CORE DESIGN FOR NEUTRON FLUX MAXIMIZATION IN RESEARCH REACTORS

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Objective

Study different core configurations of a pool type multipurpose research reactor to:

- ***maximize the neutron flux delivered to the reflector,***
- ***produce an acceptable life cycle (~ 40 days),***
- ***allow irradiation positions in the inner reflector.***

Reason

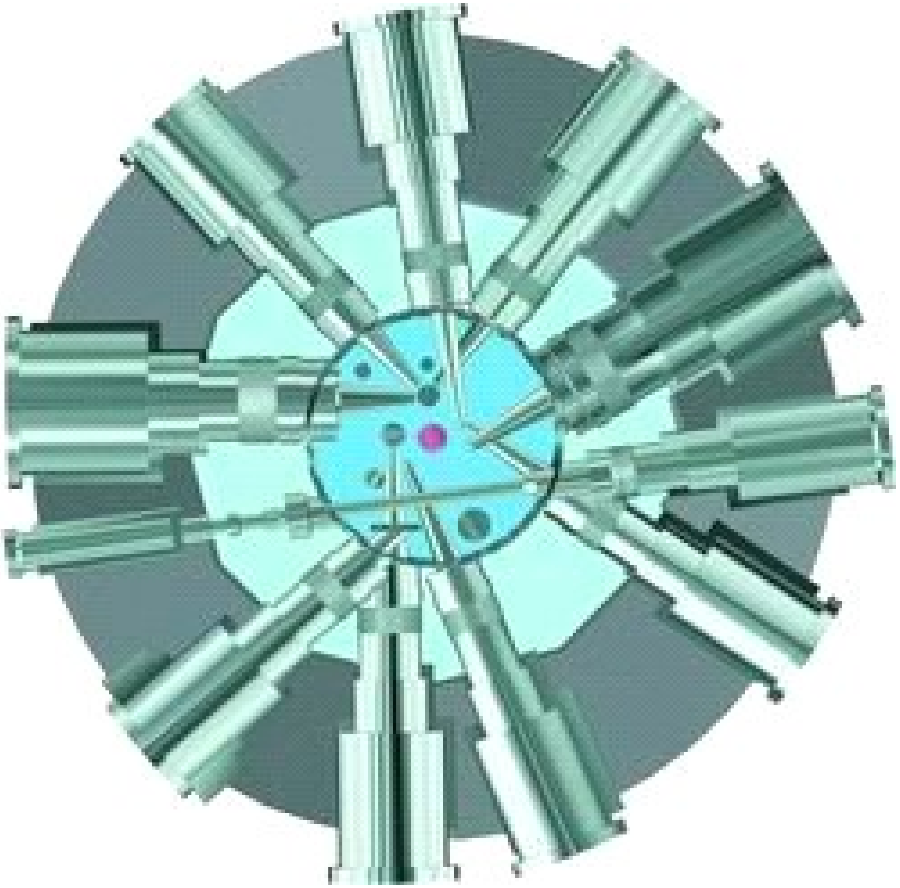
The intensity of neutron sources in a research reactor defines types of applications and rates of production. Competitiveness of the reactor.

Outline

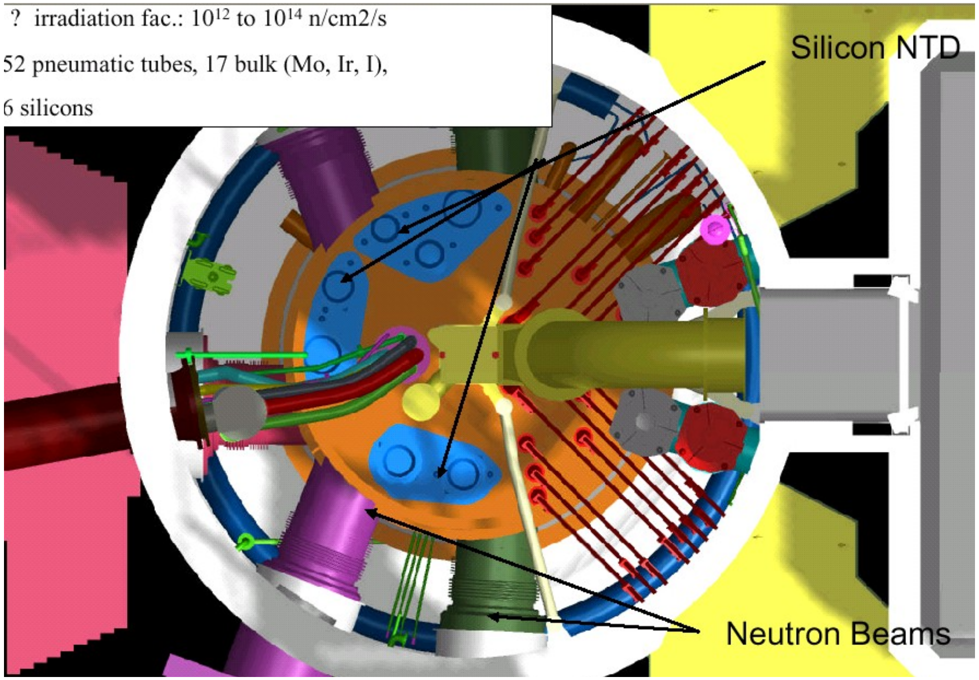
- ✓ ***Modern research reactors examples and neutron flux requirements.***
- ✓ ***Comments about FRM-II design.***
- ✓ ***Tools to model neutronic behavior in research reactors.***
- ✓ ***Our simplified model of FRM-II.***
- ✓ ***Alternative model and goals.***
- ✓ ***Compromise solution.***
- ✓ ***Neutron flux levels and life cycle of compromise solution.***
- ✓ ***Summary and conclusions.***

Modern research reactors

FRM-II (Germany)



*OPAL (Australia)**



*Under construction

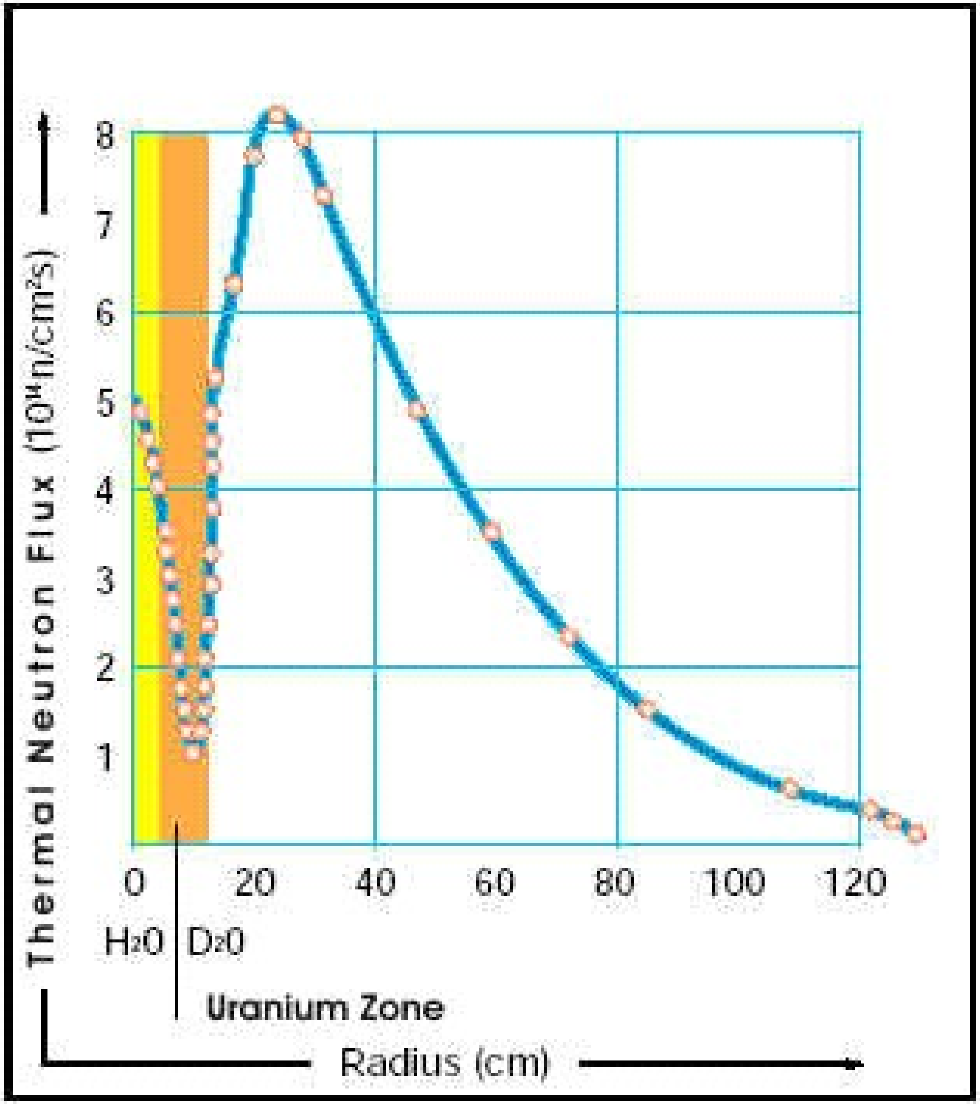
Research reactors overview

	Flux(th) $*10^{14}$	Fuel	Enrichment	Power (MW)	Flux(th) $*10^{13}$/MW
HFIR	25.5	U_3O_8-Al	N/A	85	**3.0**
FRM-II	8.0	U_3Si_2-Al	93%	20	**4.0**
HANARO	5.0	U_3SiAl	20%	30	**1.7**
JRR-3M	3.0	U_3Si_2	20%	10	**3.0**
JHR*	7.4	UMo_7	<20%	100	**0.7**
OPAL**	3.2	U_3Si_2-Al	20%	20	**1.6**

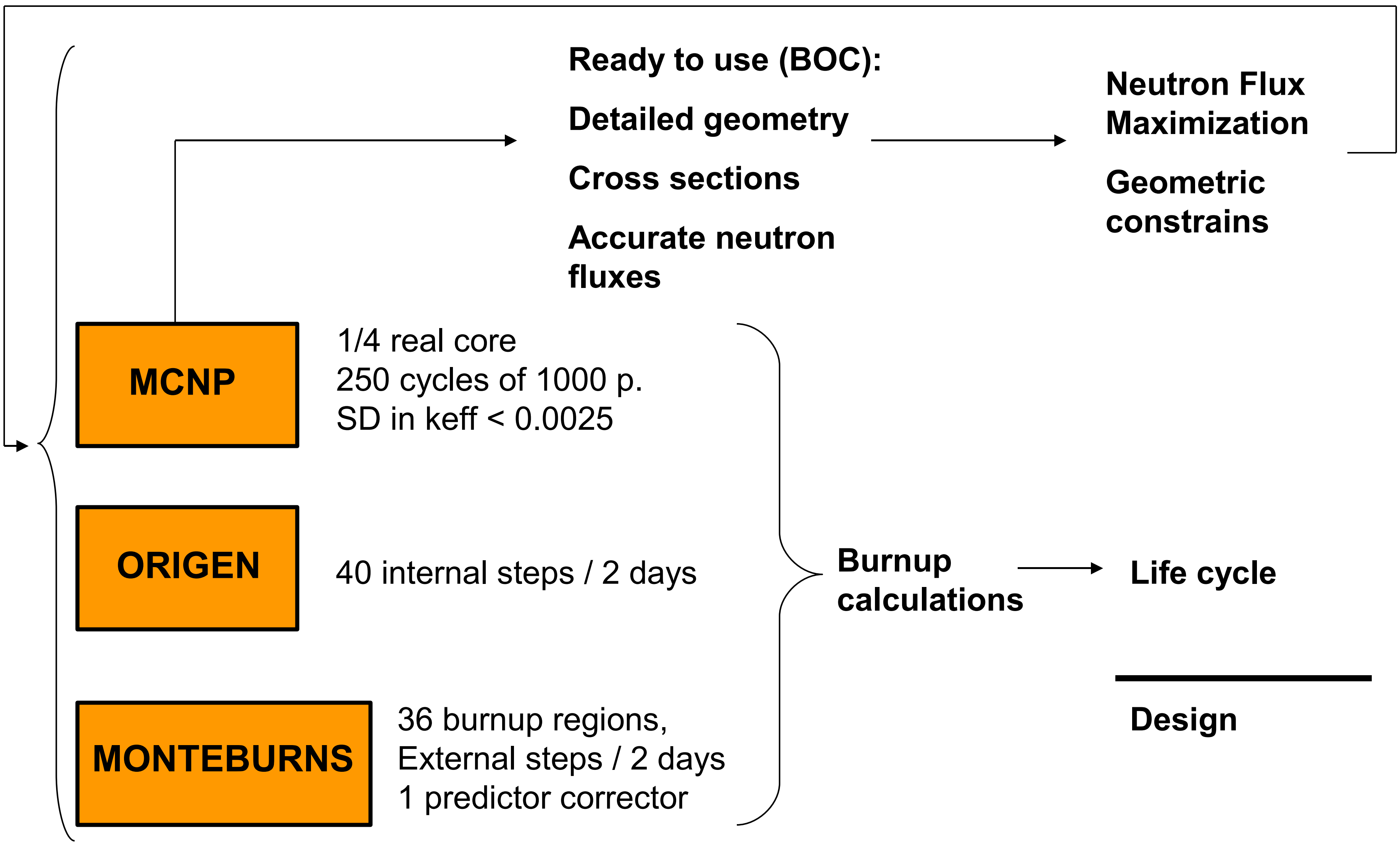
*Projected
**Under construction

FRM-II

- Single, cylindrical fuel element (5.9cm to 12.15cm, 70cm height).
- 113 involuted, curved fuel plates.
- uranium silicide-aluminium dispersion (1.5g/cm³ and 3.0g/cm³).
- Enrichment factor 93%.
- Life cycle 52 days.

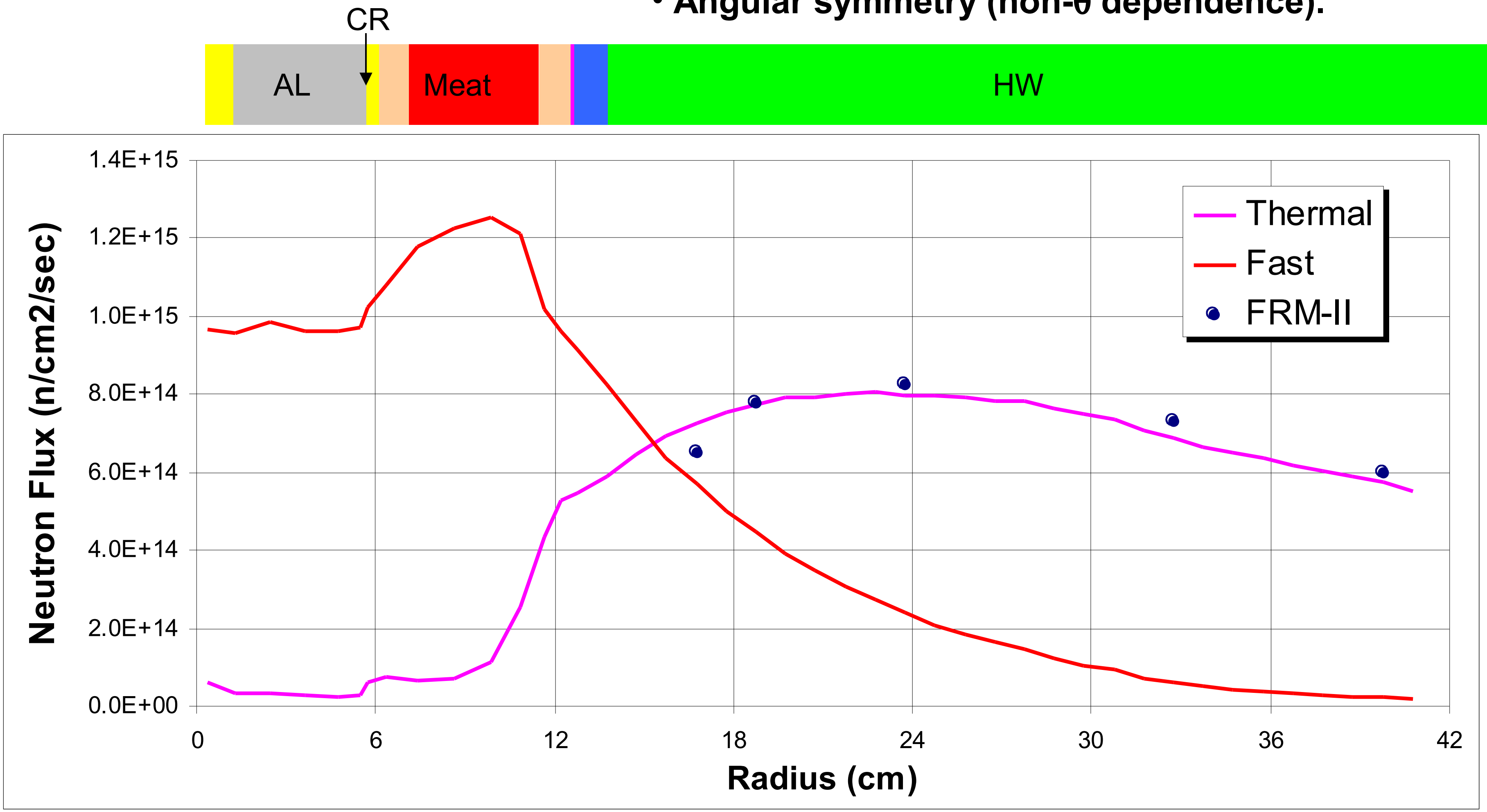


Computational tools to accurately model neutronic behavior of research reactors



MCNP simplified model of FRM-II

- **Core modeled as an homogeneous mixture,**
- **Reflector modeled without any facilities,**
- **Angular symmetry (non-θ dependence).**



Basic variations of FRM-II model

Constrains

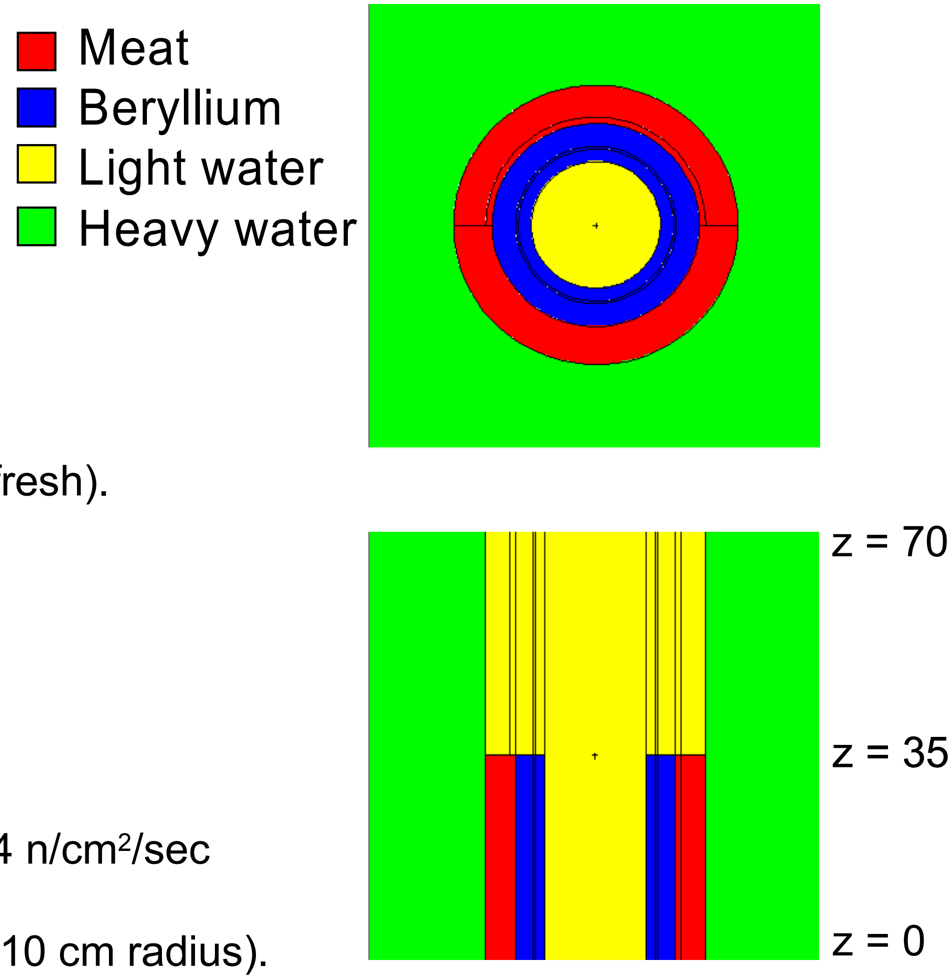
- Inner irradiation zone.
- Relatively long fuel cycle (> 40 days).
- 20 % enrichment

Assumption

- 10 MW of power.
- Meat U_3Si_2 of 4.8 gr/cm^3, 20 % enrichment (fresh).
- Outer reflector heavy water.
- Core height 70 cm.
- Core modeled as a homogeneous mixture.

Goals

- Unperturbed thermal peak greater than 4E14 n/cm^2/sec (equivalent to 8E14 n/cm^2/sec for 20 MW).
- Inner irradiation zone greater than 350 cm^2 (10 cm radius).
- Life cycle greater than 40 days.



Basic variations of FRM-II model

Parameter: inner and outer core radii

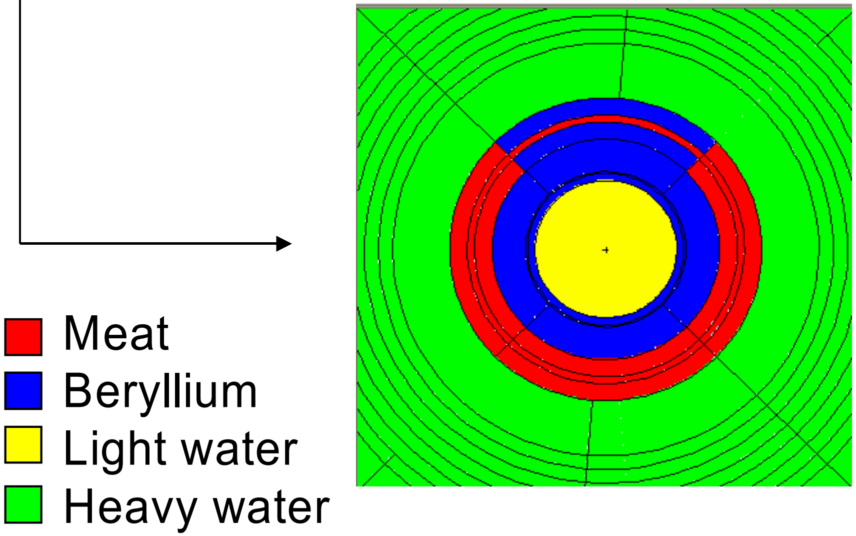
Case	I	II	III	IV	V	VI
Inner core radius (cm)	15	15	15	14	16	17
Outer core radius (cm)	20	19	18	17	20	20
Multiplication factor	**1.15**	**1.10**	**1.03**	**1.02**	**1.12**	**1.07**
U5 ratio to FRM-II (Kg/Kg)	1.4	1.1	0.8	0.7	1.1	0.9
MTF ($*10^{14}$)	**2.31**	**2.74**	**3.06**	**3.11**	**2.58**	**2.77**

Case	VII	VIII	IX	X	XI
Inner core radius (cm)	20	19	15	15-16	15-15.5
Outer core radius (cm)	23	20	16	19-20	19.5-20
Multiplication factor	**1.12**	**0.87**	**0.78**	**1.00**	**0.86**
U5 ratio to FRM-II (Kg/Kg)	1.0	0.3	0.2	0.5	0.1
MTF ($*10^{14}$)	**2.55**	**4.13**	**4.47**	**3.20**	**3.88**

Conclusion: for acceptable life cycles (i.e. greater than 40 days), maximum thermal neutron fluxes are far lower than the value expected as a goal.

A compromise solution, asymmetric core model

- Thin cores produce high fluxes,
- Thick cores produce acceptable life cycles,
- Multipurpose Reactor → high thermal fluxes in one region of the reflector,
- Other applications do not require such high thermal fluxes.

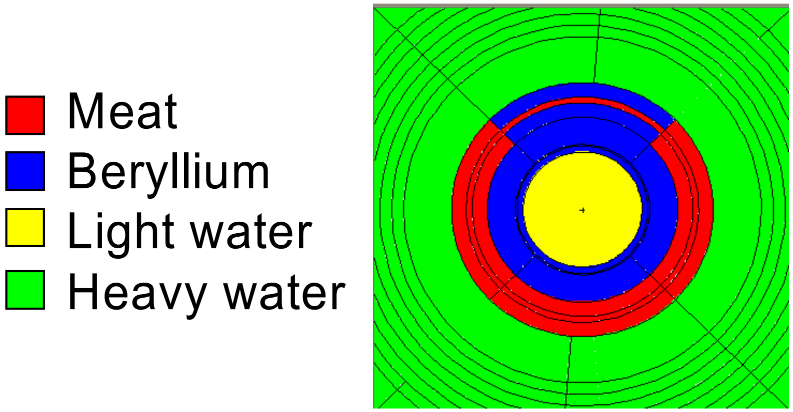


Asymmetric core may produce these results

Asymmetric core model

Parameters:

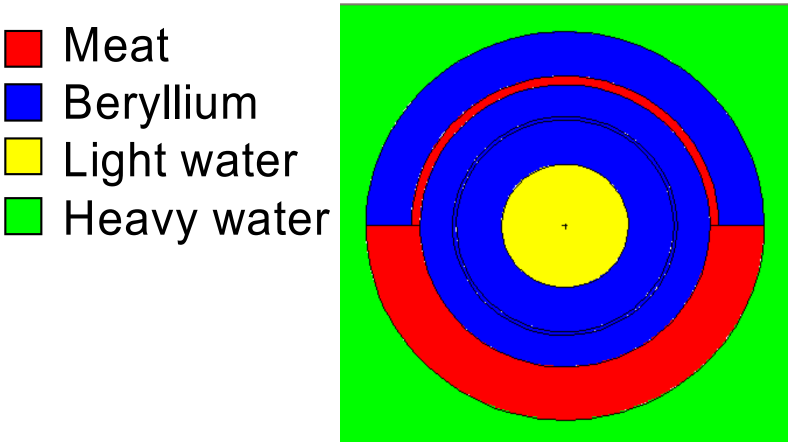
- **Thick core section inner radius**
- **Thick core section outer radius**
- **Thin core section inner radius**
- **Thin core section outer radius**
- **Angular aperture thin section**



Case	I	II	III	IV	V	VI	VII
Thick core inner radius (cm)	15	15	15	16	15	16	16
Thick core outer radius (cm)	20	20	20	22	20	22	22
Thin core inner radius (cm)	17	17	17	18.5	17	18.5	16
Thin core outer radius (cm)	18	18	18	19.5	18	19.5	17
Angular aperture thin section (º)	90	120	150	150	180	180	180
Multiplication factor	**1.11**	**1.09**	**1.08**	**1.15**	**1.07**	**1.11**	**1.12**
MTF center thin section (*10E14)	2.2	2.12	1.96	1.74	1.73	1.56	0.87
MTF center thick section (*10E14)	**3.01**	**3.57**	**4.04**	**3.78**	**4.4**	**3.86**	**4.05**

Asymmetric core (case VIII)

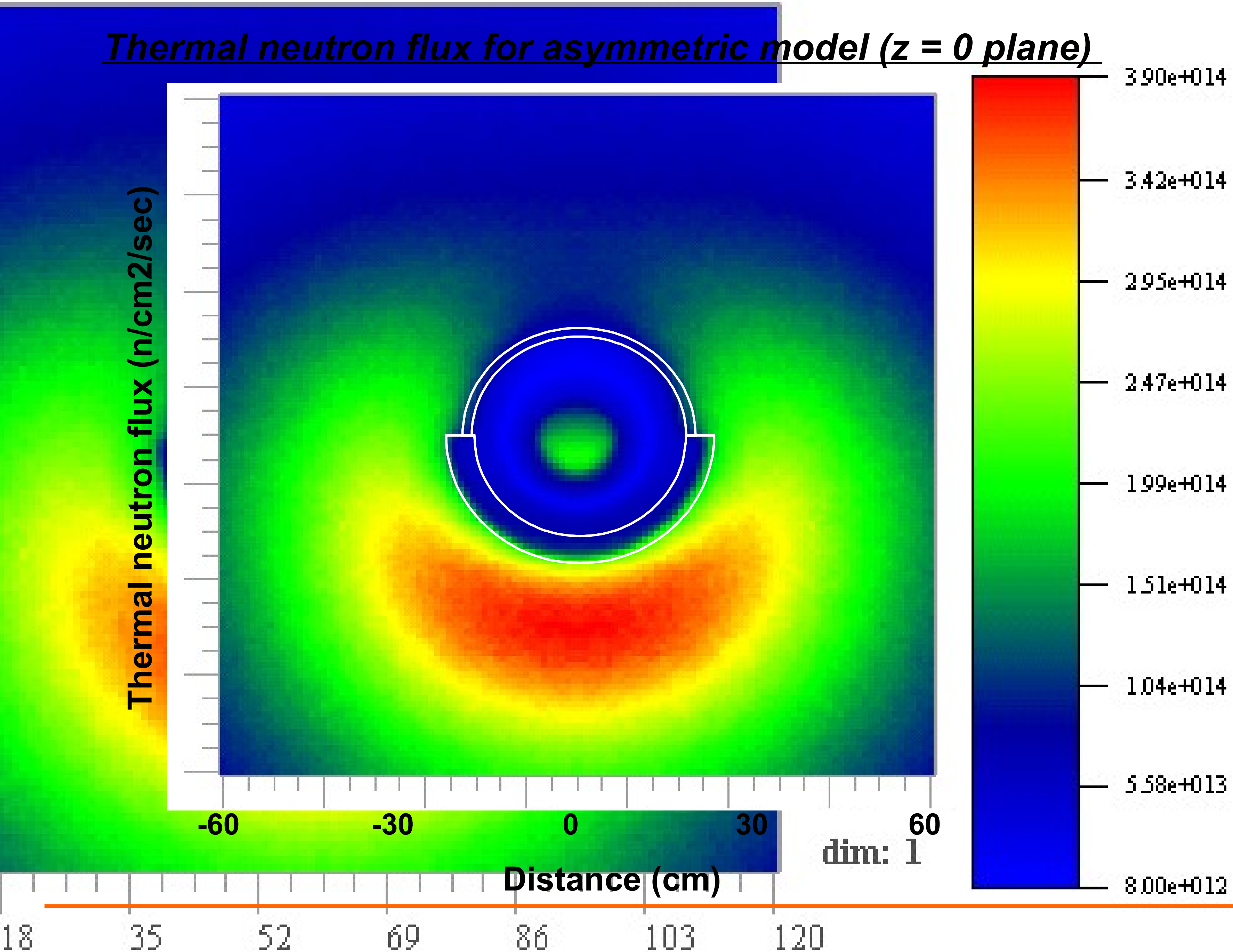
Core thick section	**Inner radius (cm)**	**16**
	Outer radius (cm)	**22**
Core thin section	**Inner radius (cm)**	**16**
	Outer radius (cm)	**17**
Total core	**Volume (cm³)**	**28700**
	Height (cm)	**70**
	U5 (kg)-20%	**4.71**
Inner irradiation zone	**External radius (cm)**	**7**



Case	k_{eff}
Critical with Hf-CR from 11.0 to 11.4 cm	1.000
Base case	1.162
Black absorber from 0-7 cm	1.080
Be from 0-7 cm	1.230
Heavy Water from 0-7 cm	1.231

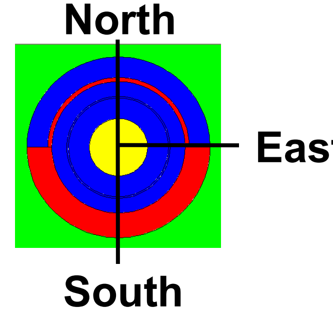
→ **Life cycle of 41 days with marginal reactivity of 6.8% (Δk/k)**

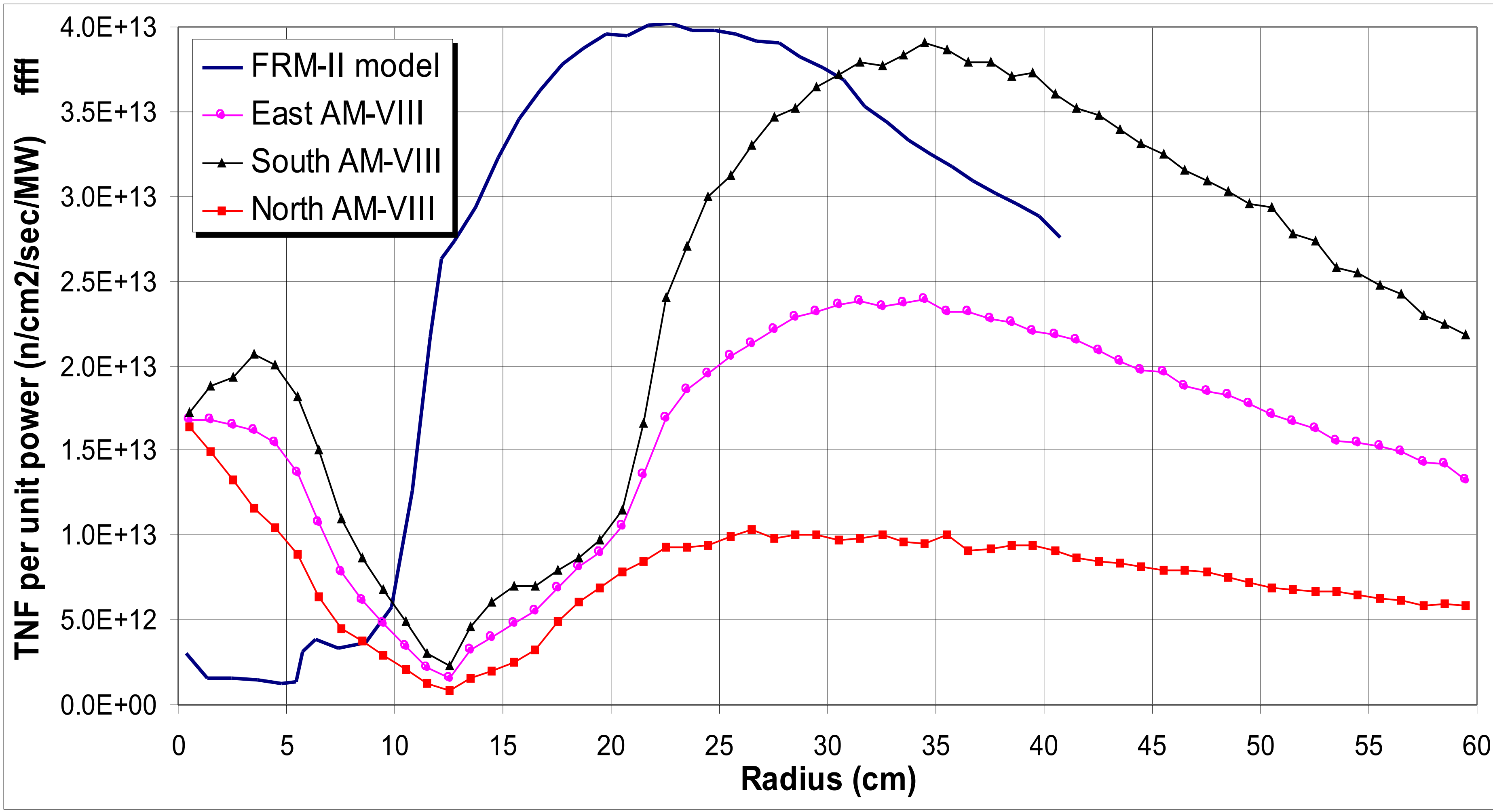
Thermal neutron flux for asymmetric model (z = 0 plane)



Detailed thermal neutron flux for asymmetric model

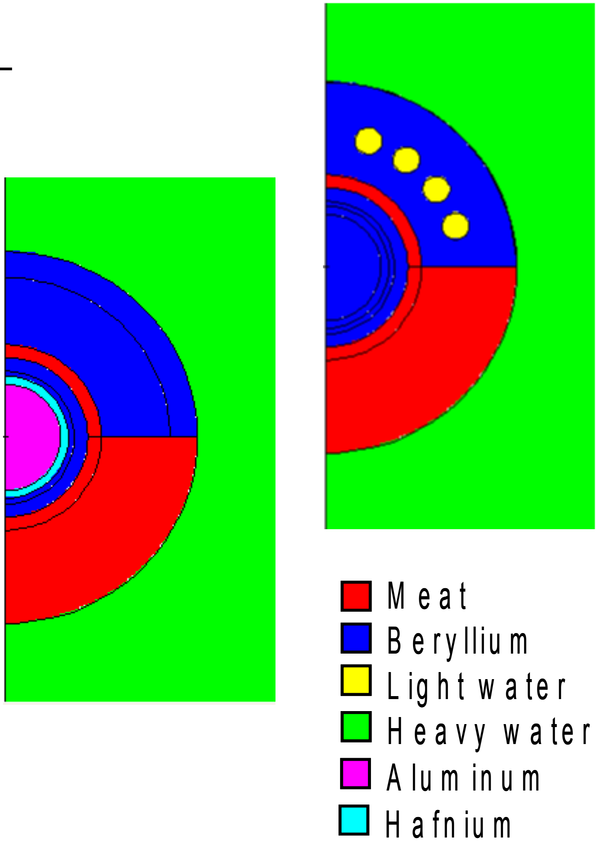
Meat
Beryllium
Light water
Heavy water





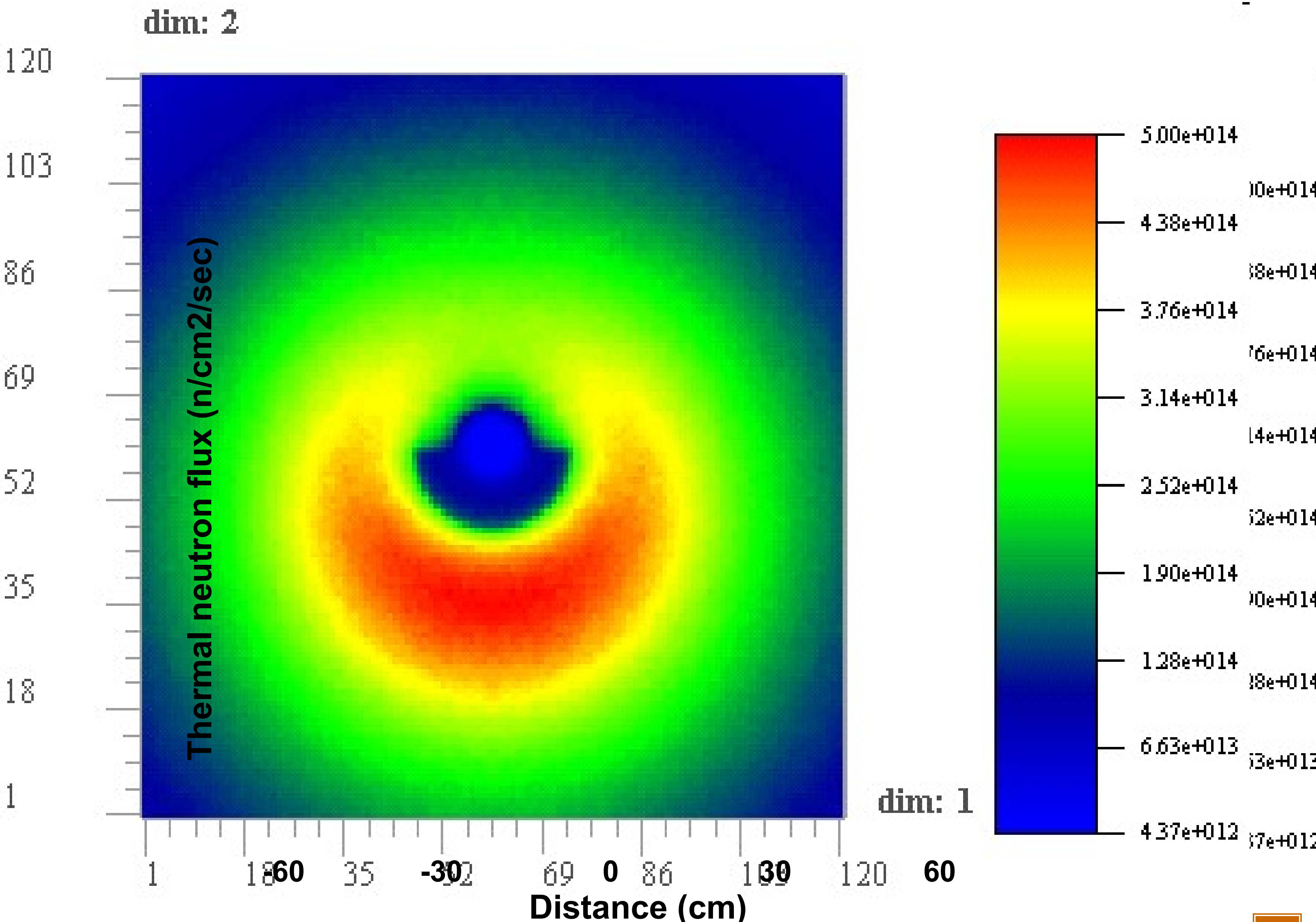
Asymmetric compact core with shorter life

Core thick section	**Inner radius (cm)**	**6**
	Outer radius (cm)	**14**
Core thin section	**Inner radius (cm)**	**6**
	Outer radius (cm)	**7**
Total core	**Volume (cm³)**	**19022**
	Height (cm)	**70**
	U5 (kg)-20%	**3.12**

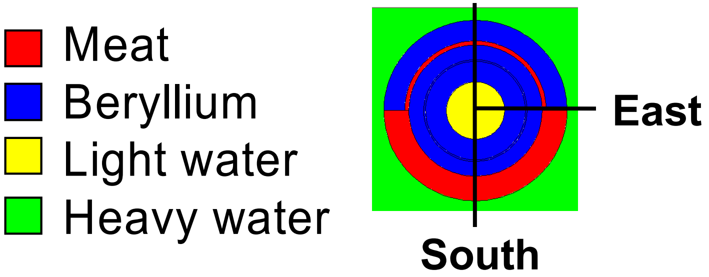


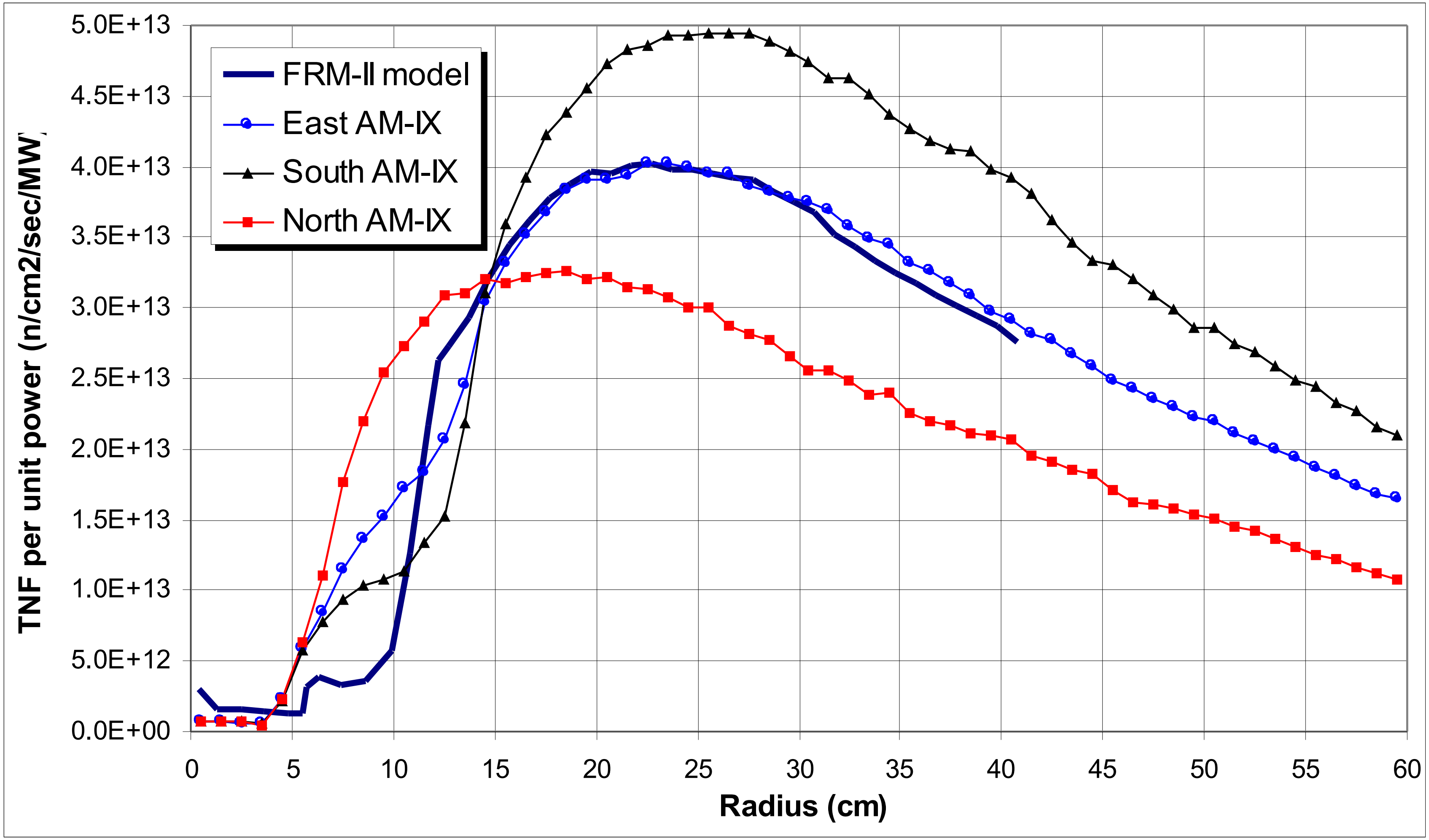
Case	**k_{eff}**
Critical with Hf-CR from 11.0 to 11.4 cm	1.000
Base case	1.152
8 holes of 2 cm of diameter of light water	1.141

Life cycle of 25 days with marginal reactivity of 5.8% (Δk/k)


dim: 2
120
103
86
69
52
35
18
1
Thermal neutron flux (n/cm2/sec)
dim: 1
1
18
35
52
69
86
103
120
-60
-30
0
30
60
Distance (cm)
5.00e+014
4.38e+014
3.76e+014
3.14e+014
2.52e+014
1.90e+014
1.28e+014
6.63e+013
4.37e+012

Detailed thermal neutron flux for asymmetric compact core





Summary and conclusions:

- The asymmetric design allows to reach an unperturbed thermal peak per unit power comparative to the FRM-II one. In addition, using L.E.U, the life cycle is conservatively estimated in 41 days.

- The asymmetric model produces a high thermal neutron flux zone (~ 3.9E14 n/cm^2/sec), moderate thermal neutron flux zone (~ 2.4E14 n/cm^2/sec), and low thermal neutron flux zone (~ 1E14 n/cm^2/sec).

- The design also presents a inner irradiation zone to irradiate materials that could be designed to be characterized by a higher fast/thermal flux ratio than the one obtained in the reflector.

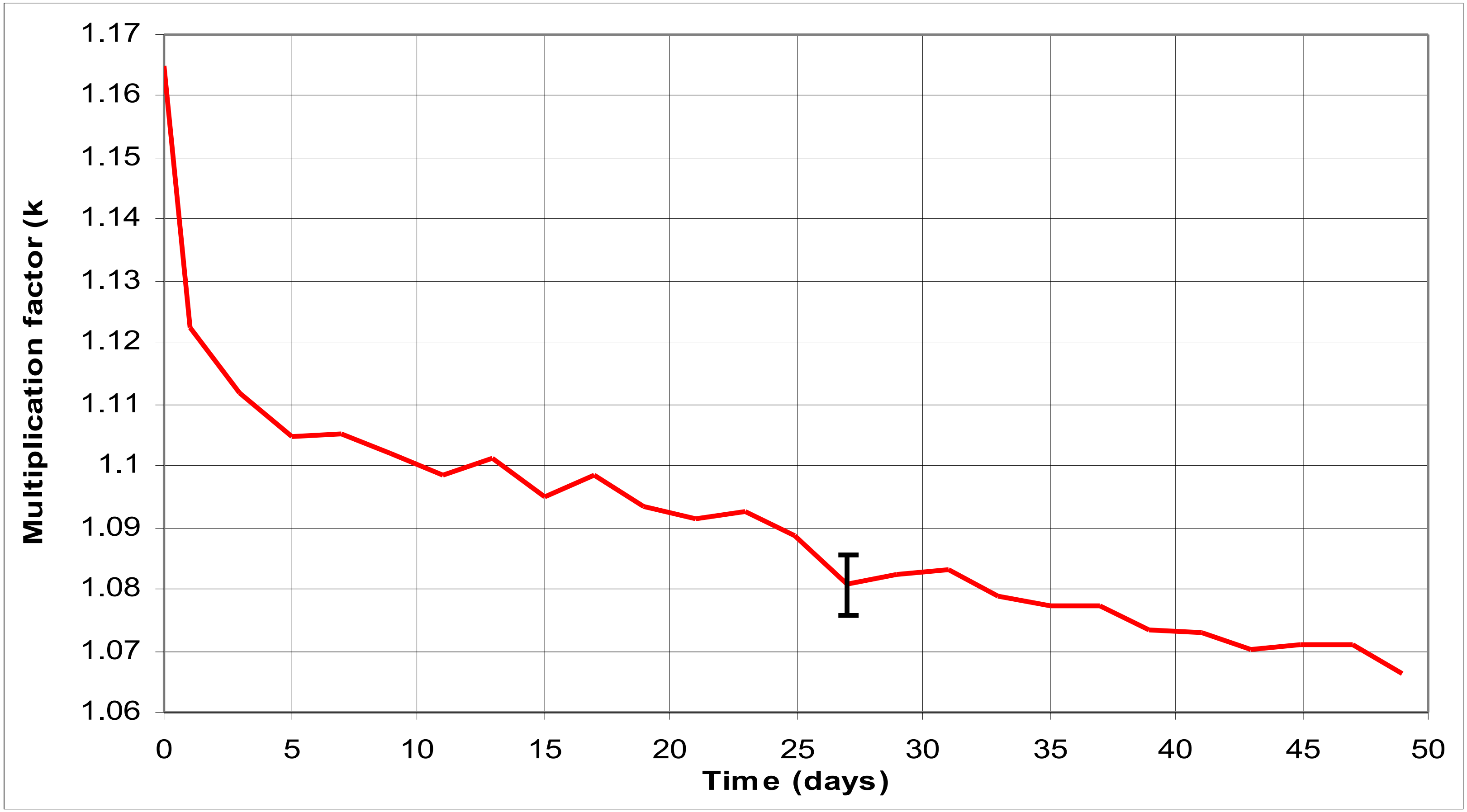
- The asymmetric compact core produces a high thermal neutron flux zone (~ 4.9E14 n/cm^2/sec), moderate thermal neutron flux zone (~ 4.0E14 n/cm^2/sec), and low thermal neutron flux zone (~ 3.2E14 n/cm^2/sec). The life cycle is estimated in 25 days.

Usage of Research Reactors

	Purpose	Requirements
Cold Neutron Source	Structure research, molecular motion	High flux, CNS, beams
Thermal Neutron Source	Structure research, radiography, neutron therapy	High flux, beams
Fast and hot neutron sources	Fast neutron irradiation, neutron therapy	High flux, hot source or fissile material, beams
Isotope production	Production of radioisotopes for medical, military, and scientific purposes.	Irradiation positions
Industrial processing	Neutron transmutation doping	Location for huge crystals, stable and homogeneous flux
Material testing and irradiation	Test and design of materials for use in fission and fusion reactors.	In core and out core testing locations
Teaching and training applications	Reactor theory, dosimetry, instrumentation	

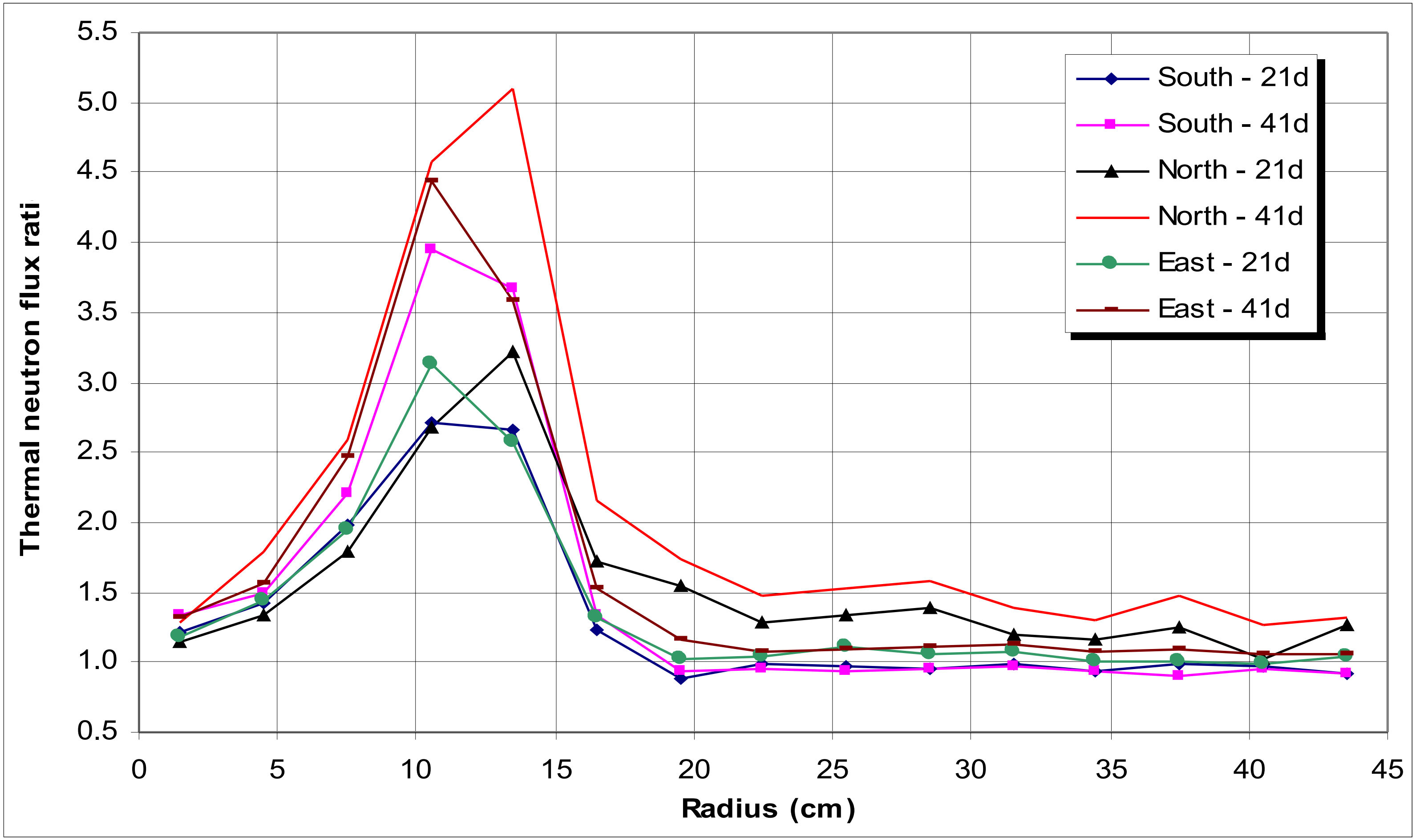
Burnup calculations I

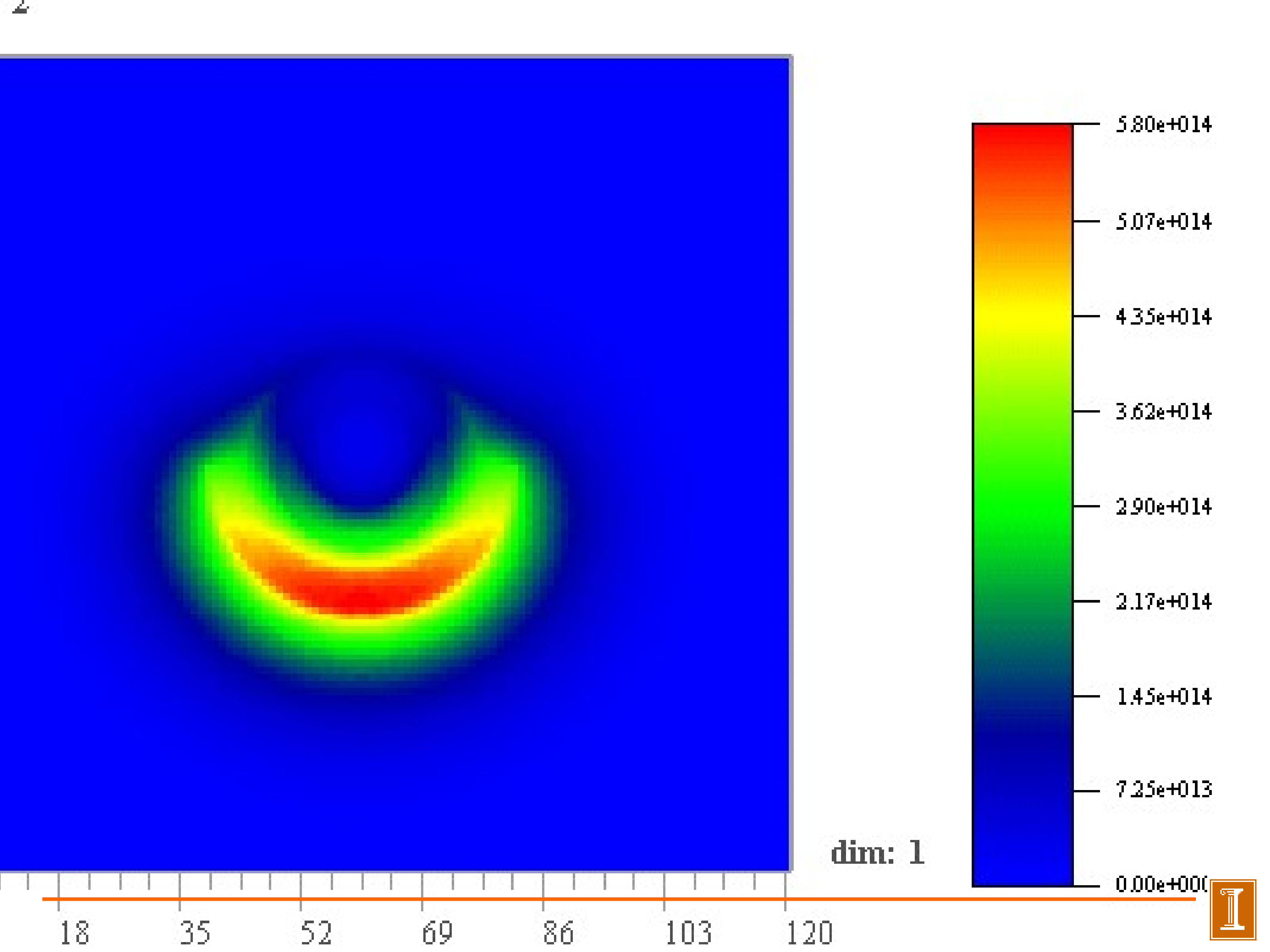
Core divided in 36 different regions,
Steps for MCNP calculation every 2 days,
Error in keff = 0.005, two SD



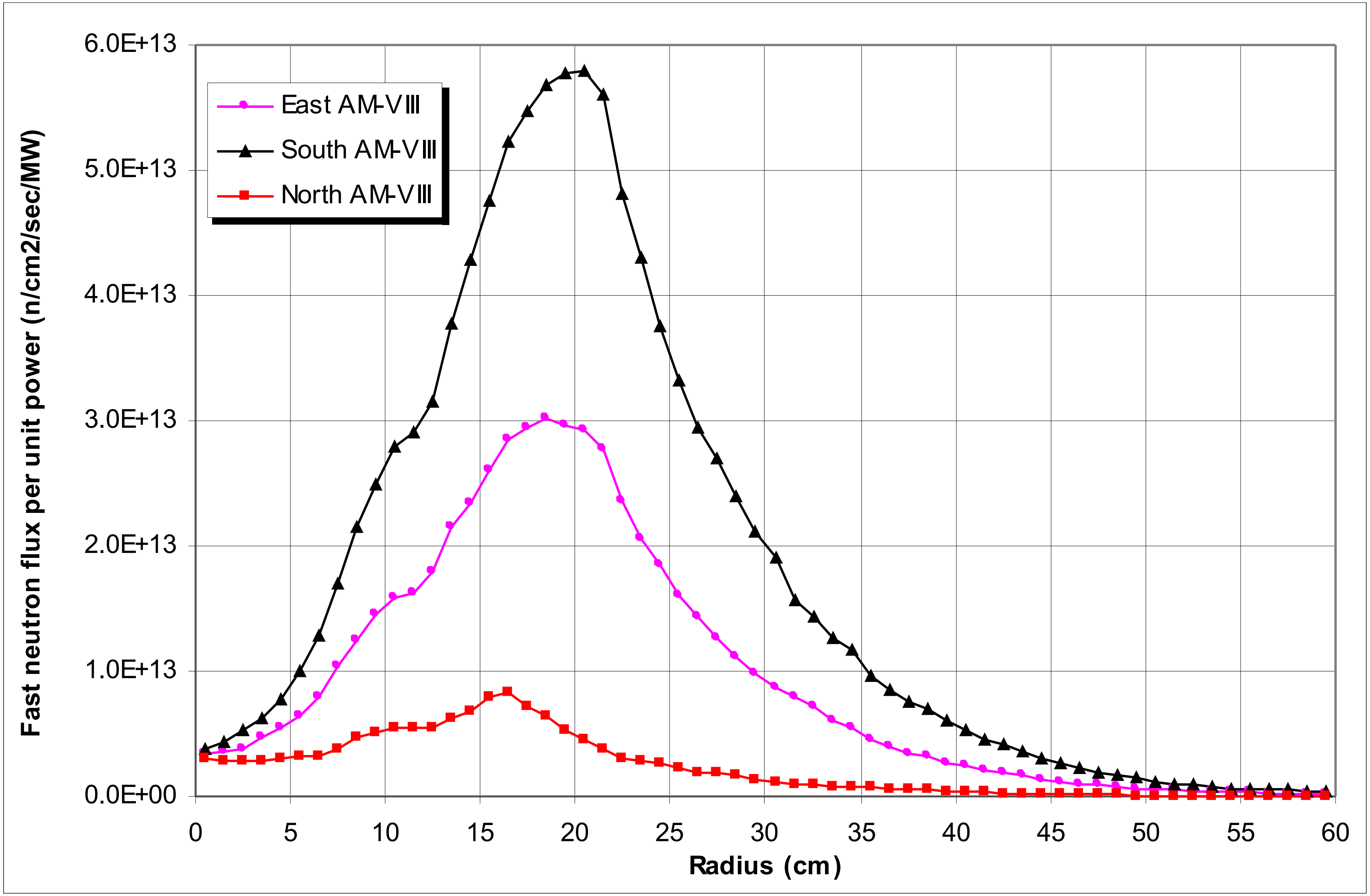
Burnup calculations II

Flux in cubes of 3 cm edges (too big),
Critical calculation, then the peak is due to CR withdraw,
Power in south region is slightly decreasing and power in north region is increasing with burnup




5.80e+014
5.07e+014
4.35e+014
3.62e+014
2.90e+014
2.17e+014
1.45e+014
7.25e+013
dim: 1
18
35
52
69
86
103
120

Fast flux II



6.0E+13
5.0E+13
4.0E+13
3.0E+13
2.0E+13
1.0E+13
0.0E+00
Fast neutron flux per unit power (n/cm2/sec/MW)
0
5
10
15
20
25
30
35
40
45
50
55
60
Radius (cm)
East AM-VIII
South AM-VIII
North AM-VIII

Thermal flux comparison

Area in z = 0 plane (cm^2)	FRM-II simplified model	AM-IX	AM-IX areas as % of FRM-II
>2.0E13 $n \cdot cm^{-2}s^{-1}MW^{-1}$	7439	8236	110
>3.0E13 $n \cdot cm^{-2}s^{-1}MW^{-1}$	3921	4210	107
>3.5E13 $n \cdot cm^{-2}s^{-1}MW^{-1}$	2413	2584	106
>4.0E13 $n \cdot cm^{-2}s^{-1}MW^{-1}$	-	1378	-

Burnup calculation compact core