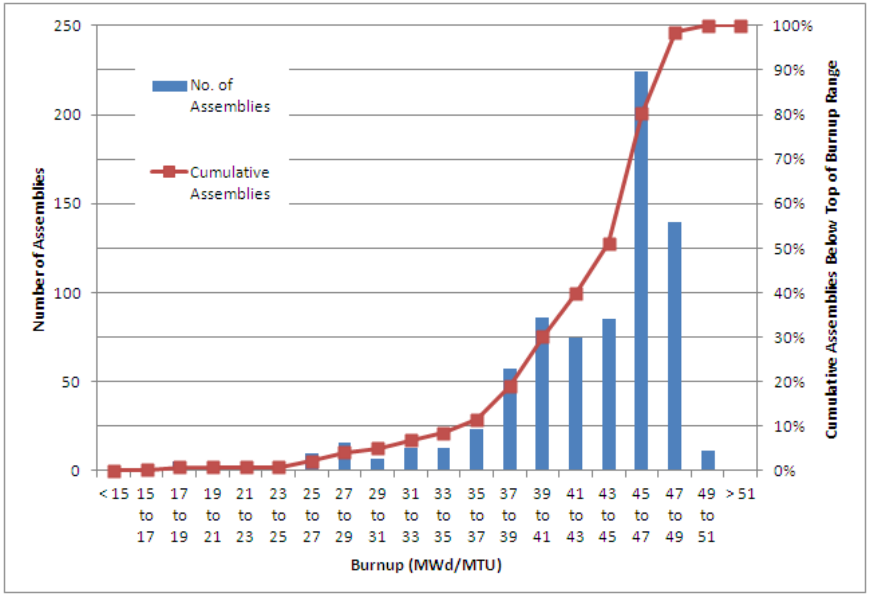
	Number of Assemblies		Average burnup (GWd/MTU)	
Year	**BWR**	**PWR**	**BWR**	**PWR**
2000	4603	3122	**38.3**	**44.9**
2001	3617	2896	**40.1**	**45.5**
2002	4148	3765	**40.2**	**46.0**
2003	4584	3585	**39.5**	**46.4**
2004	4431	2669	**42.8**	**46.9**
2005	4075	3704	**42.8**	**46.6**
2006	3995	3516	**43.1**	**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**

GC-859 Reported Average Assembly-Average Discharge Burnup(6)

- **NRC limit of 62 GWd/MTU peak rod-average burnup**
- **Limits to much higher burnup:**
  - 5 w/o ^{235}U enrichment
  - Cycle length (18, 24 months in US)



Watts Barr Unit 1 Cycles 1-10 Discharge Burnup(7)



Calvert Cliffs 24 Loaded 32P DSCs as of April 2013(8)

Gap Prioritization - 2012

Gap	Priority	Gap	Priority
Thermal Profiles	**1**	Neutron poisons – Thermal aging	7
Stress Profiles	**1**	Moderator Exclusion	8
Monitoring – External	2	**Cladding – Delayed Hydride Cracking**	**9**
Welded canister – Atmospheric corrosion	2	Examination of the fuel at the INL	10
Fuel Transfer Options	**3**	**Cladding – Creep**	**11**
Monitoring – Internal	4	Fuel Assembly Hardware – SCC	11
Welded canister – Aqueous corrosion	5	Neutron poisons – Embrittlement	11
Bolted casks – Fatigue of seals & bolts	5	**Cladding – Annealing of radiation damage**	**12**
Bolted casks – Atmospheric corrosion	5	**Cladding – Oxidation**	**13**
Bolted casks – Aqueous corrosion	5	Neutron poisons – Creep	13
Drying Issues	6	Neutron poisons – Corrosion	13
Burnup Credit	7	Overpack – Freeze-thaw	14
Cladding – Hydride reorientation	**7**	Overpack – Corrosion of embedded steel	14

Imminent need

Immediate to facilitate demonstration early start

Near-term High or Very High

Long-term High

Near-term Medium or Medium High

Long-term Medium

Gap Prioritization – 2014

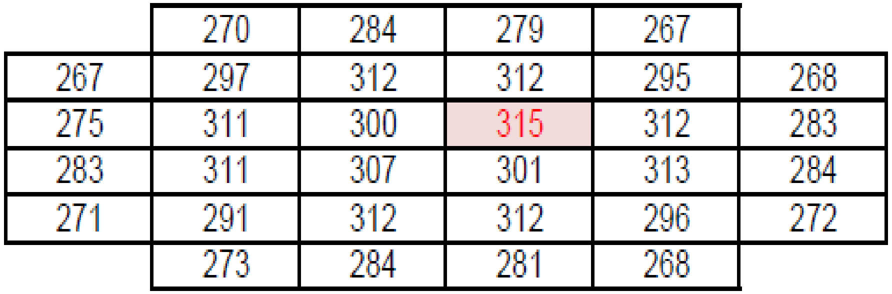
Gap[a]	Updated Prioritization	Original Prioritization	Basis for Change in Scoring/Prioritization
Thermal Profiles	1	1	N/A
Stress Profiles	1	1	N/A
Monitoring - External	2	2	N/A
Welded Canister – Atmospheric Corrosion	2	2	N/A
Drying Issues	3	6	N/A
Monitoring - Internal	4	4	No longer a pre-requisite to the HBU Confirmatory Demo
Cladding – H_2 Effects: Hydride Reorientation and Embrittlement	4	7	N/A
Neutron Poisons – Thermal Aging	4	7	N/A
Moderator Exclusion	5	8	N/A
Fuel Transfer Options	6	3	No longer a pre-requisite to the HBU Confirmatory Demo or a near-term need because DOE is pursuing a dry opening of the cask.
Welded Canister – Aqueous Corrosion	6	5	No longer a near-term need because aqueous conditions are unlikely to occur for a sufficient time to cause breach of confinement during the initial license period.
Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts	6	5	No longer a near-term need because of the progress being made by the international community.
Bolted Casks - Atmospheric Corrosion	6	5	No longer a near-term need because of industry changes to weather cover designs, testing and maintenance.

Integrated Approach to Closing Cladding Gaps

- **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 to brittle 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 materials properties**

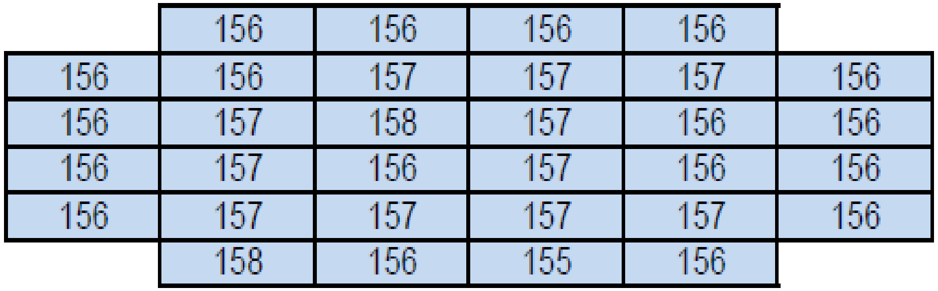
Clad Temperatures

- **Develop realistic thermal profiles**
  - Remove conservative assumptions in thermal models
  - Use actual and realistic times for drying and transfer times
  - Actual, not design basis, decay heat loadings
  - Remove conservatisms in assembly decay heat calculations
  - Actual, not conservative, ambient conditions (assumed 100°F average)
- **Realistic temperatures expected to be well below the 400°C regulatory guidance**
  - Used in numerous calculations for creep, He release, pressure calculations, etc.



	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 Clad 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 Clad Temperature (°C)

Example of Industry-Calculated Temperatures[8]

For NUHOMS 32P (21.12 kW/DSC)

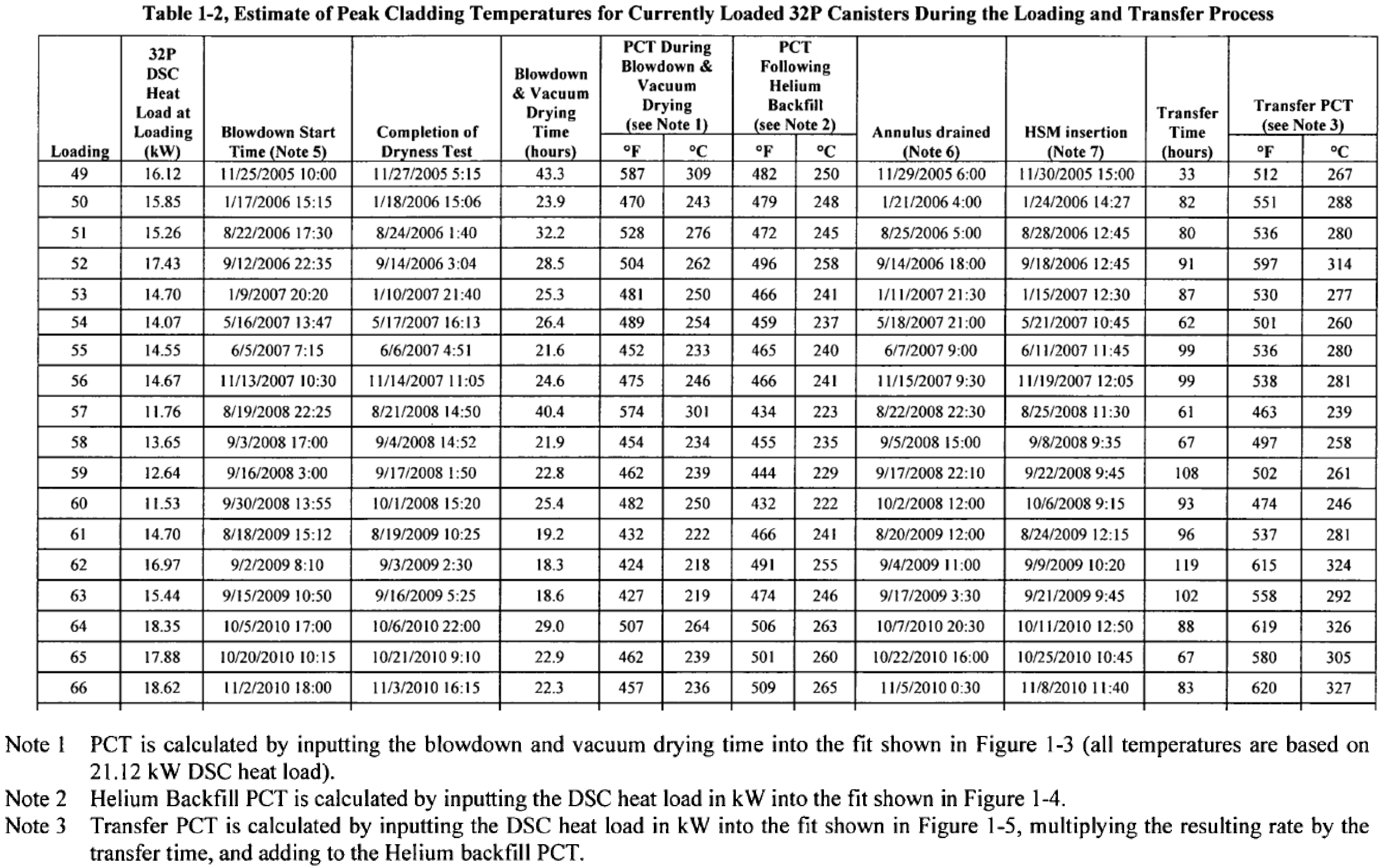


Table 1-2, Estimate of Peak Cladding Temperatures for Currently Loaded 32P Canisters During the Loading and Transfer Process

Loading	32P DSC Heat Load at Loading (kW)	Blowdown Start Time (Note 5)	Completion of Dryness Test	Blowdown & Vacuum Drying Time (hours)	PCT During Blowdown & Vacuum Drying (see Note 1)		PCT Following Helium Backfill (see Note 2)		Annulus drained (Note 6)	HSM insertion (Note 7)	Transfer Time (hours)	Transfer PCT (see Note 3)	
					°F	°C	°F	°C				°F	°C
49	16.12	11/25/2005 10:00	11/27/2005 5:15	43.3	587	309	482	250	11/29/2005 6:00	11/30/2005 15:00	33	512	267
50	15.85	1/17/2006 15:15	1/18/2006 15:06	23.9	470	243	479	248	1/21/2006 4:00	1/24/2006 14:27	82	551	288
51	15.26	8/22/2006 17:30	8/24/2006 1:40	32.2	528	276	472	245	8/25/2006 5:00	8/28/2006 12:45	80	536	280
52	17.43	9/12/2006 22:35	9/14/2006 3:04	28.5	504	262	496	258	9/14/2006 18:00	9/18/2006 12:45	91	597	314
53	14.70	1/9/2007 20:20	1/10/2007 21:40	25.3	481	250	466	241	1/11/2007 21:30	1/15/2007 12:30	87	530	277
54	14.07	5/16/2007 13:47	5/17/2007 16:13	26.4	489	254	459	237	5/18/2007 21:00	5/21/2007 10:45	62	501	260
55	14.55	6/5/2007 7:15	6/6/2007 4:51	21.6	452	233	465	240	6/7/2007 9:00	6/11/2007 11:45	99	536	280
56	14.67	11/13/2007 10:30	11/14/2007 11:05	24.6	475	246	466	241	11/15/2007 9:30	11/19/2007 12:05	99	538	281
57	11.76	8/19/2008 22:25	8/21/2008 14:50	40.4	574	301	434	223	8/22/2008 22:30	8/25/2008 11:30	61	463	239
58	13.65	9/3/2008 17:00	9/4/2008 14:52	21.9	454	234	455	235	9/5/2008 15:00	9/8/2008 9:35	67	497	258
59	12.64	9/16/2008 3:00	9/17/2008 1:50	22.8	462	239	444	229	9/17/2008 22:10	9/22/2008 9:45	108	502	261
60	11.53	9/30/2008 13:55	10/1/2008 15:20	25.4	482	250	432	222	10/2/2008 12:00	10/6/2008 9:15	93	474	246
61	14.70	8/18/2009 15:12	8/19/2009 10:25	19.2	432	222	466	241	8/20/2009 12:00	8/24/2009 12:15	96	537	281
62	16.97	9/2/2009 8:10	9/3/2009 2:30	18.3	424	218	491	255	9/4/2009 11:00	9/9/2009 10:20	119	615	324
63	15.44	9/15/2009 10:50	9/16/2009 5:25	18.6	427	219	474	246	9/17/2009 3:30	9/21/2009 9:45	102	558	292
64	18.35	10/5/2010 17:00	10/6/2010 22:00	29.0	507	264	506	263	10/7/2010 20:30	10/11/2010 12:50	88	619	326
65	17.88	10/20/2010 10:15	10/21/2010 9:10	22.9	462	239	501	260	10/22/2010 16:00	10/25/2010 10:45	67	580	305
66	18.62	11/2/2010 18:00	11/3/2010 16:15	22.3	457	236	509	265	11/5/2010 0:30	11/8/2010 11:40	83	620	327

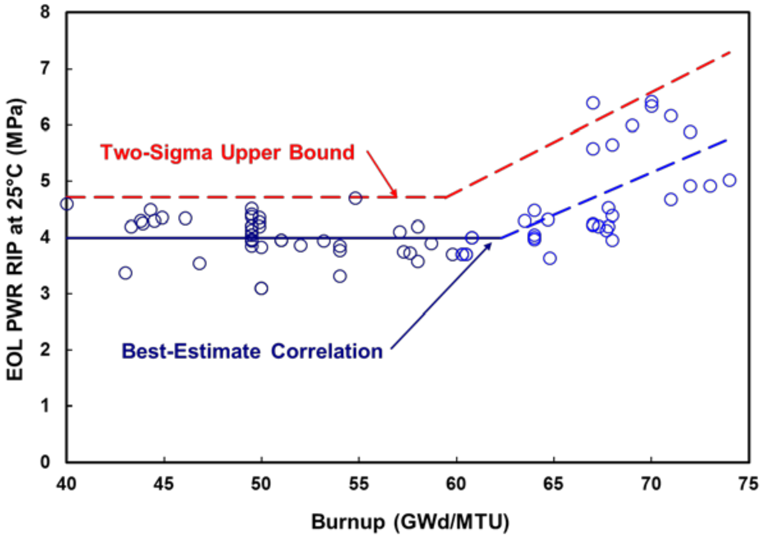
Note 1 PCT is calculated by inputting the blowdown and vacuum drying time into the fit shown in Figure 1-3 (all temperatures are based on 21.12 kW DSC heat load).

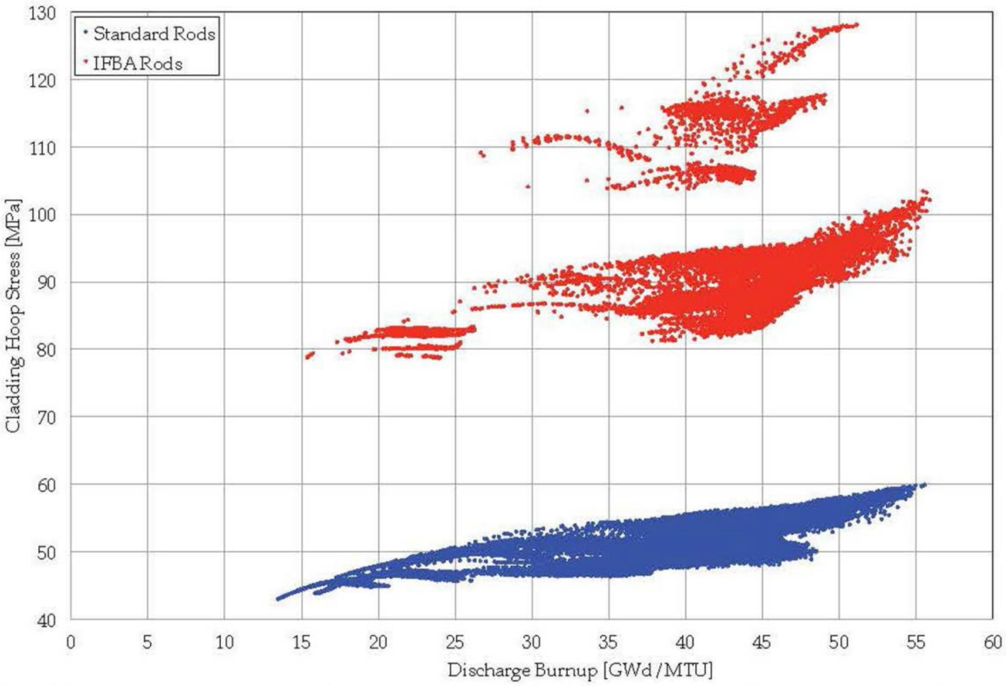
Note 2 Helium Backfill PCT is calculated by inputting the DSC heat load in kW into the fit shown in Figure 1-4.

Note 3 Transfer PCT is calculated by inputting the DSC heat load in kW into the fit shown in Figure 1-5, multiplying the resulting rate by the transfer time, and adding to the Helium backfill PCT.

Hoop Stress

- **Hoop stress is a function of**
  - End of Life Rod Internal Pressure
    - Initial He fill pressure
    - Fission gas release
    - Temperature
    - Void volume
      - Creep down/swelling
  - Clad inner diameter
  - Clad thickness (minus oxide layer)





FRAPCON predictions for Watts Bar Unit 1 rods discharged during Cycles 1-12 assuming 400°C peak clad temperature(7)

Summary

- **UFD has identified gaps associated with cladding and is pursuing closing them using an integrated approach**
- **Average discharge burnups are not as high as originally predicted they would be**
- **Further testing will focus on cladding response and performance under realistic temperatures, hoop stresses, and external stresses**
  - Indications are that peak clad temperatures are significantly lower than the 400°C regulatory guidance when conservative assumptions are removed
  - Hoop stress will have a corresponding decrease
- **Indications are that cladding, including for high burnup fuel, will continue to perform its safety functions during extended storage and normal conditions of transport**

References

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