HALEU/HBU/ATF Reactor Physics

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HALEU HBU ATF Goals

- Improve fuel cycle economy by enabling fuel to be depleted to higher burnup than the typical current maximum pin burnup limits
  - LEU+ (8%> ^{235}U>5%) refers to a subset of High Assay Low-Enriched Uranium (HALEU) (20%> ^{235}U>5%) and is considered as the near term goal
- Improve fuel system performance under accident conditions
  - Several candidates exists for Accident Tolerant Fuel (ATF)
  - FeCrAl cladding for BWRs
  - Cr_2O_3+ Al_2O_3 doped fuel for PWRs

Objectives for HALEU HBU ATF Reactor Physics Study

- Compare LEU and LEU+ cores with respect to
  - Reactivity coefficients
  - Assembly and pin peaking factor
  - Assembly and pin exposures
- Verify that findings of the Phase1 study (assembly level) is valid at the core level and highlight differences
- Provide recommendations to NRC staff to support future confirmatory analysis
- Provide discharge fuel information as input to criticality safety, decay heat studies

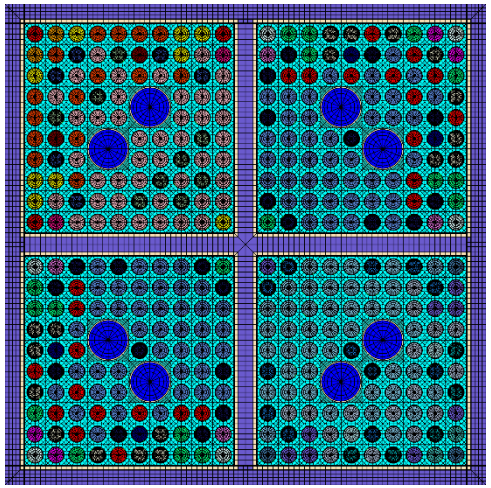
Challenges

- Reactor physics behavior is generally sensitive to core layout and assembly designs
  - Need representative equilibrium cores with contemporary core layouts and fuel assembly designs
    - BWR core design information is publicly available from initial cycles (not representative of current core design strategies)
    - 7x7 and 8x8 assembly designs in publicly available data are low in Gd or do not contain any Gd (not representative of typical BWR fuel assemblies)
    - PWR LEU+ fuel designs for concept cores are proprietary data
- Need to design new lattices and representative cores
    - BWR assembly design is not trivial (enrichments and Gd loadings change axially and radially while geometry also changes axially)
    - PWR assembly designs require new IFBA patterns

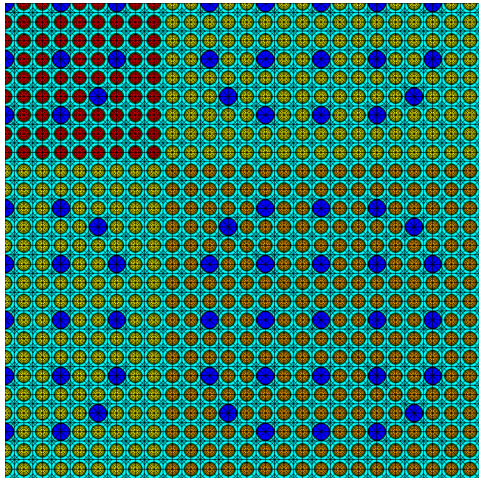
Work Plan

- Design a set of candidate modern BWR lattices with different average enrichments
- Design equilibrium 36-month cycle BWR core loading patterns using modern core design strategies
  - Simplified core optimization
- Adopt Southern Nuclear's LEU+ PWR concept core layout and operating parameters with in-house lattice designs
- Capture transition core physics using color sets of depleted, fresh, LEU, LEU+ fuel lattices

Transition Core

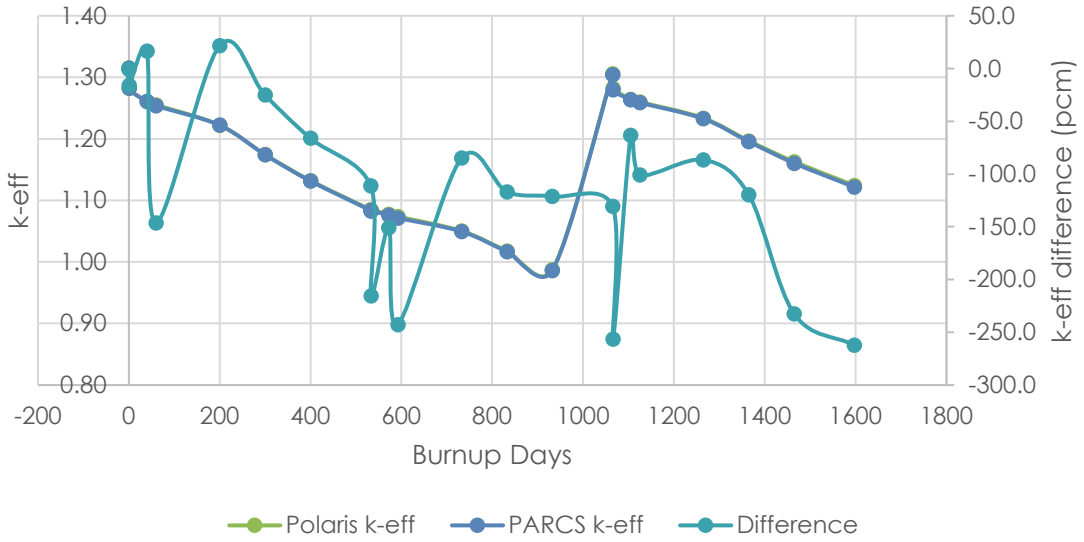


5 max wt % ZIRC-2 cladding	10 max wt % FeCrAl cladding
10 max wt % FeCrAl cladding	8 max wt % FeCrAl cladding

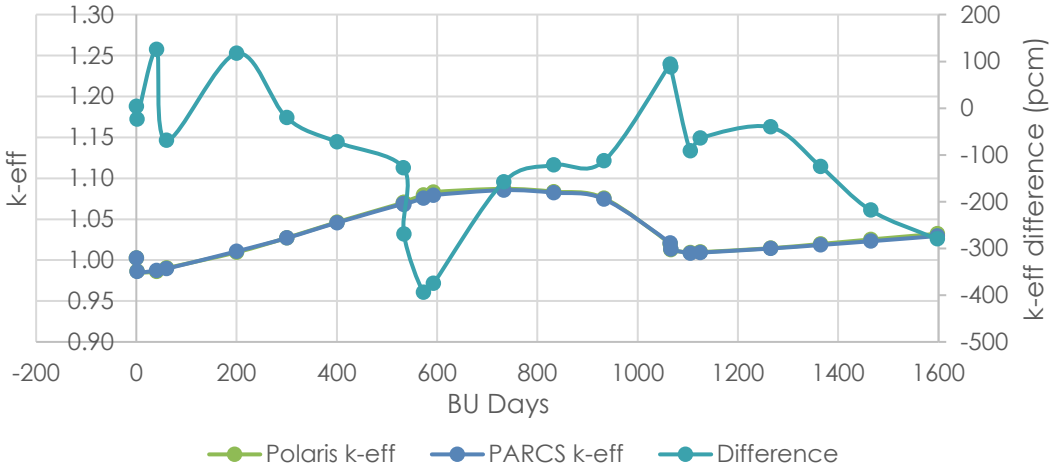


6.5% FA	8.0% FA	6.5% FA
8.0% FA	5.0% FA	8.0% FA
6.5% FA	8.0% FA	6.5% FA

BWR Colorset



PWR Colorset



PWR Core Analysis Results

LEU 4.2 %-4.6%

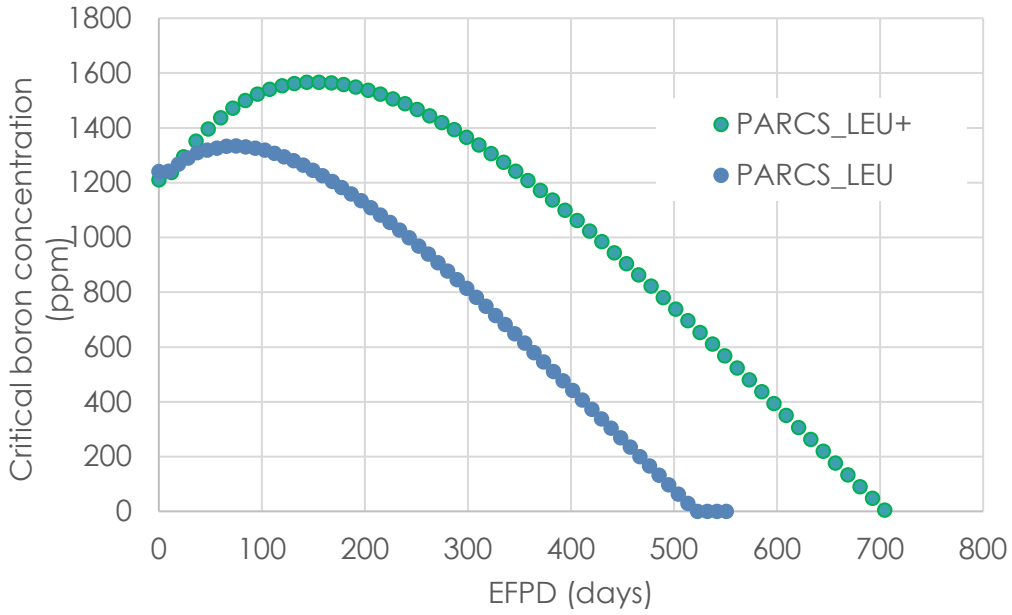
25.9	49.8	26.2	49.9	26.0	50.0	25.0	49.6
49.9	24.9	49.6	25.5	49.7	26.5	24.4	38.0
26.5	49.7	25.8	48.7	24.2	49.5	24.7	38.9
50.0	25.7	46.3	47.6	45.9	25.9	22.2	46.7
26.0	50.0	24.4	46.0	45.3	24.9	39.6	
50.1	26.5	49.4	25.9	24.9	21.2	35.9	
24.9	24.3	24.7	22.2	39.6	35.9		
49.5	38.7	38.8	46.2				

18-month cycle LEU core assembly burnup distribution (GWd/MTU)

LEU+ 5.95 %-6.2%

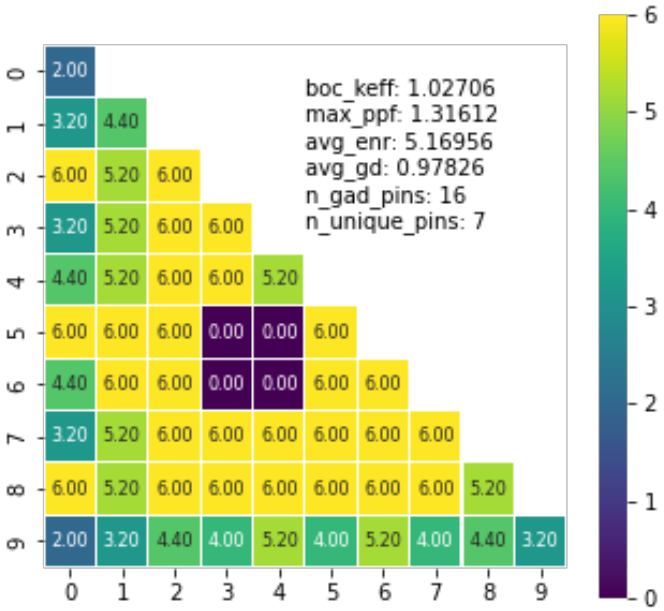
37.4	68.2	37.6	65.1	64.6	65.7	33.5	52.9
68.2	35.2	66.1	34.3	63.9	38.0	32.1	53.1
37.4	66.7	37.1	64.9	34.8	63.2	33.5	67.9
65.0	34.2	64.8	63.8	63.1	37.6	29.1	70.5
64.6	63.9	34.8	63.0	62.5	34.8	55.5	
65.7	38.0	63.2	37.6	34.8	28.9	63.2	
33.5	32.1	33.6	29.2	55.6	62.5		
52.9	53.0	68.0	71.5				

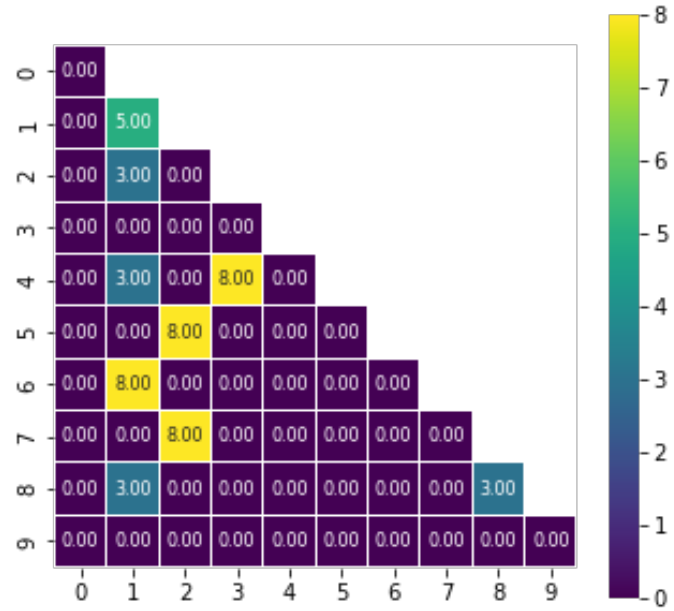
24-month cycle LEU+ core assembly burnup distribution (GWd/MTU)

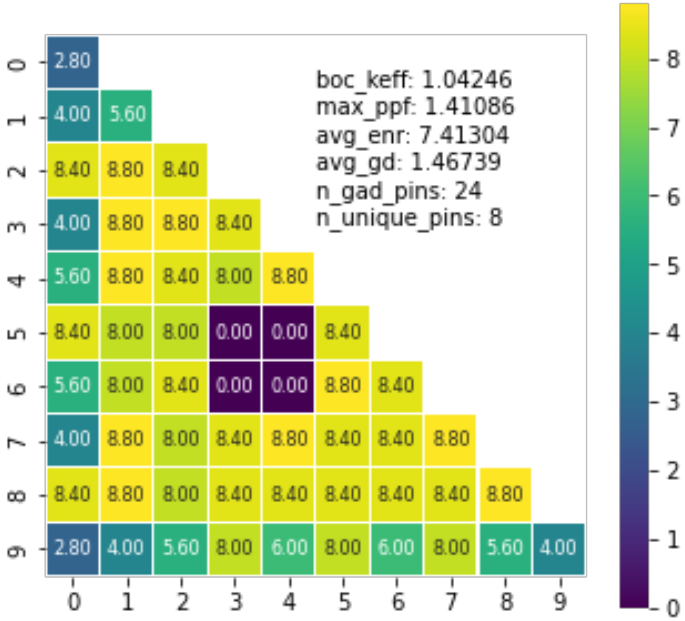


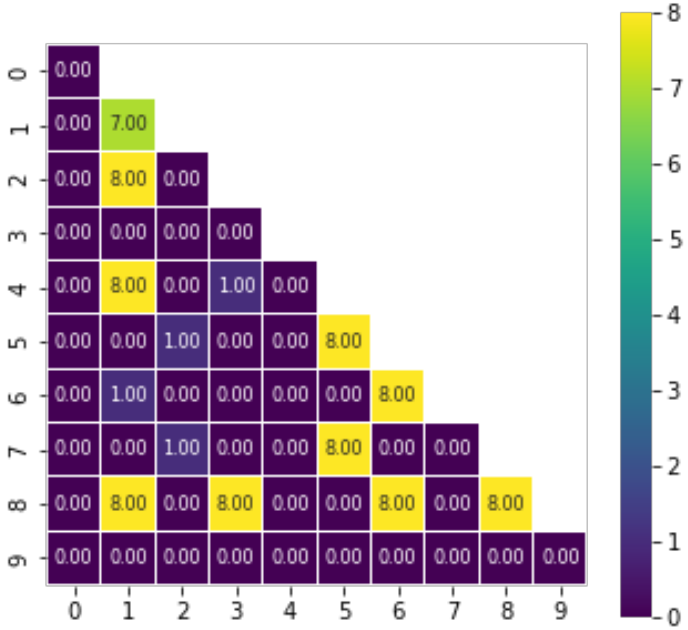
BWR Lattice Results

- Five LEU+ lattices with maximum pin enrichment values of 6, 7, 8, 9, and 10 are investigated.
- k_{inf} evolution with burnup of these assemblies are used in core design as interpolation points.

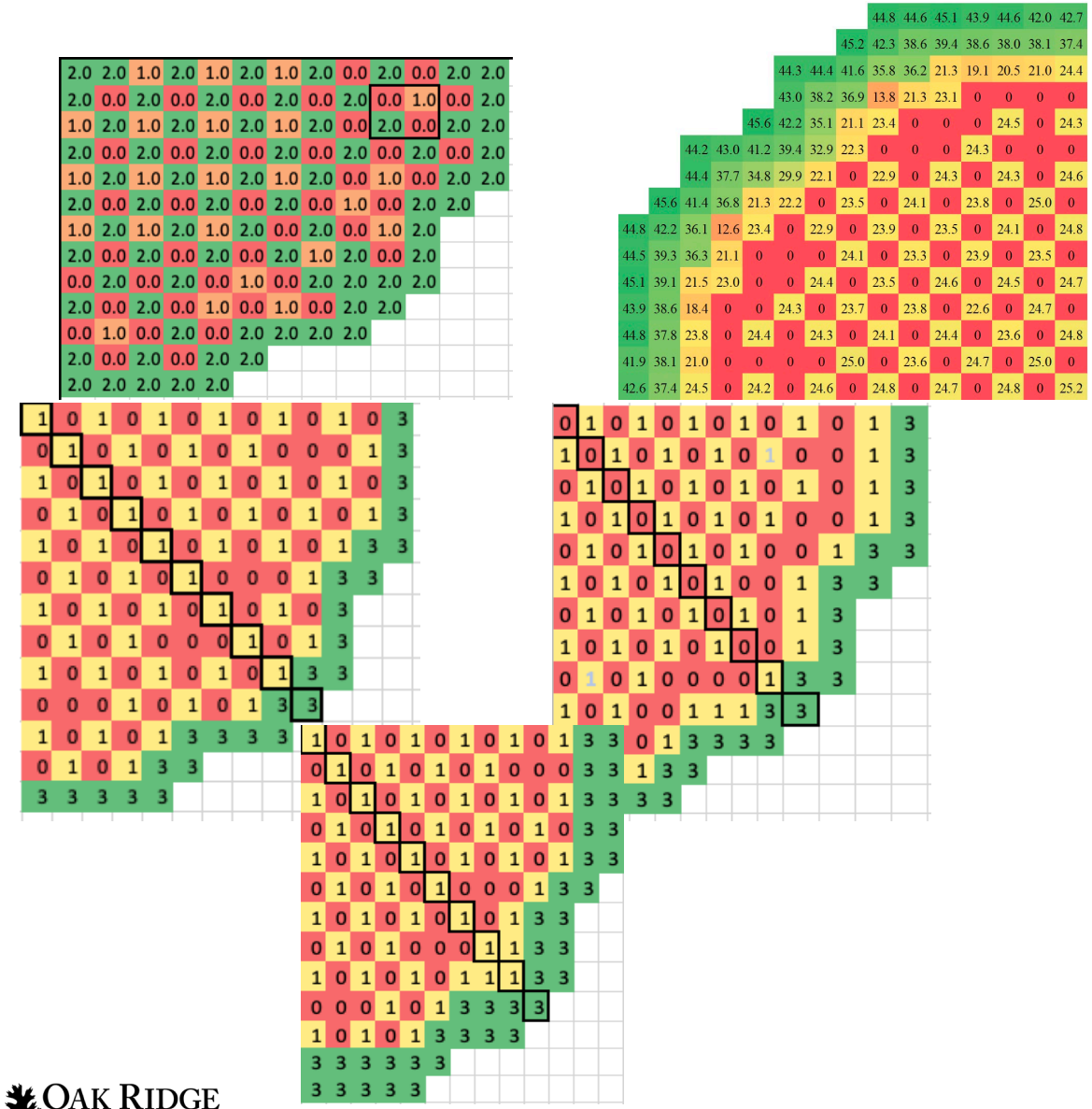








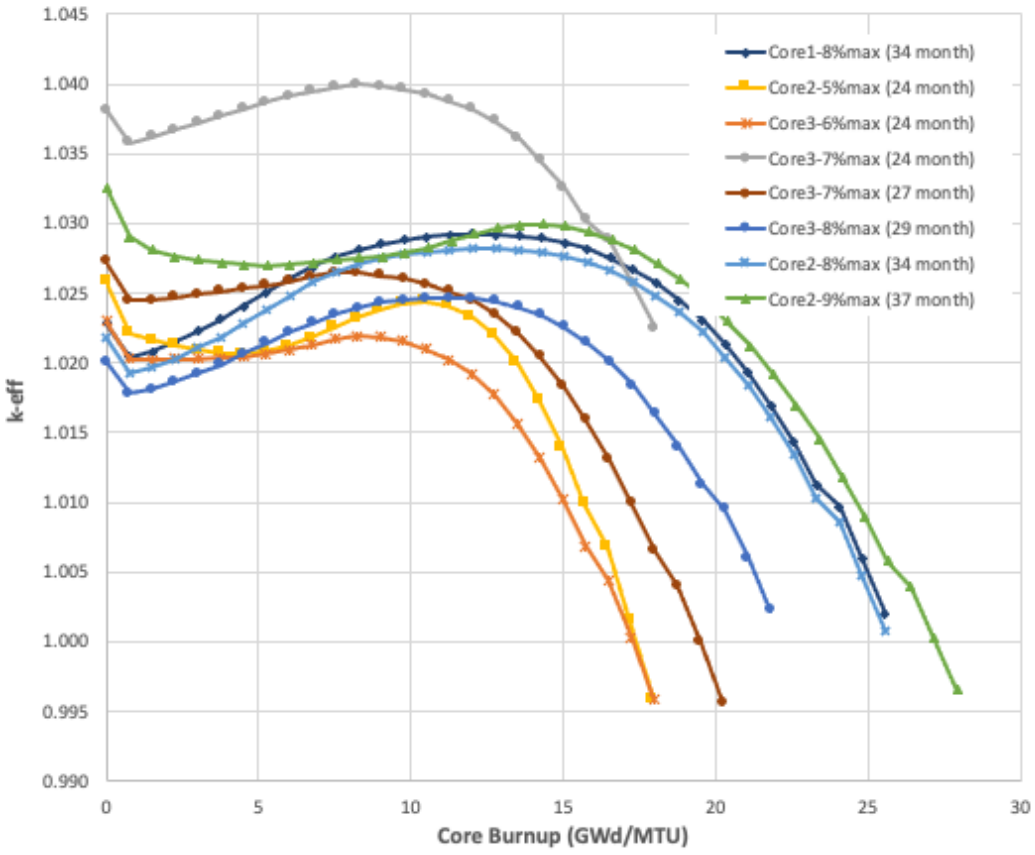
BWR Core Design



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	HFP, 0 solu	5%	6%	7%	8%				Input variables					
		4.45	5.27	5.98	6.63	Enr. Interp			FA in core	560		193	448	
	0.00E+00	1.0529	1.04899	1.05204	1.05124	1.051	1.239304		Rated power	2436	MW	3853		
	1.00E-02	1.04361	1.04093	1.04482	1.04472	1.045	1.212587		MTU/assembly	0.186	MTU	0.543		1
	5.00E-01	1.02872	1.02789	1.03314	1.03398	1.034	1.209733		Batch size	186.7			3	
	1.00E+00	1.03021	1.02952	1.03514	1.0359	1.036	1.210049		Enrichment	6.63	wt%			
	1.50E+00	1.0326	1.032	1.03806	1.03868	1.039	1.212762		Cycle length	36	months			
	2.00E+00	1.03529	1.03477	1.04134	1.04183	1.042	1.22026		Outage + maintenance	0	days			
	2.50E+00	1.03808	1.0377	1.04477	1.04515	1.045	1.227081		Cycle load factor	100	percent			
	3.00E+00	1.04083	1.04067	1.04824	1.04853	1.049	1.232495		Last cycle power penalty (20% of FA in core)	0				
	3.50E+00	1.04354	1.04362	1.05172	1.05191	1.052	1.236578		Effective full power days	1095.8			1159.524	3.176778
	4.00E+00	1.04626	1.04654	1.05521	1.05527	1.055	1.239495		Specific power at 100%	23.4				
	4.50E+00	1.04902	1.04948	1.05871	1.05865	1.059	1.241411				1st estimate			
	5.00E+00	1.05184	1.05245	1.06221	1.06203	1.062	1.242429				Location power mult	Batch power est	Batch burnup	EOC k-inf
	5.50E+00	1.05471	1.05548	1.06572	1.06542	1.065	1.242669		Batches	3				
	6.00E+00	1.05766	1.05855	1.06923	1.0688	1.069	1.242223		Avg Specific power	23.4			0	
	6.50E+00	1.06072	1.06165	1.07276	1.0722	1.072	1.239508		Batch 1	232.0	1	1.250	32033	1.121
	7.00E+00	1.06389	1.06479	1.07634	1.07561	1.076	1.23482		Batch 2	228.0	0.95	1.184	62380	0.948
	7.50E+00	1.06718	1.06799	1.07995	1.07905	1.079	1.228519		Batch 3	100.0	0.00	0.000	62380	0.948
	8.00E+00	1.07058	1.07127	1.08359	1.0825	1.083	1.220921		Batch 4	0.0	0.00	0.000	62380	0.948
	8.50E+00	1.07413	1.07463	1.08724	1.08595	1.086	1.212319		Batch 5	0.0	0.00	0.000	62380	0.948
	9.00E+00	1.07781	1.07804	1.09091	1.08942	1.089	1.202916		Core avg		0.800	1.000		1.038
	9.50E+00	1.08165	1.0815	1.09458	1.09291	1.093	1.192913							
	1.00E+01	1.08569	1.08499	1.0982	1.09641	1.096	1.182442		Discharge burnup	70579		Core average burnup		50377
	1.05E+01	1.08992	1.08849	1.10173	1.0999	1.100	1.171633							
	1.10E+01	1.09426	1.09198	1.10517	1.10337	1.103	1.160584							

- Competing objective functions
  - Need to balance batch sizes
  - Watch for burnup gradients in each batch not to exceed burnup limit for shuffling
  - Fresh fuel extends cycle length
  - Once burned fuels early cycle
  - Twice burned improves economics, lowers leakage
  - Checker board vs ring of fire, high leakage vs flat power

BWR Core Analysis Results



LEU 5%max 4.5%avg

24-month cycle LEU core assembly burnup distribution (GWd/MTU)

47.6	43.3	23.1	44.9	23.7	45.0	23.6	44.0	22.8	38.5	18.7	36.4	44.7
43.3	22.8	44.6	23.6	45.0	23.7	44.6	23.3	22.6	21.1	18.4	32.4	44.7
23.1	44.6	23.5	45.0	23.7	44.7	23.4	43.1	22.2	37.2	17.9	34.4	42.4
44.9	23.6	45.0	23.7	44.7	23.5	43.5	22.6	39.5	19.6	16.8	29.4	42.2
23.7	45.0	23.7	44.7	23.5	43.8	22.8	40.9	20.7	18.4	32.9	42.3	44.8
45.0	23.7	44.7	23.5	43.8	22.8	41.4	21.1	19.4	35.2	40.8	44.4	
23.6	44.5	23.4	43.5	22.8	41.4	21.3	36.5	17.8	36.4	41.9		
44.0	23.3	43.1	22.6	40.9	21.1	36.5	18.1	37.5	35.2	43.5		
22.8	22.6	22.2	39.5	20.7	19.4	17.8	36.1	30.8	43.3	43.3		
38.5	21.1	37.2	19.5	18.3	35.1	37.1	35.0	43.1	41.5			
18.6	18.4	17.9	16.8	32.8	42.0	41.9	43.5	43.3				
36.4	32.4	34.4	29.4	42.2	44.4							
44.7	45.3	42.4	42.1	44.8								

LEU+ 9%max 7.2%avg

36-month cycle LEU+ core assembly burnup distribution (GWd/MTU)

72.0	65.3	34.9	67.5	35.8	67.7	35.8	66.2	34.4	58.1	28.2	55.0	67.6
65.3	34.4	67.1	35.6	67.7	35.8	67.3	35.4	34.3	32.0	28.0	49.1	67.7
34.9	67.1	35.5	67.7	35.8	67.3	35.5	65.3	33.9	56.6	27.3	52.2	64.4
67.5	35.6	67.7	35.8	67.4	35.5	65.8	34.3	60.2	30.0	25.7	44.8	64.2
35.8	67.7	35.8	67.4	35.5	66.1	34.6	61.9	31.3	28.0	50.4	64.8	68.3
67.7	35.8	67.3	35.5	66.1	34.7	62.9	32.3	29.6	53.5	62.2	67.7	
35.8	67.3	35.5	65.8	34.6	62.9	32.5	55.9	27.3	55.3	63.8		
66.2	35.4	65.3	34.3	61.8	32.3	55.8	27.8	57.0	53.4	66.5		
34.4	34.3	33.9	60.1	31.3	29.5	27.3	55.1	47.3	65.9	65.5		
58.1	32.0	56.6	30.0	28.0	53.4	56.3	53.1	65.7	63.7			
28.2	28.0	27.3	25.7	50.3	64.5	63.7	66.5	65.5				
54.9	49.1	52.1	44.7	64.6	67.6							
67.5	68.6	64.3	64.1	68.2								