Summary of the University of Missouri Research Reactor HEU to LEU Fuel Conversion Feasibility Study

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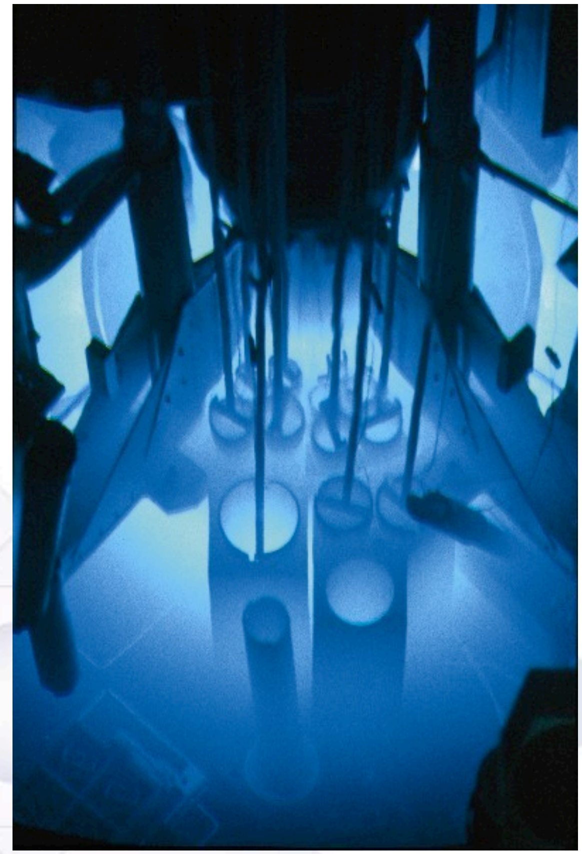

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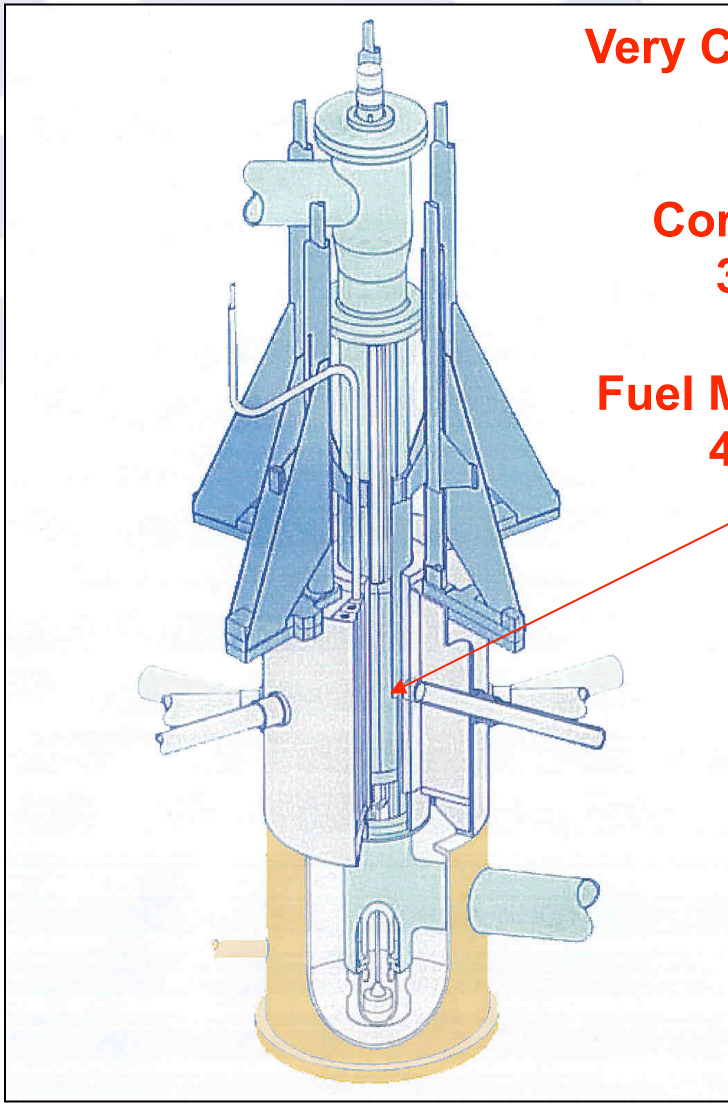
TRTR/IGORR-2010 – September 20, 2010

Knoxville, Tennessee

Reactor Core Assembly 3D View

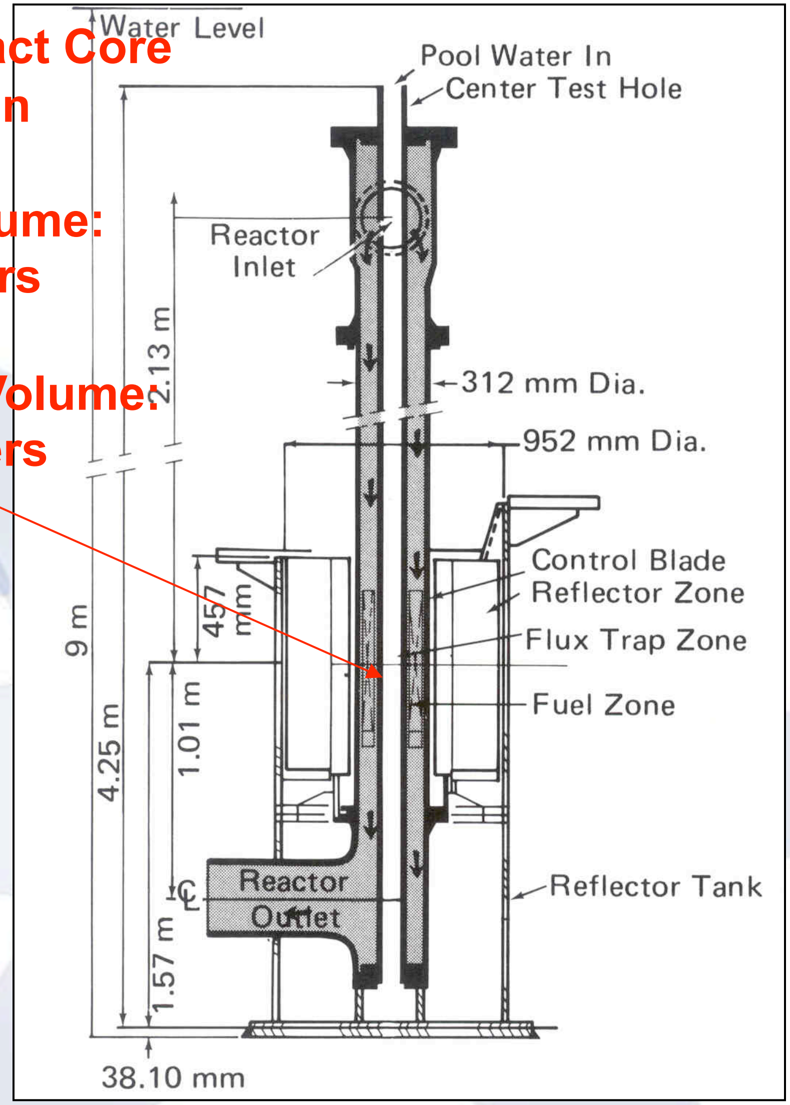
Reactor Core Assembly 2D View



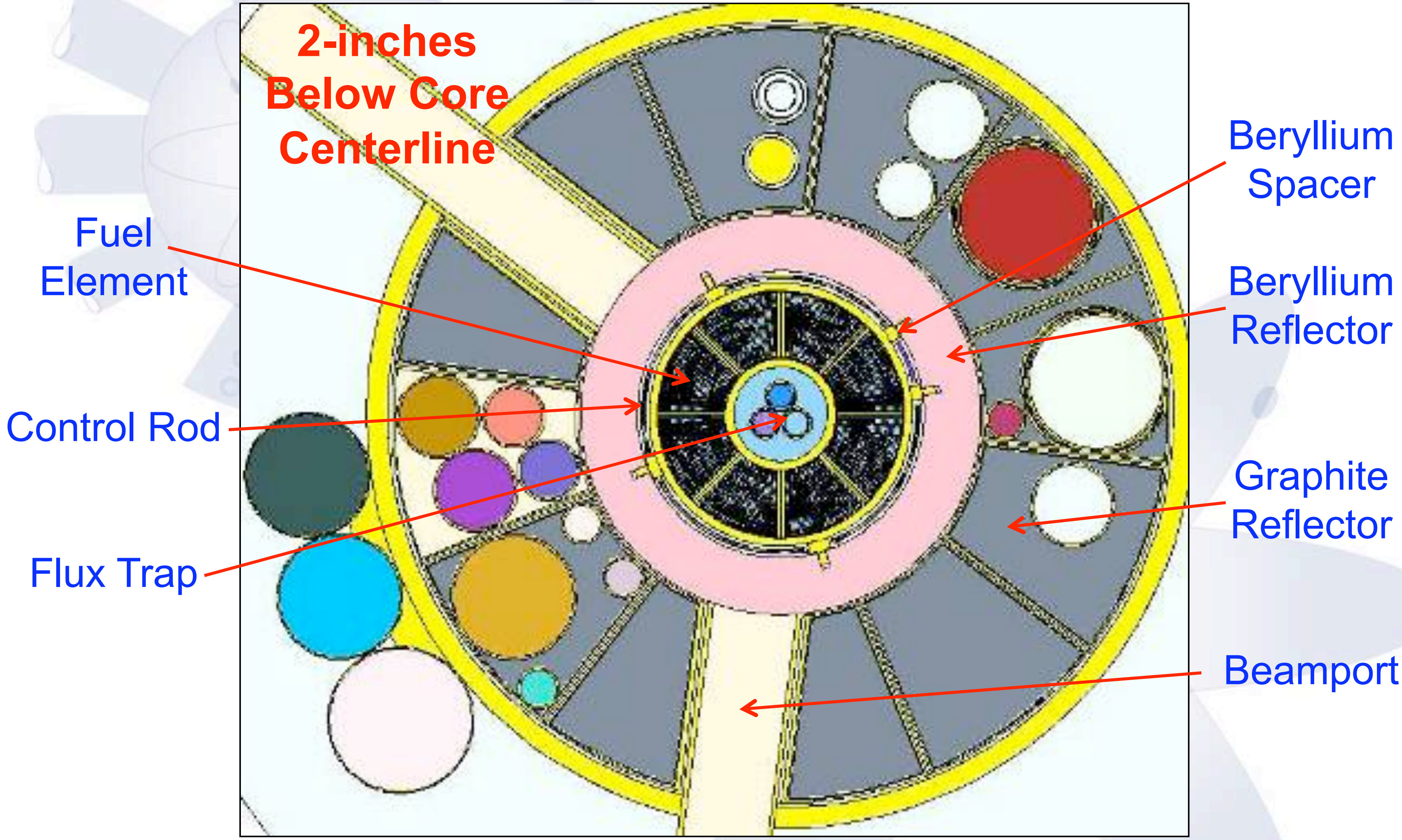
Very Compact Core Design

Core Volume: 33 liters

Fuel Meat Volume: 4.3 liters



Cross Section View of Core (MCNP Model)

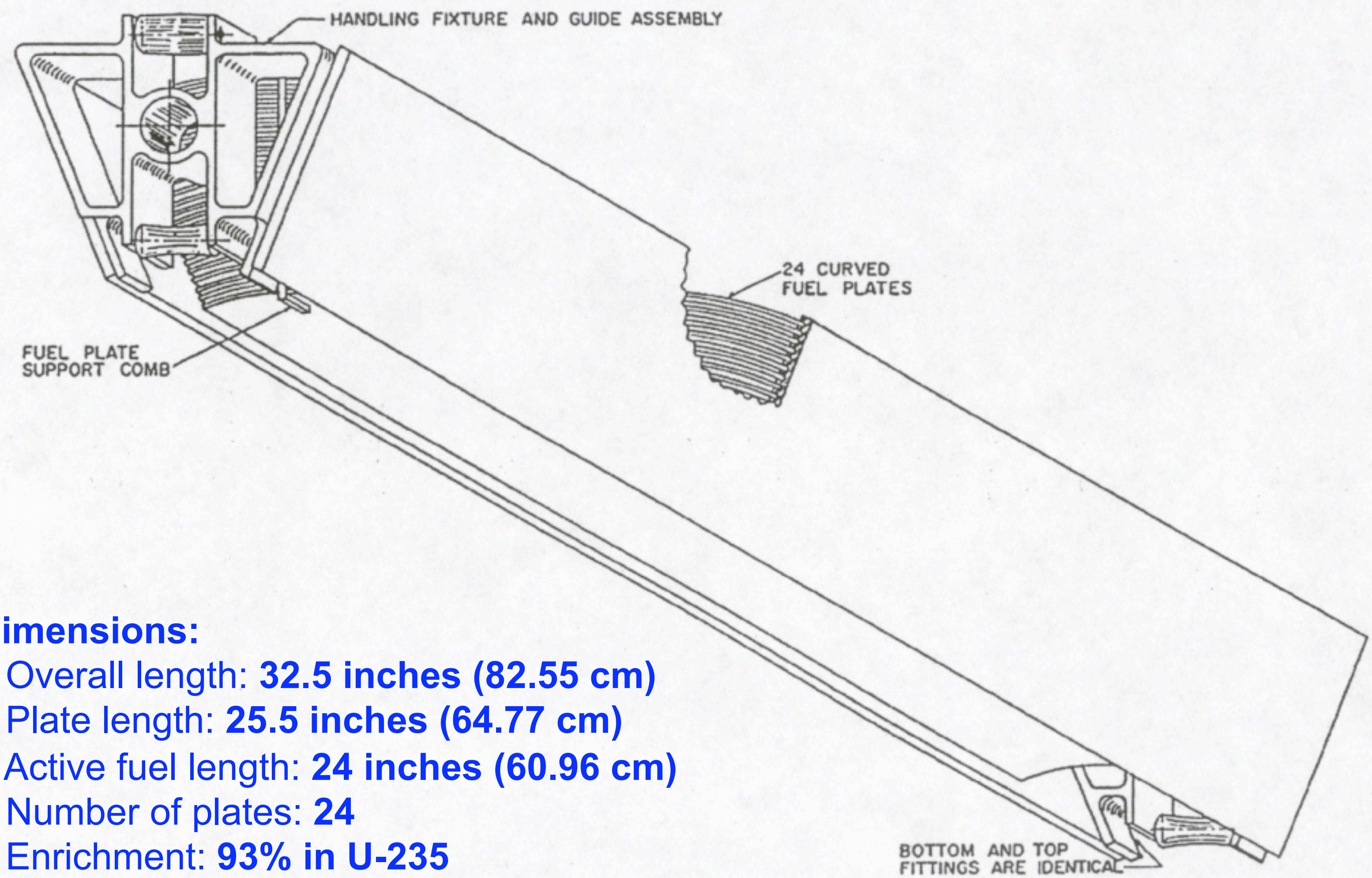


Basic Reactor Parameters

MURR is a pressurized, reflected, heterogeneous, open pool-type, which is light-water moderated and cooled

- Maximum power – **10 MW_{th}**
- Peak flux in center test hole – **6.0E14 n/cm^2-s**
- Core – **8 fuel assemblies (775 grams of U-235/assembly)**
- Control blades – **5 total: 4 Boral shim-safety, 1 SS regulating**
- Reflectors – **beryllium and graphite**
- Forced primary coolant flow rate – **3,750 gpm (237 lps)**
- Forced pool coolant flow rate – **1,200 gpm (76 lps)**
- Primary coolant temps – **120 °F (49 °C) in, 136 °F (58 °C) out**
- Primary coolant system pressure – **85 psia (586 kPa)**
- Pool coolant temps – **100 °F (38 °C) in, 106 °F (41 °C) out**
- Beamports – **three 4-inch (10 cm), three 6-inch (15 cm)**

MURR Fuel Element



Dimensions:

Overall length: **32.5 inches (82.55 cm)**
Plate length: **25.5 inches (64.77 cm)**
Active fuel length: **24 inches (60.96 cm)**
Number of plates: **24**
Enrichment: **93% in U-235**

Potential Fuel Design/Manufacturing Limitation Questions/Assumed Answers

- What is the peak fuel burnup limit?
  ~7.0E21 fissions/cc
- How thin can acceptable U-10Mo fuel foils be made?
  < 0.005-inches (0.127 mm)
- What is the thinnest nominal plate cladding thickness sufficient to contain the fission products?
  ≤ 0.010-inches (0.254 mm)
- How thin can sufficiently stiff curved fuel plates be made?
  ≤ 0.038-inches (0.965 mm)
- Magnitude of U-10Mo engineering peaking factors?
  ≤ UAl_x HEU factors
- What is the minimum cladding blister temperature?
  850 to 900 °F (454 to 482 °C)

Summary of MURR Fuel Element Specifications

Description	Current HEU Fuel	Proposed LEU Fuel
Fuel		
Material	UAl_x (mostly UAL_3)	U-10Mo
Enrichment	93% ^{235}U	19.75% ^{235}U
Thickness Plate 1 Plate 2 Plates 3-23 Plate 24	20 mil (0.508mm) 20 mil (0.508mm) 20 mil (0.508mm) 20 mil (0.508mm)	9 mil (0.229 mm) 12 mil (0.305 mm) 18 mil (0.457 mm) 17 mil (0.432 mm)
Cladding		
Material	Aluminium	
Thickness Plate 1 Plate 2 Plates 3-23 Plate 24	15 mil (0.381mm) 15 mil (0.381mm) 15 mil (0.381mm) 15 mil (0.381mm)	20 mil (0.508 mm) 13 mil (0.330 mm) 10 mil (0.254 mm) 16 mil (0.406 mm)
Fuel Element		
Number of Fuel Plates	24	
Overall Fuel Element Length	32.5 inches (82.550 cm)	
Overall Fuel Plate Length	25.5 inches (64.770 cm)	
Overall Active Fuel Length	24.0 inches (60.960 cm)	
Fuel Plate Thickness 1 & 24 Fuel Plate Thickness 2-23	50 mil (1.270mm) 50 mil (1.270mm)	49 mil (1.245mm) 38 mil (0.965mm)
Distance Between Plates (Coolant Channel)	80 mil (2.032mm)	92 mil (2.337mm)
Maximum ^{235}U Loading	775 grams	1439 grams
Fuel U-235 Density	1.42 grams/cm^3	3.03 grams/cm^3
Weight	~ 6 Kg	~ 11 Kg

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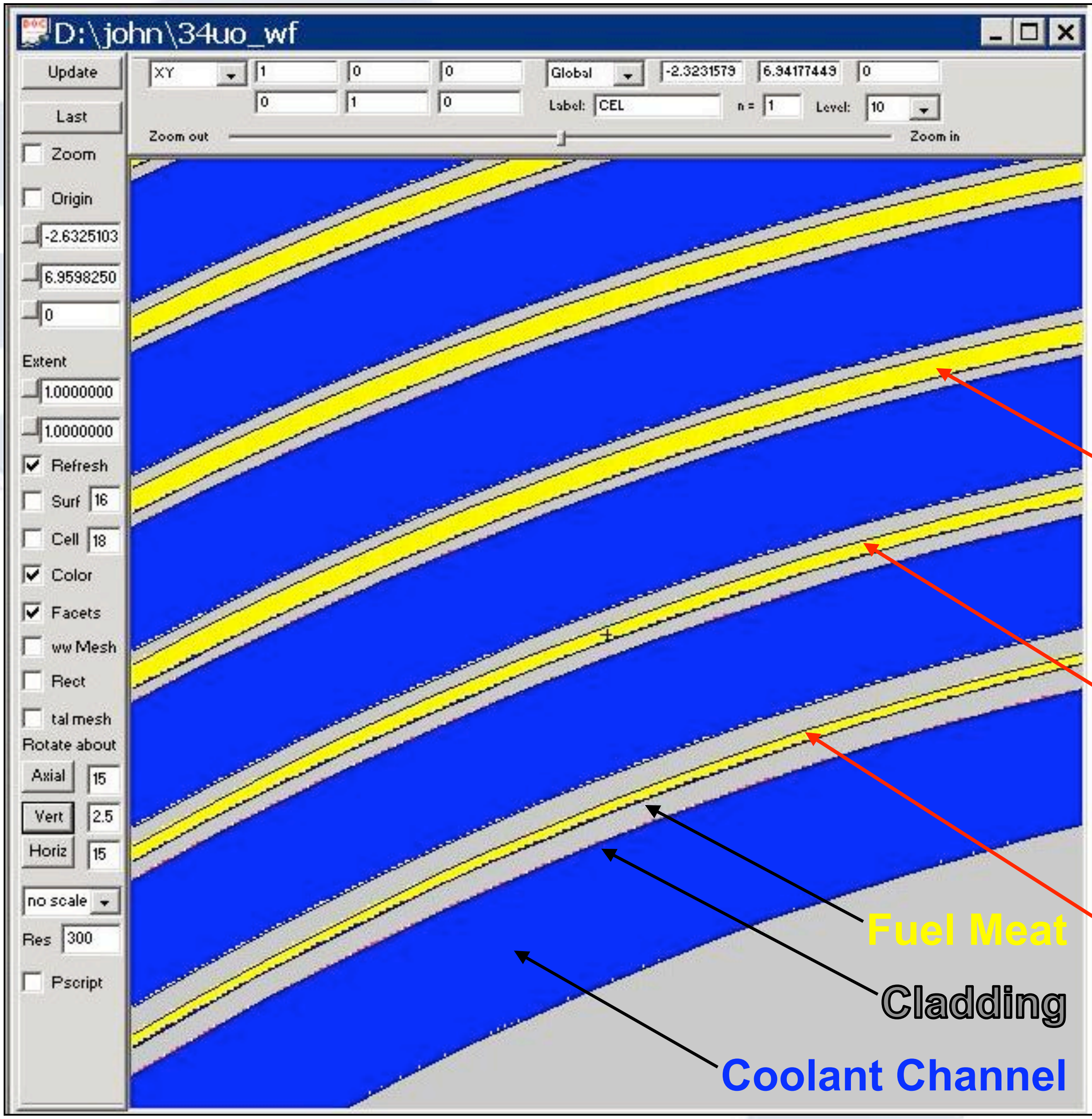


Cross-sectional View of Proposed LEU Fuel Element

Plate-24

Fuel Meat – 17 mils
Cladding – 16 mils
Total – 49 mils

Plate-3 to -23

Fuel Meat – 18 mils
Cladding – 10 mils
Total – 38 mils

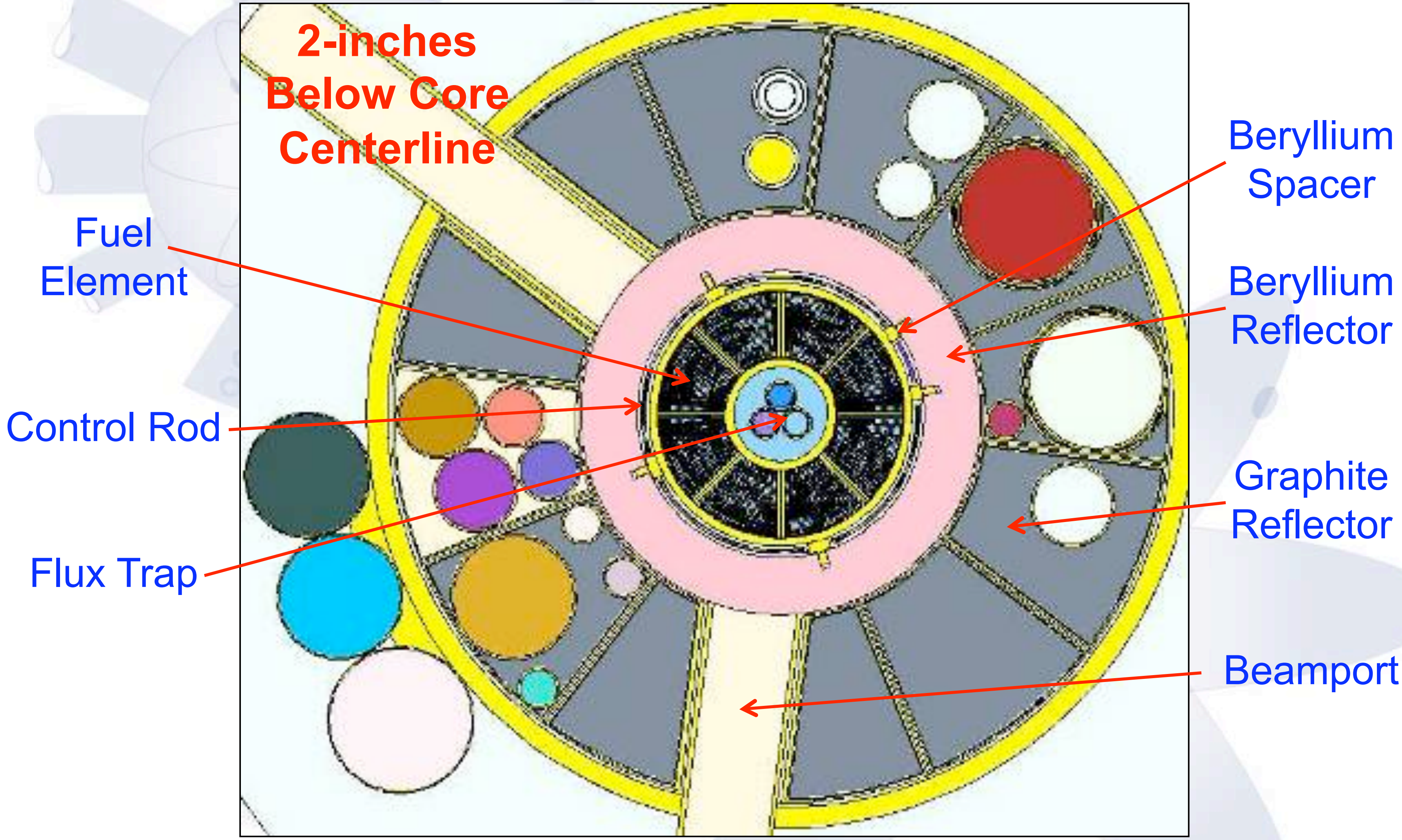
Plate-2

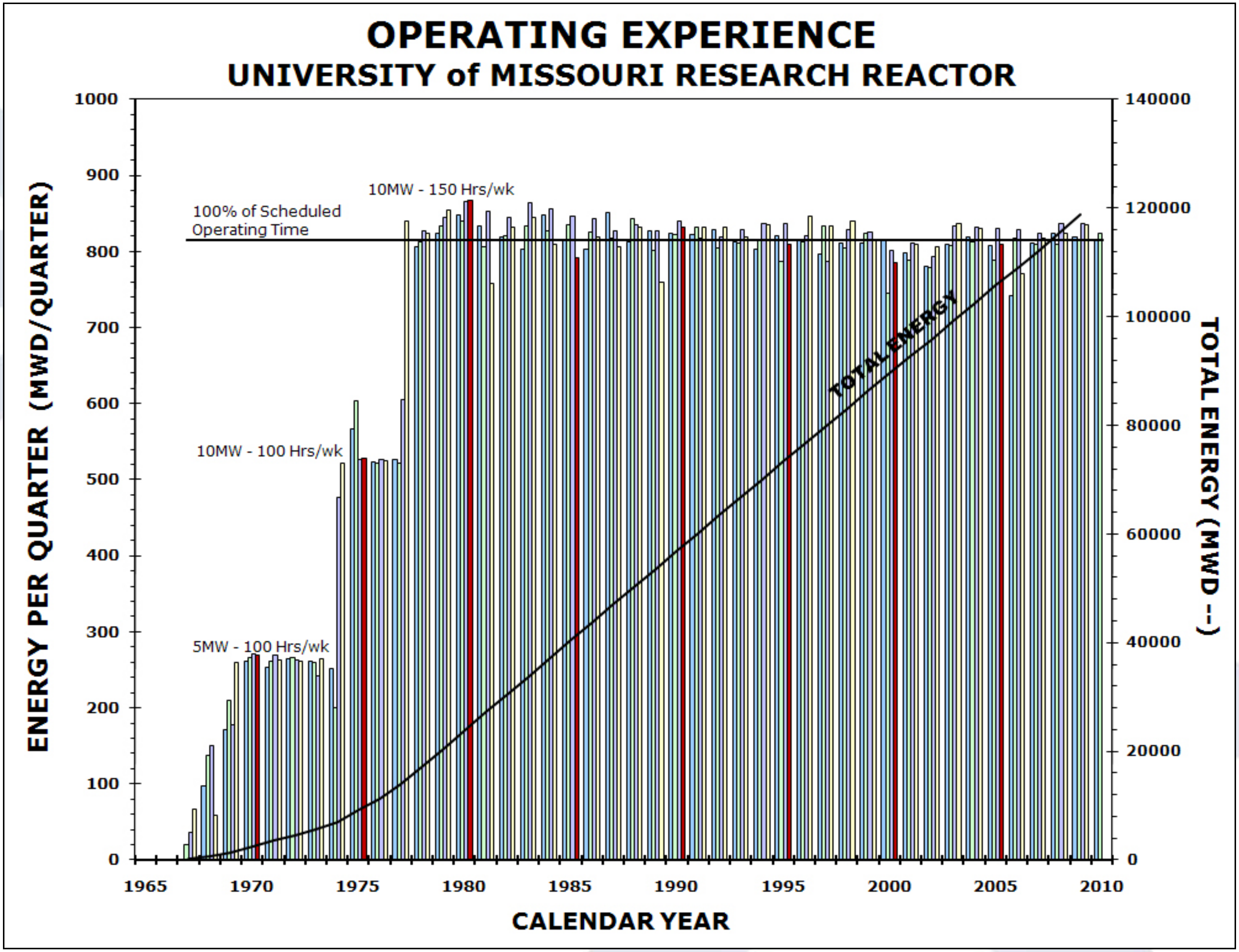
Fuel Meat – 12 mils
Cladding – 13 mils
Total – 38 mils

Plate-1

Fuel Meat – 9 mils
Cladding – 20 mils
Total – 49 mils

Cross Section View of Core (MCNP Model)

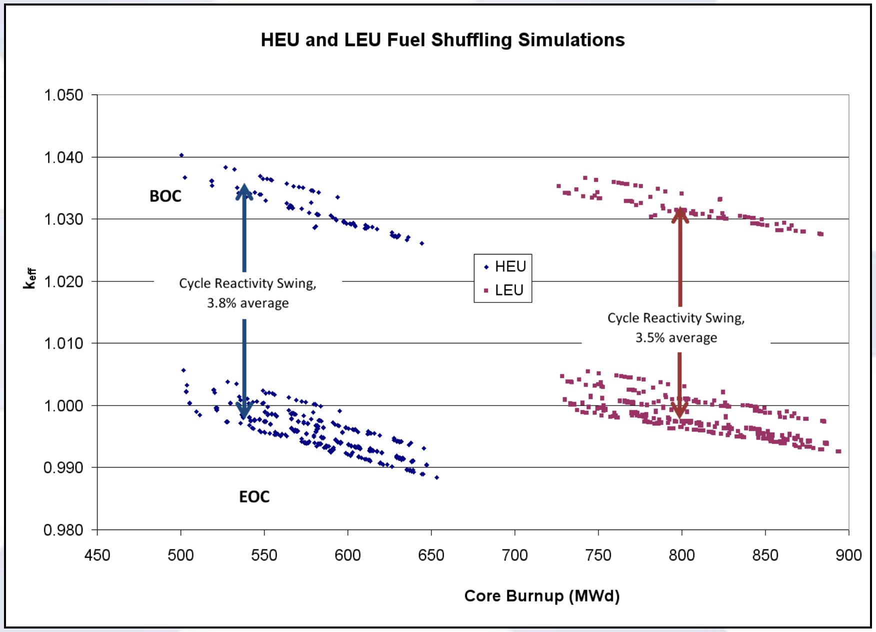



OPERATING EXPERIENCE
UNIVERSITY of MISSOURI RESEARCH REACTOR
ENERGY PER QUARTER (MWD/QUARTER)
TOTAL ENERGY (MWD --)
CALENDAR YEAR
10MW - 150 Hrs/wk
100% of Scheduled Operating Time
10MW - 100 Hrs/wk
5MW - 100 Hrs/wk
TOTAL ENERGY
0
100
200
300
400
500
600
700
800
900
1000
0
20000
40000
60000
80000
100000
120000
140000
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

Fuel Cycle Simulation

REBUS-DIF3D shuffling model developed to simulate complex cycle used in MURR for HEU and proposed LEU fuel

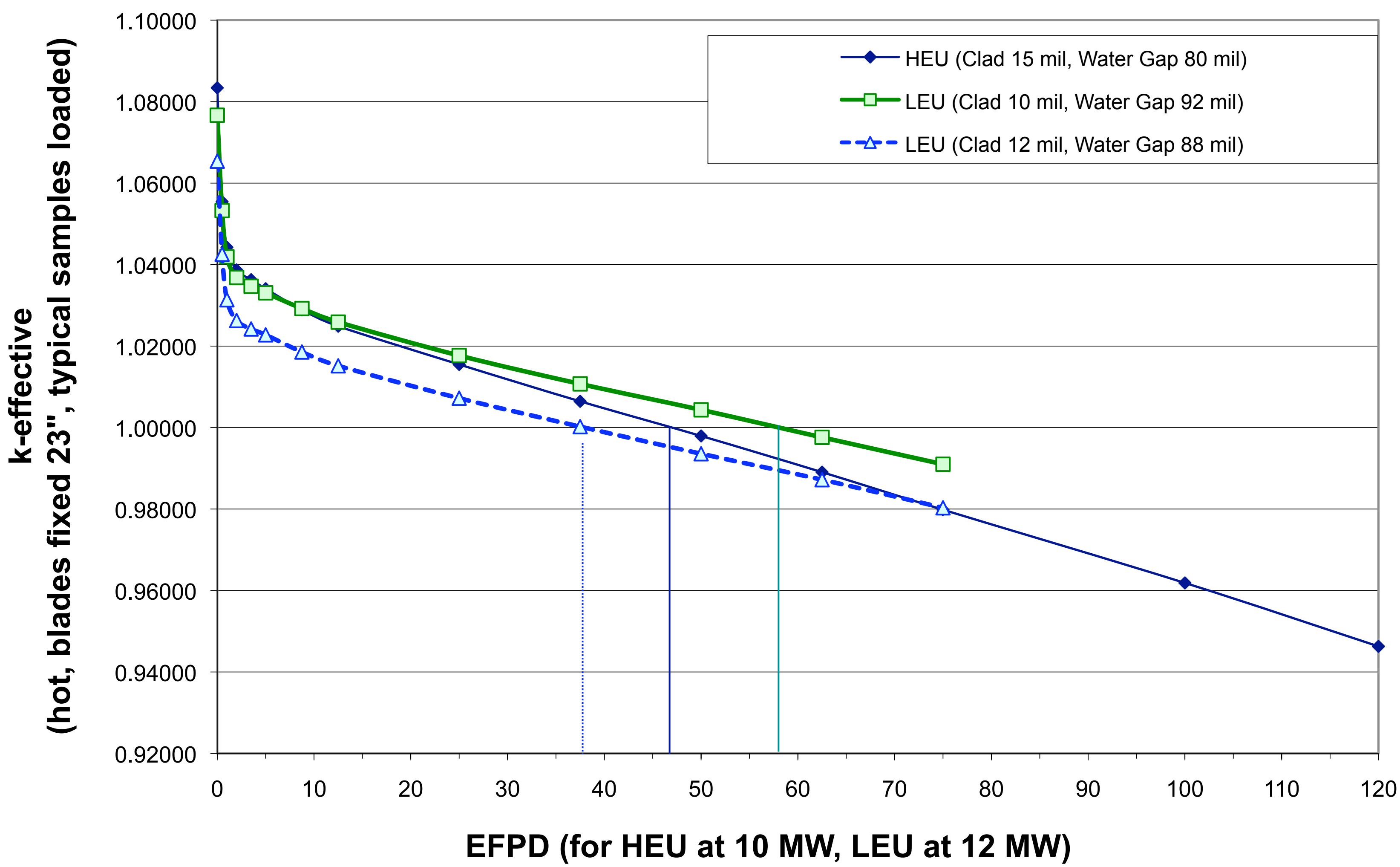
- Control blades fixed at 23 inches withdrawn; current typical reflector and flux trap loadings
- Pre-simulation cores produced 24 fuel elements with burnups ranging from 0-139 MWd (HEU) or 0-190 MWd (LEU)
- 82-week HEU core simulation; fresh elements loaded every 4-5 weeks; target burnup of 150 MWd
- 93-week LEU core simulation; fresh elements loaded every 5 weeks; target burnup of 208 MWd; reactor power increased from 10 to 12 MW
- k_{eff} for LEU core bounded by k_{eff} of HEU core
- MCNP5 used for critical rod search, 3-D power distributions, and flux levels in experimental locations



Current HEU & Proposed LEU Fuel Operating Cycles

Parameter	Current HEU Fuel	Proposed LEU Fuel
Maximum burnup:	150 MWd/element (1200 MWd/ core) due to insufficient excess reactivity – this achieves less than 1.8E+21 fissions/cc burnup; Technical Specification limit is 2.3E +21 fissions/cc	208 MWd/element (1664 MWd/ core) due to insufficient excess reactivity – this achieves less than 4E+21 fissions/cc burnup
Core MWds (control blades full out):	~670 MWd core with equilibrium xenon activity (56% of 1200 MWd)	~890 MWd core with equilibrium xenon activity (53% of 1664 MWd)
Refuelings:	Weekly – replace all eight fuel elements; fuel elements are used in 18 to 20 core loadings to achieve 145 to 150 MWd burnup at 10 MW (~24% burnup)	Weekly – replace all eight fuel elements; fuel elements are used in about 22 core loadings to achieve ~208 MWd burnup at 12 MW (~18% burnup)
Fuel Cycle:	22 elements used per year at 10 MW; 32 fuel elements in active fuel cycle	19 elements used per year at 12 MW; 32 fuel elements in active fuel cycle

REBUS-MCNP Rundowns for Fresh MURR Cores



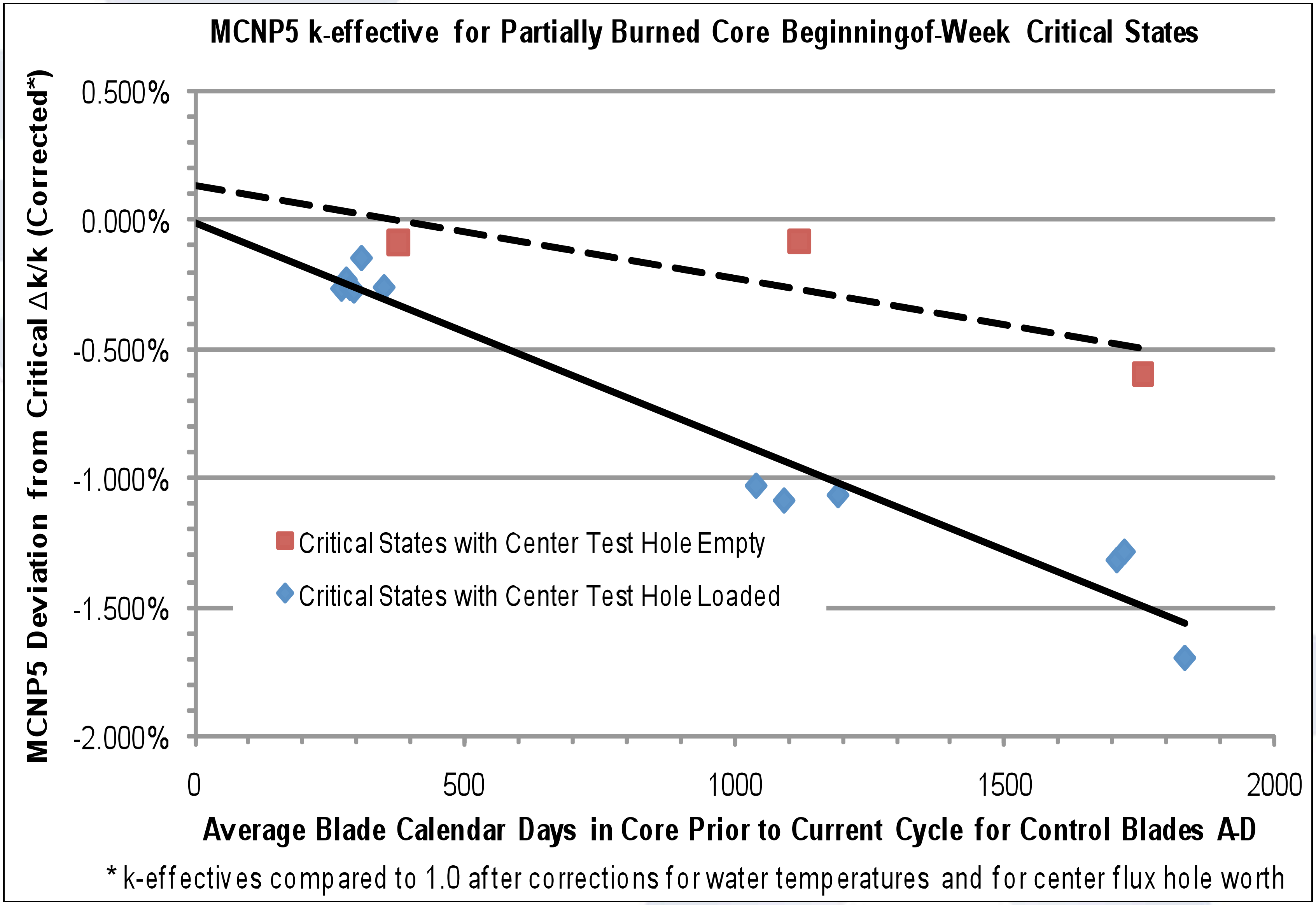
Summary of Critical States Evaluated for Partially Burned Cores

Date	Fuel Element Burnup (MWd)					Flux Trap Reactivity[1] (%Dk/k)	Ave Prior Days for Control Blades	Critical Bank Height[2] (inches withdrawn)	MCNP5 Deviation from Critical[3] (%Dk/k)
	X1/X5	X1/X6	X3/X7	X4/X8	Sum				
04/23/05	32	92	73	95	584	0.478	271	17.97	-0.263
05/02/05	38	140	44	73	590	0.474	280	18.02	-0.228
05/09/05	0	117	63	115	590	0.427	287	17.63	-0.260
05/16/05	17	137	52	82	576	0.432	294	17.93	-0.270
05/30/05	9	139	21	124	586	0.474	308	18.06	-0.144
07/11/05	29	136	40	84	578	0.464	350	17.98	-0.257
06/16/00	54	72	41	143	620	0.346	1040	17.22	-1.028
08/07/00	16	98	68	117	598	0.384	1092	17.02	-1.086
11/15/00	0	139	56	108	606	0.359	1192	16.72	-1.065
12/17/01	22	124	69	91	612	0.348	1709	16.64	-1.317
12/31/01	14	131	72	87	608	0.340	1723	16.66	-1.285
04/22/02	0	118	64	114	592	0.418	1835	16.00	-1.697
08/08/05	0	143	38	115	592	0	378	18.52	-0.087
09/04/00	24	90	50	141	610	0	1120	17.81	-0.080
02/04/02	11	136	61	96	608	0	1758	17.03	-0.594

[1] The flux trap reactivity indicates the worth of the flux trap contents relative to an empty flux trap.

[2] Critical bank heights reported here are corrected for small differences between the nominal water temperatures modelled and those measured at the critical state.

[3] MCNP deviation from critical is (k-1)/k, corrected for the difference between flux trap worth of the critical state and flux trap worth modelled with the nominal sample loading (for cases with nonzero flux trap worth).



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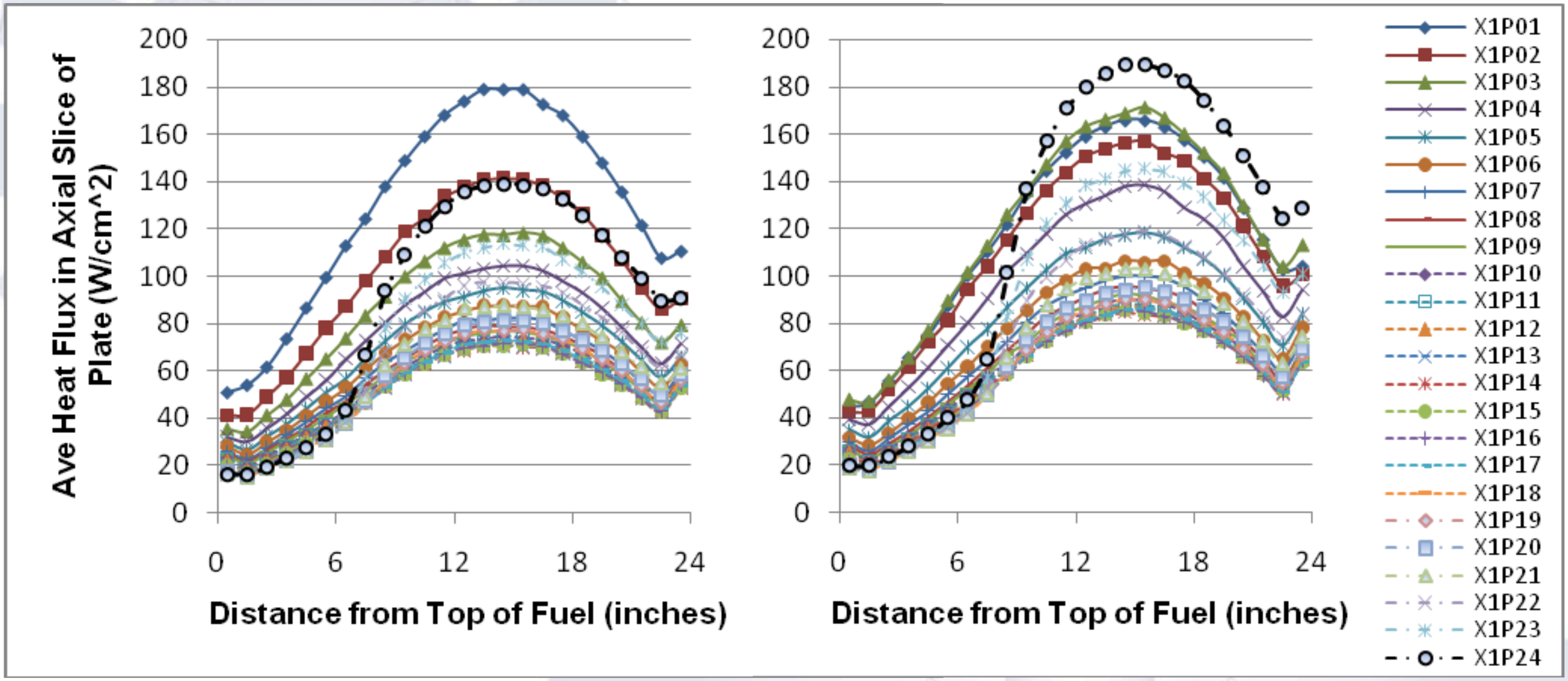
Summary of Key Hot Stripe Heat Fluxes Evaluated

Core State that may bound power peaking					Hot Stripe Heat Flux (W/cm^2) Fresh Element in Position X1				Hot Stripe Heat Flux (W/cm^2) Fresh Element in Position X5			
Fuel[1]	Case	Burnup State	Day	Flux Trap[2]	Plate 1	Plate 3	Plate 23	Plate 24	Plate 1	Plate 3	Plate 23	Plate 24
HEU 10 MW	1A	Fresh	0	Samples	126.7	91.4	67.3	76.8	128.8	94.0	69.4	80.4
	2A	Fresh	2	Samples	121.6	89.3	74.4	87.3	123.4	89.4	74.8	86.6
	3A	Week 58	0	Samples	131.7	96.6	82.6	96.6	132.3	97.6	79.3	91.8
	4A	Week 58	2	Samples	126.3	92.6	90.4	107.4	125.6	92.6	82.8	97.8
	1B	Fresh	0	Empty	133.2	94.5	66.7	77.2	133.8	96.2	70.0	80.2
	2B	Fresh	2	Empty	127.0	91.3	74.5	87.9	129.3	92.1	74.3	87.1
	3B	**Week 58**	**0**	**Empty**	**138.6**	**99.3**	**83.0**	**97.6**	**138.9**	**99.7**	**78.9**	**92.2**
	4B	**Week 58**	**2**	**Empty**	**132.9**	**94.8**	**90.8**	**109.6**	**132.1**	**93.2**	**82.8**	**97.9**
LEU 12 MW	5A	Fresh	0	Samples	116.3	134.4	84.9	100.0	119.4	136.6	90.1	107.0
	6A	Fresh	2	Samples	112.2	129.5	94.6	116.0	113.4	130.4	95.8	117.2
	7A	Week 79	0	Samples	119.0	137.6	103.3	126.6	118.4	137.7	101.3	122.3
	8A	Week 79	2	Samples	114.1	130.4	113.8	142.6	113.3	130.1	105.5	131.1
	5B	Fresh	0	Empty	124.0	139.0	85.0	100.8	125.3	140.9	90.8	108.0
	6B	Fresh	2	Empty	119.1	132.4	95.8	118.0	119.6	133.1	96.4	118.2
	7B	**Week 79**	**0**	**Empty**	**124.9**	**141.0**	**104.7**	**127.6**	**125.1**	**140.8**	**102.0**	**123.2**
	8B	**Week 79**	**2**	**Empty**	**120.3**	**133.9**	**114.3**	**145.4**	**119.4**	**132.8**	**105.7**	**131.3**

[1] Note that HEU operates at 10 MW, while 12 MW is proposed for LEU operation. Thus a 20% increase in LEU heat flux would be expected if the element was not altered (in design and underlying physics).

[2] Samples indicates a typical loading of samples in all three flux trap tubes. Empty indicates neither samples nor tubes in the flux trap (i.e., "empty island" configuration).

Comparison of Average Heat Flux in the HEU and LEU Cores



HEU Core 3B Element X1 LEU Core 7B Element X1

- MCNP5 power tallies at critical rod height used to determine peak heat flux and axially-averaged “hot stripe”
- 8 elements, 24 plates, 24 axial zones and 9 azimuthal stripes
- 5,184 tally segments/element

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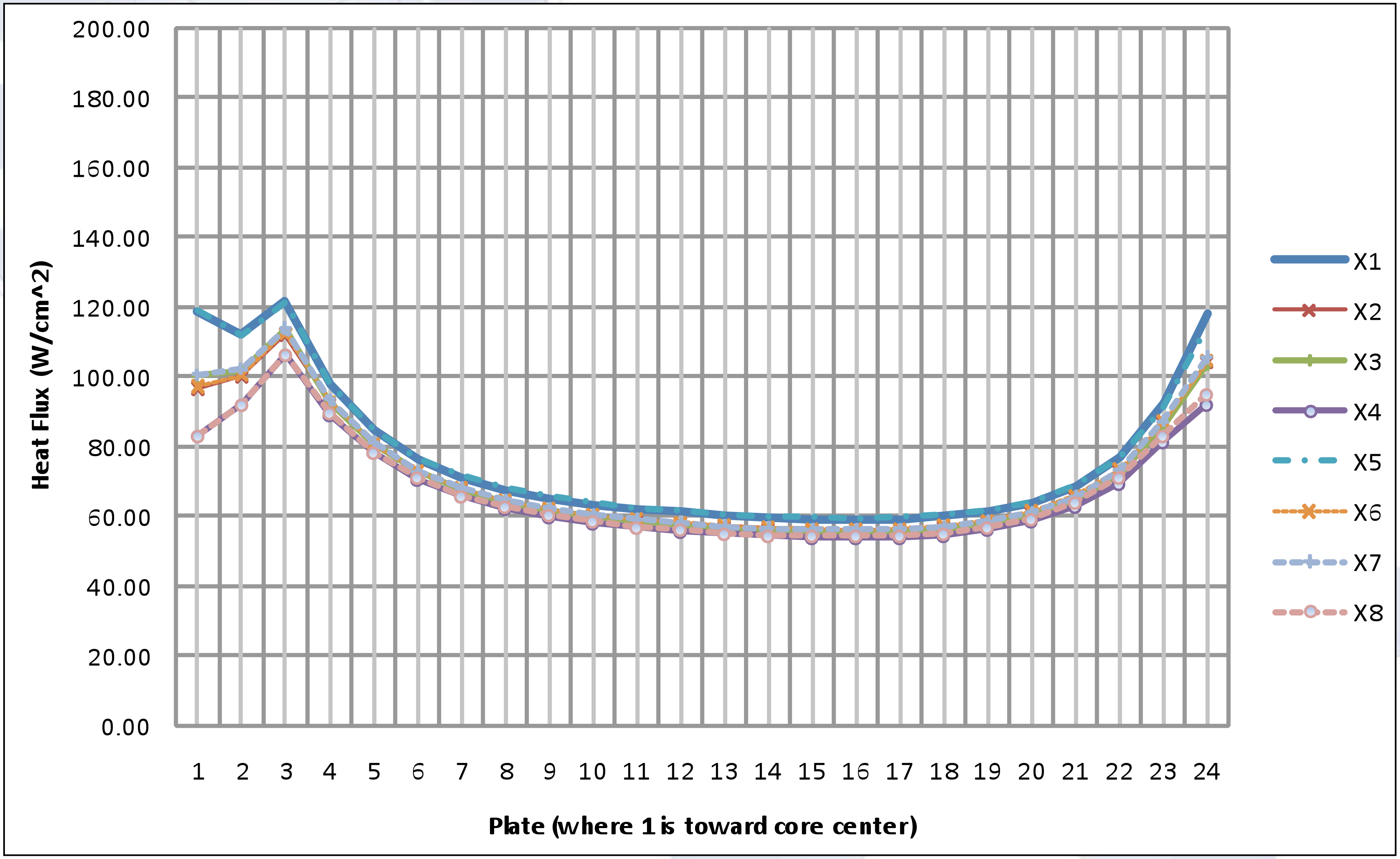
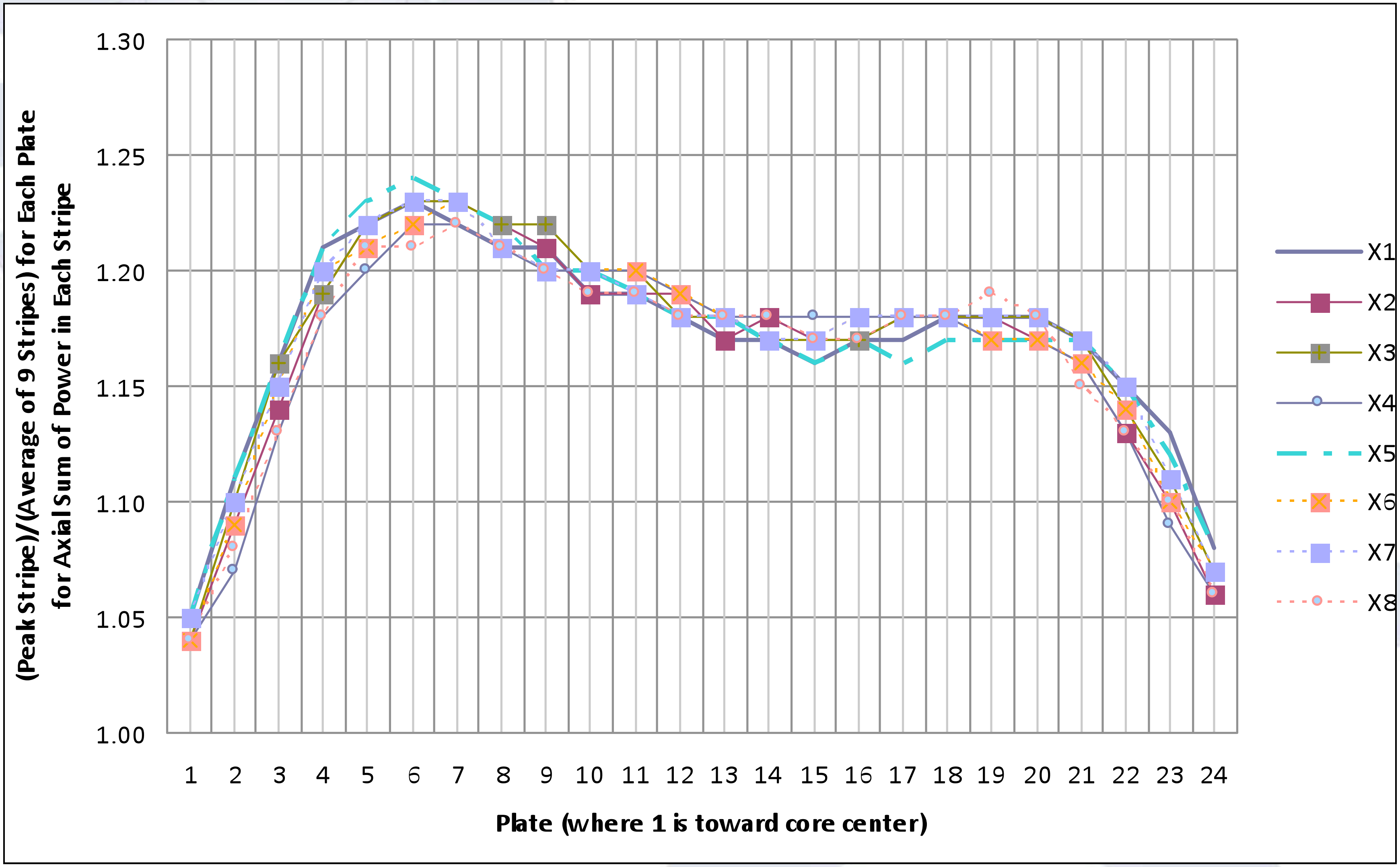
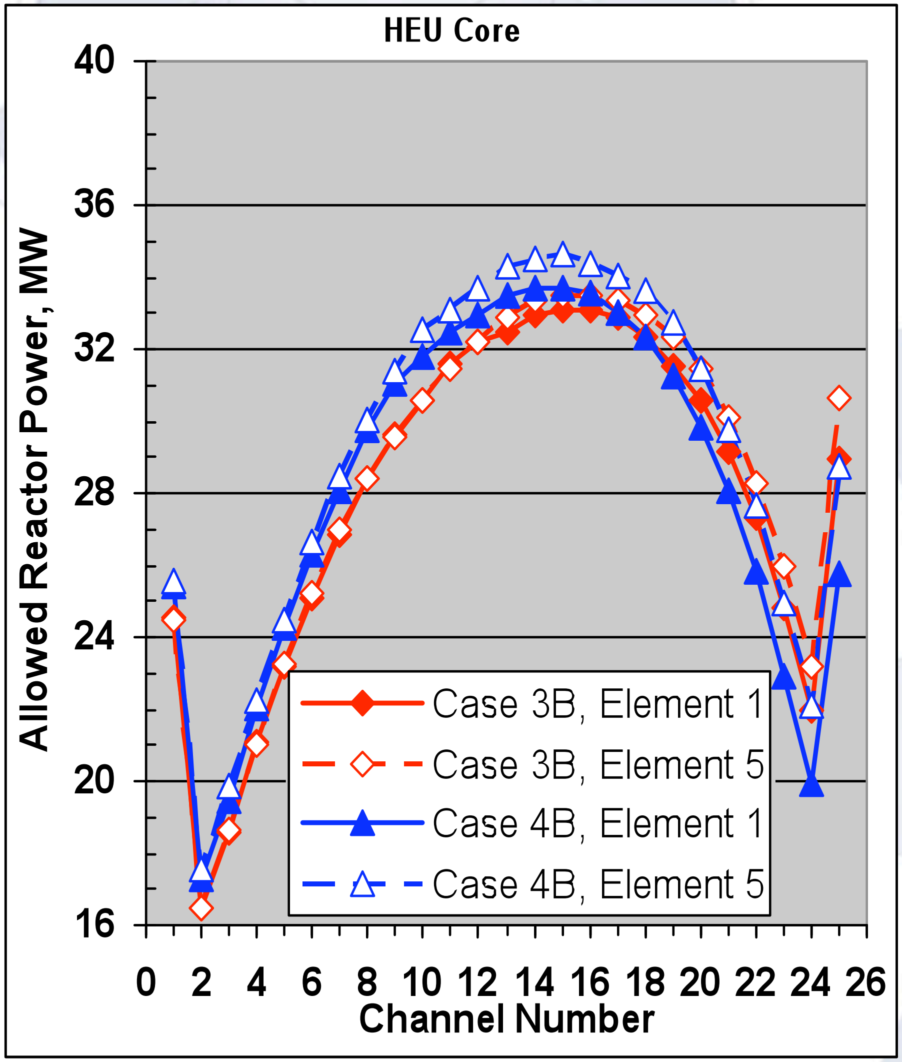
Axial Average Heat Flux in Fuel Element
Case 7B: LEU Week 79 Day 0 (Empty Flux Trap)

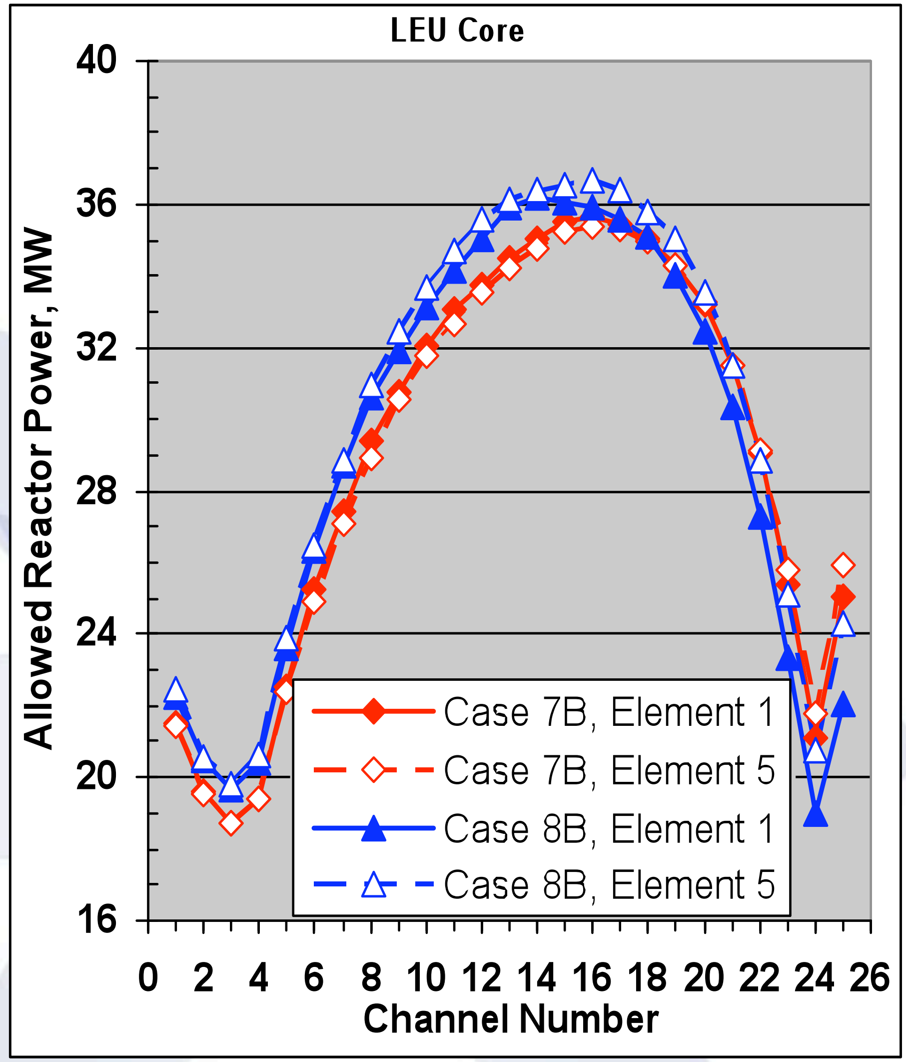


Azimuthal Peaking Factor in Fuel Element
Case 7B: LEU Week 79 Day 0 (Empty Flux Trap)



Reactor Power Predicated to Initiate Channel Flow Instability in Each Core





Flow Instability Power

Case	Element	Power, MW	Channel
HEU			
3B	1	**16.48**	2
	5	16.51	2
4B	1	17.30	2
	5	17.58	2
LEU			
7B	1	**18.73**	3
	5	18.74	3
8B	1	18.98	24
	5	19.79	3

Comparison of Day 2 LEU Fluxes & Reaction Rates to HEU (10 MW)

Metric	Neutron Energy Range					
	≤ 1 eV		> 1 eV		Sum	
LEU Core 10 MW, Week 79, Day 2 Critical Bank 23.481 inches withdrawn, Regulating Blade 15 inches withdrawn						
S-32 (n,p) reactions in FT Tube B 13-15"	n/a	n/a	95%	± 0.3%	95%	± 0.3%
Flux in FT Tube B 13-15"	87%	± 0.1%	93%	± 0.1%		
Ir-191 (n,γ) reactions in FT Tube C 17-20"	87%	± 0.3%	93%	± 1.5%	87%	± 0.3%
Ir-193 (n,γ) reactions in FT Tube C 17-20"	87%	± 0.3%	88%	± 1.9%	87%	± 0.5%
Flux in Ir wires of FT Tube C 17-20"	87%	± 0.3%	92%	± 0.4%		
Flux in Wedge #3 Row 1 P-Tube Bottom 3"	86%	± 0.1%	91%	± 0.2%		
Si-30 (n,γ) reactions in Green-5 Position	88%	± 0.0%	90%	± 1.4%	88%	± 0.1%
Flux in Green-5 Position	88%	± 0.0%	91%	± 0.1%		

Losses exceed 10% in all thermal metrics

Comparison of Day 2 LEU Fluxes & Reaction Rates to HEU (12 MW)

Metric	Neutron Energy Range					
	≤ 1 eV		> 1 eV		Sum	
LEU Core 12 MW, Week 79, Day 2 Critical Bank 23.481 inches withdrawn, Regulating Blade 15 inches withdrawn						
S-32 (n,p) reactions in FT Tube B 13-15"	n/a	n/a	113%	± 0.3%	113%	± 0.3%
Flux in FT Tube B 13-15"	104%	± 0.1%	112%	± 0.1%		
Ir-191 (n,γ) reactions in FT Tube C 17-20"	104%	± 0.4%	112%	± 1.8%	105%	± 0.4%
Ir-193 (n,γ) reactions in FT Tube C 17-20"	104%	± 0.4%	106%	± 2.3%	105%	± 0.7%
Flux in Ir wires of FT Tube C 17-20"	105%	± 0.4%	110%	± 0.5%		
Flux in Wedge #3 Row 1 P-Tube Bottom 3"	104%	± 0.1%	110%	± 0.2%		
Si-30 (n,γ) reactions in Green 5 Position	105%	± 0.0%	108%	± 1.7%	105%	± 0.2%
Flux in Green-5 Position	105%	± 0.0%	109%	± 0.1%		

Gains in all metrics

Tasks To Be Completed On LEU Fuel Conversion

- Feasibility Analysis Report was completed on September 30, 2009. The Report stated that it is possible to convert MURR to LEU fuel with the following four qualifiers:
    - Complete qualification of U-10Mo Monolithic Fuel
    - Demonstrate 38-mil fuel plates are stiff enough
    - Demonstrate fuel plates can be manufactured with 10-mil cladding
    - With approval of analysis, order MURR to convert at 12 MW
- Revise RELAP Model to handle four quadrants of 24 fuel plates with 25 coolant channels for LEU core
- Perform safety analyses
- Perform analysis to identify best way to transition from HEU to LEU using burnable poisons to meet all users flux requirements
- Thank you for your attendance, any Questions???