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CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

Safety study on reactive properties of foreseen BR2 fuel elements containing Cadmium wires instead of burnable poisons

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Objectives

- to satisfy the irradiation conditions requested by the experimental load,
- to do this by guarantying safe operation
- to make optimal economical use of the available fuel elements.

  - **to use Cadmium wires instead burnable poisons**
  - **to analyse the suitability of this alternate design**
  - **to maintain the operational characteristics of the BR2 reactor.**

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BR2 Fuel Element Geometry

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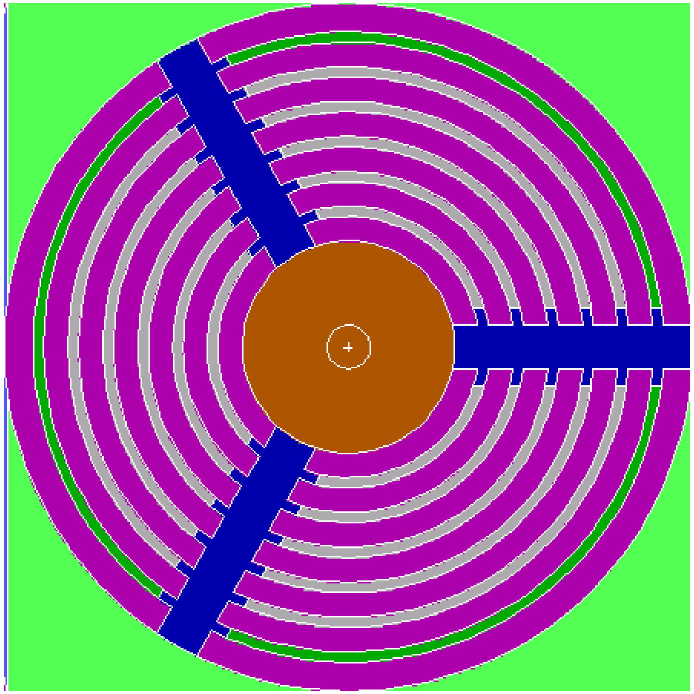
BR2 Fuel Element Geometry



- 6 concentric fuel plates
- 3 sectors and side-plates

outer diameter	3 inches	or	7.62 cm
fuel length	30 inches	or	76.2 cm
fuel thickness	0.2 inch	or	0.051 cm
plate thickness	0.5 inch	or	0.127 cm
water gap	>0.27 cm	or	0.30 cm

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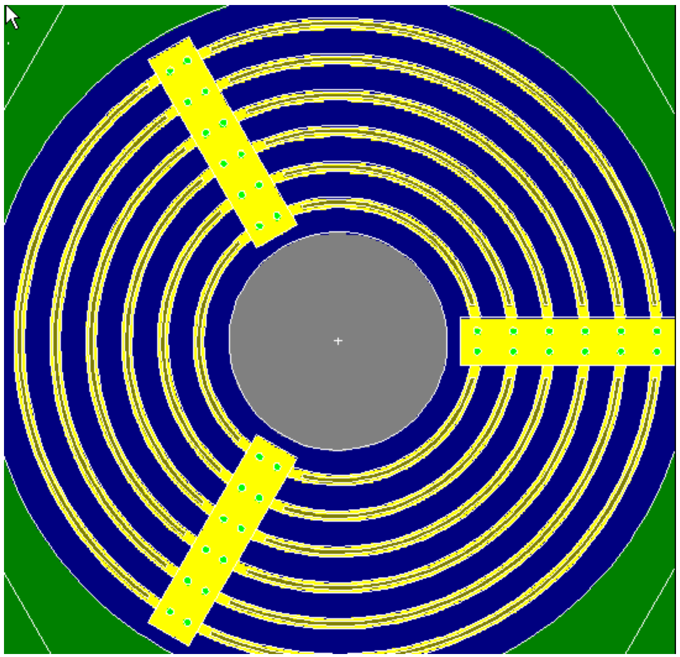
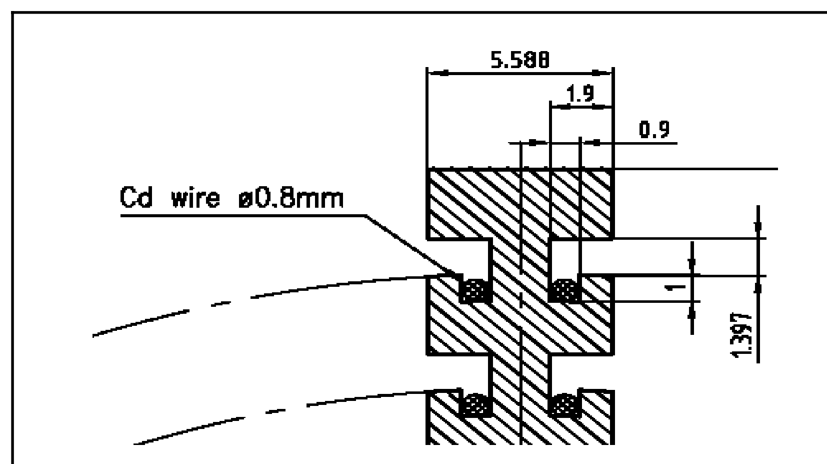
BR2 Fuel Element with Cd Wires



- side-plate width 0.22 inch or 0.56 cm
- distance between fuel and side-plate: < 0.20 cm
- distance between wires 0.26 cm
- diameter of Cadmium wires 0.08 cm
- length of Cadmium wires
  BR2 fuel length 30 inches or 76.2 cm
- Cd contains Ag 4%wt

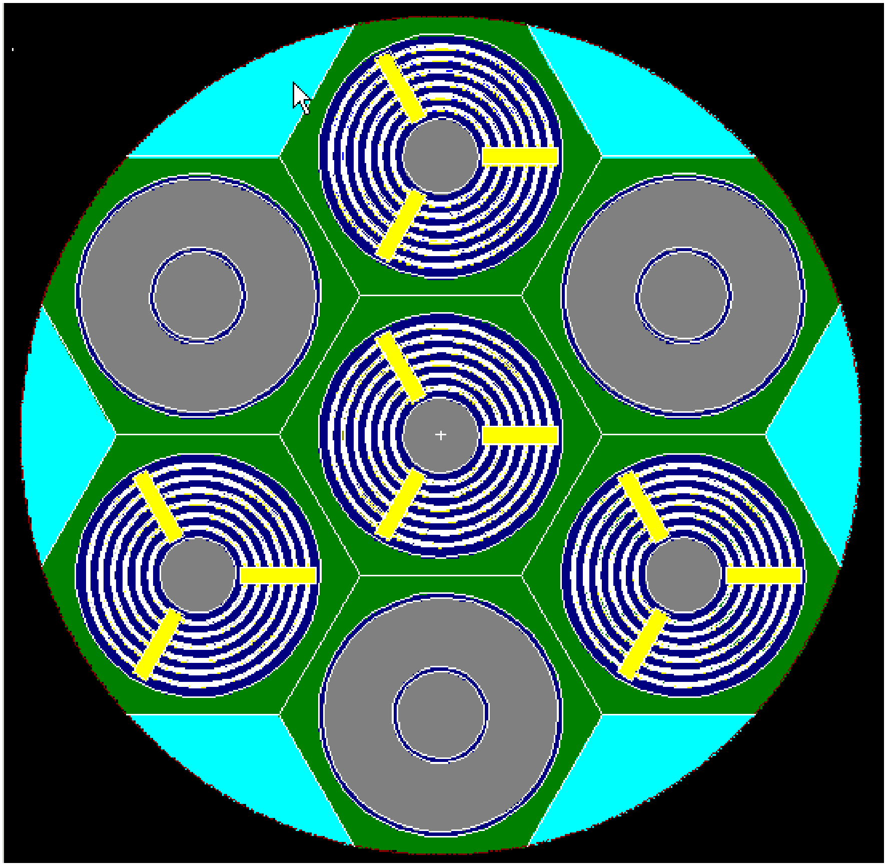


Types of BR2 Fuel Elements

	A	G	W6	W8
U-235 [g]	244	400	400	400
U-tot [g]	271	430	552	552
enrichment	93%	93%	72.5%	72.5%
U-X	$U\text{-}Al_4$	$U\text{-}Al_{x\sim3}$	$U\text{-}Al_{x\sim3}$	$U\text{-}Al_{x\sim3}$
U.tot [g/cm^3]	0.77	1.31	1.63	1.63
B.nat (B_4C) [g]	0	3.8	0	0
Sm.nat (Sm_2O_3) [g]	0	1.4	0	0
36 Cd wires diameter			0.06 cm	0.08 cm

- **but in our case HEU is 93% for W8 and W6**

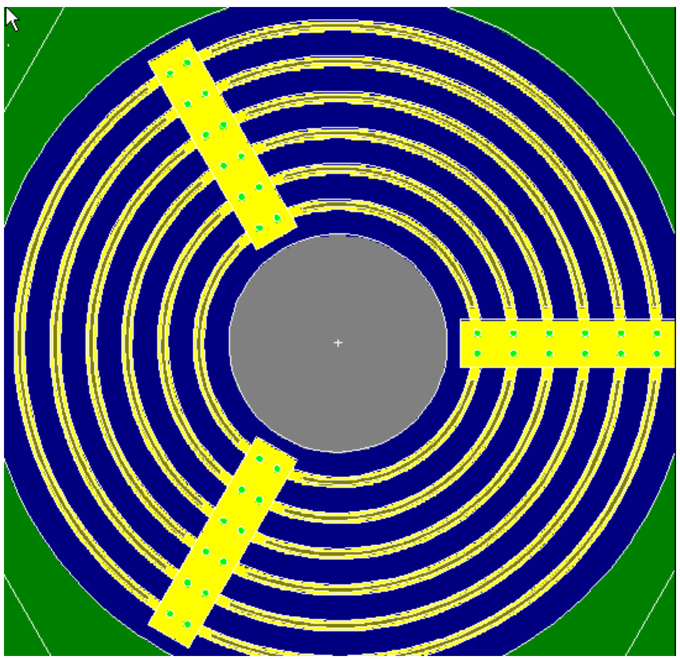
Neutron flux distribution

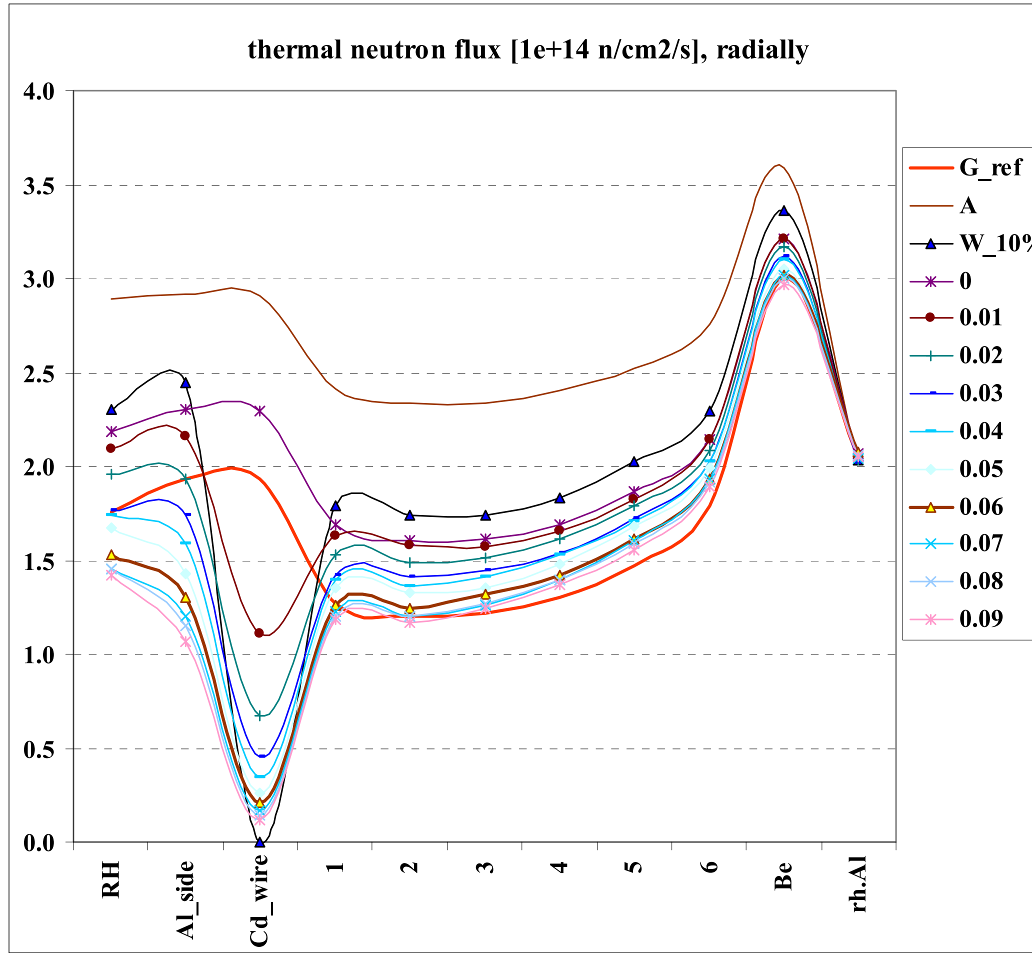


- **Analysis of neutron flux and microscopic cross-sections by the MonteCarlo code MCNP-4C**
- **small model with reflective boundary**
- **3 fuel elements type C 6n containing 330 g U-235 and inner Al basket, each developing 2 MW**
- **3 obturator Be and inner Be plug central fuel element type A, G, or W**

Thermal neutron flux Cd and fuel plates

results of RRFM-2004





Effective blackness of Cd wire

results of RRFM-2004

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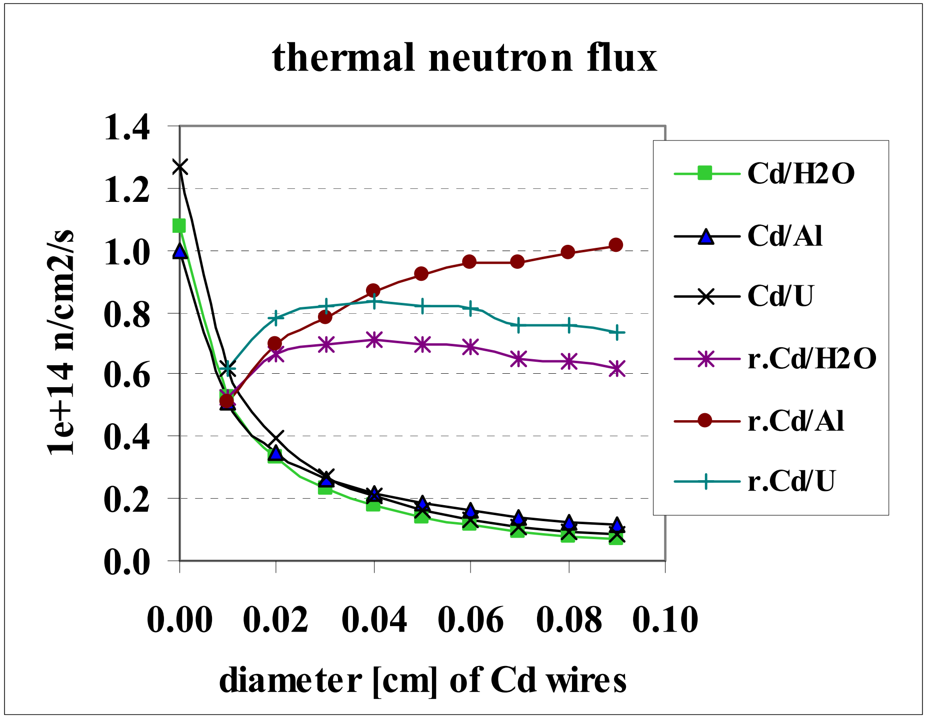

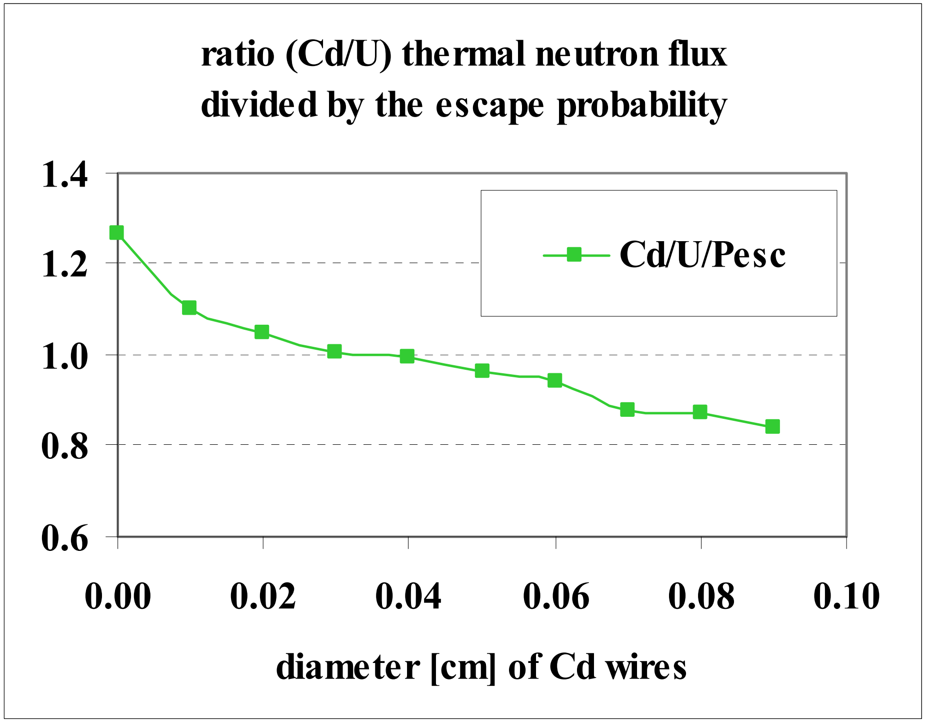

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Ratio of thermal flux in U-235 and Cd-113

first results of RRFM-2004

- the escape probability in a black cyclinder Pesc $\approx (2r\Sigma_{Cd})^{-1}$
- We found heuristically the escape probability in Cd wires meets the ratio Cd/U with the macroscopic thermal cross-section Σ_{Cd}=114 cm^{-1}.
- This eliminates the Milne's problem of extrapolated length near the side-plates.
- the ratio of the thermal neutron flux in Cadmium and Uranium is nearly proportional at escape probability : Pesc with a factor $f_{Cd} \approx 1.0$ Pesc ;
- and more accurately when burning from a Cd diameter from 0.06 until 0.02 cm : f_{Cd} / Pesc= 1.1 - 2.6 x ϕ[cm]

Burn-up of U-235

The local consumption of U-235 versus time consists of

$$\frac{\partial m}{\partial \tau} = -m.\int_{E=0}^{\infty} \sigma_{a,\,U-235}(E).\Phi(E).dE$$

where m [g/cm³] is the density in U-235

τ [s] is the irradiation time

Φ [n/cm²/s] is the local neutron flux

The burn-up value is therefore:

$$\beta = 1 - \frac{m}{m_0} = 1 - \exp(-\int_E \int_\tau \sigma_a(E).\Phi(E,\tau).dE.d\tau)$$

and the maximum burn-up is

$$\beta_{max} = 1 - \exp(-b) \quad \text{where} \quad b = \int_E \int_\tau \sigma_a(E).\Phi_{max}(E,\tau).dE.d\tau$$

Burn-up of Cd-113

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according the integral transport theory, when the media isn't a moderator,
the probability to make a collision in an homogeneous and isotropic cylindrical cell :

$$f = P_{esc} = 2\int_1^\infty K_1(y\Sigma r).I_1(y\Sigma r).dy / y^2$$

$$\text{if} \quad 2\Sigma r > 2 \quad f = \frac{1}{2\Sigma r}.(1 - \frac{3}{4}.(2\Sigma r)^{-2} - \quad ...)$$

$$\text{if} \quad 2\Sigma r < 1 \quad f = (1 + \frac{2}{3}.(2\Sigma r))^{-1}$$

Therefore the effective neutron fraction in the Cadmium wires of radius r may be written

$$2.r_0.\Sigma_{eff} = 2.r_0.n..\Sigma_{Cd}.(f \approx \frac{1}{2\Sigma_{Cd} r}).\frac{vol.Cd = \pi.r^2.L}{vol.cell = \pi.r_0^2.L} \quad \approx n.\frac{r}{r_0}$$

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Burn-up of Cd-113

Cadmium wires for replacing burnable poisons may be localised in the edge of fuel plates in the side-plates. The parameters are

_	the number of wires:	maximum is: n=36
_	initial diameter	between 0.06 and 0.08 cm
_	effective blackness	self-shielding calculation
_	velocity to be burnt	determining the cycle length

In a fuel cell where the diameter is $r_0 = 5.0635$ cm, the effective blackness of Cadmium wire is given by the following formula

$$\Sigma_{eff} = n.\Sigma_{Cd}.f.\frac{vol.Cd = \pi.r^2.L}{vol.cell = \pi.r_0^2.L}$$

where	n	is the number of wires
	f	is the self-shielding factor

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Burning Rate of Cd-113

second results of RRFM-2004

The effective burning rate of Cadmium wire related with the burn-up of U-235 :

$$\frac{\sigma_{Cd} \cdot f}{\sigma_{a,U-235}} \approx \frac{\sigma_{Cd}}{\sigma_{a,U-235}} \cdot \frac{1}{2\ \Sigma_{Cd}\ r}$$

$$\frac{1}{\Sigma_{eff}} \cdot \frac{\partial \Sigma_{eff}}{\partial \tau} = \frac{1}{r} \cdot \frac{\partial r}{\partial \tau} = -\sigma_{Cd} . \Phi_U . f \approx \frac{\sigma_{Cd} . \Phi_U}{2\ \Sigma_{Cd}\ r} \quad or \quad \frac{\partial r}{\partial \tau} = -\frac{\sigma_{Cd} . \Phi_U}{2\ \Sigma_{Cd}}$$

Considering the Westcott's cross-section at 50°C and an epithermal ratio of 0.15:

$\sigma_{w.a}$(U-235) = 667 barn

$\sigma_{w.a}$(B-10) = 3836 barn

$\sigma_{w.a}$(Cd-113) = 30730 barn

with $b = \sigma_{a,U-235} . \Phi_{th} . \tau$

it becomes: $$-\frac{\partial r}{\partial b} = \frac{1}{2\ \Sigma_{Cd}} \cdot \frac{\sigma_{a,Cd-113}}{\sigma_{a,U-235}} = \frac{1/2}{114} \cdot \frac{30730}{667} = 0.20\ cm$$

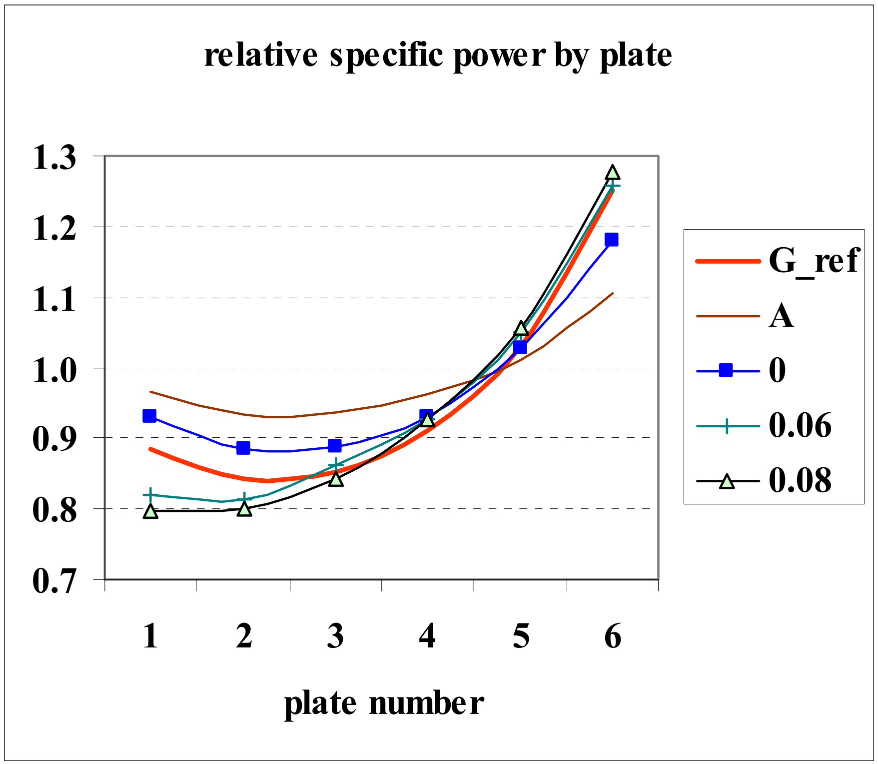
Therefore for a mean burn-up of β_{mean}=10%, β_{max}=14%

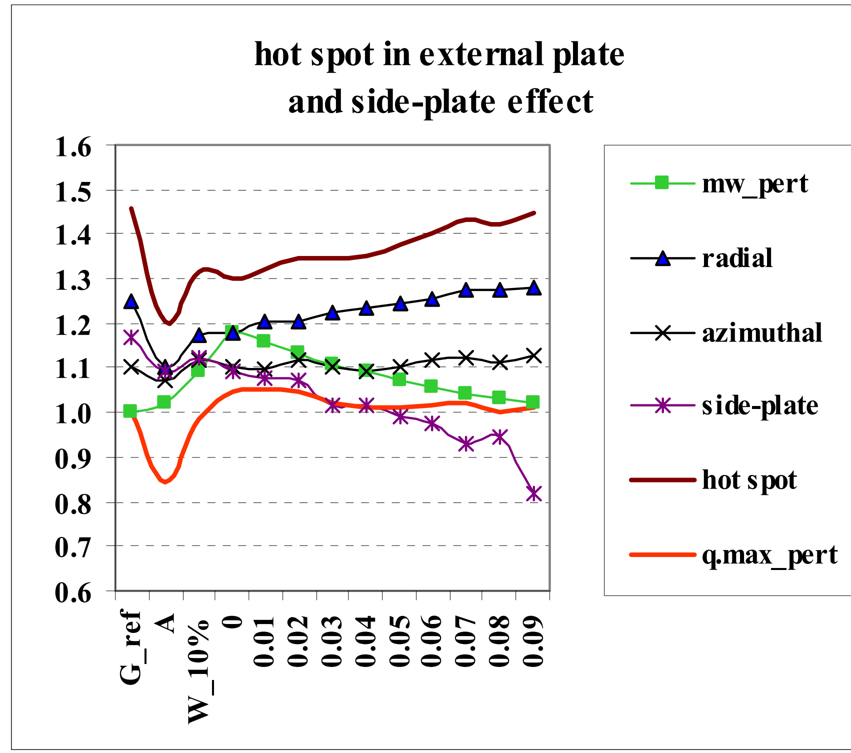
b = -ln(1-0.14) = 0.20 δr = - 0.03 cm

This determines the operation cycle length.

Radial and azimuthal hot spot calculation

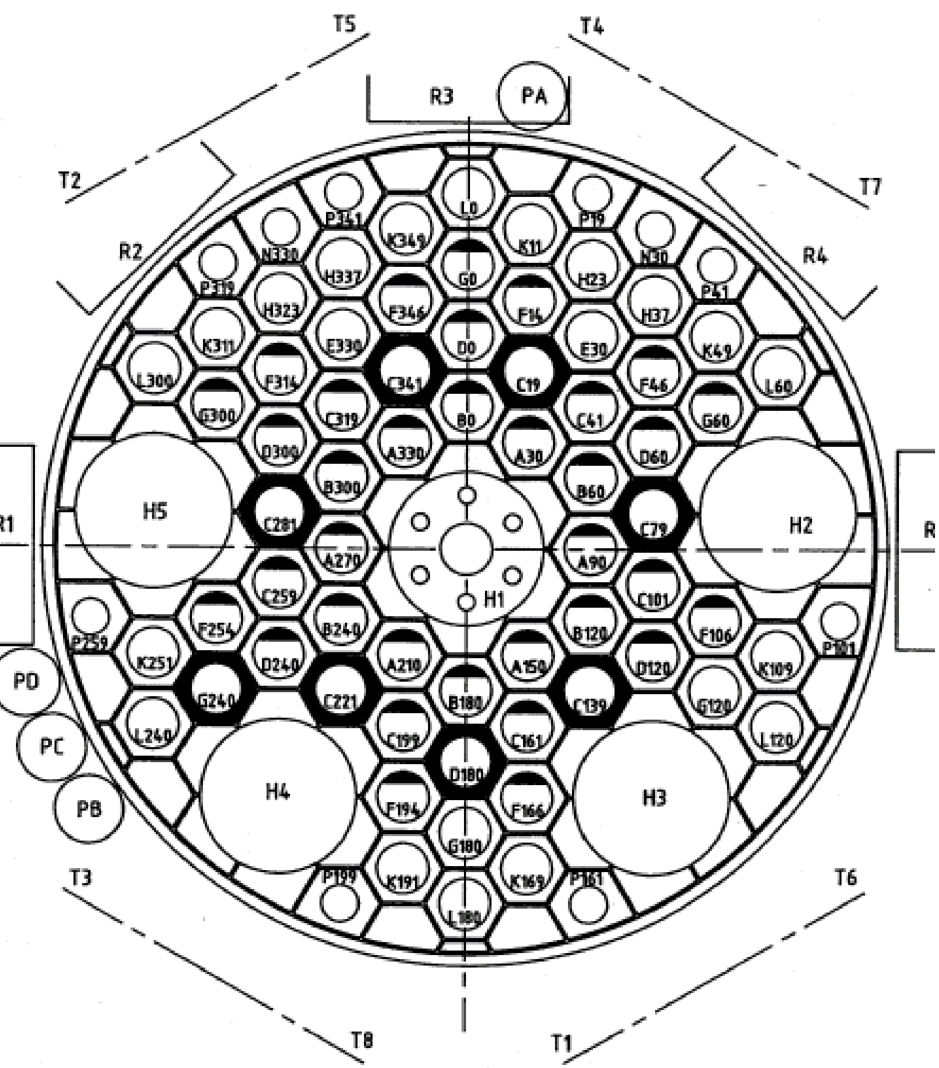
third results of RRFM-2004

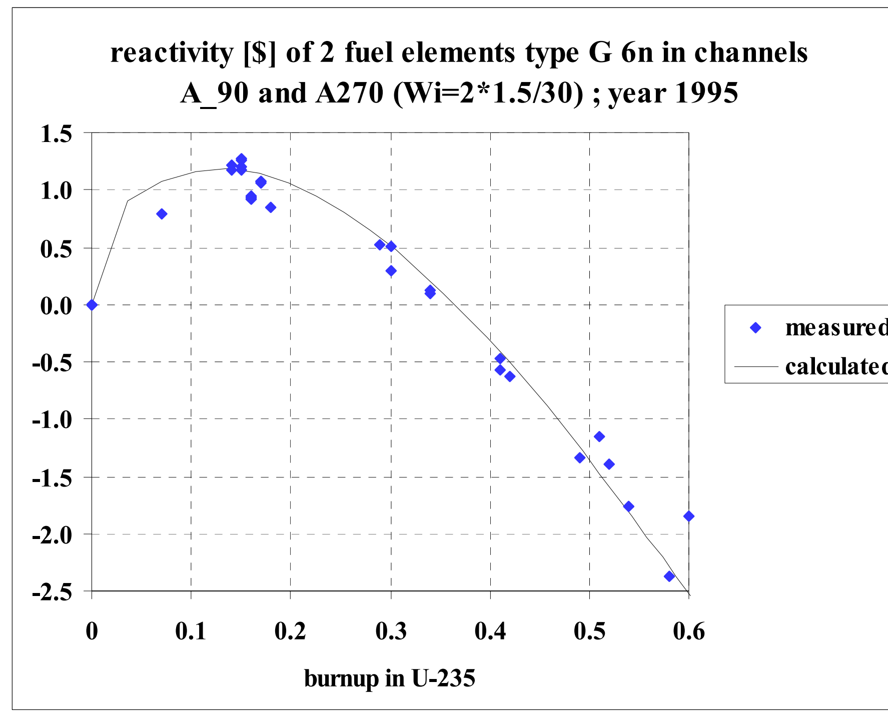




Reactivity Measurements

CONFIGURATION 10U





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Perturbation Calculation

The perturbation theory applied on the system: $\boldsymbol{B}.\,\Phi = \lambda.\boldsymbol{F}.\Phi$

gives: the variation of the eigenvalue λ

the perturbed solution $\Phi' = \Phi + \delta\Phi$

The variation of the eigenvalue is obtained
with the bilinear product by weighting the neutron importance:

$$\delta\lambda = \lambda' - \lambda = \frac{< \Phi^{+}.(\delta B - \lambda.\delta F)\Phi' >}{< \Phi^{+}.F'\Phi' >}$$

$$(B' - \lambda' F')\delta\Phi = -(\delta B - \delta(\lambda F))\Phi$$

Perturbation Calculation

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- the radial distribution of neutron flux is calculated by transport of thermal neutrons in concentric annular cells with diffusion boundary condition (which determines the epithermal ratio) = two groups theory.

- this epithermal ratio is verified
  by DCI (Co/Cd) measurement,
  and by MonteCarlo calculations.

- the maximum and mean burn-up is calculated accordingly
  at elimination it is:

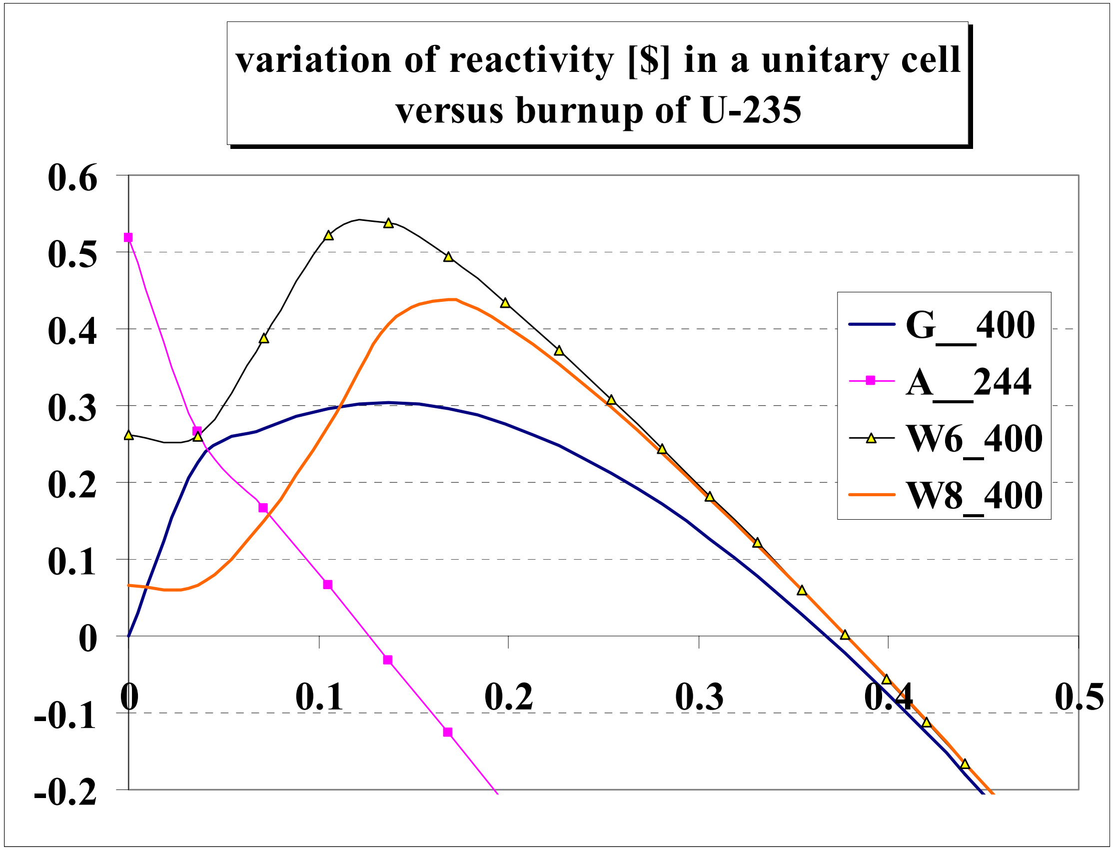
$$\beta_{\max} = 1 - \exp(-\sigma_{a.U5}.\Phi_{\max}.\tau = 1) = 63\%$$

and $$\beta_{mean} \approx 1 - (1 - \beta_{\max})^{0.70} = 50\%$$

Unitary Cell : Reactivity Variation

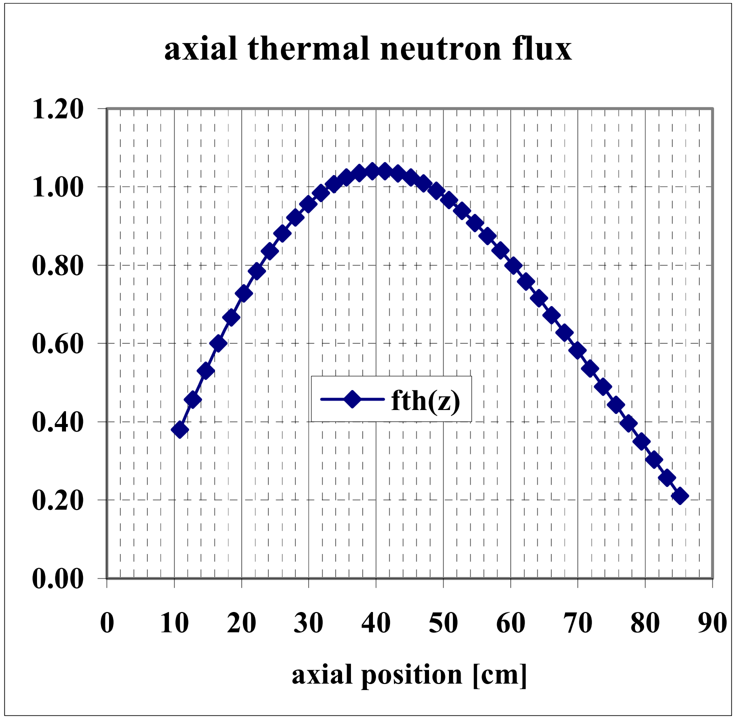
fourth results of RRFM-2004

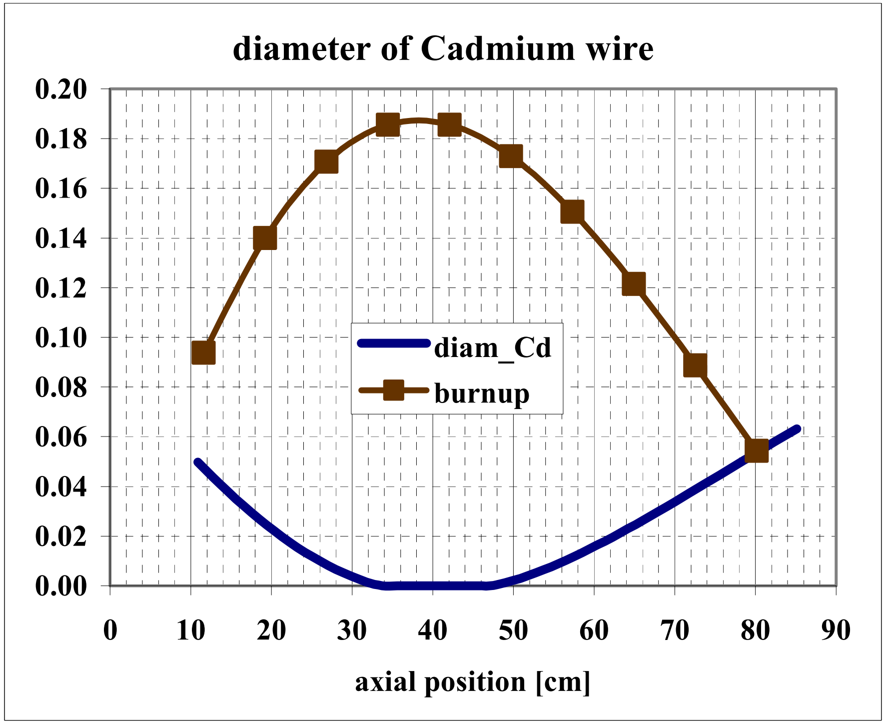
- $^{135}Xe=0$, ^{149}Sm saturated at shut-down



Reduction of the Cadmium diameter

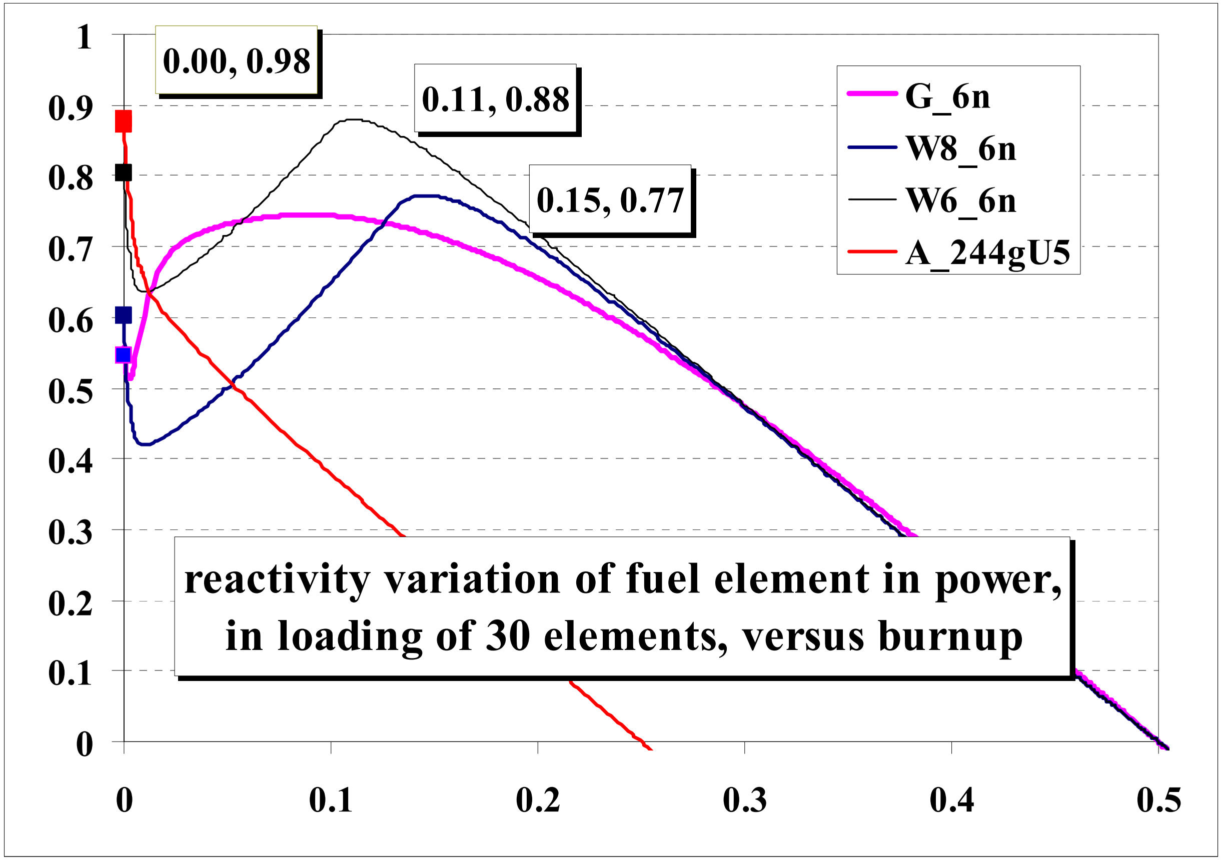
- **reduction of the Cadmium diameter 0.8 mm for mean burn-up 15%**





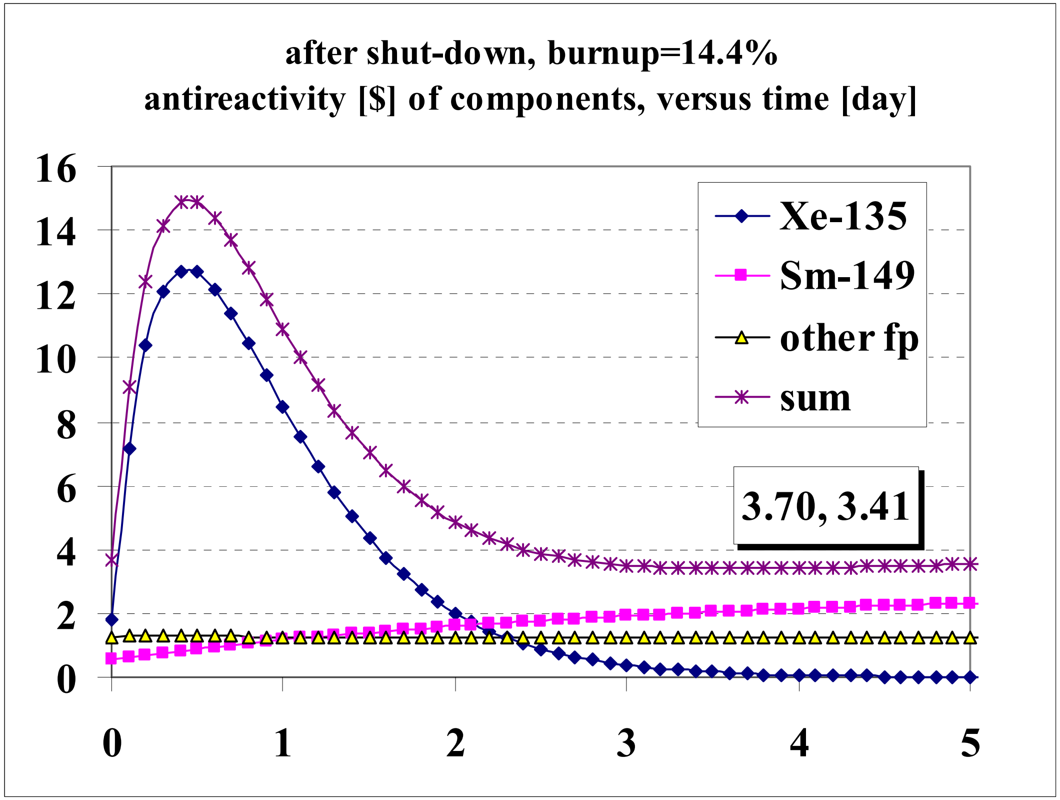
Unitary Cell : Reactivity Variation

- ^{235}U, ^{236}U, ^{237}Np, ^{238}U, ^{135}Xe, ^{149}Sm, ^{151}Sm and other fission products evaluated by MCNP-4C
- 10 axial paths

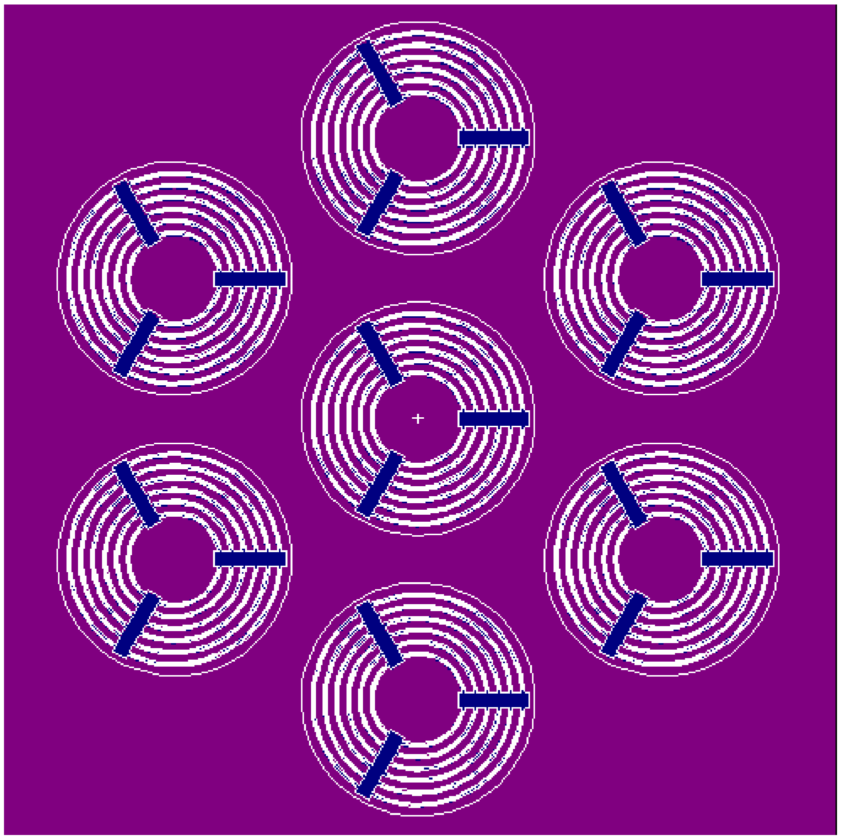


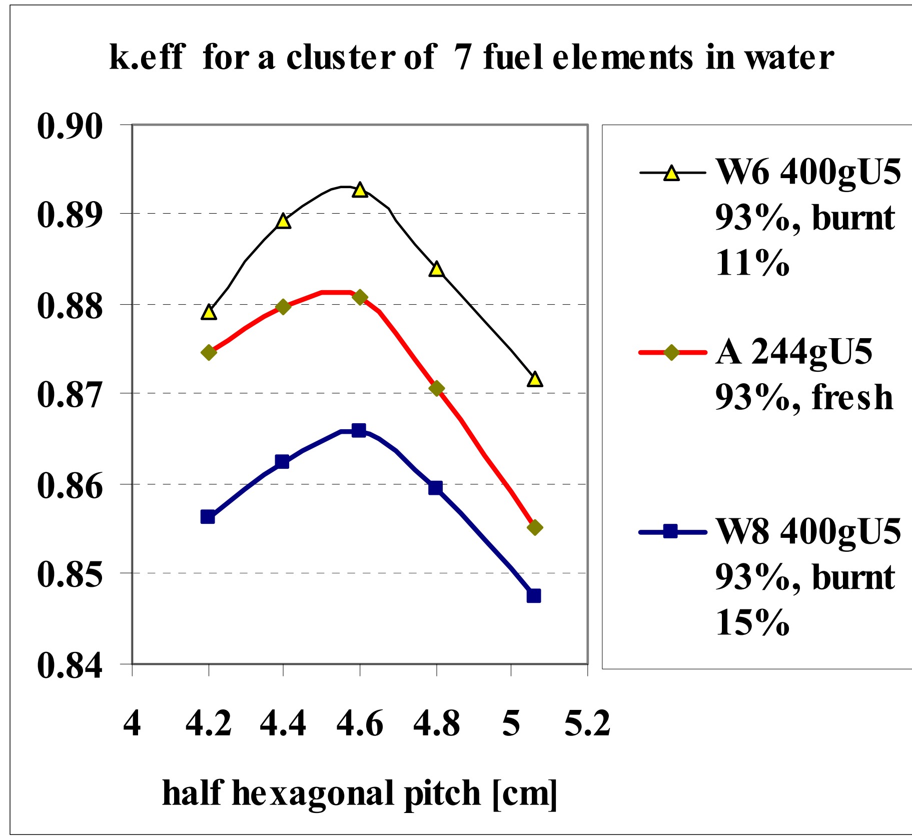
Reactivity Variation, after shut-down

- ^{235}U, ^{236}U, ^{237}Np, ^{238}U, ^{135}Xe, ^{149}Sm, ^{151}Sm and other fission products evaluated by MCNP-4C
- 10 axial paths



Criticality for a Cluster of 7 fuel elements in water





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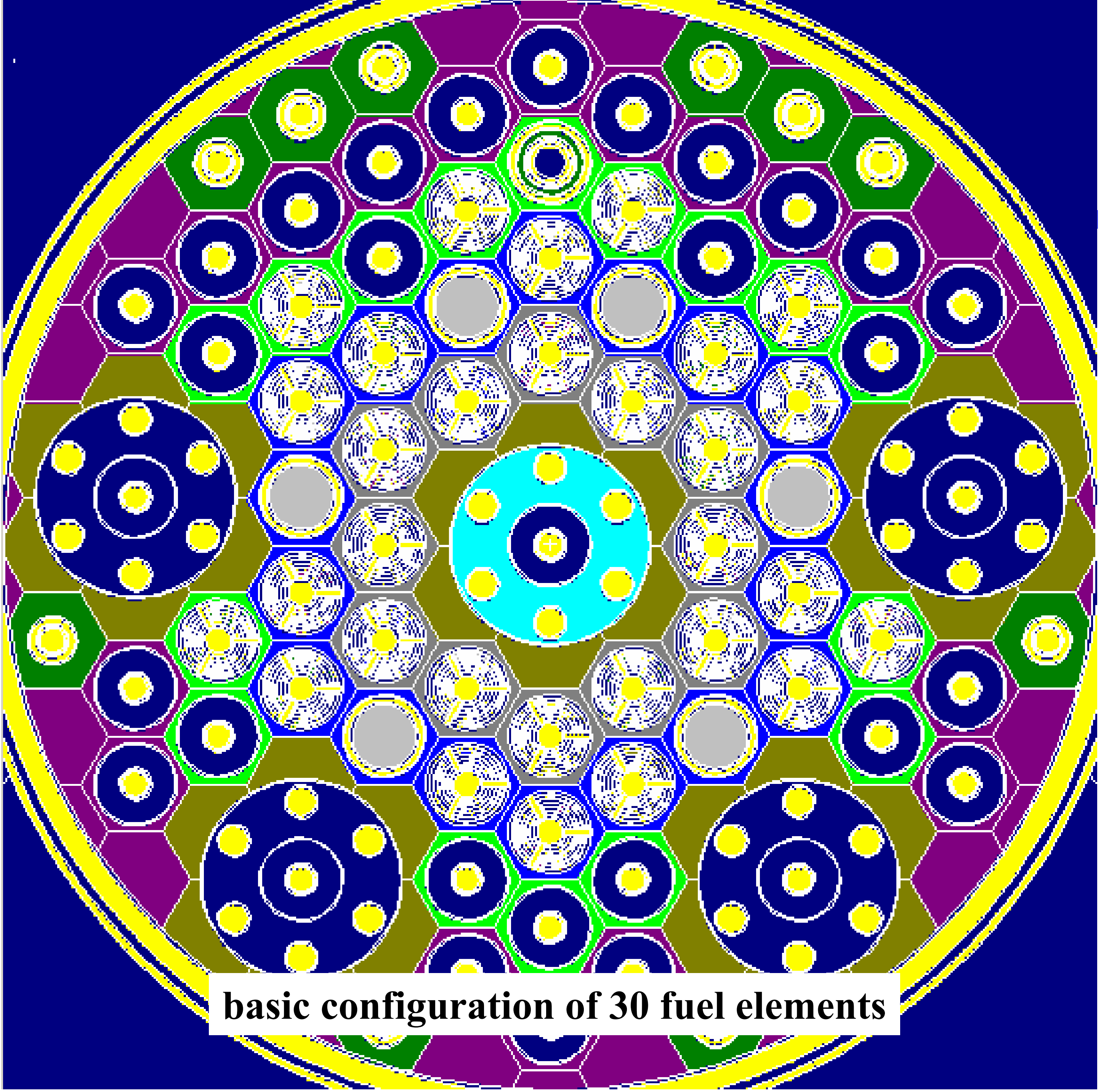


basic configuration of 30 fuel elements

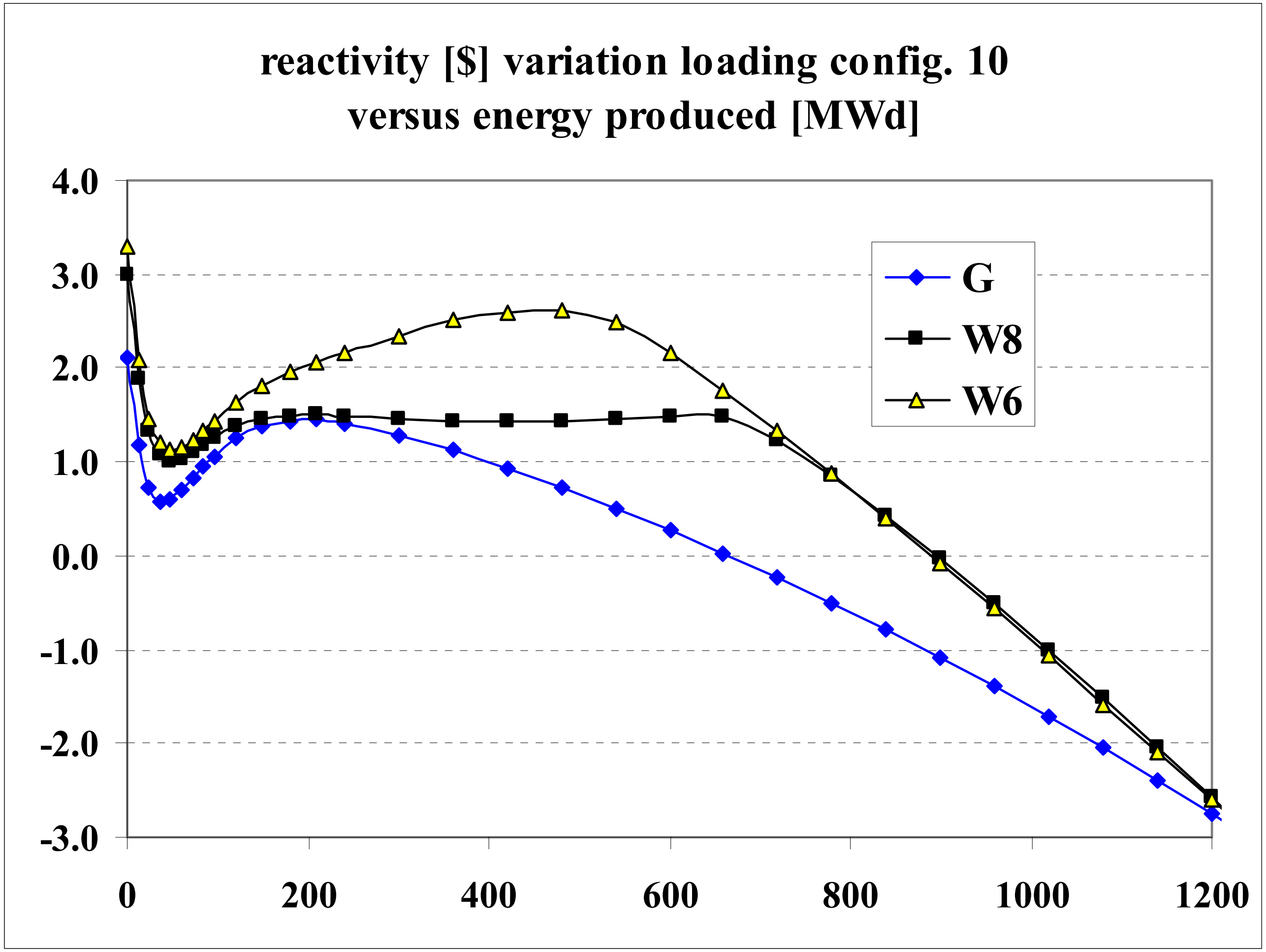
Operational BR2 Cycle

- BR2 cycles are operated
  - for 21 - 28 days at a nominal power of 26.5 MW in the central ring (channels A & B).
  - Routinely 6 - 9 fresh fuel are loaded in the second ring (channel C and D) reached a burn-up of about 15%
  - partially burnt fuel elements are loaded in the channels A and B reaching 30% and 45% burn-up;
  - after theses paths the partially burnt fuel elements are loaded in external positions.

Operational BR2 Cycle

- $^{3}He = 0$ $
- 6 fresh fuel
- 1200 MWd

movement	$
G	5.24
W8	6.12
W6	6.41



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Shim rods worth

- **6 shim worth is ~12 $**
- Xe-Sm transient = 2.7 $
- ejection of a shim rod = 2 $
- safety margin = 2.5 $
- **allowed for operation: 4.8 $**

Operational BR2 Cycle

- ^{3}He = 0 $
- 6 fresh fuel
- 1200 MWd

movement	$
G	5.24
W8	6.12
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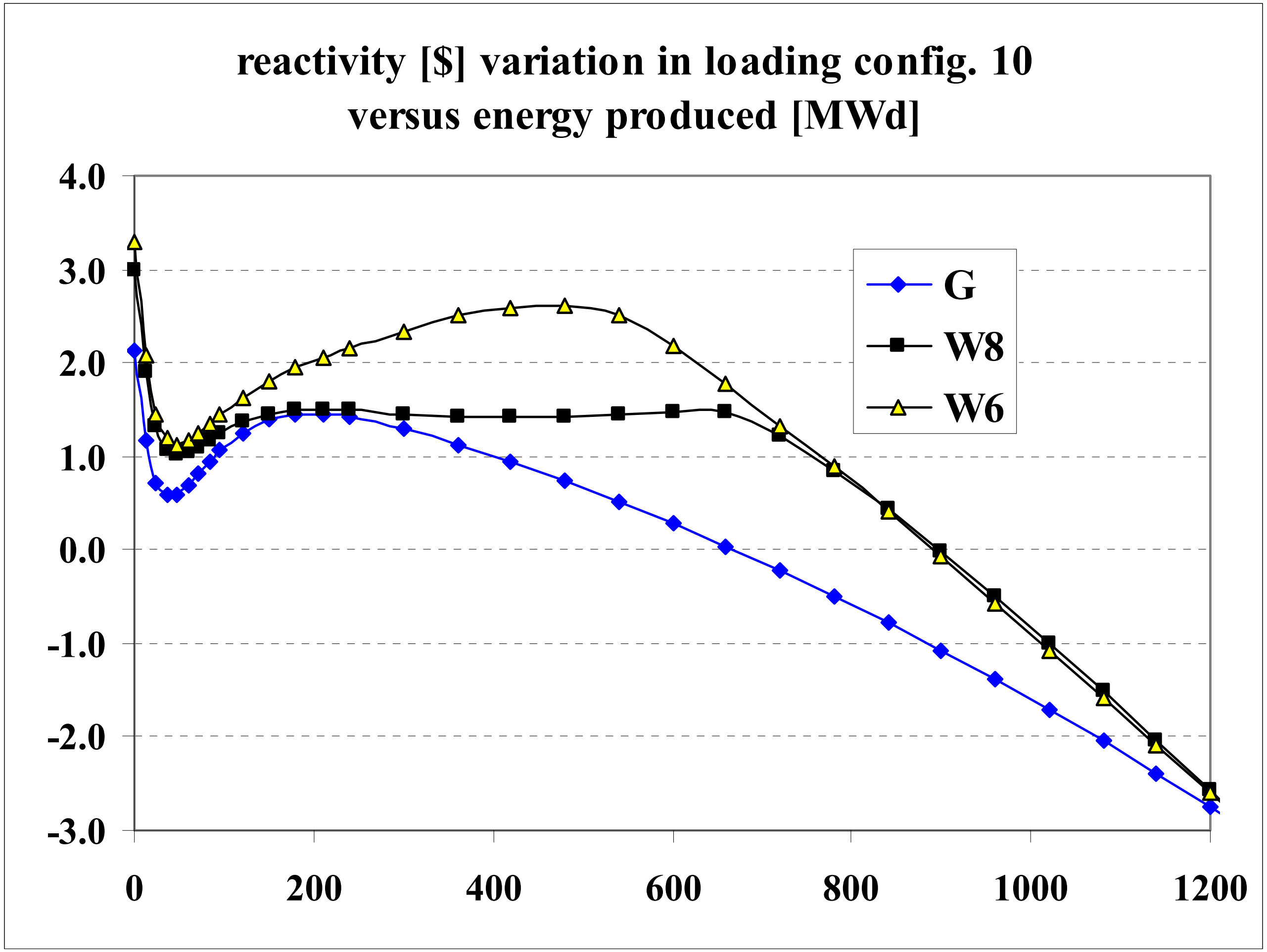
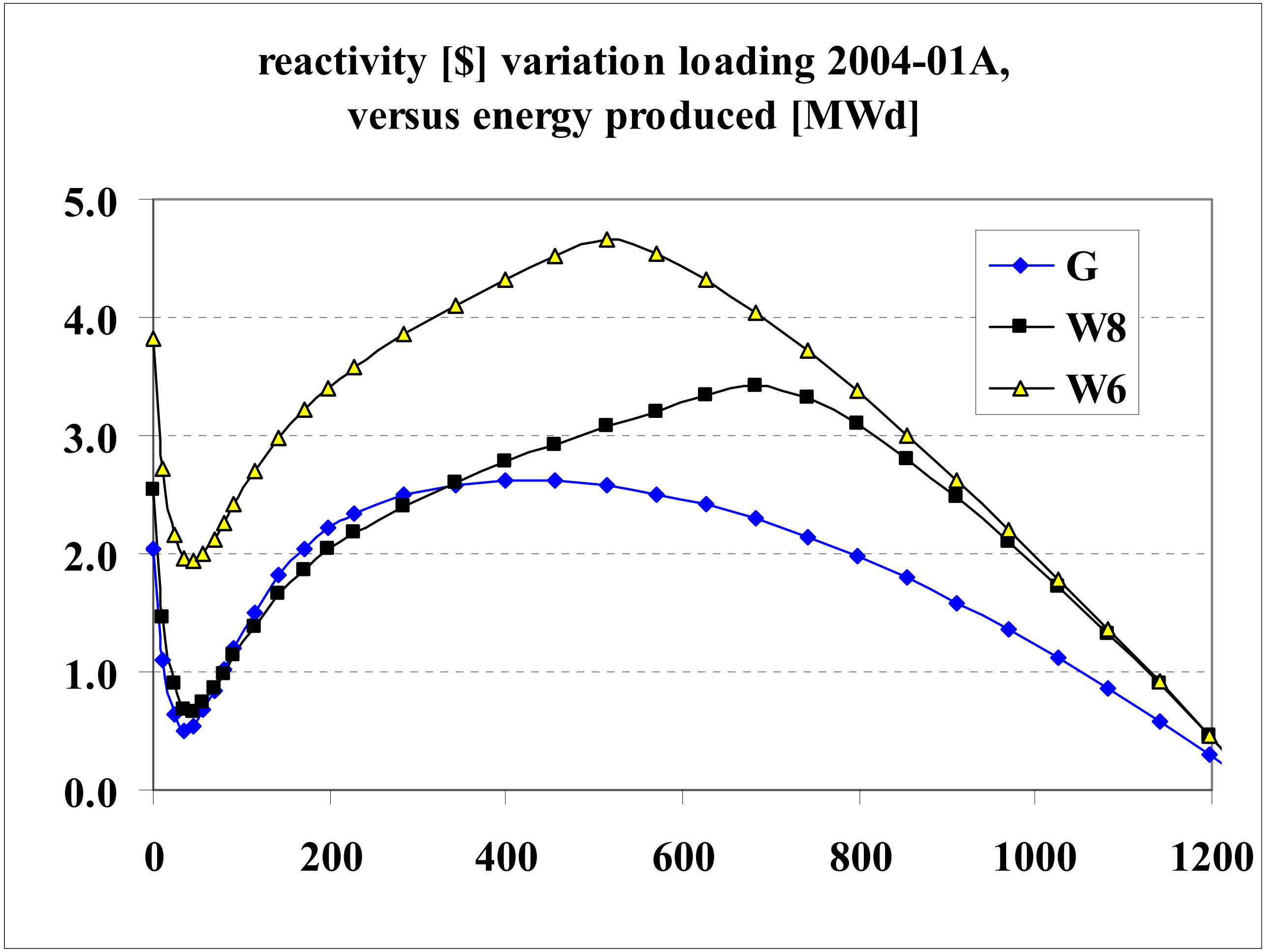


Operational BR2 Cycle

- ^3He = -3.88 $
- 6 fresh fuel
- 1200 MWd

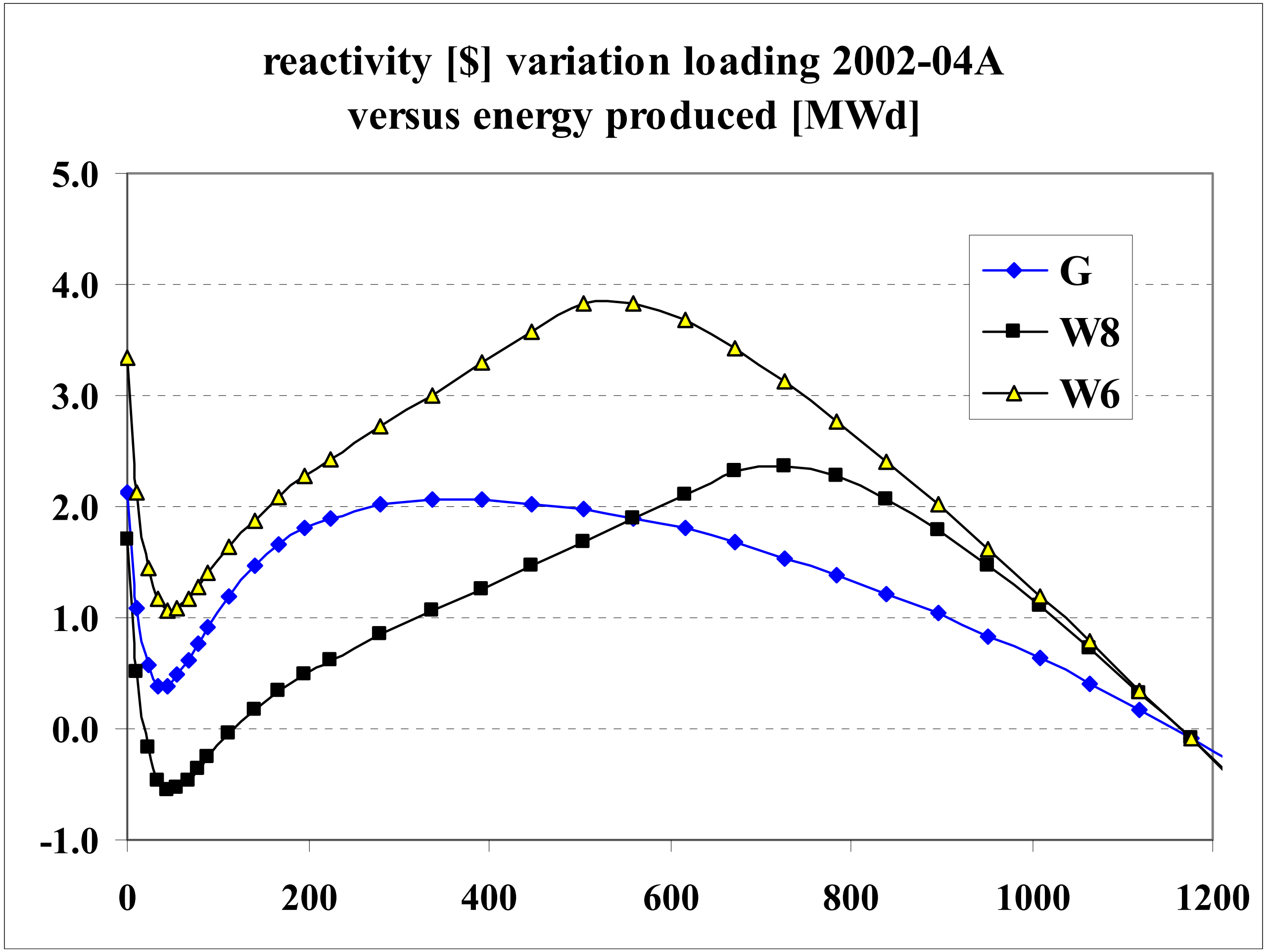
movement	$
G	2.32
W8	2.97
W6	4.20



Operational BR2 Cycle

- ^3He = -2.03 $
- 9 fresh fuel
- 1200 MWd

movement	$
G	2.34
W8	2.89
W6	4.15



Operational BR2 Cycle

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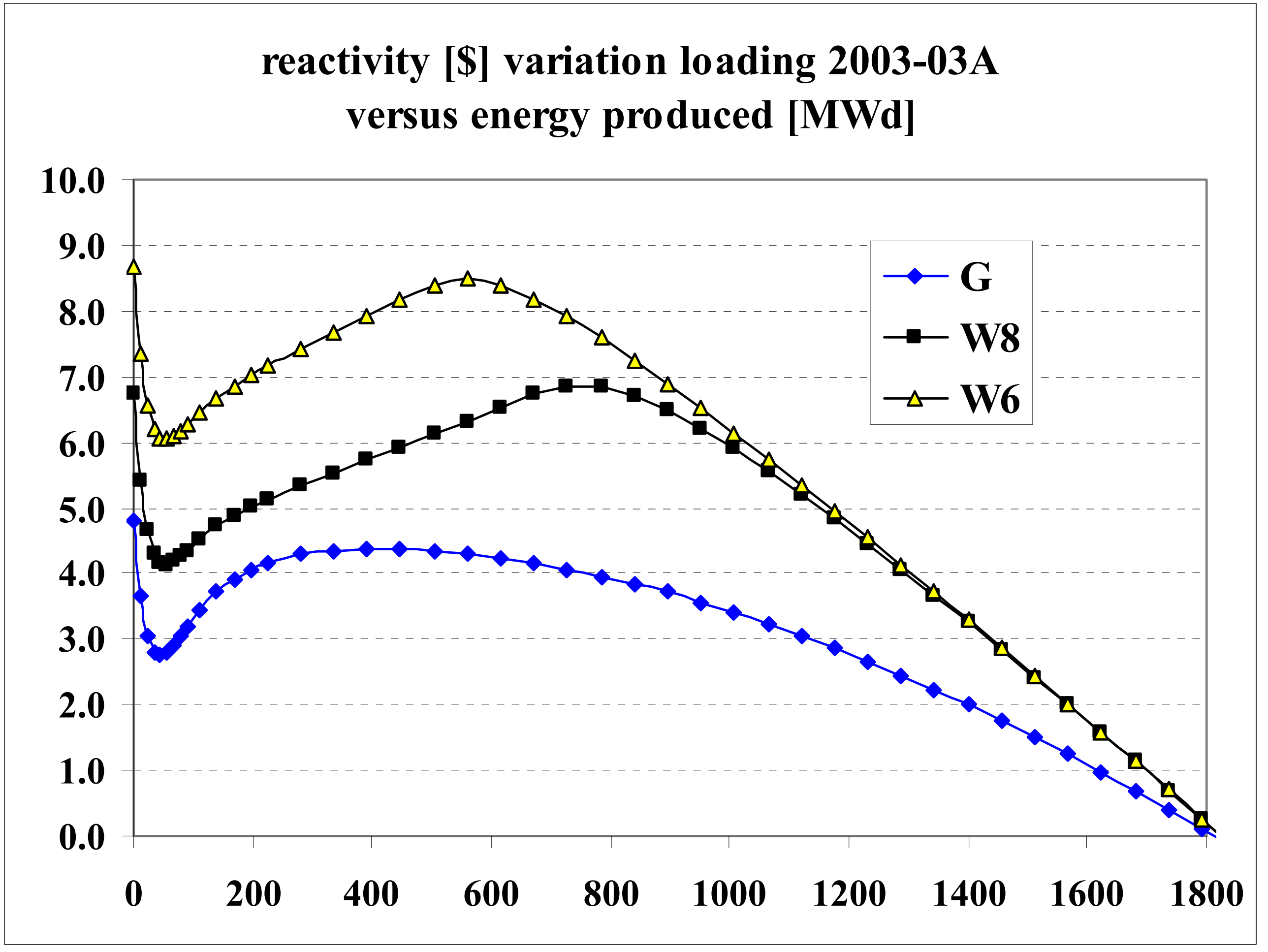
- ^{3}He = -1.06 $
- 10 fresh fuel
- 1800 MWd

movement	$
G	4.68
W8	6.59
W6	8.43



Operational BR2 Cycle

- **6 shim worth is ~12 $**
- Xe-Sm transient = 2.7 $
- ejection of a shim rod = 2 $
- safety margin = 2.5 $
- **allowed for operation: 4.8 $**

cycle	number fresh fuel	energy MWd	observed Δ$	G B-10	Cd-wire 0.8mm	Cd-wire 0.6mm
2004-01	6	1200	2.05	2.32	2.97	4.2
2002-04	9	1200	2.12	2.34	2.89	4.15
2003-03	10	1800	4.79	4.68	6.59	8.43

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Conclusion (1)

- the effective blackness of Cadmium wire has been determined.
- the burning rate of Cadmium wire has been determined.
- the hot spot factors has been determined for the parameters: radial, azimuthal and side-plate effect
- gain in reactivity of core loadings ?
  - expecting new development for the irradiation programme (Cd screened loop, SSteel IPS,...)
  - expecting reduction of fabrication costs

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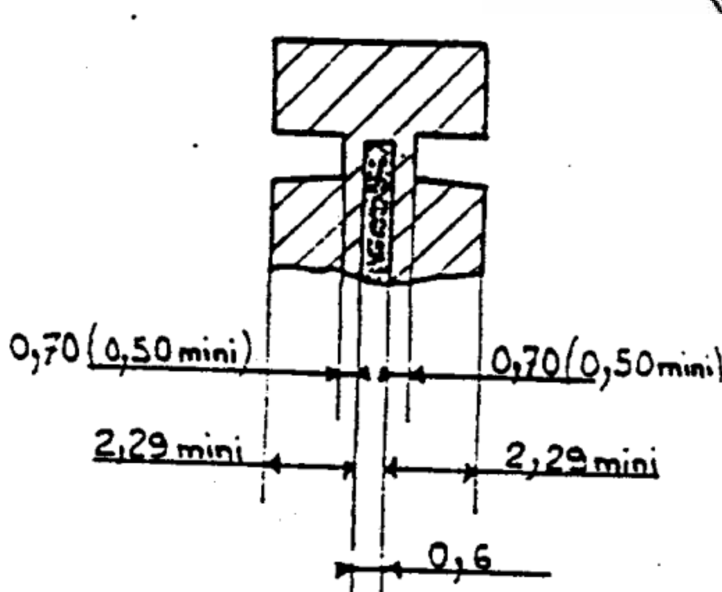
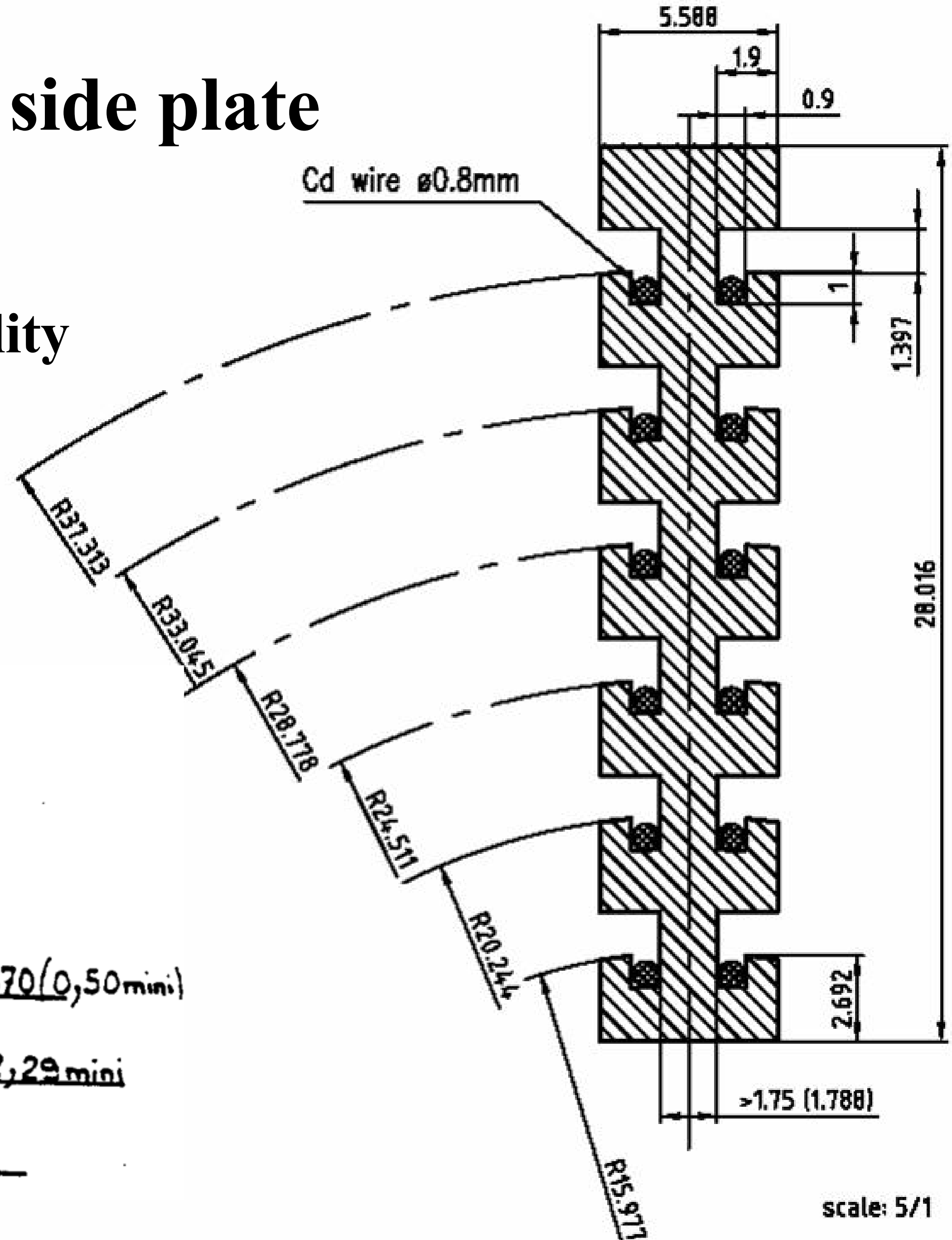
design of side plate

mechanical feasibility of side plate containing poison





Conclusion in safety point of view (2)

- **Safety consideration :**
  less reactive than the former fresh fuel element type ‘A 6n’ containing 244 g U-235 ?
-
  - **the fuel element W6 11% is not less reactive**
  - **the fuel element W8 14% is less reactive**

Conclusion for operational cycle (3)

- Operational cycle ?
  - satisfying for 21 days of operation
  - not satisfying for 28 days of operation

- searching additional control absorbers
  to be inserted in the axial position of fuel elements
  positioned in the central ring

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mechanical feasibility of side plate containing poison