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RERTR-13 Irradiation Summary Report

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SUMMARY

The Reduced Enrichment for Research and Test Reactor (RERTR) experiment RERTR-13 was designed to assess performance of different types of neutron absorbers that can be potentially used as burnable poisons in the low enriched uranium-molybdenum based dispersion and monolithic fuels.[1]

The following report summarizes the life of the RERTR-13 experiment through end of irradiation, including as-run neutronic analysis results, thermal analysis results and hydraulic testing results.

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FIGURES

TABLES

ACRONYMS

Al	Aluminum
ATR	Advanced Test Reactor
BOC	Beginning of Cycle
DAS	Data Acquisition System
EFPD	Effective Full Power Days
EOC	End of Cycle
FD	Fuel Development
GTRI	Global Threat Reduction Initiative
HIP	Hot Isostatic Pressing
L2AR	Local-to-Average Ratio
LEU	Low Enriched Uranium
MCNP	Monte Carlo N-Particle
MOC	Middle of Cycle
Mo	Molybdenum
RERTR	Reduced Enrichment Research and Test Reactor
U	Uranium
U-Mo	Uranium-Molybdenum Alloy
Zr	Zirconium

RERTR-13 Irradiation Summary Report

1. EXPERIMENT GOALS

In support of the Global Threat Reduction Initiative (GTRI) Fuel Development (FD) program (historically known as Reduced Enrichment Research and Test Reactor (RERTR)), the RERTR-13 experiment was designed to assess performance of different types of neutron absorbers that can be potentially used as burnable poisons in the low enriched uranium-molybdenum based dispersion and monolithic fuels.[1]

The RERTR-13 test assembly holds 4 capsules, designated as A, B, C and D, with A at the top of the assembly and D at the bottom. Each capsule has 2 levels, with 4 plate positions per level, for a total of 8 plate positions per capsule and 32 plate positions per assembly. Within each capsule the 8 plate positions are azimuthally designated as 1 through 4 in the upper level and 5 through 8 in the lower level. The experiment matrix for the two irradiation cycles is shown in Table 1. The material plates in capsule B were irradiated during the first cycle then replaced with aluminum dummy plates for the second cycle. The miniplates in capsule D were irradiated over both cycles. The RERTR-13 mini-plates were oriented edge on to the core with the plate identification numbers facing North (see Figure 1).

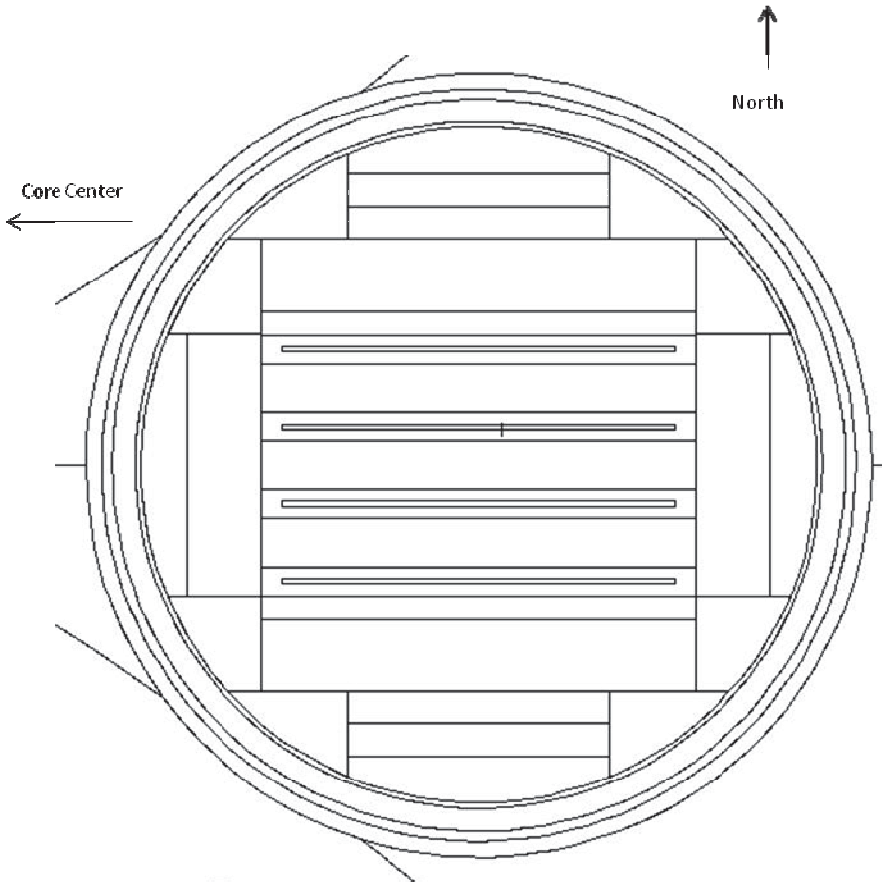

Figure 1: MCNP-Generated radial cross-section view of RERTR-13 test assembly (mini-plates C1 through C4). NOTE: Plate IDs (not shown) face north.

Table 1: RERTR-13 Experiment Matrix

ID	Capsule	Capsule Position 1	Capsule Position 2	Capsule Position 3	Capsule Position 4
13-E-DUM	Top	A1	A2	A3	A4
		Aluminum Dummy	Aluminum Dummy	Aluminum Dummy	Aluminum Dummy
	Bottom	A5	A6	A7	A8
		Aluminum Dummy	Aluminum Dummy	Aluminum Dummy	Aluminum Dummy
13-B-2	Top	B1	B2	B3	B4
		Aluminum Dummy	Aluminum Dummy	Aluminum Dummy	Aluminum Dummy
	Bottom	B5	B6	B7	B8
		B_4C-Al dispersion (Natural B) PCP0G4	Al-1.5B alloy (Enriched B) PAP0F0	ZrB_2-Al dispersion (Enriched B) PZP0E8	B_4C-Al dispersion (Enriched B) PCP0E7
13-F-DUM	Top	C1	C2	C3	C4
		Aluminum Dummy	Aluminum Dummy	Aluminum Dummy	Aluminum Dummy
	Bottom	C5	C6	C7	C8
		Aluminum Dummy	Aluminum Dummy	Aluminum Dummy	Aluminum Dummy
13-D	Top	D1	D2	D3	D4
		U-7Mo + B_4C dispersion in Al-4% Si, U235-25%, (Natural B) RCR3F1	U-7Mo + B_4C dispersion in Al-4% Si, U235-69%, (Natural B) RCR7F5	U-7Mo + ZrB_2 dispersion in Al-4% Si, U235-69%, (Natural B) RZR7F7	U-7Mo + ZrB_2 dispersion in Al-4% Si, U235-25%, (Natural B) RZR3F3
	Bottom	D5	D6	D7	D8
		Al-4.5B alloy (Enriched B) PBP0F9	Al-1.5B alloy (Enriched B) PAP0G2	ZrB_2-Al dispersion (Enriched B) PZP0E9	B_4C-Al dispersion (Enriched B) PCP0D6

2. CONSTITUENT MASSES AND DENSITIES

The nominal constituent masses and densities for plates in the B and D capsules were used for analysis and therefore are reported within this report. Table 2 summarizes the nominal constituent mass and density for the material plates irradiated in RERTR-13 and Table 3 summarizes the nominal constituent mass and density for the fuel plates irradiated in RERTR-13.

Table 2: RERTR-13 Capsule B nominal constituent masses and densities[5].

Plate Pos.	Borated Layer Thick. (mm)	Borated Layer Vol. (cc)	Borated Layer Constituent Masses (g) Al-1.5B	Al-4.5B	Al	B4C	B2Zr	B-enrich.	C	Zr	B-10	Borated Layer Constituent Densities (g/cc) Al	B-enrich.	C	Zr	B-10
B-5	0.127	0.200	--	--	0.503	0.034	--	0.0265	0.0073	--	0.0049	2.519	0.132	0.037	--	0.024
B-6	0.127	0.200	0.535	--	0.527	--	--	0.0080	--	--	0.0077	2.640	0.040	--	--	0.039
B-7	0.127	0.200	--	--	0.515	--	0.055	0.0105	--	0.044	0.0079	2.580	0.053	--	0.223	0.040
B-8	0.127	0.200	--	--	0.528	0.010	--	0.0081	0.0023	--	0.0079	2.644	0.041	0.011	--	0.040

Table 3: RERTR-13 capsule D nominal constituent masses and densities[5].

Plate Pos.	Plate Type	Fuel Phase	Fuel Meat Thick. (mm)	Fuel Meat Volume (cc)	Fuel Alloy % U-235 Enrich.	Fuel Alloy Mass (g)	Fuel Alloy Constituent Masses (g) Total U	U-235	U-238	Mo	Fuel Alloy Constituent Densities (g/cc) Total U	U-235	U-238	Mo	Fuel Alloy Total Density (g/cc)
D-1	Fuel - type 1	U-7Mo HEU disp. - borated w/B4C (natural B)	0.635	0.999	25	6.442	5.992	1.498	4.494	0.451	6.000	1.500	4.500	0.452	6.452
D-2	Fuel - type 1	U-7Mo HEU disp. - borated w/B4C (natural B)	0.635	0.999	69	6.442	5.992	4.134	1.857	0.451	6.000	4.140	1.860	0.452	6.452
D-3	Fuel - type 1	U-7Mo HEU disp. - borated w/**ZrB2** (natural B)	0.635	0.999	69	6.442	5.992	4.134	1.857	0.451	6.000	4.140	1.860	0.452	6.452
D-4	Fuel - type 1	U-7Mo HEU disp. - borated w/**ZrB2** (natural B)	0.635	0.999	25	6.442	5.992	1.498	4.494	0.451	6.000	1.500	4.500	0.452	6.452

Table 3: RERTR-13 capsule D nominal constituent masses and densities[5]. (continued)

Plate Pos.	Matrix Total Mass (g)	Matrix Phase Masses (g) Al4Si	Al	Si	B4C/ ZrB2	B-nat.	C/Zr	B-10
D-1	1.701	1.663	1.597	0.067	0.038	0.030	0.008	0.0054
D-2	1.701	1.663	1.597	0.067	0.038	0.030	0.008	0.0054
D-3	1.791	1.636	1.571	0.065	**0.154**	0.030	**0.125**	0.0054
D-4	1.791	1.636	1.571	0.065	**0.154**	0.030	**0.125**	0.0054

3. EXPERIMENT HARDWARE

The experiment hardware configuration is identical to that used in the RERTR-7A, -7B, -8, -9A, -9B, -10A and -10B experiments. A list of irradiation hardware drawings used for analysis is given in Table 4.

Table 4: RERTR Irradiation Hardware Drawing List.

Drawing Number	Drawing Title
DWG-630223	RERTR ATR Large B-Position Irradiation Experiment Assembly
DWG-630233	ATR Large B-Position Basket
DWG-630231	ATR Top Spacer Assembly
DWG-630225	ATR Upper Spacer Assembly
DWG-630229	ATR Bottom Spacer Assembly
DWG-630227	ATR Large B-Position Fuel Capsule Assembly
DWG-630237	Fuel Capsule
DWG-630239	Capsule Cap
DWG-630244	RERTR Mini-Plate

The RERTR miniplate irradiation assembly, (see Figure 2) shows the main components of the test assembly, which include the bottom spacer, upper and top spacers, experiment capsules and basket. The bottom spacer elevates the experiment capsules to the correct location in the core. The upper and top spacers allow the operators to assure that the experiment is seated fully into the basket. All spacers are similar to the capsule design except the spacers do not have the grooves for the plates. The capsules hold the fuel plates; a capsule cap is welded onto the top of the capsule to keep the plates from sliding out during handling and irradiation. The miniplate drawing (DWG-630244) and RERTR miniplate capsule assembly are shown in Figure 3, Figure 4, Figure 5 and Figure 6, respectively. Each capsule has a notch at the top and a groove at the bottom which allow the capsules to stack and align properly into the core. The basket holds the test assembly in the reactor during irradiation, the notches on the outer wall allow for bypass coolant flow to cool the outer wall. The basket has two guide bars on the inside wall to guide the assembly into the baskets.

Figure 2: RERTR miniplate irradiation assembly.

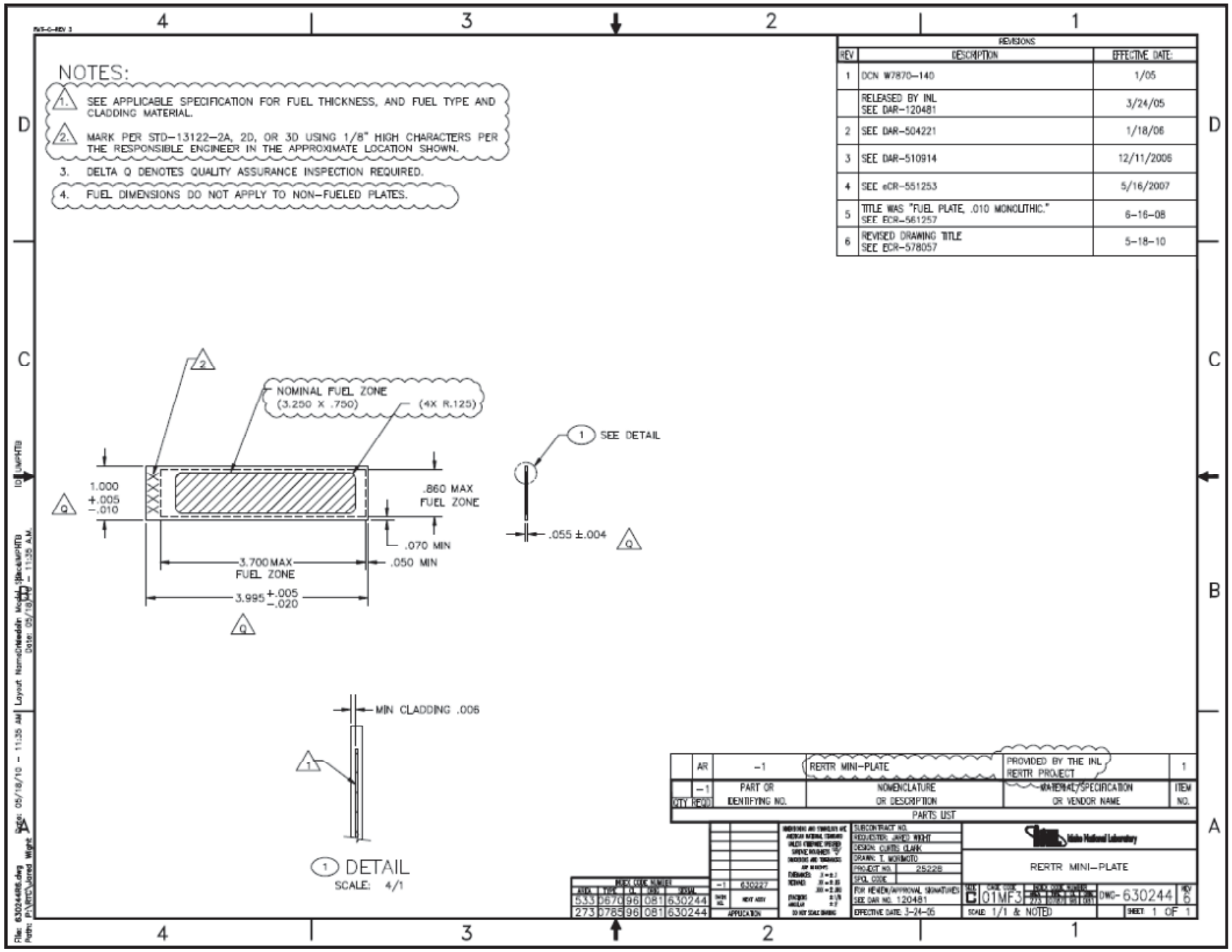

Figure 3: DWG-630244: RERTR monolithic fuel miniplate.

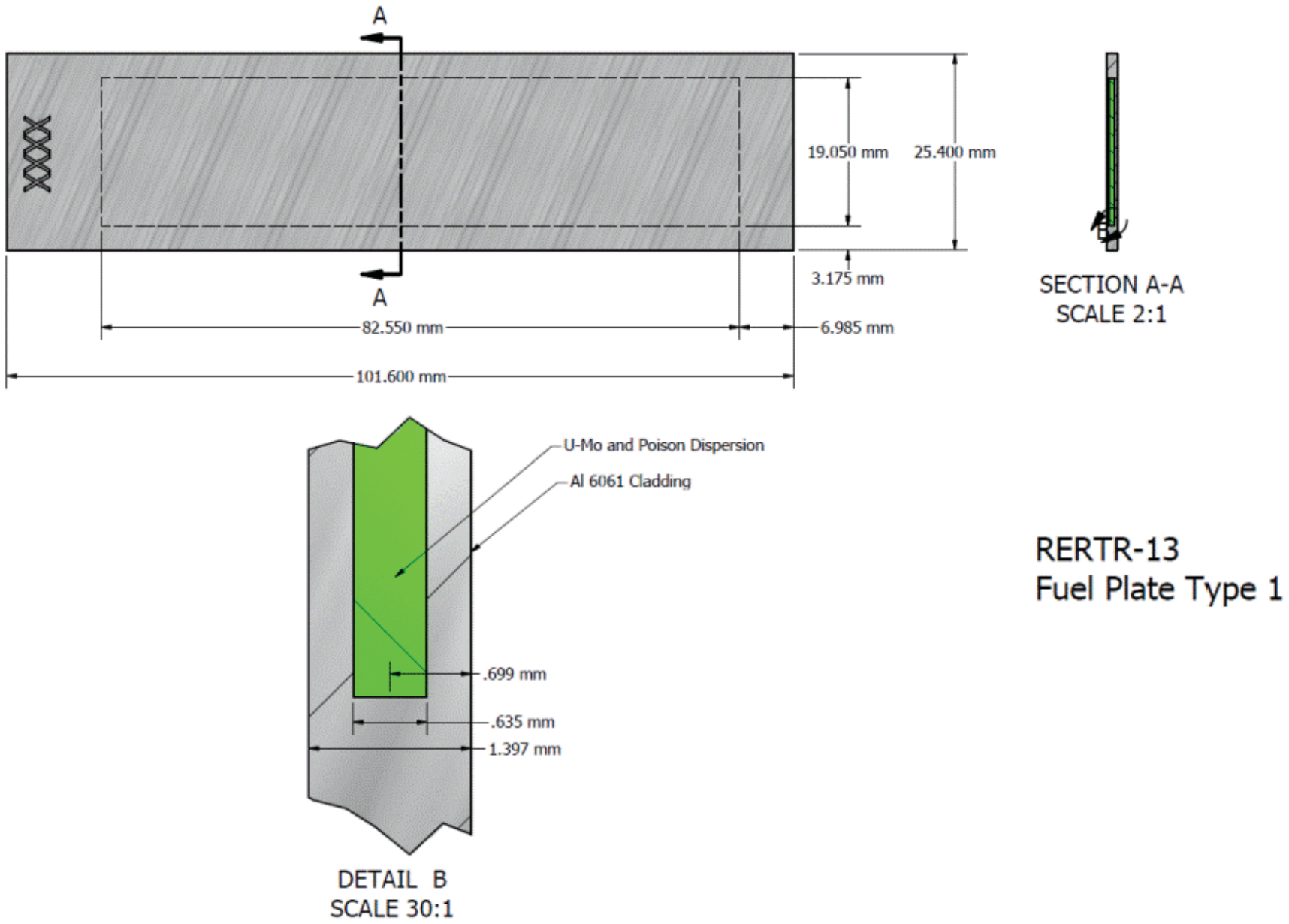

Figure 4: RERTR-13 detailed fuel plate sketch.

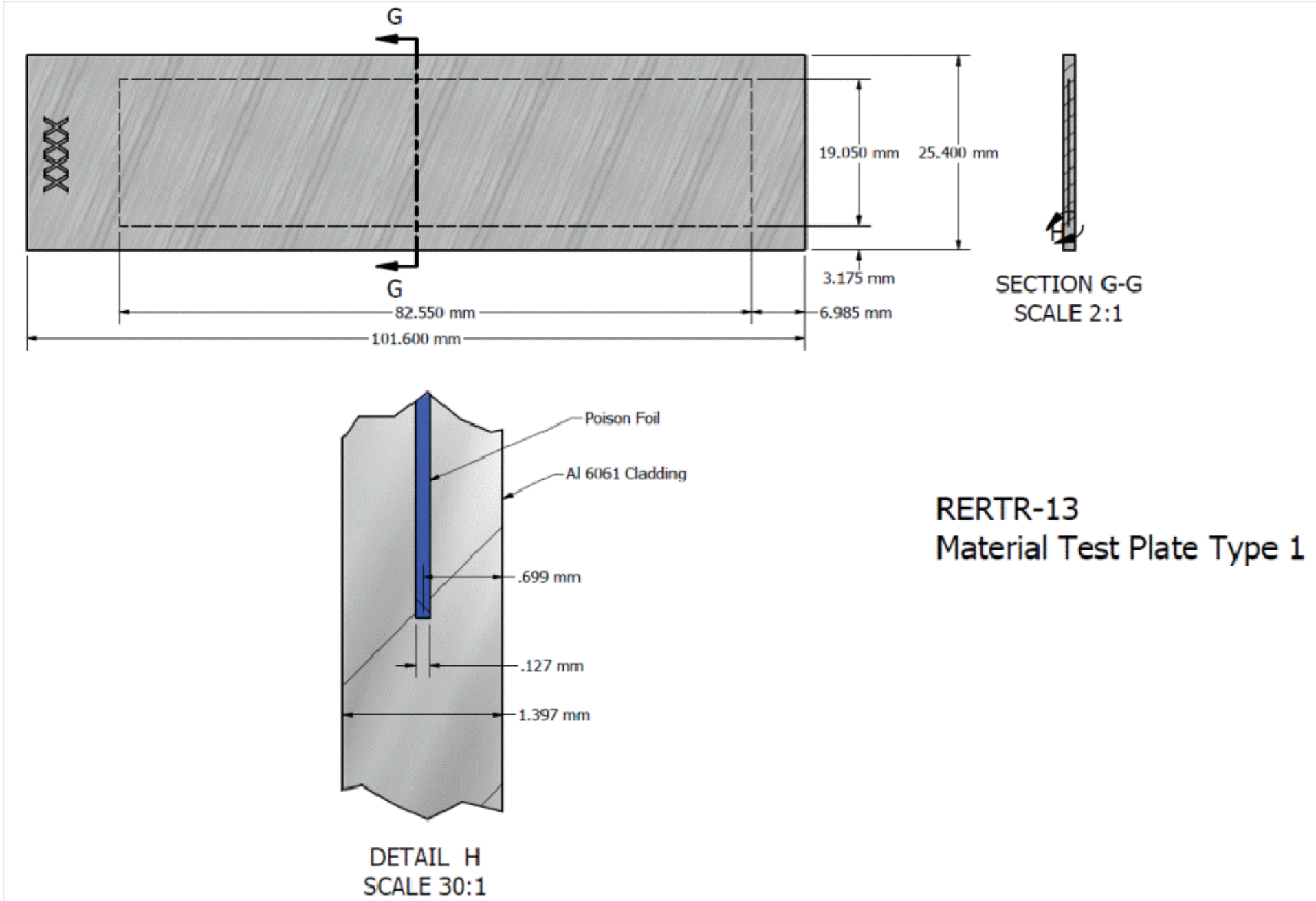

Figure 5: RERTR-13 detailed material plate sketch.

Figure 6: RERTR capsule assembly.

4. IRRADIATION HISTORY

The RERTR-13 test assembly was irradiated in cycle 151A and cycle 151B. RERTR-13-1 and RERTR-13-2 were irradiated in the large-B position B-10. The power of position B-10 is represented by the east lobe power which is the average of the NE, C and SE lobe powers, E = (NE + C + SE)/3. Cycle 151A ran for a total of 56.1 EFPDs at an average total core power of 101.7 MW (east lobe power of 19.7 MW) and cycle 151B ran for a total of 51.3 EFPDs at an average total core power of 101.5 MW (east lobe power of 19.9 MW).

There was one mid-cycle SCRAM during cycle 151A from with a duration of 3 days from 12/25/2011 – 12/28/2011. There were two mid-cycle SRAMs during cycle 151B from 3/22/2012 – 3/25/2012 and 3/27/2012 – 4/7/2012, total duration of with a duration of 14 days. This information is tabulated in Table 5.

Table 5: Irradiation History for RERTR-13

ATR CYCLE	RERTR-13 Capsules Irradiated	Dates Irradiated	Cycle EFPDs	Mid-Cycle Scram Decay Days	East Lobe Source Power (MW)	Total Core Power (MW)
151A	B, D	12/14/2011 – 02/11/2012	56.1	3	19.7	101.7
151B	D	03/01/2012 – 05/05/2012	51.3	14	19.9	101.5

The power history for each cycle is obtained as in ATR Surveillance Report from the ATR Data Acquisition System (DAS). The plots of each lobe power on an hourly basis are shown in Figure 7 and Figure 8 for cycle 151A and 151B, respectively.

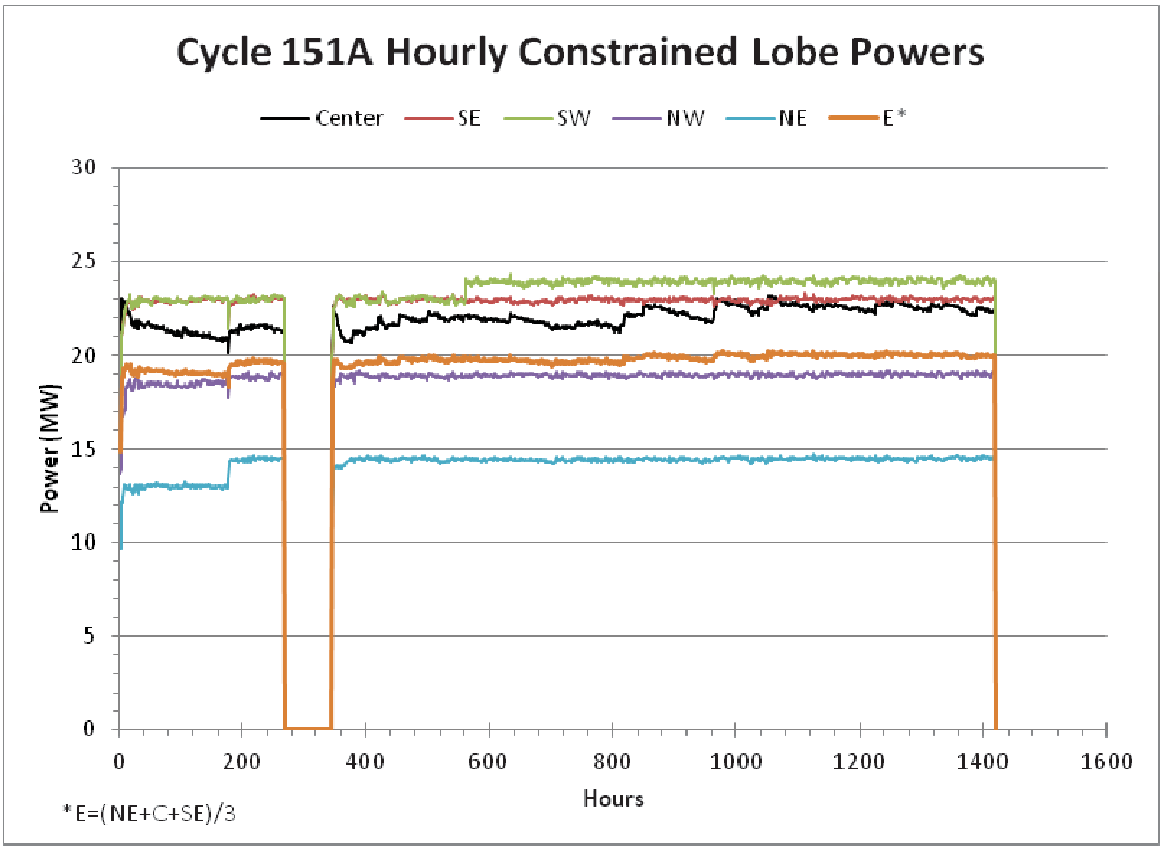

Figure 7: Hourly lobe power history for ATR Cycle 151A.

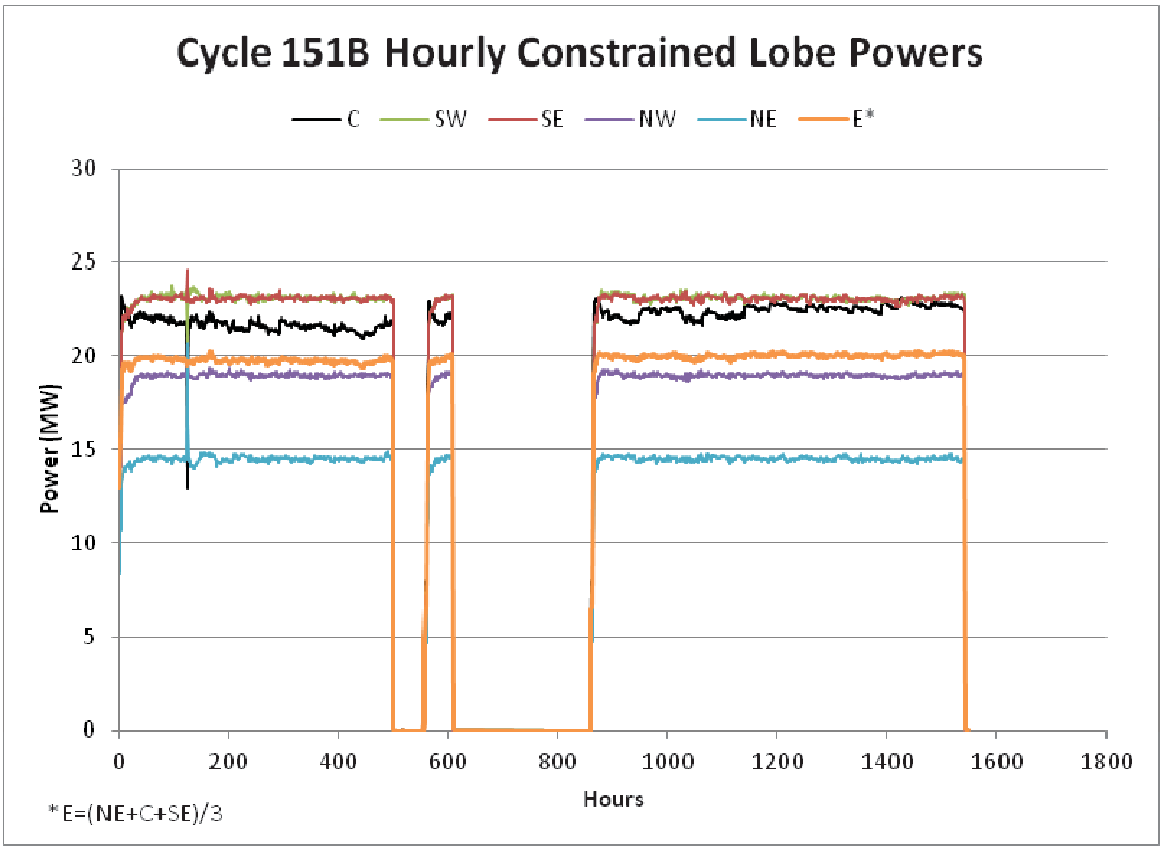

Figure 8. Hourly lobe power history for ATR Cycle 151B.

5. AS-RUN NUCLEAR ANALYSIS

5.1 Neutronics

The as-run calculations were performed using the irradiation history in Table 5 and the Monte Carlo N-Particle (MCNP) code. The calculated as-run fission heat rates, fission densities, and as-run U-235 burnup results for the fueled miniplates reported have an uncertainty band (1σ) of 2.5%.[5,6] The time intervals used to calculate the average plate power and burnup are shown in Table 6. The average plate power and burnup for the time intervals for cycle 151A are shown in Table 7 through Table 10. The average plate power and burnup for the time intervals for cycle 151B are shown in Table 11 through Table 14. The plots of the power and fission density as a function of the ATR Cycle time interval are presented in Appendix A.

Table 6: Cycle Breakdown

Time Interval	151A (days)	151B (days)
BOC	1.00E-04	1.00E-4
MOC 1	15.0	23.0
MOC 2	19.0	16.0
EOC	22.1	12.3
Total EFPDs	56.1	51.3
Cumulative	56.1	107.4

The MCNP-calculated neutronic results reported were calculated using the nominal miniplates dimensions shown in section 2.

Table 7: Cycle 151A BOC As-Run HGR and Depletion Results for RERTR-13-1 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.7 MW, 0EFPD[5].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-B-2	B-1	Blank	3.30E+14	--	--	--	--	--	--
	B-2	Blank	3.33E+14	--	--	--	--	--	--
	B-3	Blank	3.36E+14	--	--	--	--	--	--
	B-4	Blank	3.37E+14	--	--	--	--	--	--
	B-5	PCP0G4	2.97E+14	217.29	--	--	--	--	--
	B-6	PAP0F0	2.85E+14	301.01	--	--	--	--	--
	B-7	PZP0E8	2.86E+14	312.85	--	--	--	--	--
	B-8	PCP0E7	2.93E+14	325.52	--	--	--	--	--
RERTR-13-D	D-1	RCR3F1	3.06E+14	--	--	3259.68	103.49	--	--
	D-2	RCR7F5	3.15E+14	--	--	5951.20	188.95	--	--
	D-3	RZR7F7	3.23E+14	--	--	6129.81	194.62	--	--
	D-4	RZR3F3	3.18E+14	--	--	3434.14	109.03	--	--
	D-5	PBP0F9	1.93E+14	483.11	--	--	--	--	--
	D-6	PAP0G2	2.06E+14	189.67	--	--	--	--	--
	D-7	PZP0E9	2.09E+14	205.32	--	--	--	--	--
	D-8	PCP0D6	2.16E+14	222.42	--	--	--	--	--

Table 8: Cycle 151A MOC1 As-Run HGR and Depletion Results for RERTR-13-1 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.7 MW, 15 EFPD[5].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-B-2	B-1	Blank	3.08E+14	--	--	--	--	--	--
	B-2	Blank	3.11E+14	--	--	--	--	--	--
	B-3	Blank	3.13E+14	--	--	--	--	--	--
	B-4	Blank	3.12E+14	--	--	--	--	--	--
	B-5	PCP0G4	2.92E+14	139.34	38.87%	--	--	--	--
	B-6	PAP0F0	2.81E+14	209.10	35.30%	--	--	--	--
	B-7	PZP0E8	2.81E+14	210.96	35.44%	--	--	--	--
	B-8	PCP0E7	2.87E+14	212.82	36.84%	--	--	--	--
RERTR-13-D	D-1	RCR3F1	2.75E+14	--	22.74%	2667.08	84.68	1.46E+20	4.42%
	D-2	RCR7F5	2.76E+14	--	15.86%	4696.51	149.11	2.66E+20	3.02%
	D-3	RZR7F7	2.77E+14	--	16.28%	4634.00	147.13	2.74E+20	3.02%
	D-4	RZR3F3	2.79E+14	--	23.85%	2674.05	84.90	1.54E+20	4.63%
	D-5	PBP0F9	1.94E+14	403.53	20.71%	--	--	--	--
	D-6	PAP0G2	2.05E+14	150.19	23.87%	--	--	--	--
	D-7	PZP0E9	2.08E+14	157.12	24.86%	--	--	--	--
	D-8	PCP0D6	2.14E+14	164.81	26.83%	--	--	--	--

Table 9: Cycle 151A MOC2 As-Run HGR and Depletion Results for RERTR-13-1 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.7 MW, 34 EFPD[5].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-B-2	B-1	Blank	3.01E+14	--	--	--	--	--	--
	B-2	Blank	3.01E+14	--	--	--	--	--	--
	B-3	Blank	3.03E+14	--	--	--	--	--	--
	B-4	Blank	3.05E+14	--	--	--	--	--	--
	B-5	PCP0G4	2.93E+14	81.76	67.97%	--	--	--	--
	B-6	PAP0F0	2.85E+14	132.35	64.16%	--	--	--	--
	B-7	PZP0E8	2.88E+14	136.73	63.91%	--	--	--	--
	B-8	PCP0E7	2.90E+14	133.31	65.30%	--	--	--	--
RERTR-13-D	D-1	RCR3F1	2.75E+14	--	41.63%	2635.23	83.67	2.98E+20	8.98%
	D-2	RCR7F5	2.79E+14	--	29.60%	4832.46	153.43	5.33E+20	6.00%
	D-3	RZR7F7	2.78E+14	--	29.80%	4794.48	152.22	5.38E+20	6.00%
	D-4	RZR3F3	2.77E+14	--	42.53%	2668.98	84.74	3.06E+20	9.21%
	D-5	PBP0F9	1.99E+14	329.92	41.90%	--	--	--	--
	D-6	PAP0G2	2.07E+14	117.92	46.89%	--	--	--	--
	D-7	PZP0E9	2.14E+14	123.17	48.20%	--	--	--	--
	D-8	PCP0D6	2.19E+14	123.75	51.00%	--	--	--	--

Table 10: Cycle 151A EOC As-Run HGR and Depletion Results for RERTR-13-1 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.7 MW, 56.1 EFPD[5].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-B-2	B-1	Blank	3.02E+14	--	--	--	--	--	--
	B-2	Blank	3.01E+14	--	--	--	--	--	--
	B-3	Blank	3.04E+14	--	--	--	--	--	--
	B-4	Blank	3.06E+14	--	--	--	--	--	--
	B-5	PCP0G4	3.03E+14	43.22	85.87%	--	--	--	--
	B-6	PAP0F0	2.99E+14	71.76	83.53%	--	--	--	--
	B-7	PZP0E8	3.02E+14	74.72	83.38%	--	--	--	--
	B-8	PCP0E7	3.03E+14	71.51	84.17%	--	--	--	--
RERTR-13-D	D-1	RCR3F1	2.77E+14	--	58.44%	2608.55	82.82	4.74E+20	14.23%
	D-2	RCR7F5	2.81E+14	--	43.61%	4849.79	153.98	8.56E+20	9.59%
	D-3	RZR7F7	2.81E+14	--	43.67%	4796.15	152.28	8.58E+20	9.59%
	D-4	RZR3F3	2.80E+14	--	59.29%	2627.94	83.44	4.84E+20	14.55%
	D-5	PBP0F9	2.10E+14	257.73	61.31%	--	--	--	--
	D-6	PAP0G2	2.18E+14	85.87	66.83%	--	--	--	--
	D-7	PZP0E9	2.24E+14	87.49	68.30%	--	--	--	--
	D-8	PCP0D6	2.28E+14	84.15	70.9%	--	--	--	--

Table 11: Cycle 151B BOC As-Run HGR and Depletion Results for RERTR-13-2 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.9 MW, 0EFPD[6].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-D	D-1	RCR3F1	2.87E+14	--	58.44%	2760.67	87.65	4.74E+20	14.23%
	D-2	RCR7F5	2.93E+14	--	43.61%	5112.12	162.31	8.56E+20	9.59%
	D-3	RZR7F7	2.95E+14	--	43.67%	5117.77	162.49	8.58E+20	9.59%
	D-4	RZR3F3	2.92E+14	--	59.29%	2799.04	88.87	4.84E+20	14.55%
	D-5	PBP0F9	2.18E+14	271.51	61.31%	--	--	--	--
	D-6	PAP0G2	2.29E+14	90.08	66.83%	--	--	--	--
	D-7	PZP0E9	2.32E+14	91.91	68.30%	--	--	--	--
	D-8	PCP0D6	2.36E+14	87.93	70.90%	--	--	--	--

Table 12: Cycle 151B MOC1 As-Run HGR and Depletion Results for RERTR-13-2 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.9 MW, 23 EFPD[6].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-D	D-1	RCR3F1	2.78E+14	--	71.72%	2504.30	79.51	6.63E+20	19.83%
	D-2	RCR7F5	2.84E+14	--	56.13%	4801.33	152.44	1.21E+21	13.44%
	D-3	RZR7F7	2.89E+14	--	56.18%	4904.23	155.71	1.21E+21	13.50%
	D-4	RZR3F3	2.89E+14	--	72.50%	2646.83	84.04	6.76E+20	20.19%
	D-5	PBP0F9	2.25E+14	178.82	76.86%	--	--	--	--
	D-6	PAP0G2	2.37E+14	56.68	81.47%	--	--	--	--
	D-7	PZP0E9	2.40E+14	56.70	82.70%	--	--	--	--
	D-8	PCP0D6	2.44E+14	52.79	84.51%	--	--	--	--

Table 13: Cycle 151B MOC2 As-Run HGR and Depletion Results for RERTR-13-2 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.9 MW, 39EFPD[6].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-D	D-1	RCR3F1	3.39E+14	--	78.16%	3522.17	111.83	7.83E+20	23.37%
	D-2	RCR7F5	3.42E+14	--	63.01%	6570.18	208.60	1.44E+21	15.99%
	D-3	RZR7F7	3.45E+14	--	63.22%	6607.63	209.79	1.44E+21	16.11%
	D-4	RZR3F3	3.42E+14	--	79.09%	3522.29	111.83	8.02E+20	23.94%
	D-5	PBP0F9	2.77E+14	186.85	84.32%	--	--	--	--
	D-6	PAP0G2	2.89E+14	55.17	88.03%	--	--	--	--
	D-7	PZP0E9	2.91E+14	52.95	89.05%	--	--	--	--
	D-8	PCP0D6	2.94E+14	48.24	90.32%	--	--	--	--

Table 14: Cycle 151B EOC As-Run HGR and Depletion Results for RERTR-13-2 in B-10 Scaled to As-Run Cycle Average East Source Power of 19.9 MW, 51.3 EFPD[6].

Capsule ID	Plate Position	Plate ID	BA/Fuel Neutron Flux (n/cm^2-sec)	Burnable Absorber		Fuel			
				Power Density (W/cc)	% Depletion B-10 (%)	Fission Power Density (W/cc)	Surface Heat Flux (W/cm^2)	Fission Density (fissions/cc)	% Depletion U-235 (%)
RERTR-13-D	D-1	RCR3F1	3.30E+14	--	83.70%	3297.79	104.70	9.13E+20	27.17%
	D-2	RCR7F5	3.33E+14	--	69.32%	6173.80	196.02	1.68E+21	18.66%
	D-3	RZR7F7	3.36E+14	--	69.52%	6231.69	197.86	1.69E+21	18.77%
	D-4	RZR3F3	3.34E+14	--	84.44%	3310.72	105.12	9.32E+20	27.74%
	D-5	PBP0F9	2.85E+14	127.16	90.15%	--	--	--	--
	D-6	PAP0G2	2.96E+14	37.03	92.79%	--	--	--	--
	D-7	PZP0E9	2.96E+14	35.08	93.46%	--	--	--	--
	D-8	PCP0D6	2.98E+14	31.84	94.26%	--	--	--	--

5.2 Gradients

MCNP-calculated power gradients have not yet been performed for this experiment.

6. HYDRAULIC TESTING

A fully assembled irradiation test vehicle (with simulated fuel plates) was used for testing. The test vehicle was fabricated such that the orifice plates could be easily changed. The hydraulic resistance of the RERTR Large B-Position irradiation test vehicle with various orifice plate sizes were calculated, the results are shown in Table 15.

Table 15: Loss Coefficients for the RERTR Irradiation Test Vehicle Components[7]

Orifice Dia. (mm)	K/A^2 ($1/m^4$)	ATR Coolant Flow Rate (cm^3/sec)
10	5.3041×10^8	1252
9	8.2181×10^8	1046
8	1.6961×10^9	757
7.32	2.9022×10^9	588
7	3.0058×10^9	579
6	4.0784×10^9	500
5	101743×10^{10}	298
Bypass	2.7958×10^8	--
Vehicle	1.4161×10^8	2727

Based on the results from the hydraulic testing, the orifice was removed leaving the capsule in the "Vehicle" configuration to provide an ATR coolant flow rate through the capsules of 2727 cm^3/sec.[8]

7. AS-RUN THERMAL ANALYSIS

The thermal as-run analysis was performed using the as-built geometry, MCNP-calculated surface heat flux (W/cm^2) and nominal coolant channel flow rate. ABAQUS[9] was used to calculate the coolant channel temperatures and plate surface temperatures.

The heat transfer correlation used to calculate these temperatures was calculated from the Colburn equation (equation 5-50c from Reference 10):

$$Nu = \frac{hD}{k} = 0.023 Re^{0.8} Pr^{0.3}$$

Where Nu is the Nusselt number, h is the heat transfer coefficient, D is the hydraulic diameter, k is the thermal conductivity, Re is the Reynolds number and Pr is the Prandlt number.

The thermal analysis was performed using the beginning of life L2ARs shown in Section 0.

7.1 Coolant Channel Temperature

The coolant temperature was analyzed at the five flow channels in the capsule[11] (see Figure 9). For each interval, the coolant temperature was plotted as a function of location along the test assembly with 0.0 in. being at the top of the assembly. These plots are shown in Figure 10 through Figure 17.

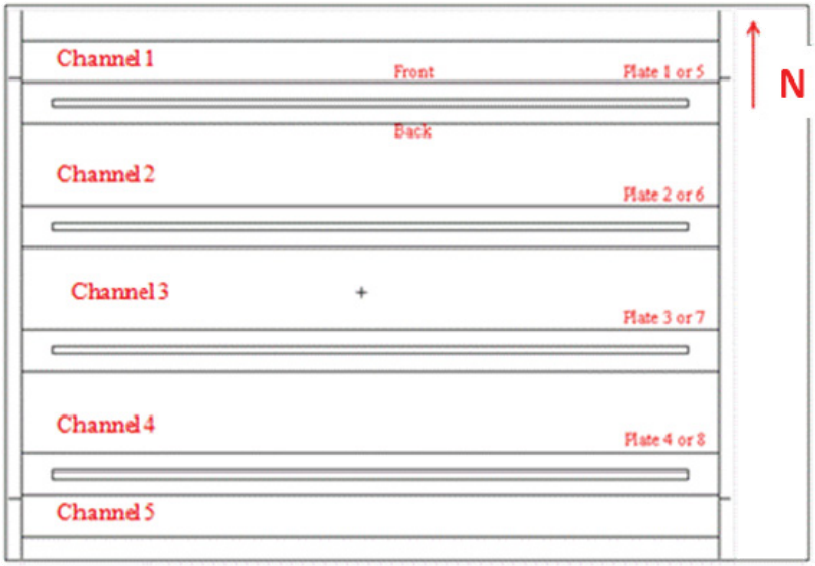

Figure 9: RERTR-13 capsule cross section with the plate IDs (not shown) and plate 1 facing north.

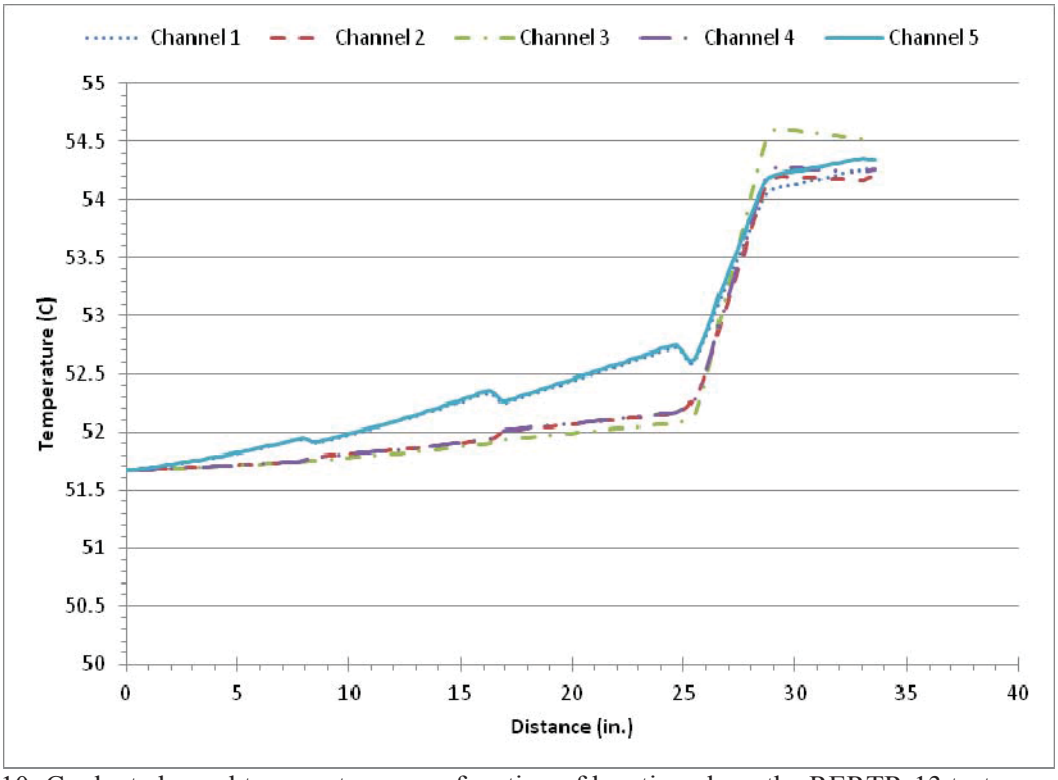

Figure 10: Coolant channel temperatures as a function of location along the RERTR-13 test assembly at BOC 151A (0.0 EFPD).

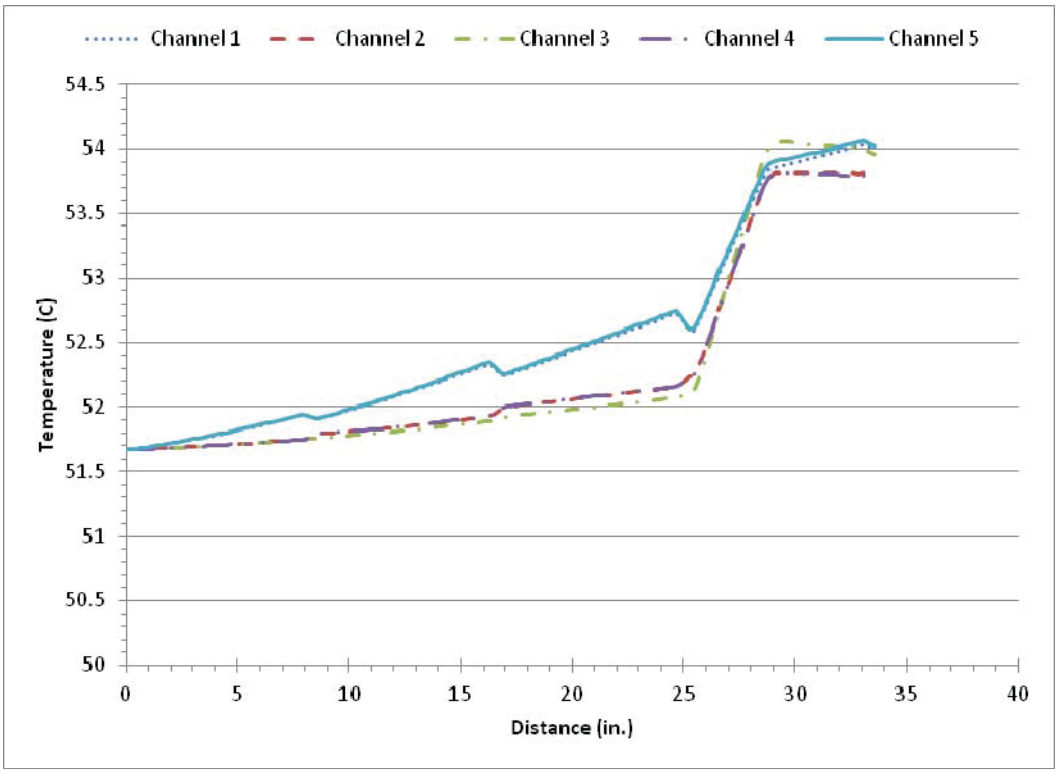

Figure 11: Coolant channel temperature as a function of location along the RERTR-13 test assembly at MOC1 151A (15.0 EFPD).

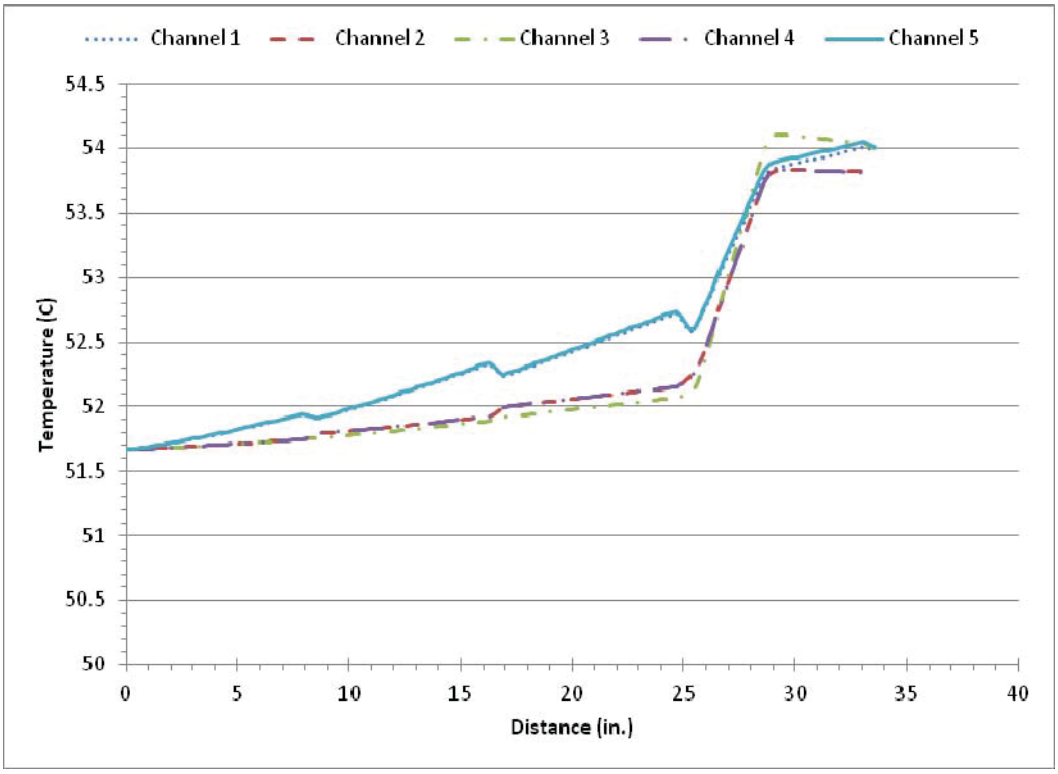

Figure 12: Coolant channel temperature as a function of location along the RERTR-13 test assembly at MOC2 151A (34.0 EFPD).

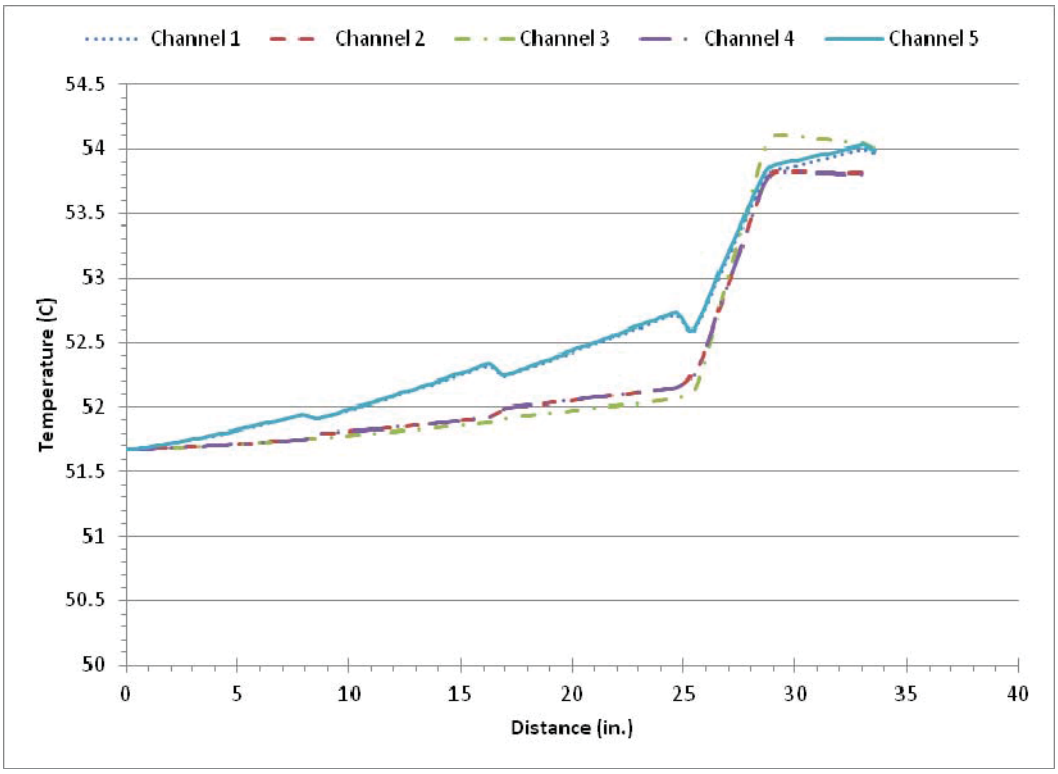

Figure 13: Coolant channel temperature as a function of location along the RERTR-13 test assembly at EOC 151A (56.1 EFPD).

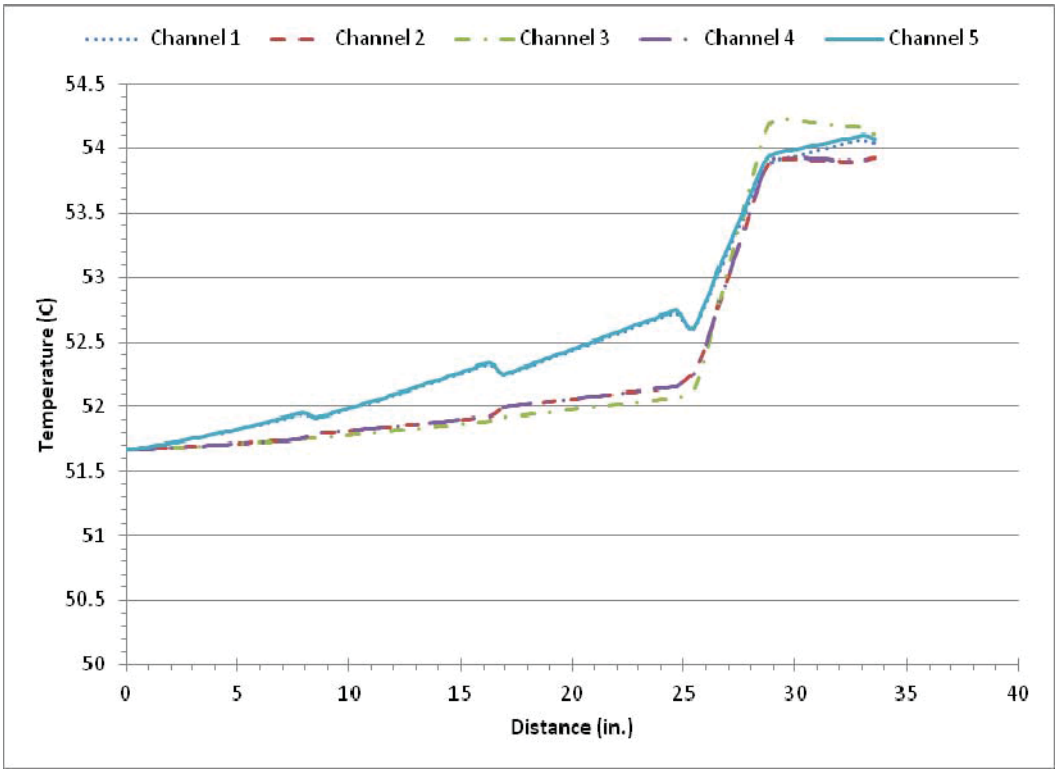

Figure 14: Coolant channel temperature as a function of location along the RERTR-13 test assembly at BOC 151B (0.0 EFPD).

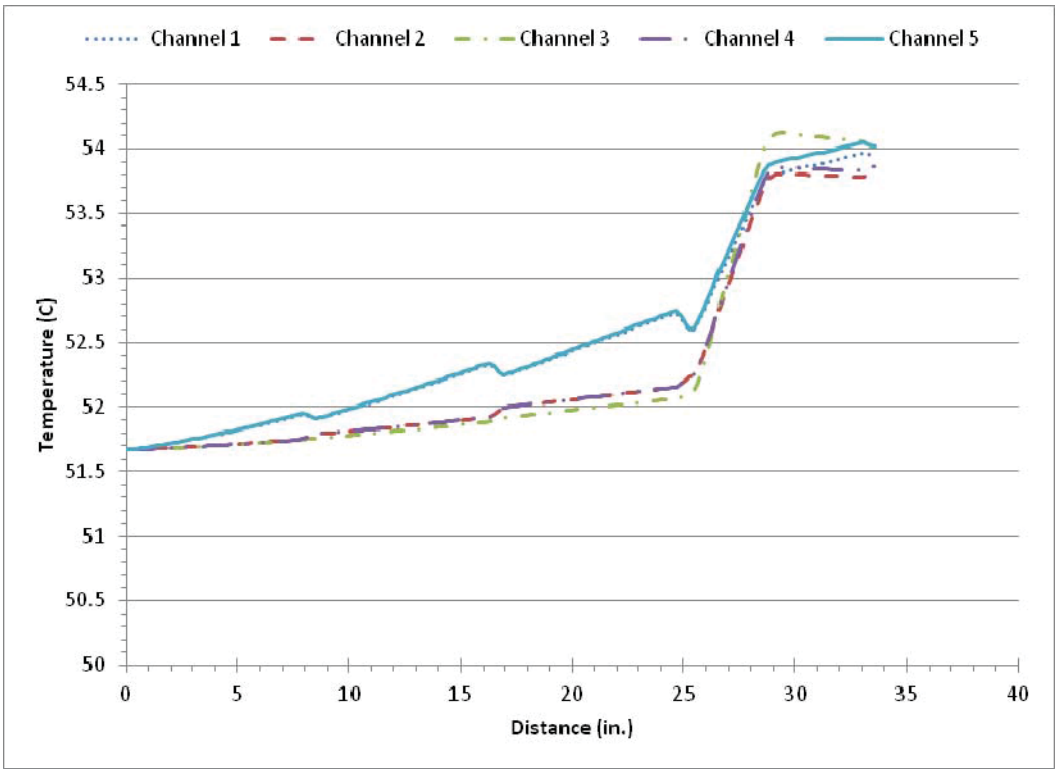

Figure 15: Coolant channel temperature as a function of location along the RERTR-13 test assembly at MOC1 151B (23.0 EFPD).

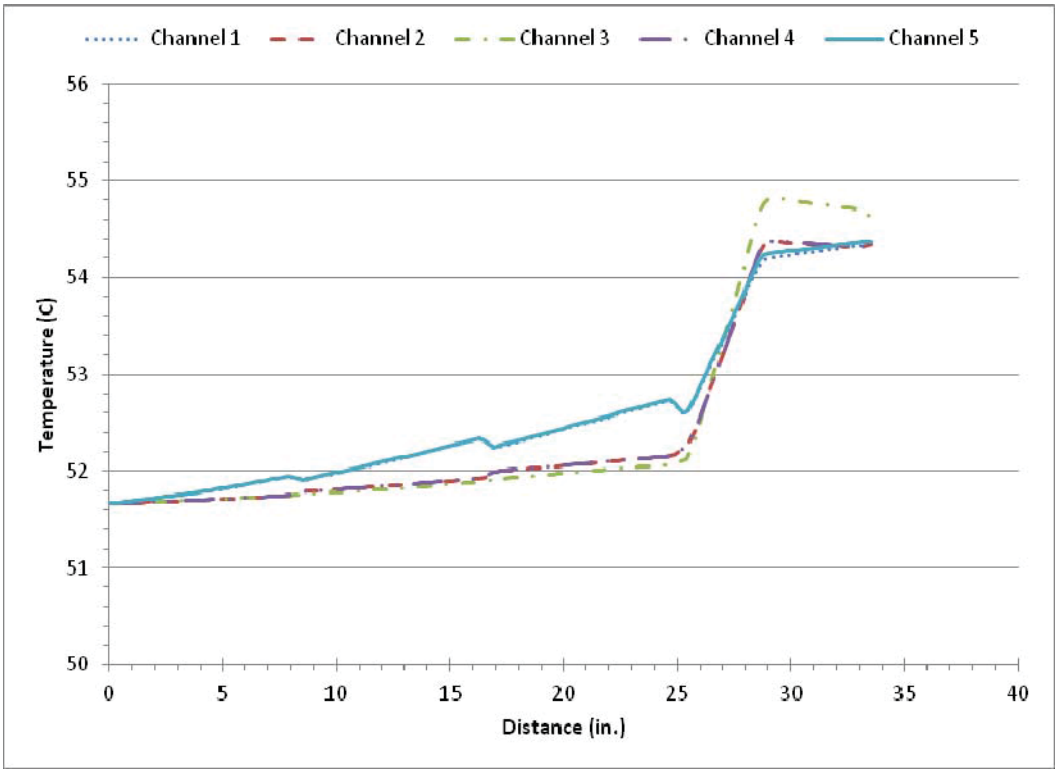

Figure 16: Coolant channel temperature as a function of location along the RERTR-13 test assembly at MOC2 151B (39.0 EFPD).

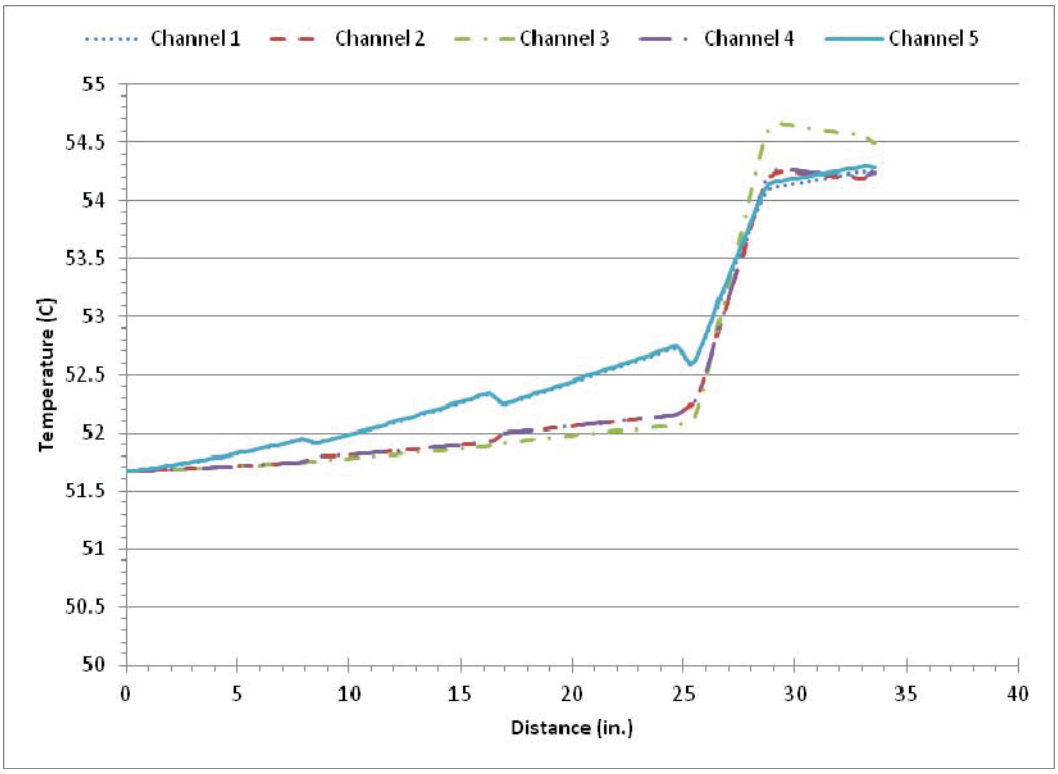

Figure 17: Coolant channel temperature as a function of location along the RERTR-13 test assembly at EOC 151B (51.3 EFPD).

7.2 Plate Surface Temperature

The minimum, maximum and average plate surface temperatures over the fuel zone on each side of the plate are shown in Table 16 through Table 31, where the plate ID is facing north[11] (see Figure 9).

Table 16: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151A, BOC (0.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.34	53.02	52.68
B-6	PAP0F0	52.20	52.75	52.47
B-7	PZP0E8	52.20	52.75	52.47
B-8	PCP0E7	52.34	52.96	52.62
D-1	RCR3F1	58.27	76.20	69.25
D-2	RCR7F5	61.44	89.68	78.98
D-3	RZR7F7	61.66	90.79	79.70
D-4	RZR3F3	58.36	76.24	69.28
D-5	PBP0F9	54.47	55.03	54.84
D-6	PAP0G2	54.35	54.70	54.50
D-7	PZP0E9	54.45	54.89	54.68
D-8	PCP0D6	54.39	54.83	54.58

Table 17: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151A, BOC (0.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.27	52.89	52.50
B-6	PAP0F0	52.19	52.74	52.46
B-7	PZP0E8	52.21	52.76	52.49
B-8	PCP0E7	52.41	53.10	52.80
D-1	RCR3F1	58.10	75.15	68.50
D-2	RCR7F5	61.42	89.86	79.01
D-3	RZR7F7	61.69	90.65	79.68
D-4	RZR3F3	58.55	77.36	70.07
D-5	PBP0F9	54.44	54.94	54.76
D-6	PAP0G2	54.41	54.86	54.65
D-7	PZP0E9	54.40	54.75	54.56
D-8	PCP0D6	54.42	54.93	54.65

Table 18: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151A, MOC1 (15.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.29	52.96	52.59
B-6	PAP0F0	52.15	52.69	52.38
B-7	PZP0E8	52.14	52.68	52.36
B-8	PCP0E7	52.28	52.89	52.50
D-1	RCR3F1	57.38	72.29	66.47
D-2	RCR7F5	59.71	82.76	73.95
D-3	RZR7F7	59.60	82.52	73.71
D-4	RZR3F3	57.24	71.39	65.85
D-5	PBP0F9	54.18	54.74	54.52
D-6	PAP0G2	53.98	54.34	54.10
D-7	PZP0E9	54.02	54.38	54.19
D-8	PCP0D6	54.02	54.48	54.16

Table 19: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151A, MOC1 (15.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.22	52.83	52.42
B-6	PAP0F0	52.14	52.68	52.36
B-7	PZP0E8	52.15	52.69	52.38
B-8	PCP0E7	52.34	53.02	52.68
D-1	RCR3F1	57.22	71.35	65.81
D-2	RCR7F5	59.69	82.86	73.96
D-3	RZR7F7	59.63	82.41	73.71
D-4	RZR3F3	57.40	72.37	66.52
D-5	PBP0F9	54.14	54.62	54.39
D-6	PAP0G2	54.01	54.38	54.18
D-7	PZP0E9	53.98	54.34	54.10
D-8	PCP0D6	54.07	54.60	54.29

Table 20: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151A, MOC2 (34.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.26	52.92	52.53
B-6	PAP0F0	52.10	52.64	52.30
B-7	PZP0E8	52.10	52.63	52.29
B-8	PCP0E7	52.22	52.83	52.41
D-1	RCR3F1	57.33	72.08	66.32
D-2	RCR7F5	59.89	83.51	74.50
D-3	RZR7F7	59.82	83.42	74.36
D-4	RZR3F3	57.23	71.37	65.83
D-5	PBP0F9	54.14	54.69	54.43
D-6	PAP0G2	53.96	54.34	54.09
D-7	PZP0E9	54.03	54.39	54.19
D-8	PCP0D6	53.98	54.46	54.13

Table 21: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151A, MOC2 (34.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.14	52.79	52.36
B-6	PAP0F0	52.09	52.63	52.28
B-7	PZP0E8	52.10	52.64	52.30
B-8	PCP0E7	52.29	52.97	52.59
D-1	RCR3F1	57.17	71.16	65.67
D-2	RCR7F5	59.87	83.63	74.51
D-3	RZR7F7	59.84	83.31	74.35
D-4	RZR3F3	57.39	72.34	66.50
D-5	PBP0F9	54.10	54.58	54.32
D-6	PAP0G2	54.03	54.39	54.19
D-7	PZP0E9	53.97	54.34	54.10
D-8	PCP0D6	54.05	54.58	54.25

Table 22: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151A, EOC (56.1 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.23	52.89	52.48
B-6	PAP0F0	52.07	52.60	52.23
B-7	PZP0E8	52.05	52.59	52.22
B-8	PCP0E7	52.12	52.79	52.35
D-1	RCR3F1	57.29	71.90	66.19
D-2	RCR7F5	59.91	83.60	74.57
D-3	RZR7F7	59.82	83.43	74.37
D-4	RZR3F3	57.17	71.11	65.64
D-5	PBP0F9	54.09	54.63	54.35
D-6	PAP0G2	53.91	54.31	54.05
D-7	PZP0E9	54.01	54.36	54.15
D-8	PCP0D6	53.91	54.42	54.08

Table 23: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151A, EOC (56.1 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
B-5	PCP0G4	52.08	52.77	52.32
B-6	PAP0F0	52.05	52.59	52.22
B-7	PZP0E8	52.07	52.60	52.24
B-8	PCP0E7	52.25	52.92	52.52
D-1	RCR3F1	57.13	70.99	65.55
D-2	RCR7F5	59.89	83.72	74.58
D-3	RZR7F7	59.84	83.31	74.36
D-4	RZR3F3	57.33	72.06	66.30
D-5	PBP0F9	54.06	54.52	54.24
D-6	PAP0G2	54.01	54.36	54.15
D-7	PZP0E9	53.92	54.31	54.05
D-8	PCP0D6	54.01	54.54	54.19

Table 24: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151B, BOC (0.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	57.53	72.93	66.93
D-2	RCR7F5	60.29	85.08	75.64
D-3	RZR7F7	60.28	85.25	75.68
D-4	RZR3F3	57.43	72.23	66.43
D-5	PBP0F9	54.17	54.71	54.43
D-6	PAP0G2	54.00	54.40	54.15
D-7	PZP0E9	54.11	54.46	54.26
D-8	PCP0D6	54.01	54.51	54.17

Table 25: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151B, BOC (0.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	57.37	71.98	66.26
D-2	RCR7F5	60.27	85.21	75.66
D-3	RZR7F7	60.30	85.12	75.67
D-4	RZR3F3	57.60	73.21	67.12
D-5	PBP0F9	54.14	54.61	54.33
D-6	PAP0G2	54.10	54.46	54.26
D-7	PZP0E9	54.01	54.41	54.15
D-8	PCP0D6	54.10	54.62	54.28

Table 26: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151B, MOC1 (23.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	57.15	71.21	65.71
D-2	RCR7F5	59.86	83.33	74.38
D-3	RZR7F7	59.98	84.03	74.81
D-4	RZR3F3	57.21	71.25	65.74
D-5	PBP0F9	54.02	54.57	54.25
D-6	PAP0G2	53.87	54.30	54.02
D-7	PZP0E9	54.01	54.37	54.14
D-8	PCP0D6	53.90	54.43	54.07

Table 27: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151B, MOC1 (23.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	56.99	70.34	65.09
D-2	RCR7F5	59.84	83.47	74.39
D-3	RZR7F7	60.00	83.92	74.80
D-4	RZR3F3	57.37	72.20	66.41
D-5	PBP0F9	54.00	54.46	54.15
D-6	PAP0G2	54.00	54.36	54.13
D-7	PZP0E9	53.90	54.32	54.05
D-8	PCP0D6	54.02	54.55	54.19

Table 28: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151B, MOC2 (39.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	58.67	77.90	70.45
D-2	RCR7F5	62.28	92.95	81.37
D-3	RZR7F7	62.31	93.34	81.55
D-4	RZR3F3	58.50	76.82	69.68
D-5	PBP0F9	54.43	54.93	54.63
D-6	PAP0G2	54.33	54.75	54.52
D-7	PZP0E9	54.51	54.86	54.68
D-8	PCP0D6	54.30	54.79	54.47

Table 29: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151B, MOC2 (39.0 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	58.49	76.80	69.67
D-2	RCR7F5	62.26	93.15	81.41
D-3	RZR7F7	62.33	93.15	81.51
D-4	RZR3F3	58.68	77.93	70.47
D-5	PBP0F9	54.42	54.86	54.59
D-6	PAP0G2	54.50	54.87	54.68
D-7	PZP0E9	54.33	54.76	54.52
D-8	PCP0D6	54.34	54.86	54.52

Table 30: As-run minimum, maximum and average plate surface temperatures over fuel zone on the north side of the plate for capsules irradiated in Cycle 151B, EOC (51.3 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	58.34	76.45	69.43
D-2	RCR7F5	61.74	90.86	79.84
D-3	RZR7F7	61.80	91.34	80.09
D-4	RZR3F3	58.19	75.50	68.74
D-5	PBP0F9	54.31	54.81	54.48
D-6	PAP0G2	54.20	54.64	54.39
D-7	PZP0E9	54.39	54.72	54.54
D-8	PCP0D6	54.19	54.69	54.36

Table 31: As-run minimum, maximum and average plate surface temperatures over fuel zone on the south side of the plate for capsules irradiated in Cycle 151B, EOC (51.3 EFPD)

Plate Location	Plate ID	Minimum Temperature (C)	Maximum Temperature (C)	Average Temperature (C)
D-1	RCR3F1	58.16	75.41	68.68
D-2	RCR7F5	61.72	91.04	79.87
D-3	RZR7F7	61.82	91.17	80.06
D-4	RZR3F3	58.37	76.57	69.51
D-5	PBP0F9	54.29	54.73	54.44
D-6	PAP0G2	54.38	54.72	54.54
D-7	PZP0E9	54.21	54.65	54.39
D-8	PCP0D6	54.24	54.78	54.42

8. REFERENCES

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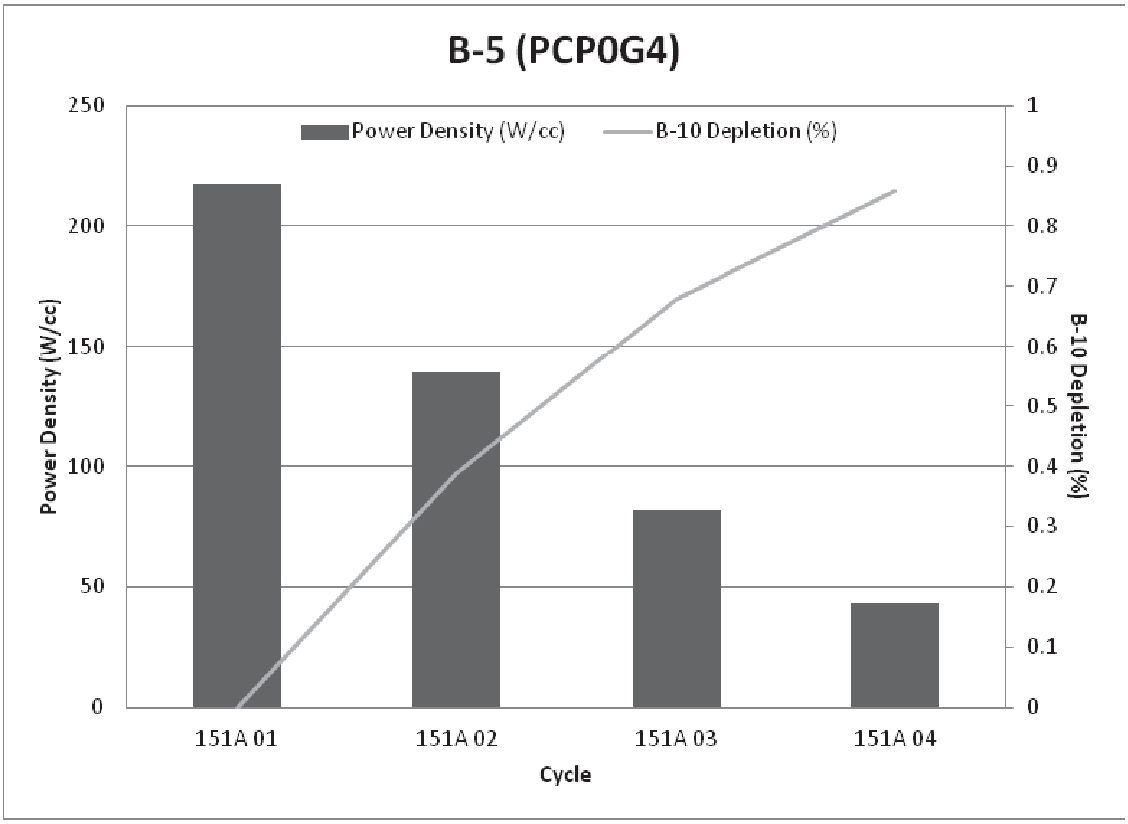
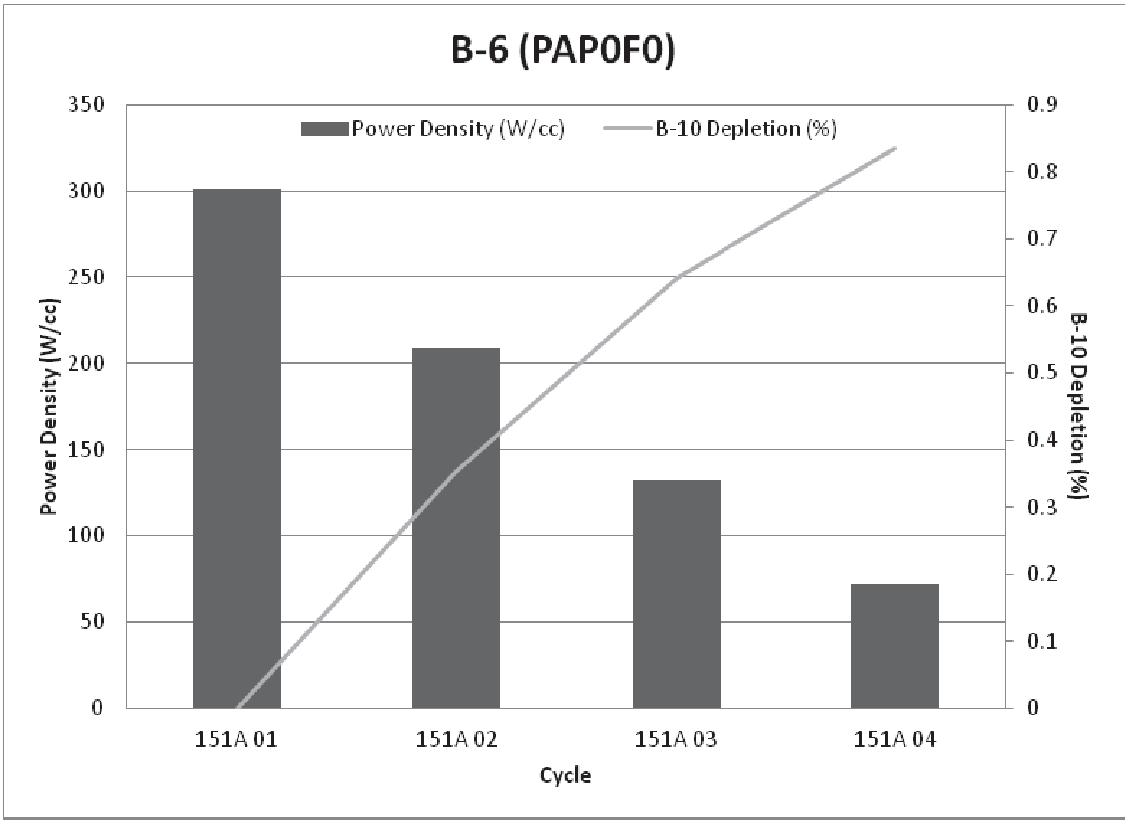
Appendix A

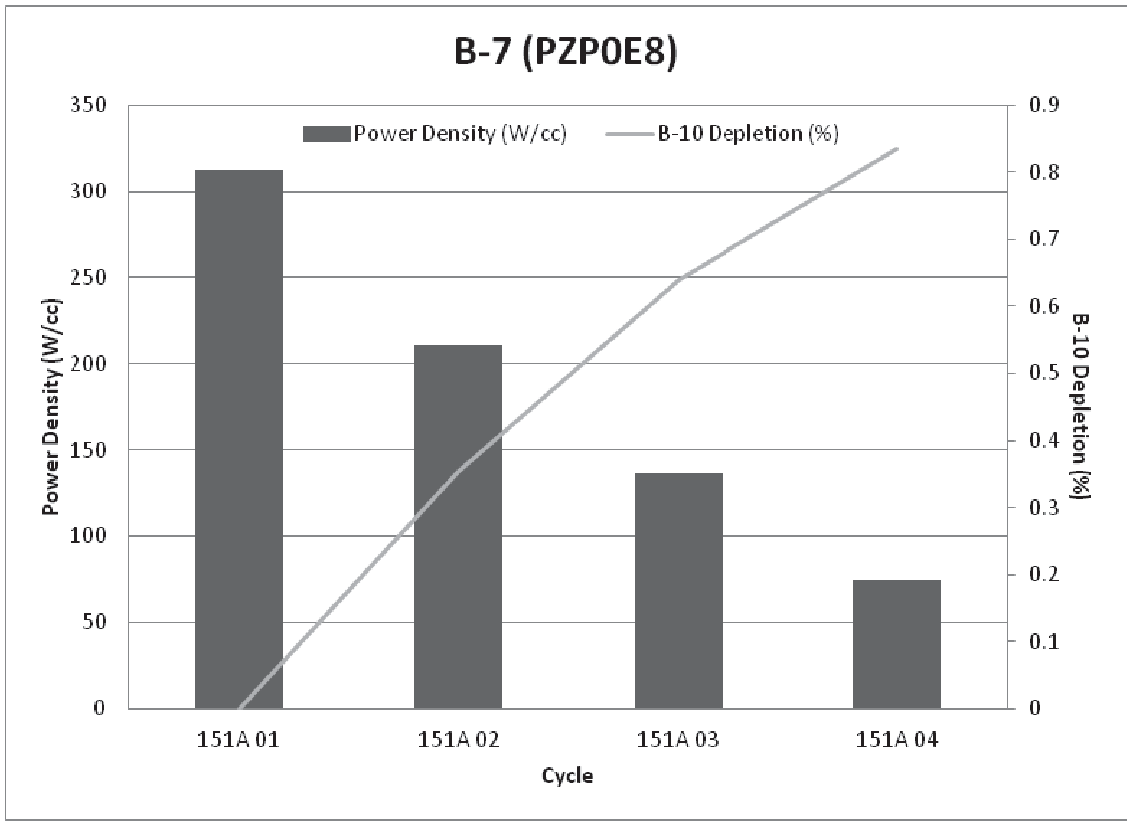
Individual Plate Power and Fission Density Plots

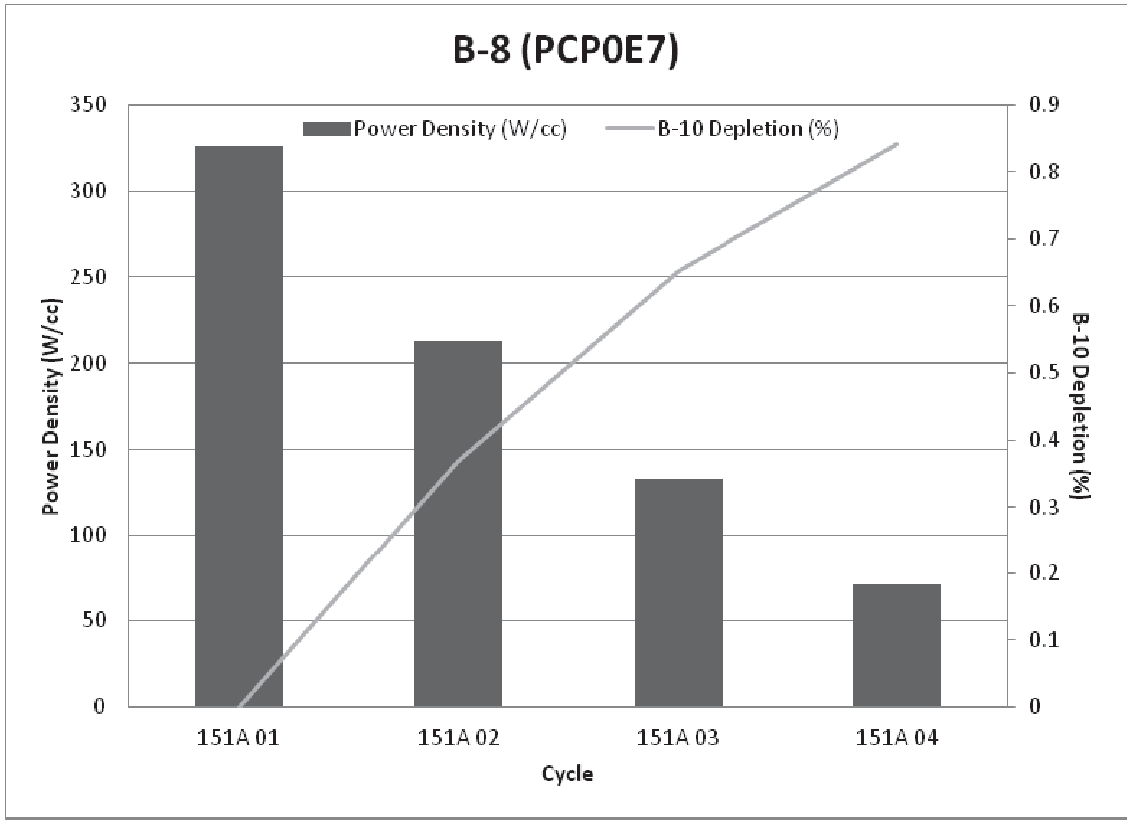
Appendix A
Individual Plate Power and Fission Density Plots

A-1. Capsule B

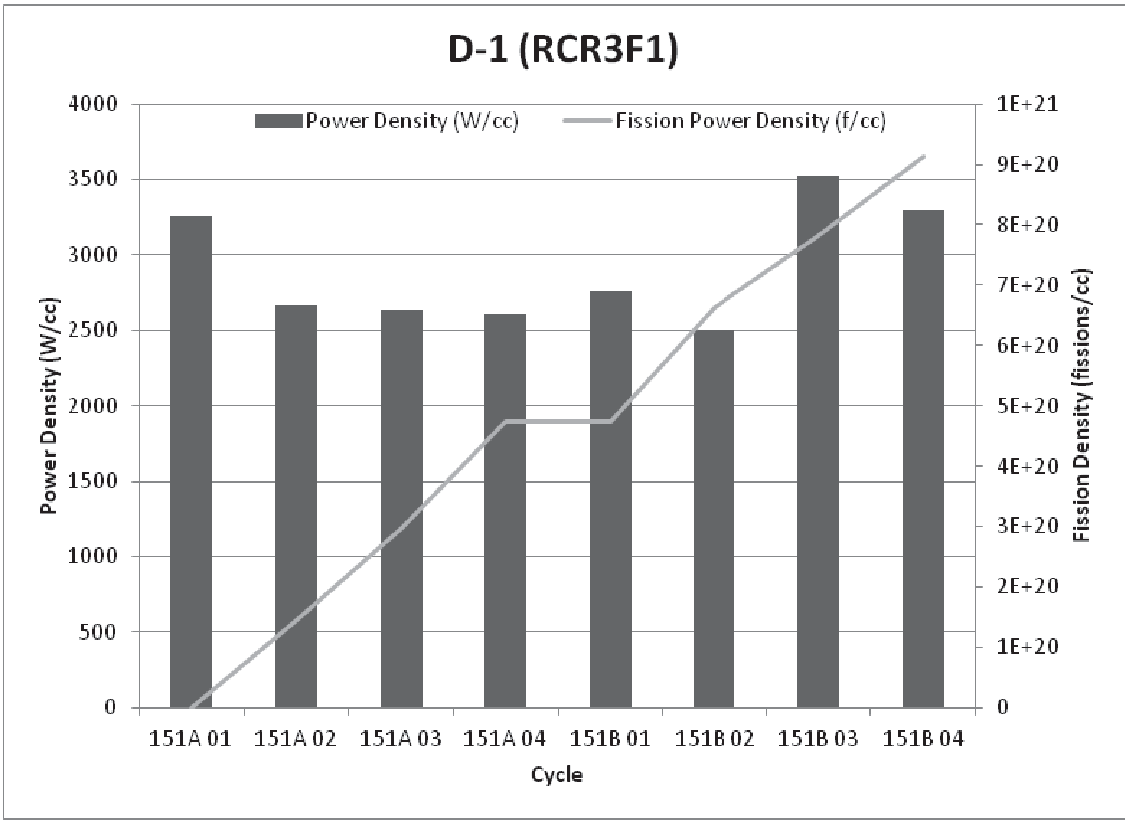


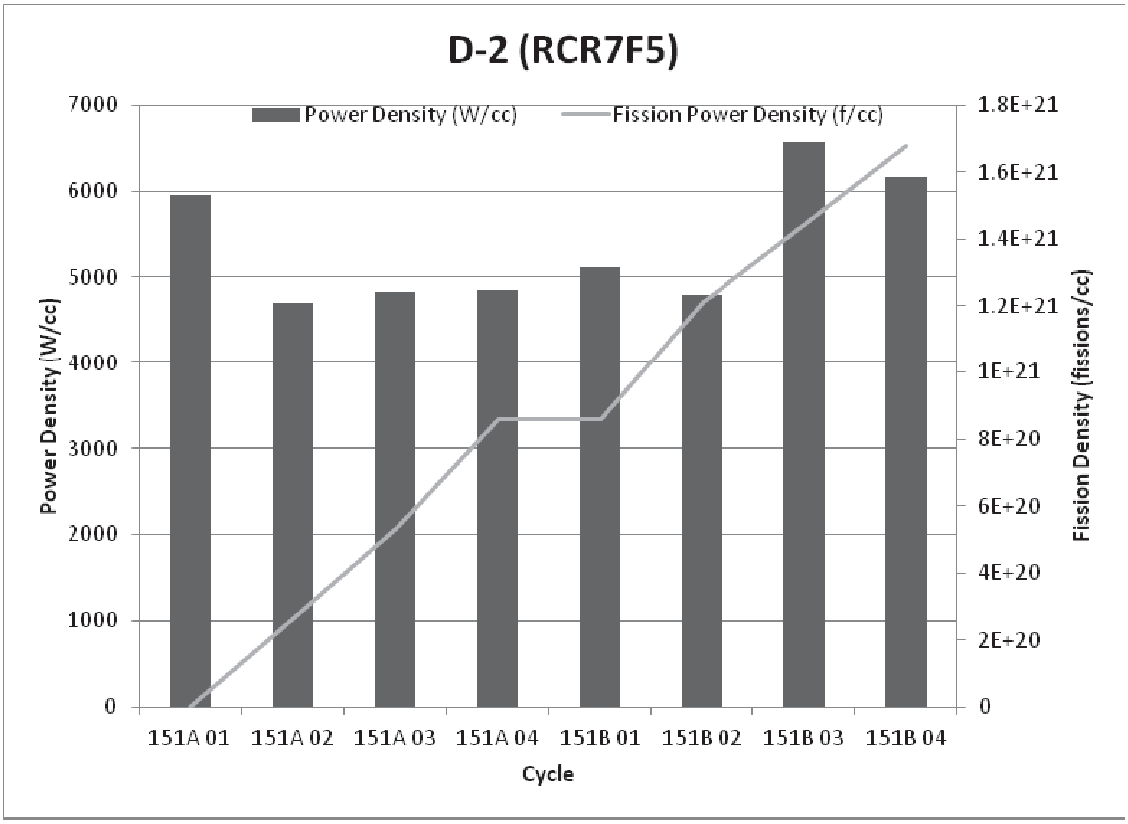


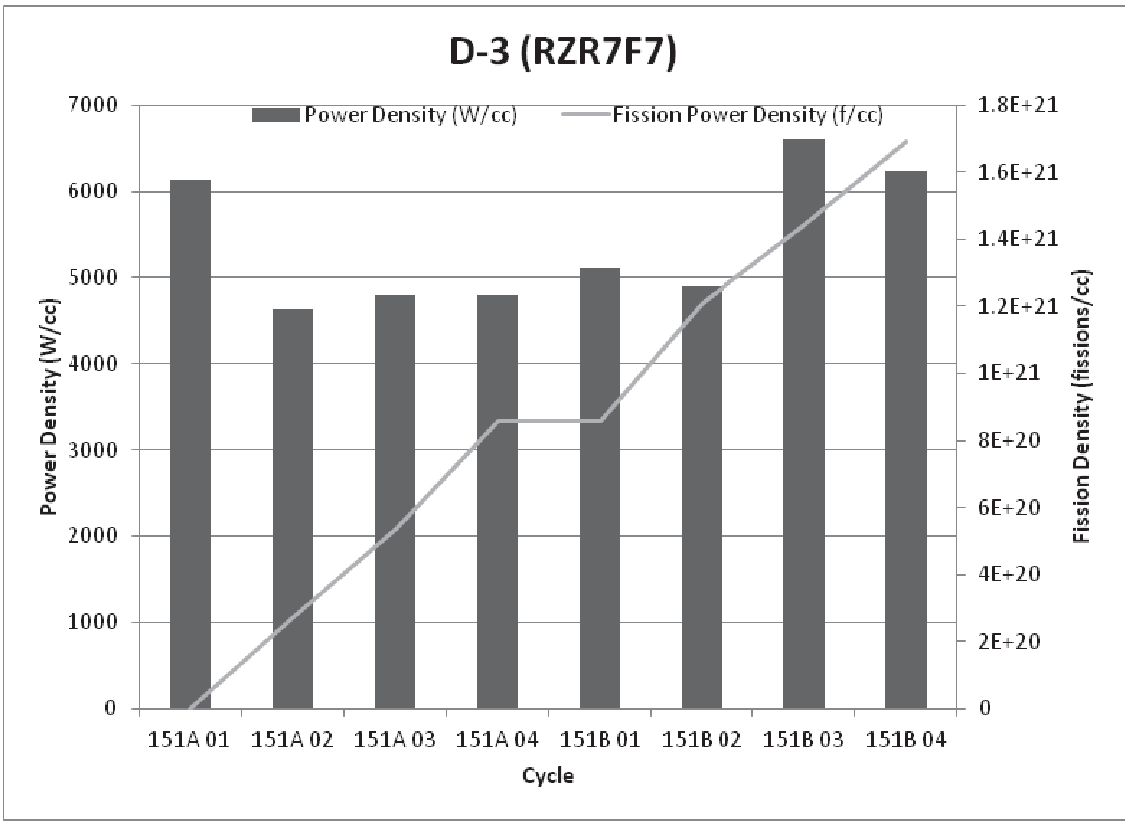

B-7 (PZP0E8)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
350
300
250
200
150
100
50
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
Cycle

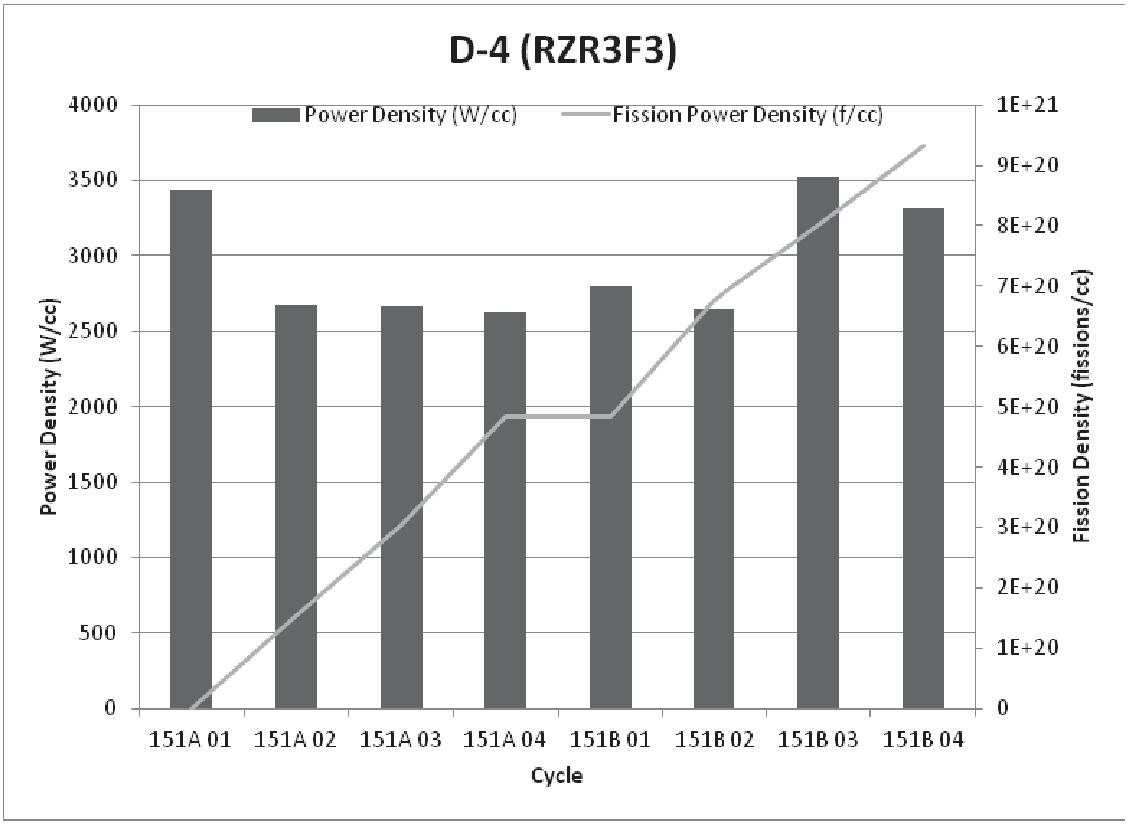

B-8 (PCP0E7)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
350
300
250
200
150
100
50
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
Cycle

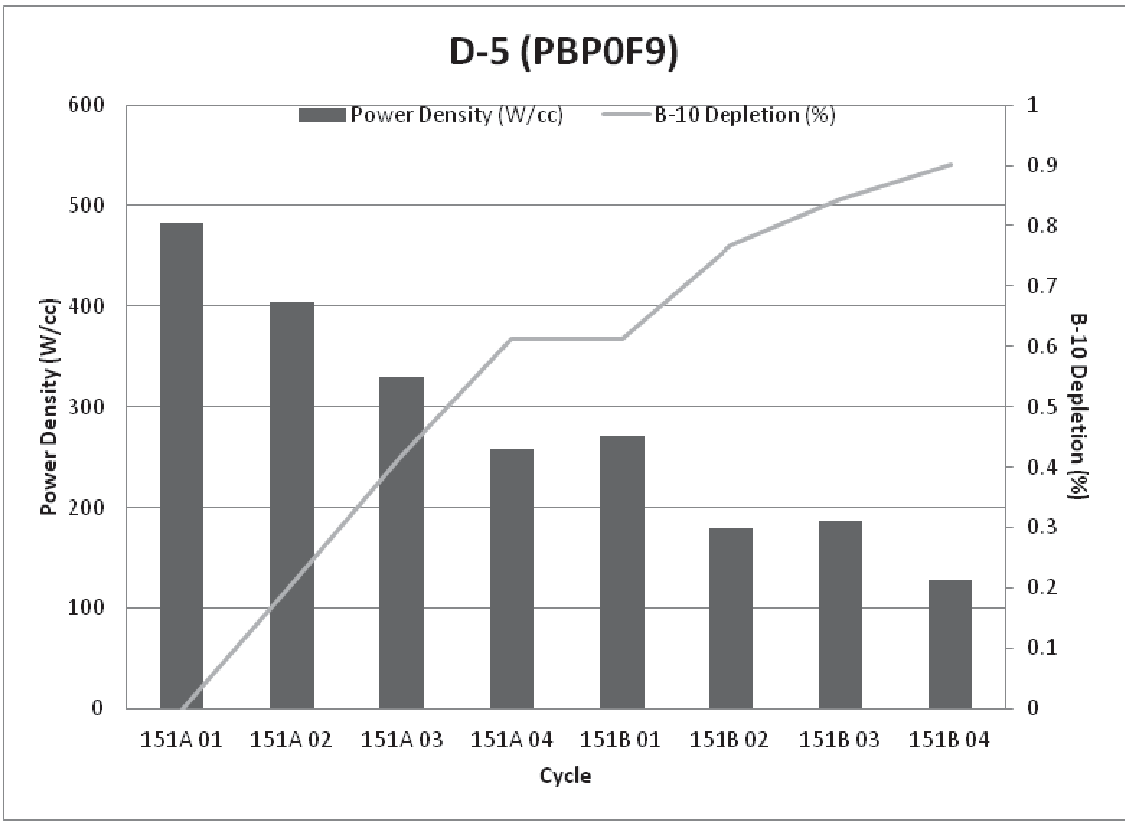
A-2. Capsule D

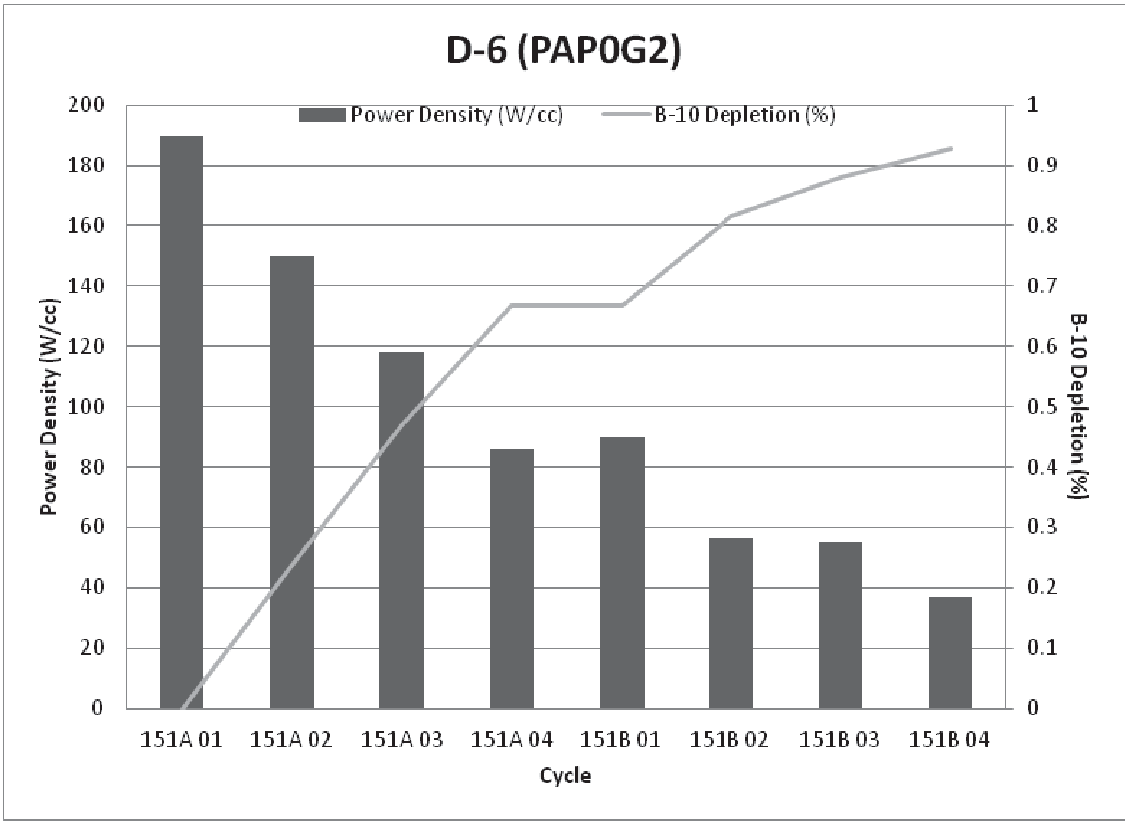

D-1 (RCR3F1)
Power Density (W/cc)
Fission Power Density (f/cc)
Power Density (W/cc)
Fission Density (fissions/cc)
4000
3500
3000
2500
2000
1500
1000
500
0
1E+21
9E+20
8E+20
7E+20
6E+20
5E+20
4E+20
3E+20
2E+20
1E+20
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle

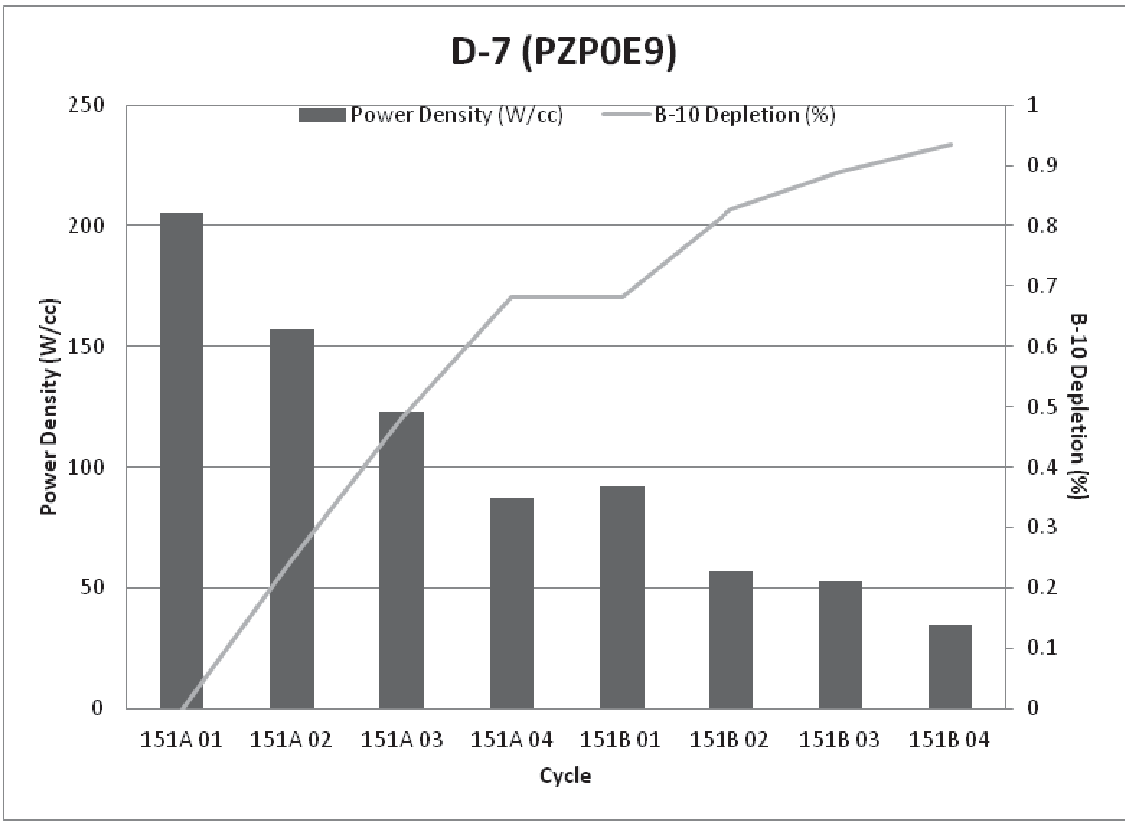

D-2 (RCR7F5)
Power Density (W/cc)
Fission Power Density (f/cc)
Power Density (W/cc)
Fission Density (fissions/cc)
7000
6000
5000
4000
3000
2000
1000
0
1.8E+21
1.6E+21
1.4E+21
1.2E+21
1E+21
8E+20
6E+20
4E+20
2E+20
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle

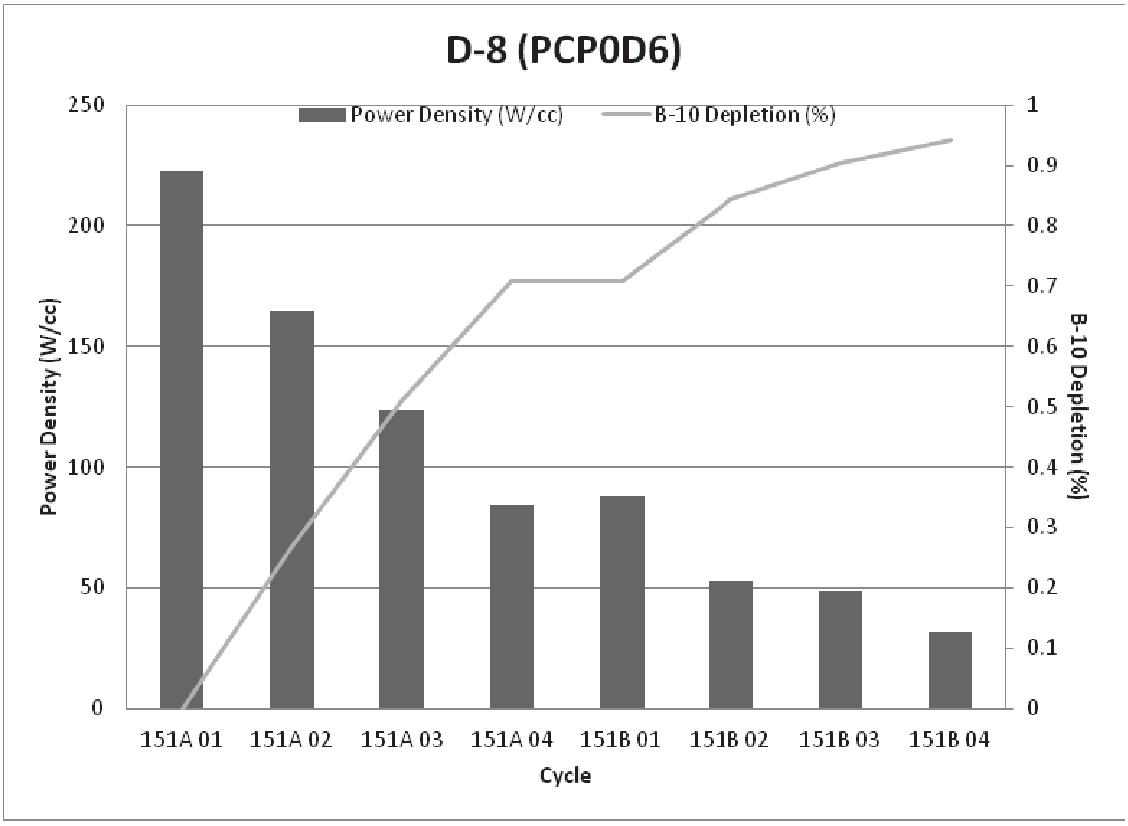

D-3 (RZR7F7)
Power Density (W/cc)
Fission Power Density (f/cc)
Power Density (W/cc)
Fission Density (fissions/cc)
7000
6000
5000
4000
3000
2000
1000
0
1.8E+21
1.6E+21
1.4E+21
1.2E+21
1E+21
8E+20
6E+20
4E+20
2E+20
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle


D-4 (RZR3F3)
Power Density (W/cc)
Fission Power Density (f/cc)
Power Density (W/cc)
Fission Density (fissions/cc)
4000
3500
3000
2500
2000
1500
1000
500
0
1E+21
9E+20
8E+20
7E+20
6E+20
5E+20
4E+20
3E+20
2E+20
1E+20
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle


D-5 (PBP0F9)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
600
500
400
300
200
100
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle


D-6 (PAP0G2)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
200
180
160
140
120
100
80
60
40
20
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle


D-7 (PZP0E9)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
250
200
150
100
50
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle


D-8 (PCP0D6)
Power Density (W/cc)
B-10 Depletion (%)
Power Density (W/cc)
B-10 Depletion (%)
250
200
150
100
50
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
151A 01
151A 02
151A 03
151A 04
151B 01
151B 02
151B 03
151B 04
Cycle