Modeling a Pin-Type Fuel Assembly for a Small Fluoride Salt Cooled High Temperature Reactor (FHR).

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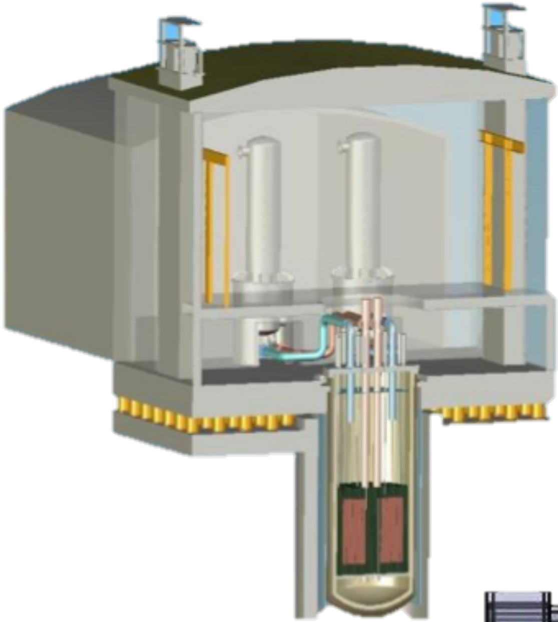
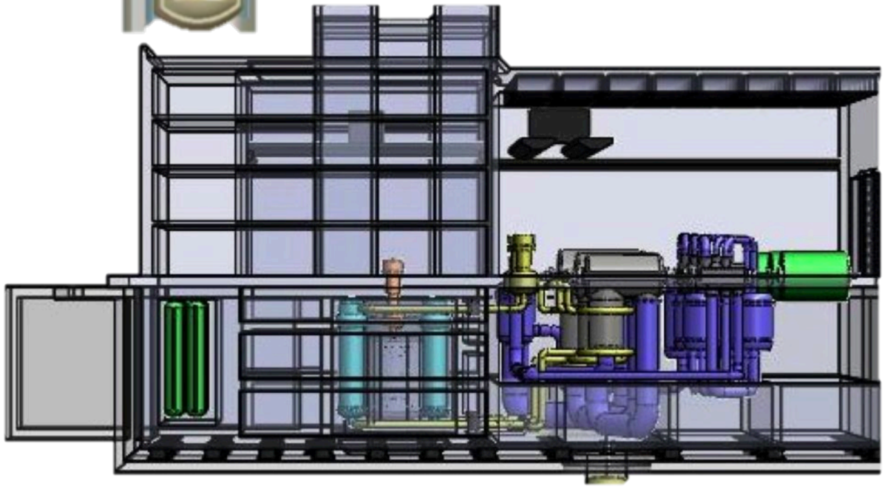
What is FHR?

- New concept – A decade old. (AHTR, LS-VHTR)
- Fluoride Salt Cooled (FLiBe)
- Operates at high temperature (>700°C)
- Low system pressure (<1 Mpa)
- High volumetric heat capacity (4670 kJ/m^3 °C)
- About 30% arguably less expensive than LWR – reduced equipment size



Oak Ridge
1500 MWe
3400 MWt

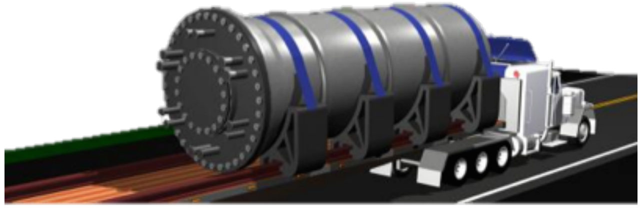


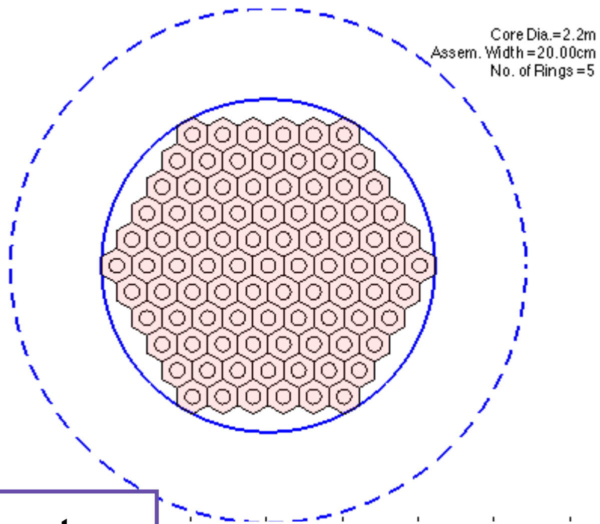
Berkeley
410 MWe
900 MWt

Cited from Charles Forsberg, Presentation of FHR, 2012

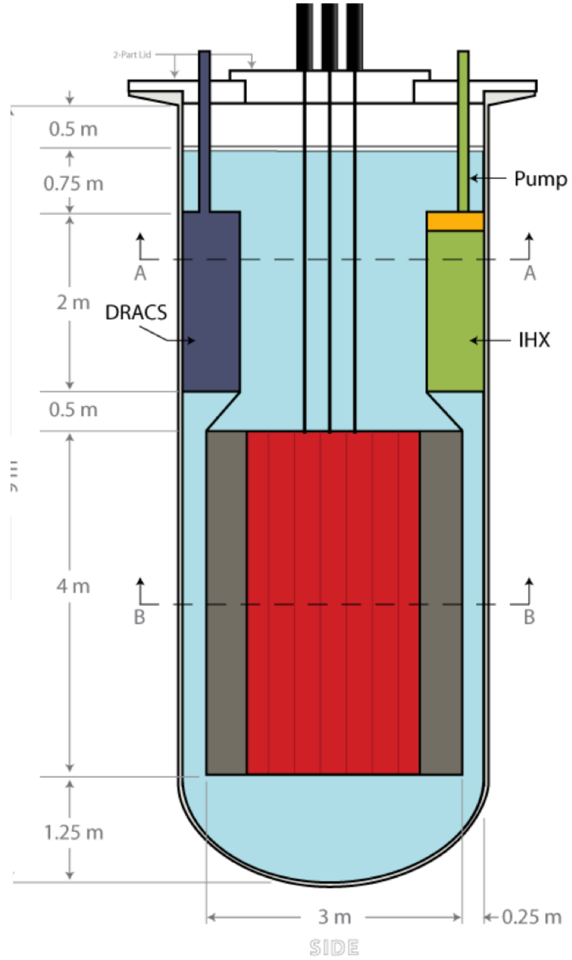
Small FHR?

- Concept based on Smahtr (Oak Ridge) and LS-VHTR
- **UO_2 fuel** with **SiC** cladding
- Moderated by **graphite** block
- Easy to be transported by a standard 53 ft truck.
- 1 core fuel batch. No flexibility for optimisation by fuel management.





3 m diameter
91 Assem.

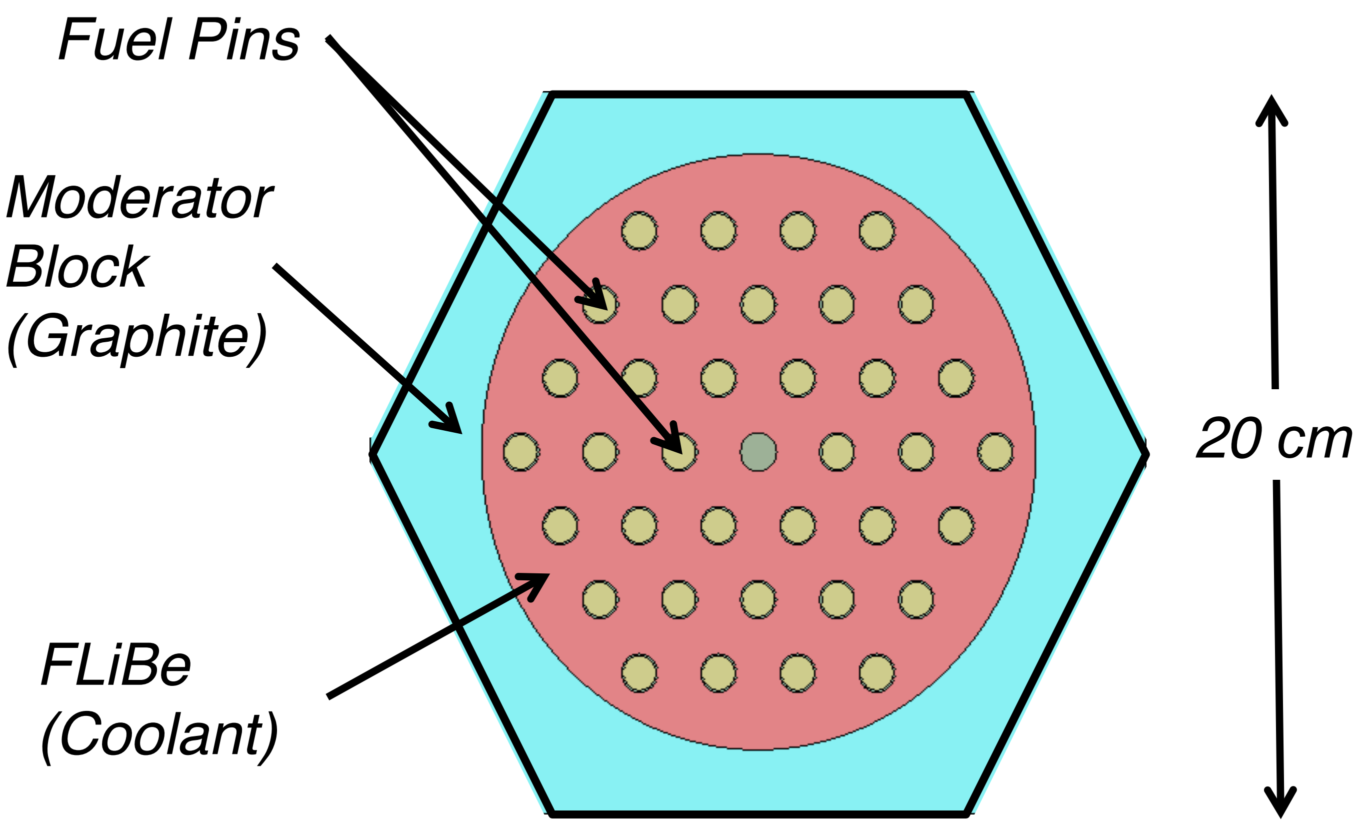


Oak Ridge
125 MWt

Cited from Sherrell Greene, Smahtr, 2008

Research Objective

Requirements: 1) Sustainable at least 13 months (396 days)
2) Avoid Positive Temperature Coefficient of Reactivity (TCR)



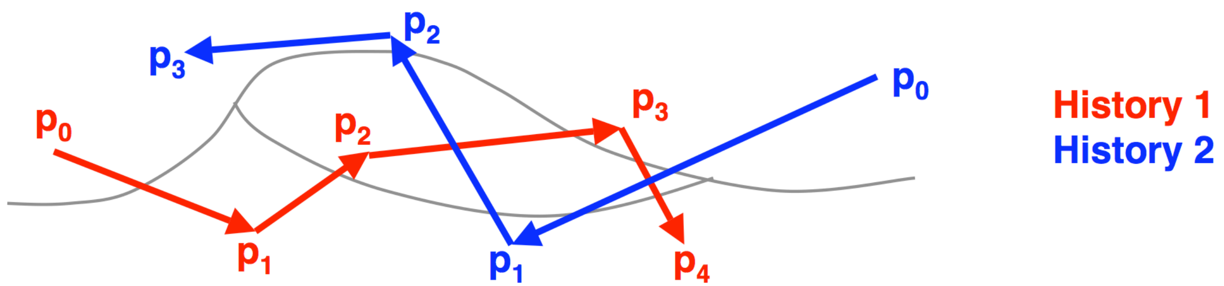
How?: 1) Vary the thickness of the graphite
2) Change the enrichment %

What? 1) Optimum configuration
2) Minimum %wt required.

Method : SERPENT CODE

What is Serpent?

- Non-deterministic Neutronic Code
- Based on Monte Carlo
  - Others: MCNP and MONK
- Random Sampling. Generating **histories** of neutrons
- **Tallies**- keeping track of the events of interest (absorption, scattering and etc.)

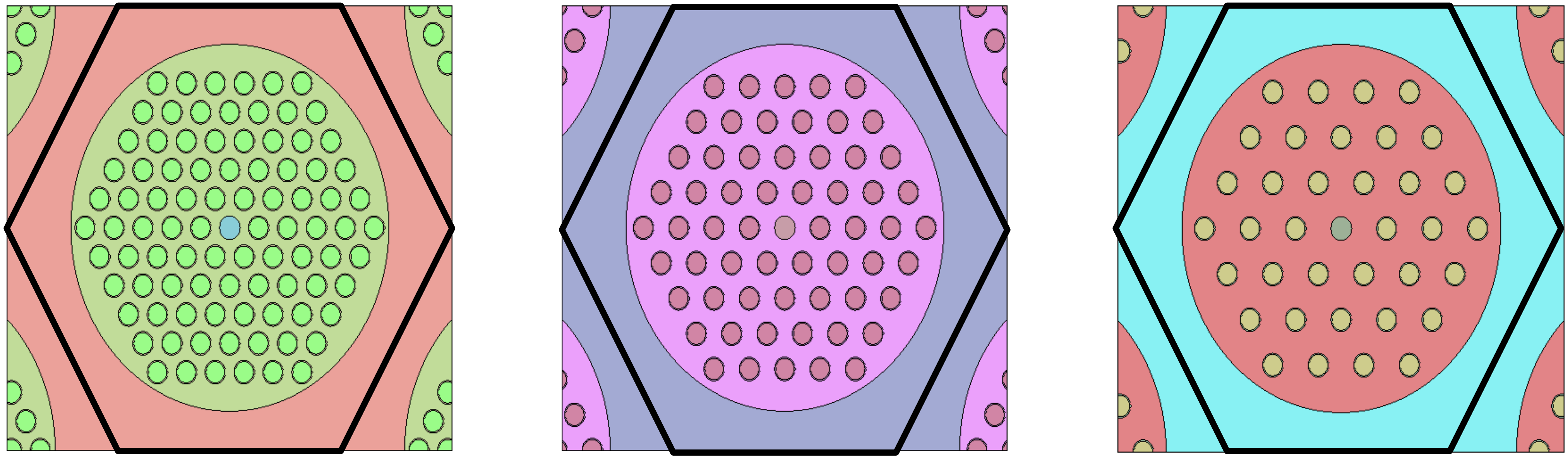


- Find k-inf, Temperature coefficient of reactivity, and fuel depletion

WIMS –

- Deterministic approach to solve Boltzmann transport Equation
- Used during verification process.

Reactor Core Model and Operating Temperature

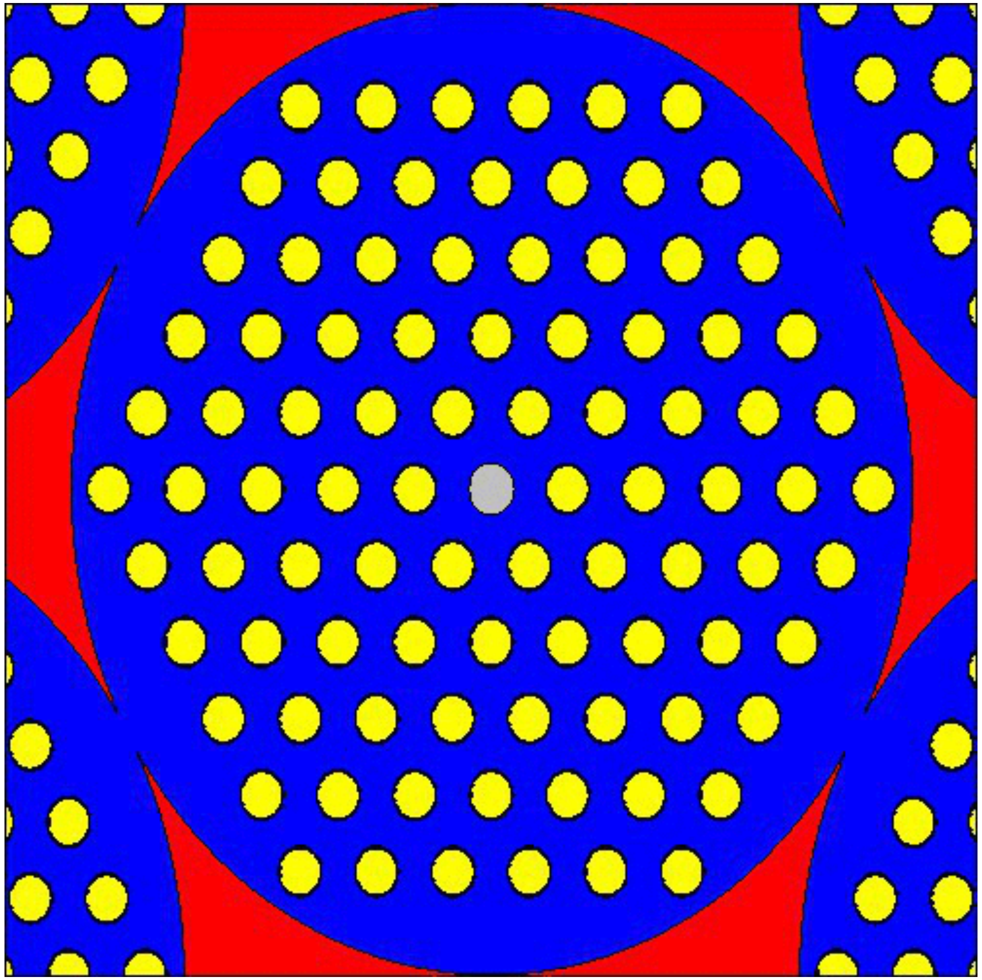


Parameter	Values
Fuel Temp	1200 °C
Clad temperature	900 °C
FLiBe temperature	750 °C
Graphite Moderator temp	750 °C
Enrichment	5% to 20%

- 5, 4, 3 rings
- To find TCR, new *k-inf* . All temperatures are perturbed by 30°C. Density of Flibe is change accordingly.
- TCR:

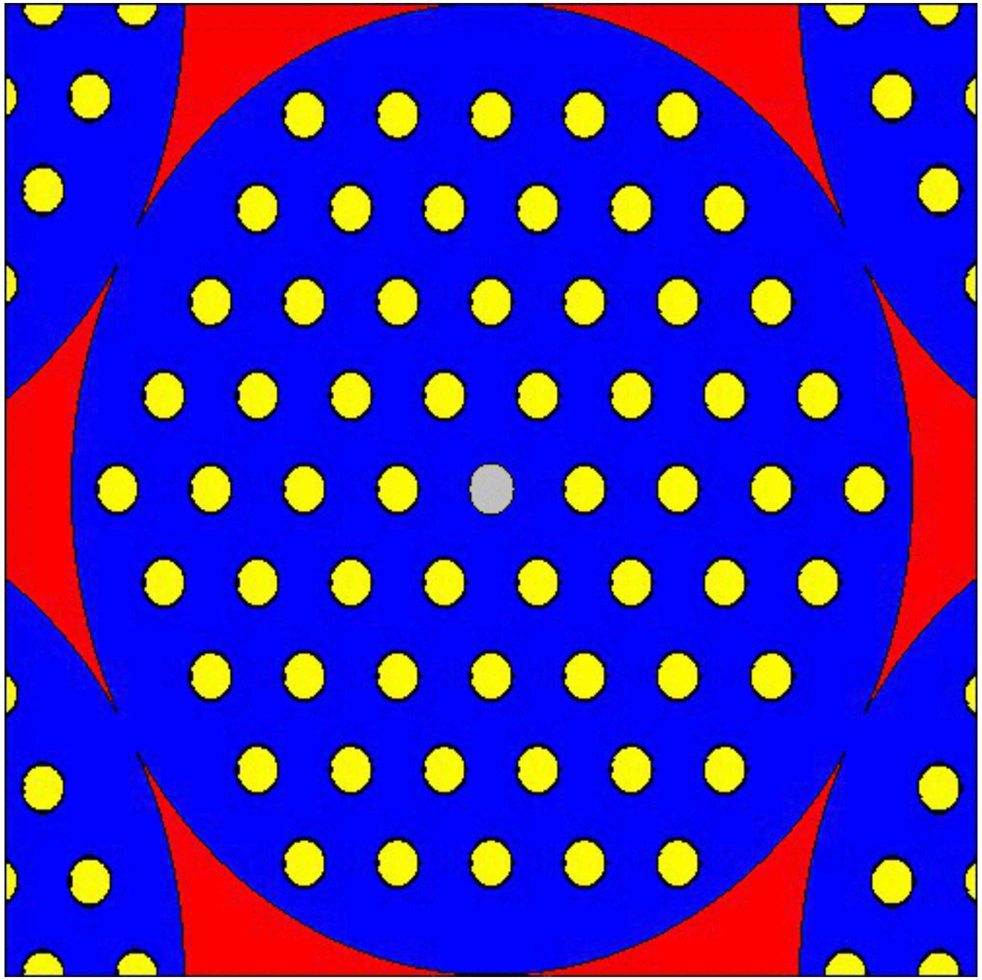
$$\alpha_c = \frac{k_{new} - k_{norm}}{k_{norm}\, k_{new}\, \Delta T_c}$$

Model 1 : 5 rings (Triangle lattice)



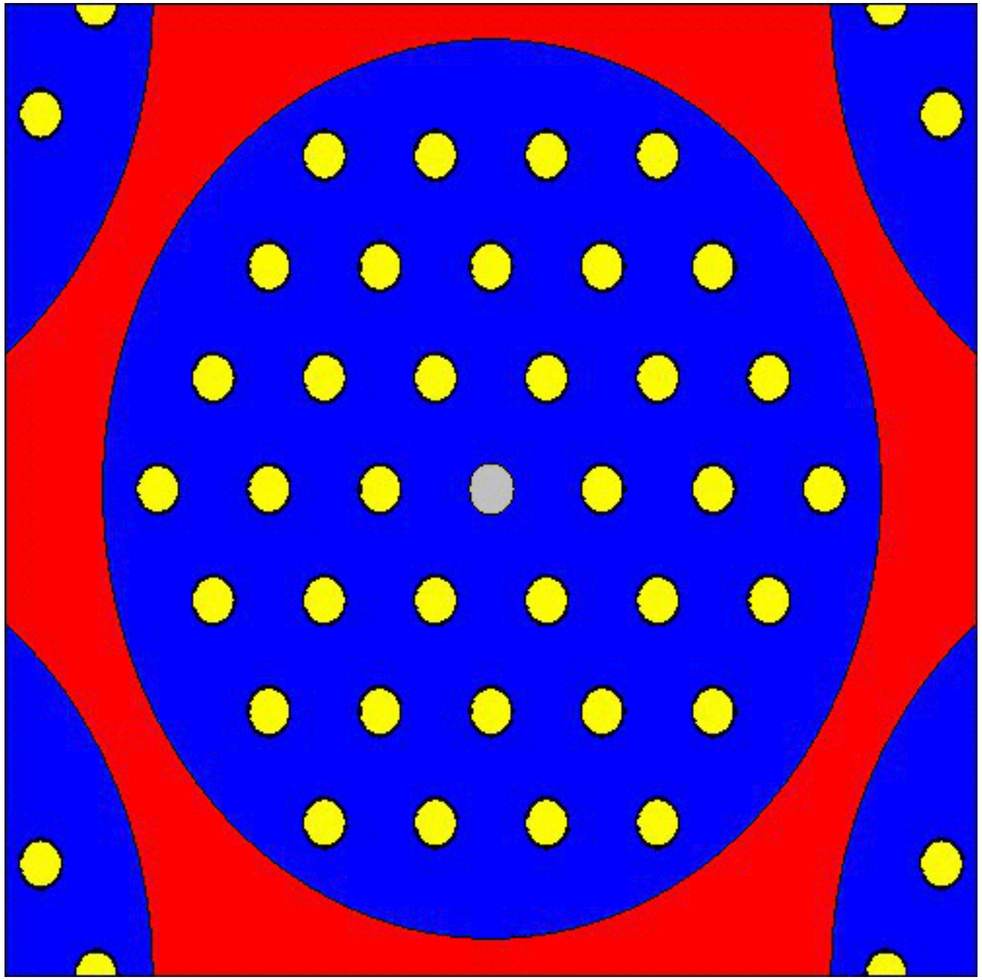
- ***90*** UO_2 fuel pins
- Fuel Loading = ***2426*** kg
- Moderator thickness is increased by ***0.5*** cm for every change.
- ***13*** different variations

Model 2 : 4 rings (Triangle lattice)



- ***60*** UO_2 fuel pins
- Fuel Loading = ***1617*** kg
- Moderator thickness is increased by ***0.5*** cm for every change.
- ***18*** different variations

Model 3 : 3 rings (Triangle Lattice)

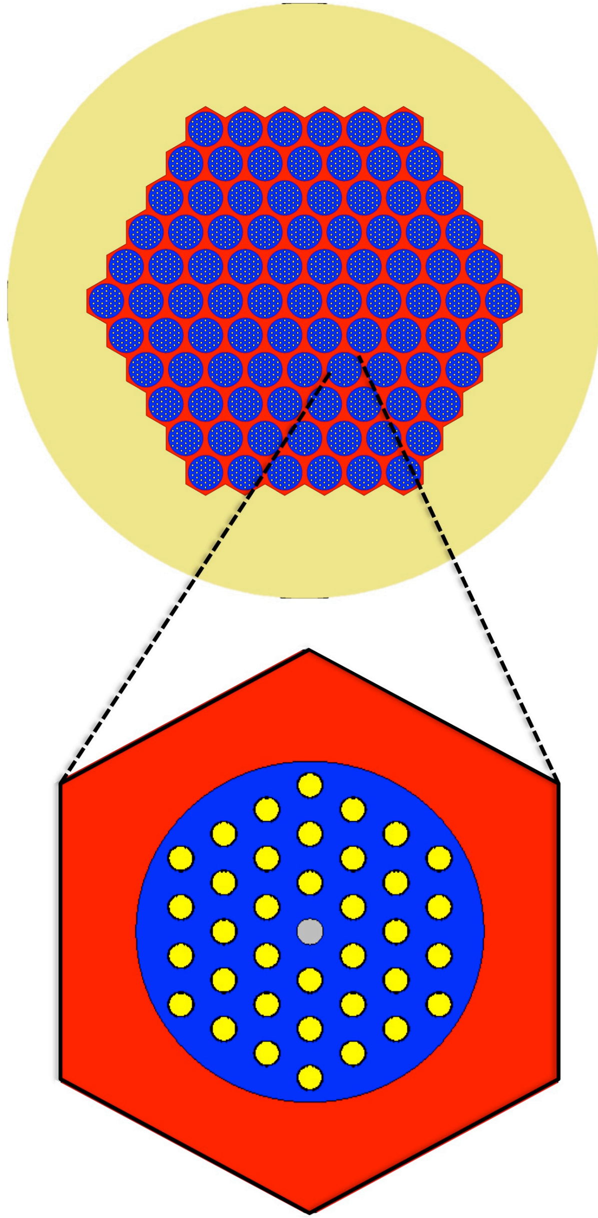


- ***36*** UO_2 fuel pins
- Fuel Loading = ***970*** kg
- Moderator thickness is increased by ***0.5*** cm for every change.
- ***23*** different variations

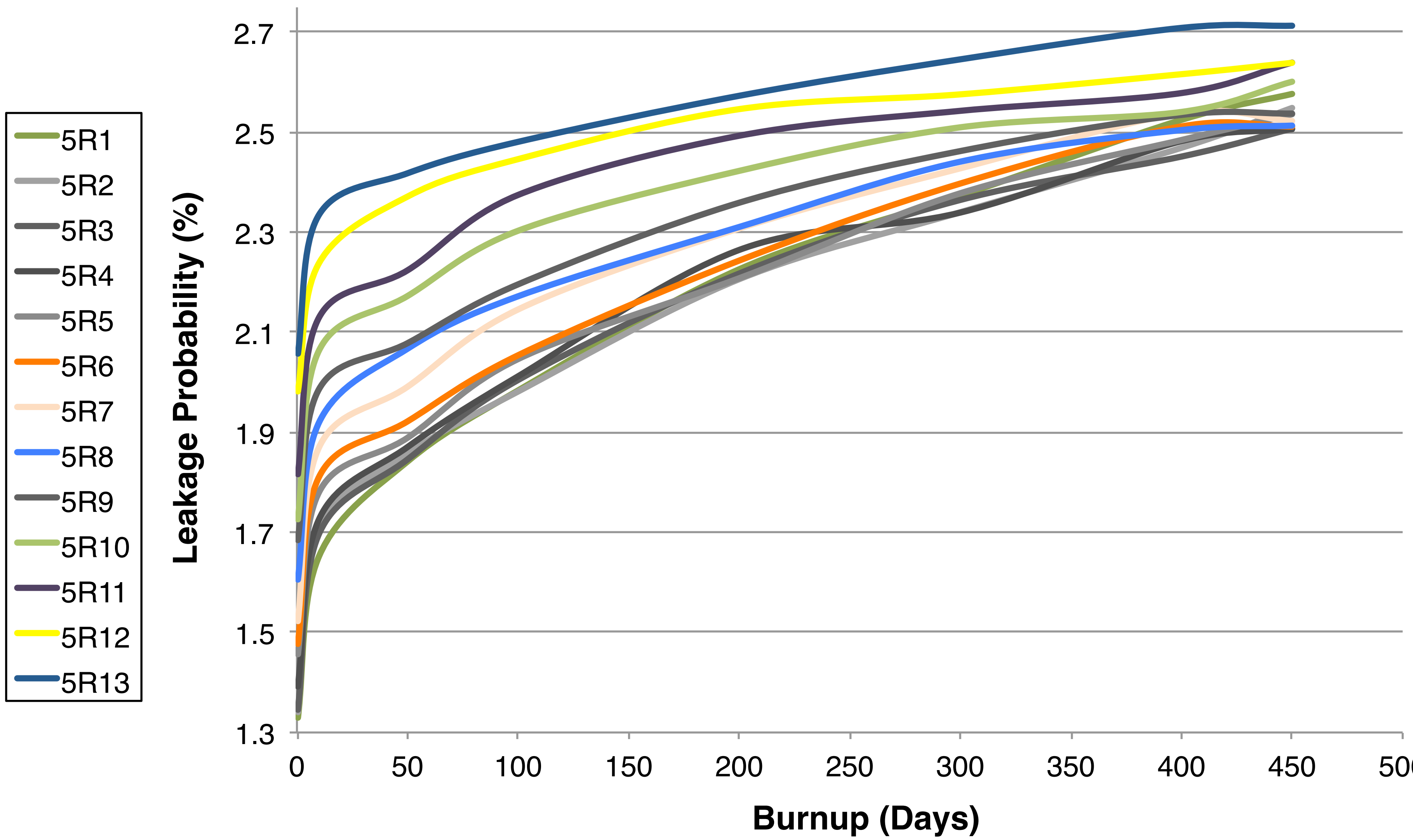
		3 Rings (36 Fuel Pins)		4 Rings (60 Fuel Pins)		5 Rings (90 Fuel Pins)	
Variations	Channel Diameter (cm)	Gap (cm)	Graphite/FLiBe/Fuel (Volume %)	Gap (cm)	Graphite/FLiBe/Fuel (Volume %)	Gap (cm)	Graphite/FLiBe/Fuel (Volume %)
1	20	1.79	9.31 / 83.26 / 7.43	1.15	9.31 / 78.31 / 12.38	0.75	9.31 / 72.12 / 18.57
2	19.5	1.72	13.79 / 78.78 / 7.43	1.10	13.79 / 73.83 / 12.38	0.70	13.79 / 67.64 / 18.57
3	19	1.65	18.15 / 74.42 / 7.43	1.04	18.15 / 69.47 / 12.38	0.66	18.15 / 63.28 / 18.57
4	18.5	1.57	22.40 / 70.17 / 7.43	0.99	22.40 / 65.22 / 12.38	0.61	22.40 / 59.03 / 18.57
5	18	1.50	26.54 / 66.03 / 7.43	0.93	26.54 / 61.08 / 12.38	0.57	26.54 / 54.89 / 18.57
6	17.5	1.43	30.57 / 62.01 / 7.43	0.88	30.57 / 57.05 / 12.38	0.52	30.57 / 50.86 / 18.57
7	17	1.36	34.48 / 58.10 / 7.43	0.82	34.48 / 53.14 / 12.38	0.48	34.48 / 46.95 / 18.57
8	16.5	1.29	38.27 / 54.30 / 7.43	0.77	38.27 / 49.35 / 12.38	0.43	38.27 / 43.15 / 18.57
9	16	1.22	41.96 / 50.61 / 7.43	0.71	41.96 / 45.66 / 12.38	0.39	41.96 / 39.47 / 18.57
10	15.5	1.15	45.53 / 47.04 / 7.43	0.65	45.53 / 42.09 / 12.38	0.34	45.53 / 35.90 / 18.57
11	15	1.07	48.99 / 43.58 / 7.43	0.60	48.99 / 38.63 / 12.38	0.30	48.99 / 32.44 / 18.57
12	14.5	1.00	52.33 / 40.24 / 7.43	0.54	52.33 / 35.29 / 12.38	0.25	52.33 / 29.10 / 18.57
13	14	0.93	55.56 / 37.01 / 7.43	0.49	55.56 / 32.06 / 12.38	0.20	55.56 / 25.87 / 18.57
14	13.5	0.86	58.68 / 33.89 / 7.43	0.43	58.68 / 28.94 / 12.38		
15	13	0.79	61.68 / 30.89 / 7.43	0.38	61.68 / 25.94 / 12.38		
16	12.5	0.72	64.57 / 28.00 / 7.43	0.32	64.57 / 23.05 / 12.38		
17	12	0.65	67.35 / 25.22 / 7.43	0.27	67.35 / 20.27 / 12.38		
18	11.5	0.57	70.02 / 22.56 / 7.43	0.21	70.02 / 17.60 / 12.38		
19	11	0.50	72.57 / 20.01 / 7.43				
20	10.5	0.43	75.00 / 17.57 / 7.43				
21	10	0.36	77.33 / 15.24 / 7.43				
22	9.5	0.29	79.54 / 13.03 / 7.43				
23	9	0.22	81.64 / 10.94 / 7.43				

Leakage Probability

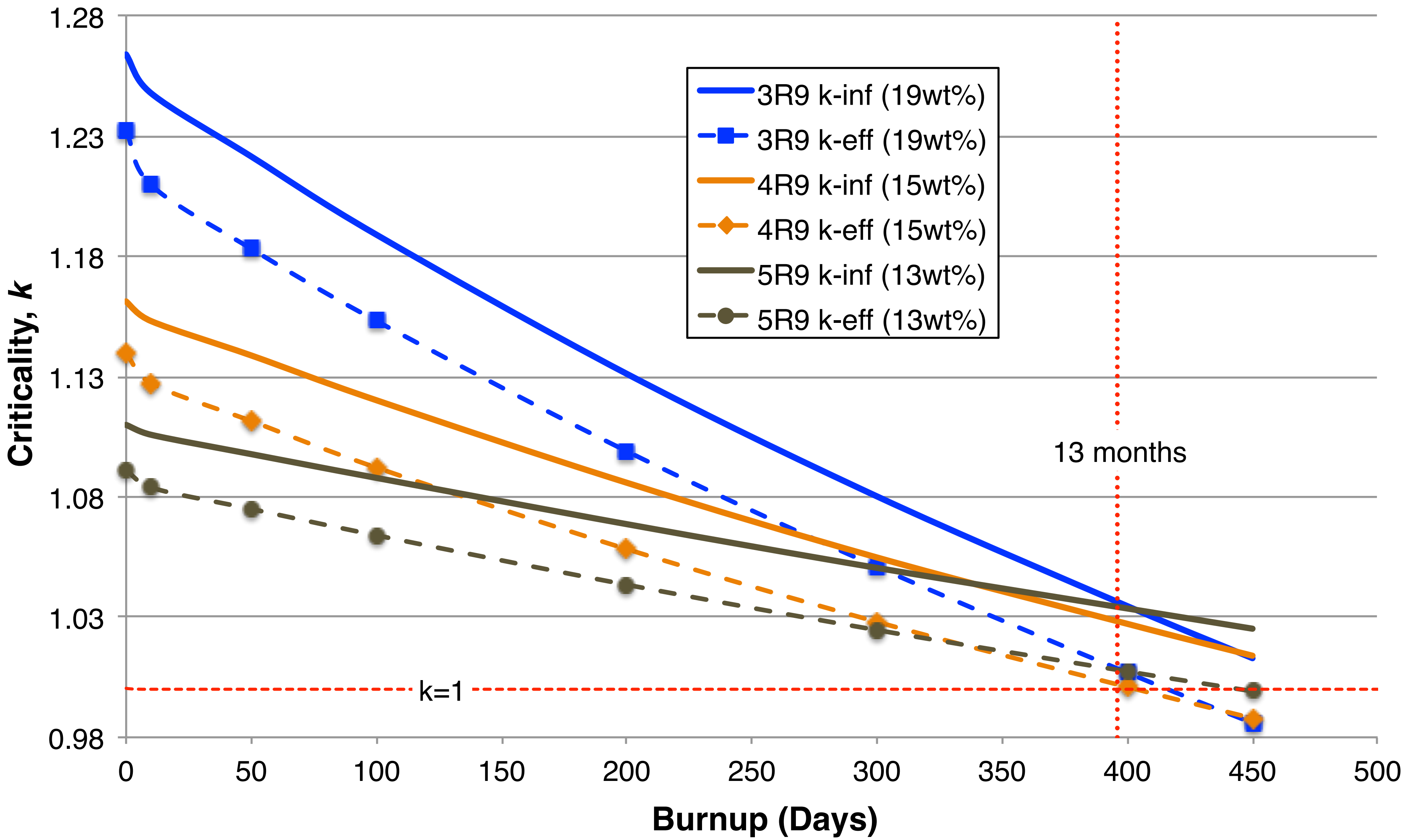
- Leakage Probability is required to estimate fuel cycle lifetime.
- Typical PWR analysis : 3%, LS-VHTR analysis: 5%
- Our studied configurations have
  - different compositions and structure (pin spacing and number of rings/pins).
  - also smaller size than PWR or LS-VHTR.
  - a reflector of 30 cm thickness surrounding the core.
- Hence, proper leakage analysis is required – performing full core calculation for all variations at 20wt.% (highest possible enrichment). Finding K-effective for the core, the compare with k-infinity of lattice analysis to find the leakage probability.



Leakage Probability (For 5-ring assemblies at 20wt.%)



Finding Fuel lifetime (after application of leakage probability)



Results : 3-ring configurations

Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	BOL Fuel TC (PCM/K)
3R4	20%	7	-0.68	-2.55
3R5	20%	15	-0.30	-1.67
3R6	20%	35	-0.06	-1.05
3R7	20%	37	-0.61	-2.47
3R8	19%	6	-0.04	-1.23
3R9	19%	20	-0.79	-2.07
3R10	19%	34	-1.70	-2.20
3R11	18%	6	-1.03	-1.89
3R12	18%	22	-0.02	-0.85
3R13	17%	6	-0.50	-1.74
3R14	17%	14	-0.43	-0.43
3R15	17%	33	-1.61	-2.59
3R16	16%	10	-0.41	-0.48
3R17	16%	33	-0.55	-2.64
3R18	15%	12	-0.09	-0.73
3R19	15%	34	-0.31	-1.91
3R20	14%	16	-0.36	-1.44
3R21	14%	40	-1.05	-2.43
3R22	13%	20	-0.88	-2.35
3R23	12%	2	-0.19	-0.86

Results : 4-ring configurations

Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	BOL Fuel TC (PCM/K)
4R1	17%	64	0.13	-3.52
4R2	17%	79	0.58	-2.28
4R3	17%	89	0.30	-1.03
4R4	16%	8	-0.17	-3.48
4R5	16%	19	-0.53	-2.42
4R6	16%	37	-0.10	-1.33
4R7	16%	50	0.41	-0.74
4R8	16%	72	-0.11	-1.87
4R9	15%	7	0.28	-1.93
4R10	15%	30	-0.29	-2.38
4R11	15%	57	0.06	-1.17
4R12	15%	80	0.55	-2.00
4R13	14%	28	-0.20	-0.89
4R14	14%	58	0.14	-3.37
4R15	13%	11	0.02	-3.05
4R16	13%	44	0.27	-1.91
4R17	13%	78	0.03	-1.99
4R18	12%	39	0.05	-1.71

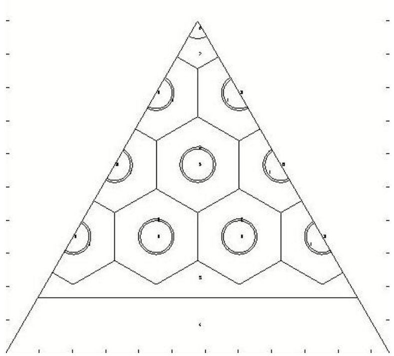
Results : 5-ring configurations

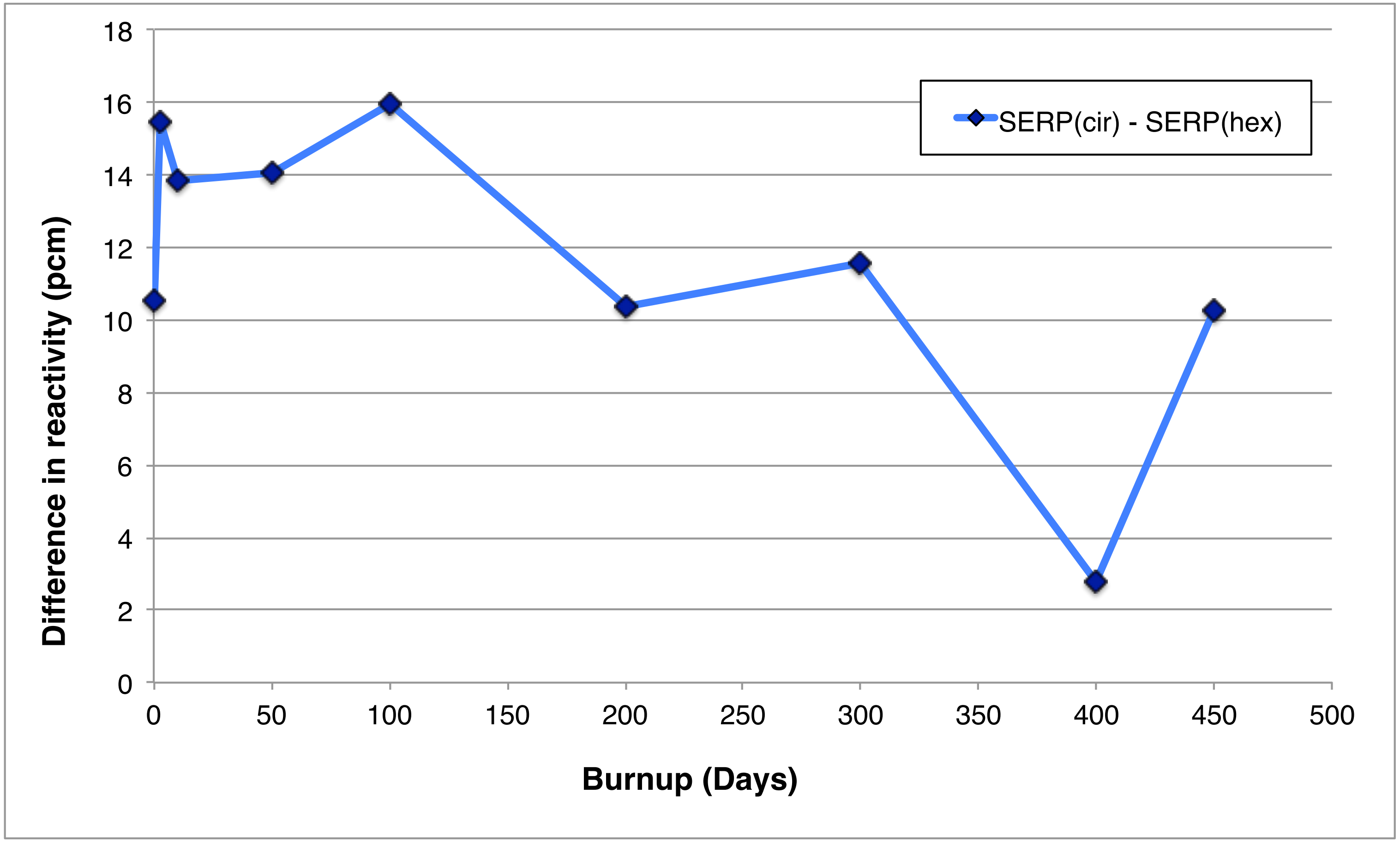
Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	BOL Fuel TC (PCM/K)
5R1	15%	162	1.60	-2.39
5R2	14%	13	1.16	-2.30
5R3	14%	40	0.20	-2.81
5R4	14%	58	0.04	-3.97
5R5	14%	83	1.12	-1.70
5R6	14%	104	0.54	-1.60
5R7	14%	129	0.48	-3.28
5R8	13%	11	0.47	-2.23
5R9	13%	47	0.97	-2.54
5R10	13%	89	0.66	-1.57
5R11	13%	124	0.42	-1.98
5R12	12%	13	0.93	-1.39
5R13	12%	58	0.09	-3.74

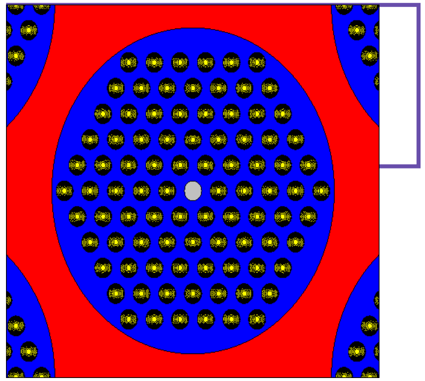
WIMS verification

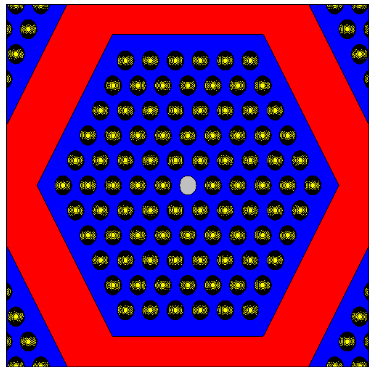
WIMS – Cactus (not Cactus3D) has limited modeling capability.
The coolant channel hexagonal instead of circular.

Comparing hexagonal and circular channels below:-

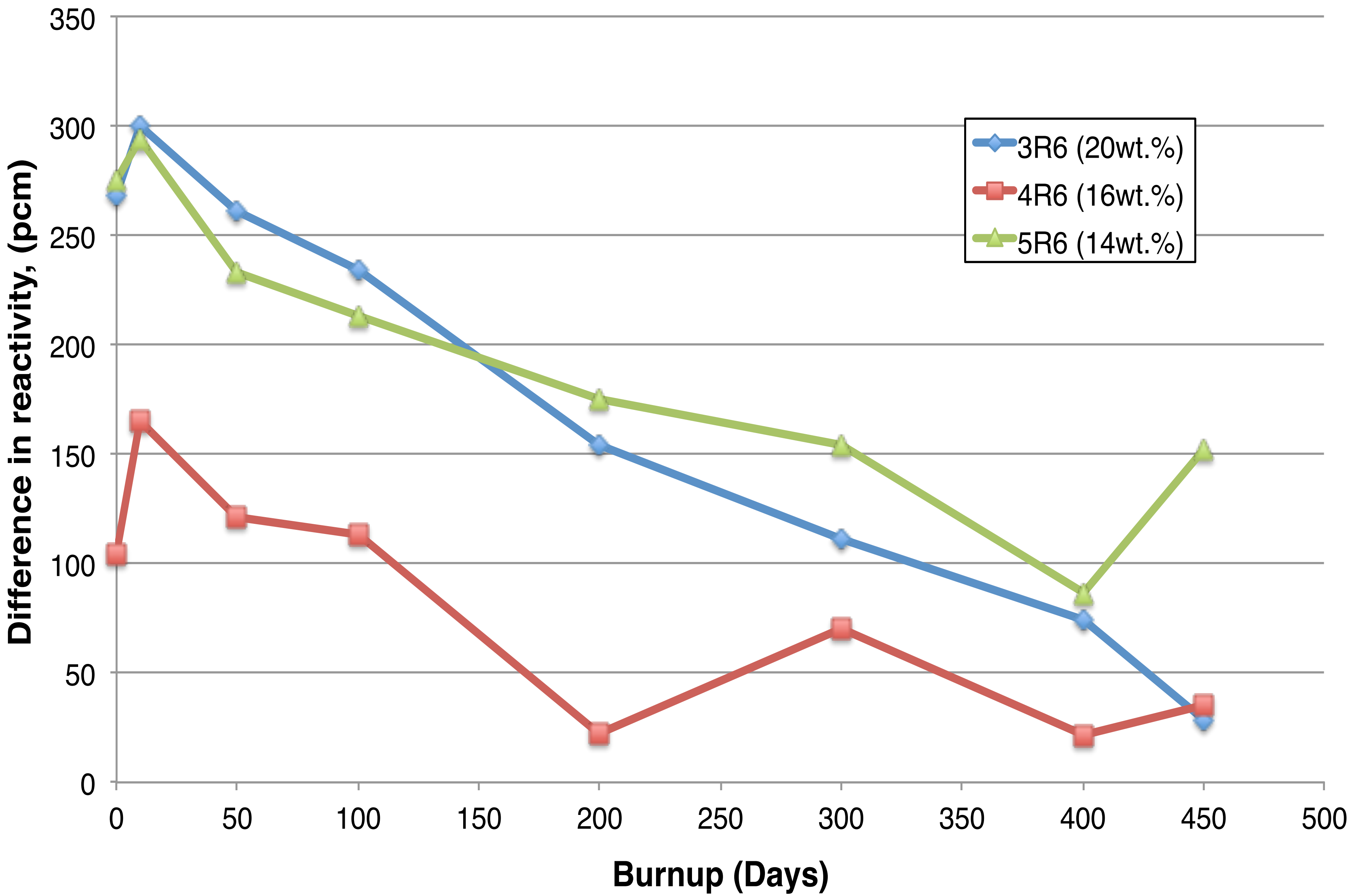








WIMS verification (Comparing reactivitiy for 3R6, 4R6 and 5R6)



WIMS verification (Compare 5 ring (5R) cycle length estimation)

Variations	*Enrichment*	*Number of days (WIMS)*	*Number of days (Serpent)*	*Difference (days)*	*Percentage difference (%)*
5R1	15%	615.48	558.42	57.07	10.22
5R2	14%	429.45	408.93	20.52	5.02
5R3	14%	453.66	435.52	18.14	4.16
5R4	14%	479.77	453.86	25.91	5.71
5R5	14%	507.26	479.02	28.24	5.90
5R6	14%	537.66	499.67	37.99	7.60
5R7	14%	568.61	525.32	43.30	8.24
5R8	13%	418.79	407.23	11.55	2.84
5R9	13%	459.48	442.99	16.49	3.72
5R10	13%	501.39	485.29	16.10	3.32
5R11	13%	544.43	520.17	24.26	4.66
5R12	12%	422.47	408.98	13.49	3.30
5R13	12%	474.68	453.94	20.74	4.57

Verification WIMS (comparing CTC for 3R)

Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	**WIMS CTC BOL (pcm/K)**
3R4	20%	7	-0.68	-0.6312981
3R5	20%	15	-0.30	-0.596883
3R6	20%	35	-0.06	-0.5664939
3R7	20%	37	-0.61	-0.5200554
3R8	19%	6	-0.04	-0.5540882
3R9	19%	20	-0.79	-0.4833491
3R10	19%	34	-1.70	-0.4396353
3R11	18%	6	-1.03	-0.4408294
3R12	18%	22	-0.02	-0.3791492
3R13	17%	6	-0.50	-0.3589988
3R14	17%	14	-0.43	-0.3030051
3R15	17%	33	-1.61	-0.2472416
3R16	16%	10	-0.41	-0.2210131
3R17	16%	33	-0.55	-0.1773535
3R18	15%	12	-0.09	-0.1514365
3R19	15%	34	-0.31	-0.1272149
3R20	14%	16	-0.36	-0.1114624
3R21	14%	40	-1.05	-0.08303
3R22	13%	20	-0.88	-0.0696847
3R23	12%	2	-0.19	-0.0636878

Verification WIMS (comparing CTC for 4R)

Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	**WIMS CTC at BOL (pcm/K)**
4R1	17%	64	0.13	0.488
4R2	17%	79	0.58	0.430
4R3	17%	89	0.30	0.376
4R4	16%	8	-0.17	0.252
4R5	16%	19	-0.53	0.213
4R6	16%	37	-0.10	0.182
4R7	16%	50	0.41	0.157
4R8	16%	72	-0.11	0.135
4R9	15%	7	0.28	0.063
4R10	15%	30	-0.29	0.059
4R11	15%	57	0.06	0.043
4R12	15%	80	0.55	0.050
4R13	14%	28	-0.20	0.012
4R14	14%	58	0.14	-0.007
4R15	13%	11	0.02	-0.033
4R16	13%	44	0.27	-0.028
4R17	13%	78	0.03	-0.038
4R18	12%	39	0.05	-0.059

Verification WIMS (comparing CTC for 5R)

Variations	Minimum Enrichment Required for 13 months (396 days)	Extra days (after 396 days)	BOL Coolant TC (PCM/K)	***WIMS CTC at BOL (pcm/K)***
5R1	15%	162	1.60	0.88
5R2	14%	13	1.16	0.81
5R3	14%	40	0.20	0.76
5R4	14%	58	0.04	0.70
5R5	14%	83	1.12	0.64
5R6	14%	104	0.54	0.58
5R7	14%	129	0.48	0.52
5R8	13%	11	0.47	0.43
5R9	13%	47	0.97	0.34
5R10	13%	89	0.66	0.31
5R11	13%	124	0.42	0.26
5R12	12%	13	0.93	0.18
5R13	12%	58	0.09	0.13

Observation/Future work

- Difference in WIMS and SERPENT less than 500 pcm – main reason different number of energy group structures used by WIMS (172 groups).
- 5 million histories are not sufficient to capture the coolant temperature coefficient effect.
- 5 ring configuration has longer fuel lifecycle (important for small reactor).
- Disadvantage of 5 ring assemblies is positive coolant temperature coefficient.
- The 5R assemblies are overmoderated due to the presence of SiC cladding that comes with the fuel pins.
- Future work: Coupling neutronic analysis with thermal hydraulic analysis. 3D and full core analyses are also considered.

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Leakage Probability (Comparing 20wt.% and 13wt.%)