FAST NEUTRON FLUENCE IN BERYLLIUM BLOCKS

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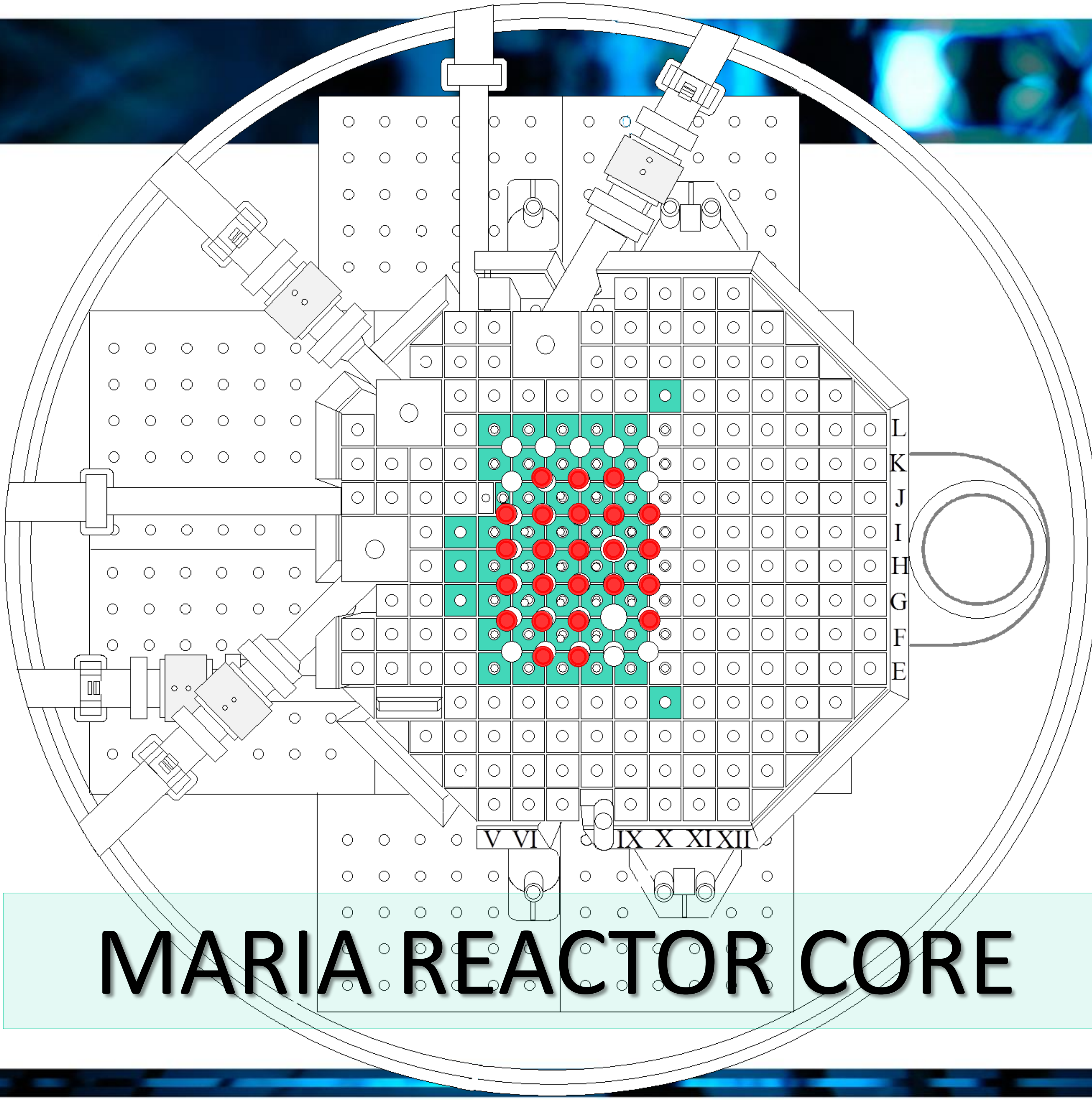


As a moderator: beryllium matrix, consisted of 45 beryllium blocks.

MARIA REACTOR CORE

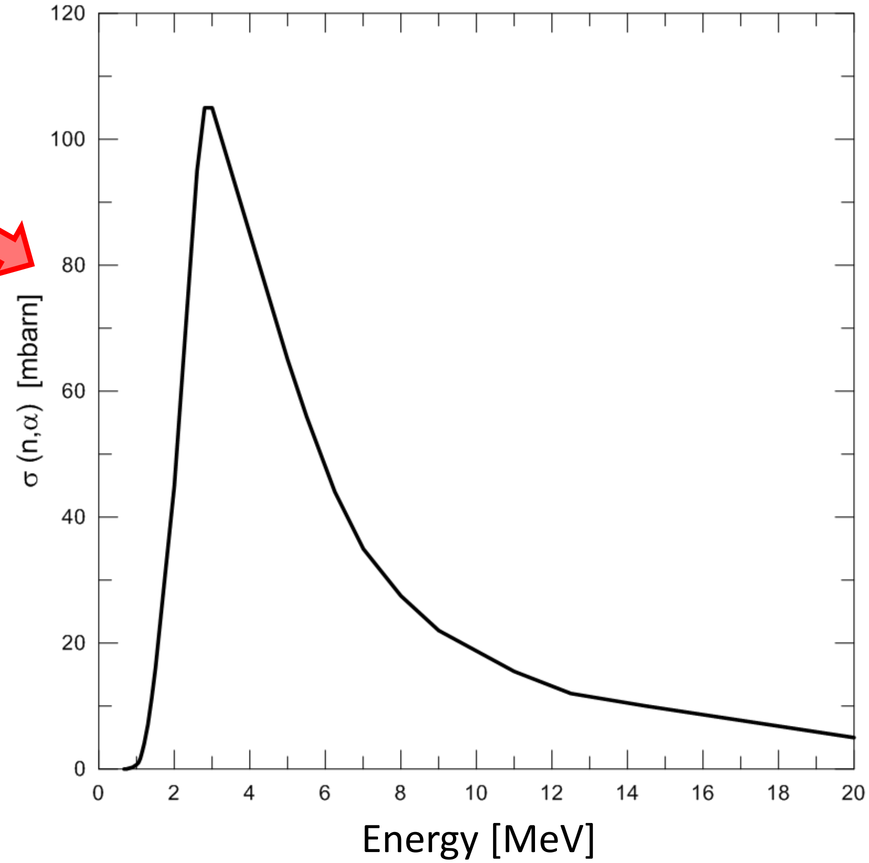
BERYLLIUM POISSONING

$$^{9}_{4}Be(n,\alpha)^{6}_{2}He \xrightarrow{\beta^{-}(0,8s)} {}^{6}_{3}Li$$

$$^{6}_{3}Li(n,\alpha)^{3}_{1}H$$

$$^{3}_{1}H \xrightarrow{\beta^{-}(12,35\ y)} {}^{3}_{2}He$$

$$^{3}_{2}He(n,p)^{3}_{1}H$$

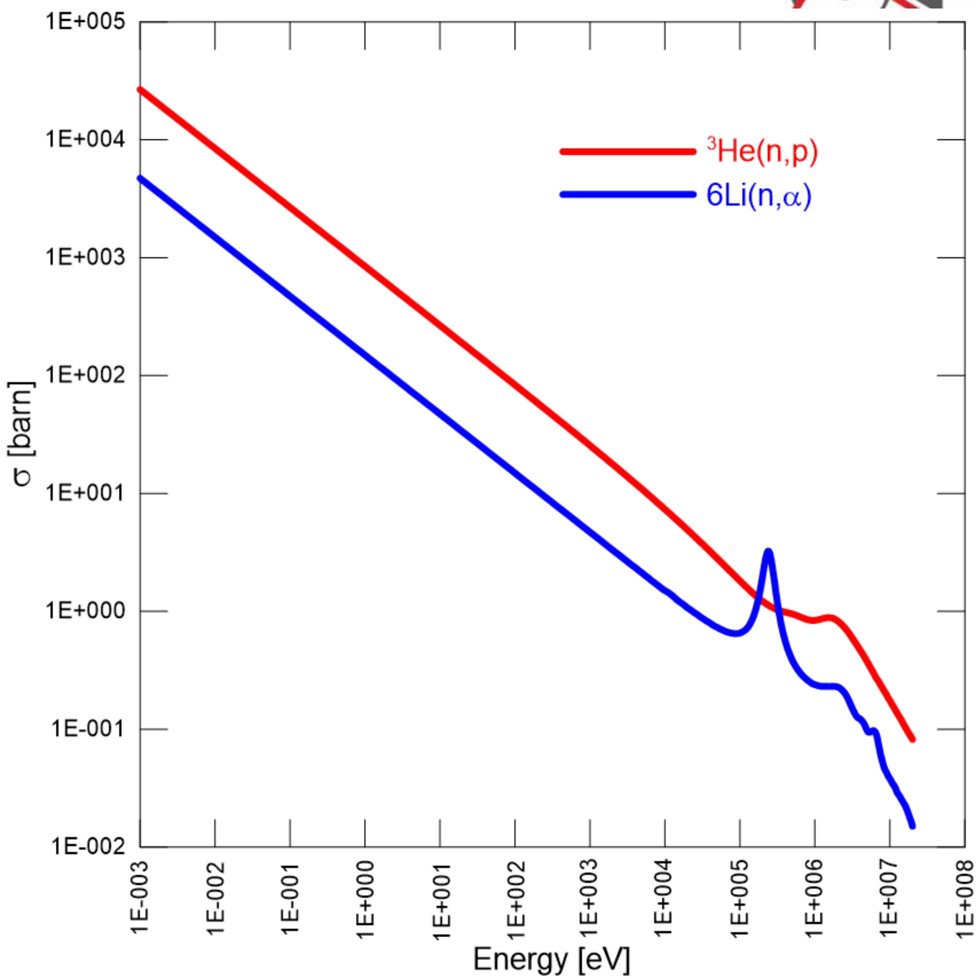


^{6}Li and ^{3}He - strong absorbers of thermal neutrons

BERYLLIUM POISSONING

$$ {}^{6}_{3}Li(n,\alpha){}^{3}_{1}H $$

$$ {}^{3}_{2}He(n,p){}^{3}_{1}H $$



Strong poisoning effect to the core – reduction of excess reactivity

BERYLLIUM DEGENERATION

Besides the poisoning effect, over time and increasing numer of absorbed neutrons, nuclear and mechanical properties of beryllium matrix deteriorate. This is mostly related to the generation of gases in the beryllium:

Tritium **^{3}H**,

Helium **^{3}He**,

α particle (helium-4),

protons (hydrogen).

FAST NEUTRON FLUENCE

Fast fluence is a measure of fast neutrons dose in beryllium block's volume throughout it's life, until the moment t.

$$F(t) = \int_0^t \varphi_f dt$$

The value of beryllium block fluence does not show directly the material damage level, but it is the simpliest criterion of the material degeneration evaluation, including gas generation.

FAST NEUTRON FLUENCE

Limit specified in the Operational Safety Analysis Report of MARIA Reactor sounds:

„Maximum fluence of fast neutrons (E_n > 0.5 MeV) in beryllium blocks can not exceed $2 \cdot 10^{22}$ n/cm^2".

BATEMAN'S EQUATIONS

$$\frac{dN_b}{dt} = -N_b \sigma_f \varphi_f \qquad (1)$$

$$\frac{dN_l}{dt} = N_b \sigma_f \varphi_f - N_l \sigma_l \varphi \qquad (2)$$

$$\frac{dN_t}{dt} = N_l \sigma_l \varphi - \lambda_t N_t + N_h \sigma_h \varphi \qquad (3)$$

$$\frac{dN_h}{dt} = \lambda_t N_t - N_h \sigma_h \varphi \qquad (4)$$

N_b, N_l, N_t, N_h - beryllium, litium, tritium and helium concentrations,

σ_f - beryllium microscopic cross section for (n, α) reaction,

φ_f - average fast neutron flux density in beryllium,

$\sigma_l = 940$ [barn] - ^{6}Li microscopic cross section (2200 m/s) for (n, α)

φ - average thermal neutron flux density in beryllium,

$\lambda_t = 1.78 \cdot 10^{-9}$ [s^{-1}] - tritium decay constant,

$\sigma_h = 5333$ [barn] - ^{3}He microscopic cross section (2200 m/s) for (n, p) reaction.

BATEMAN'S EQUATIONS

By adding equations (2), (3) and (4), we obtain:

$$\frac{d}{dt}(N_l + N_h + N_t) = N_b \sigma_f \varphi_f$$

We can assume, that (unlike the changes of ^6Li, ^3H and ^3He concentrations) the value of N_b during operation is almost constant. Therefore integrating both sides of above equation one obtains:

$$\Delta(N_l + N_h + N_t) = N_b \sigma_f \int_0^t \varphi_f dt$$

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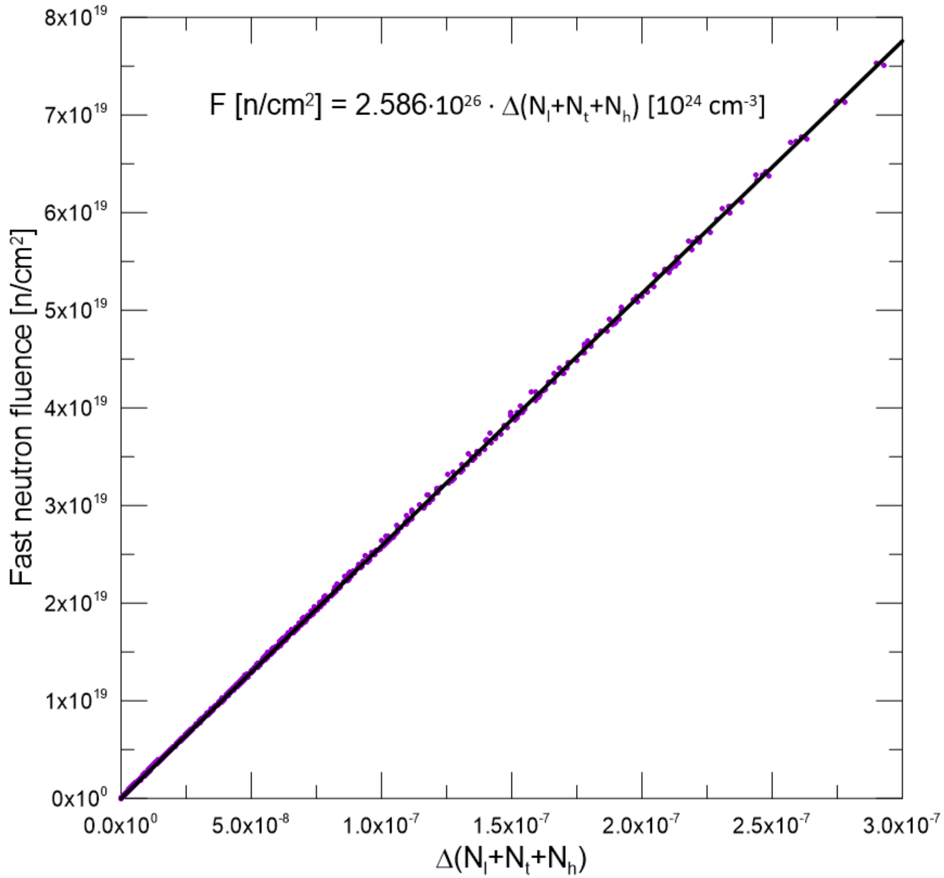
$$\boxed{\Delta(N_l + N_h + N_t) = N_b \sigma_f \int_0^t \varphi_f dt}$$

ISOTOPE CONCENTRATION METHOD

The sum of ^{6}Li, ^{3}H and ^{3}He concentrations is linearly dependent on fast neutron fluence.



The result of diffusion calculations (group structure for MARIA operation model) for fresh beryllium matrix and fresh fuel elements, for hypothetical, 20-day-long operation of the reactor.

Constant of proportionality equals to 258.6 cm can be interpreted as average mean free path of fast neutron for the reaction $^{9}Be(n,\alpha)^{6}He$, *i.e.* inverse of effective macroscopic cross section:

$$1/N_b\sigma_f$$

ISOTOPE CONCENTRATION

Examples of ^{6}Li, ^{3}H and ^{3}He concentrations as a function of fast neutron fluence

Fast neutron fluence [n/cm²]	6Li [ppm]	3H [ppm]	3He [ppm]
$1.4 \cdot 10^{19}$	0.25	0.18	0.03
$8.5 \cdot 10^{21}$	10	250	24

Above fluences are achievable respectively within days and years in MARIA reactor core.

Thus, the verification of Isotope Concentration Method by means of SIMS (Secondary Ion Mass Spectrometry) measurements of concentrations of ^{6}Li, ^{3}H or ^{3}He is achievable with Be samples (coupons) irradiated in several locations of MARIA core within realistic time period.

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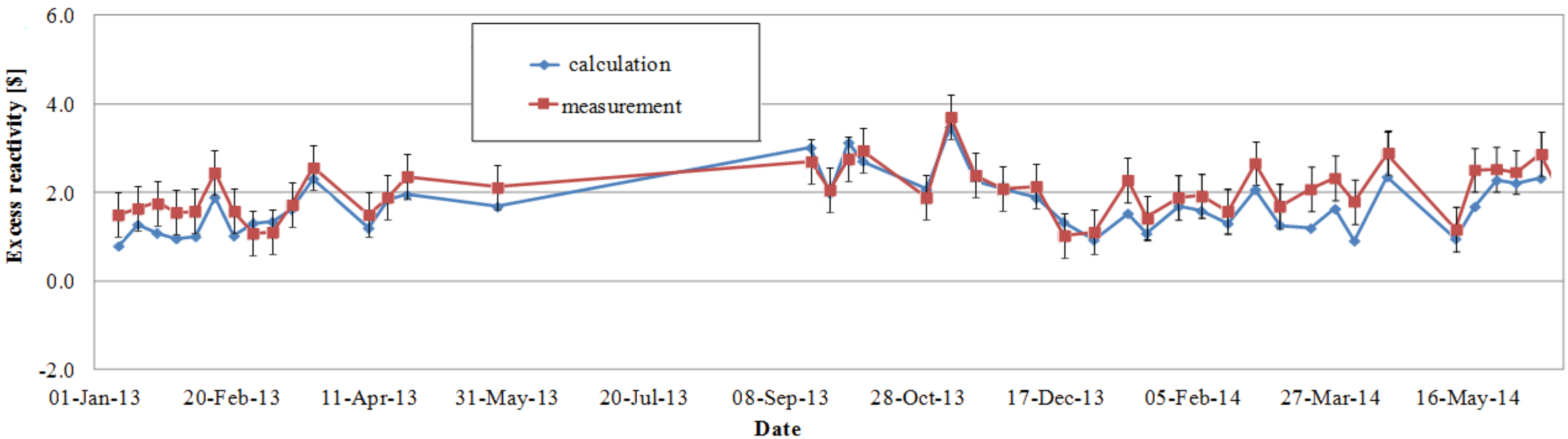
EXCESS REACTIVITY

The agreement of excess reactivity measurements and follow-up calculations indirectly confirms compliance of ^{6}Li and ^{3}He

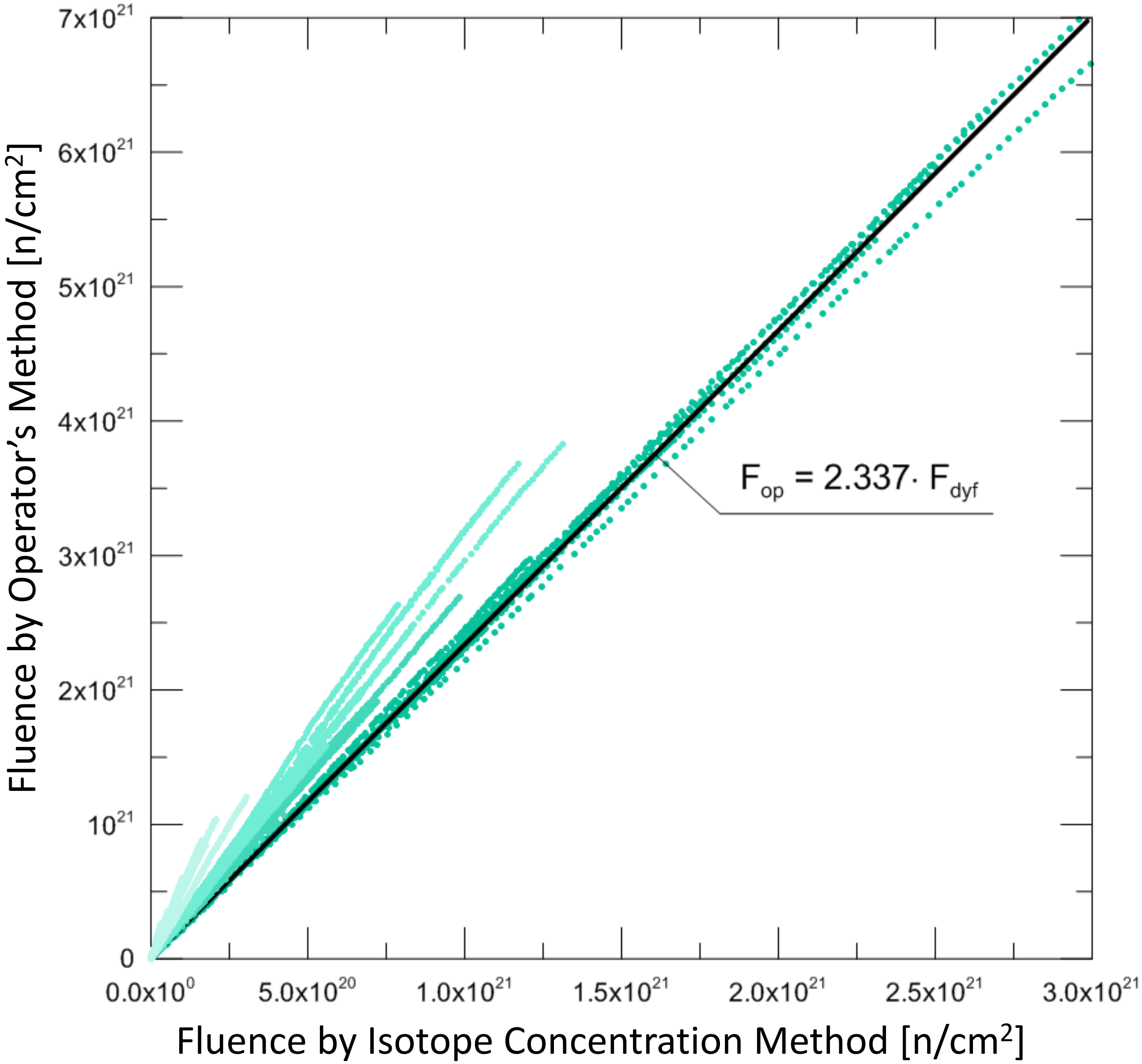


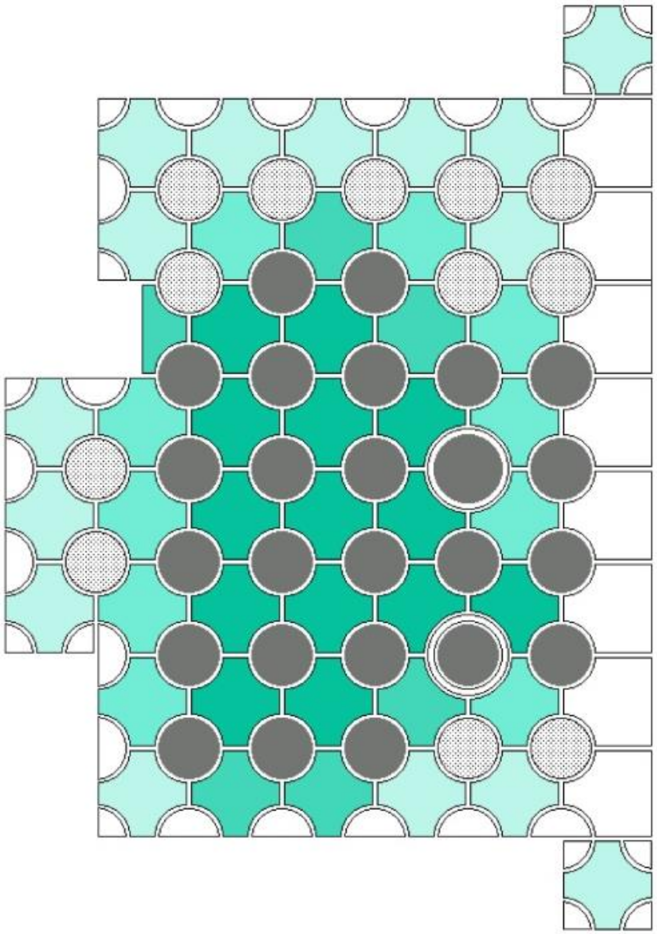
Dynamics of ^{3}H to ^{3}He transition is especially noticeable durig long break of reactor operation. After over 1 year break in MARIA operation in 2004 the agreement of measured and calculated excess reactivity was ~0.1$.

FLUENCE DETERMINATION

Isotope Concentration Method (average fluence in block)	Operator's Method (old method)
Diffusion model calculations (by-product of excess reactivity calculations)	Calculations based on power measurements of fuel assemblies neighbouring concidered beryllium block.
The sum of ^{6}Li, ^{3}H i ^{3}He concentrations	Function of fluences from neighbouring fuel elements.

COMPARISON OF METHODS





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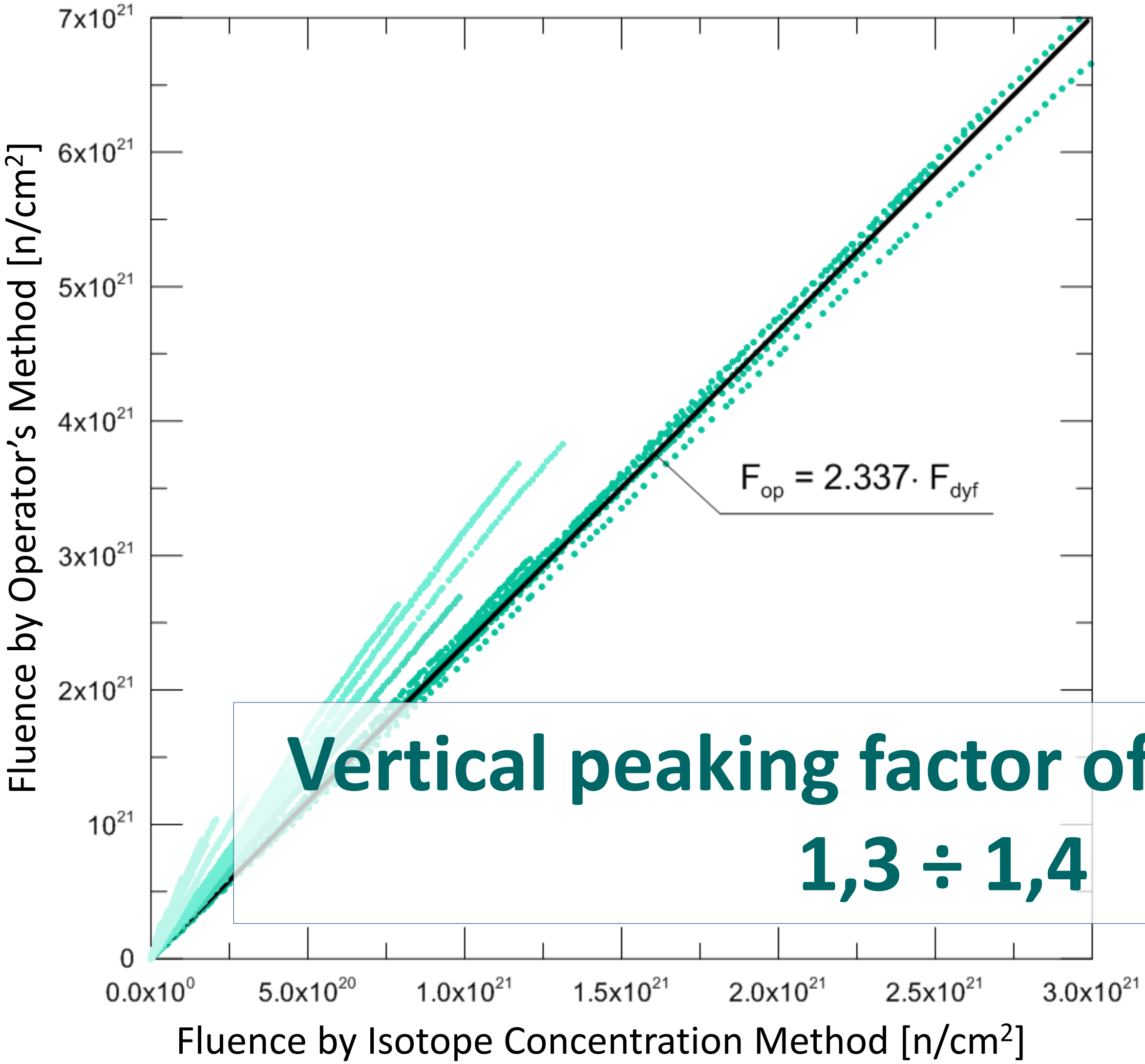
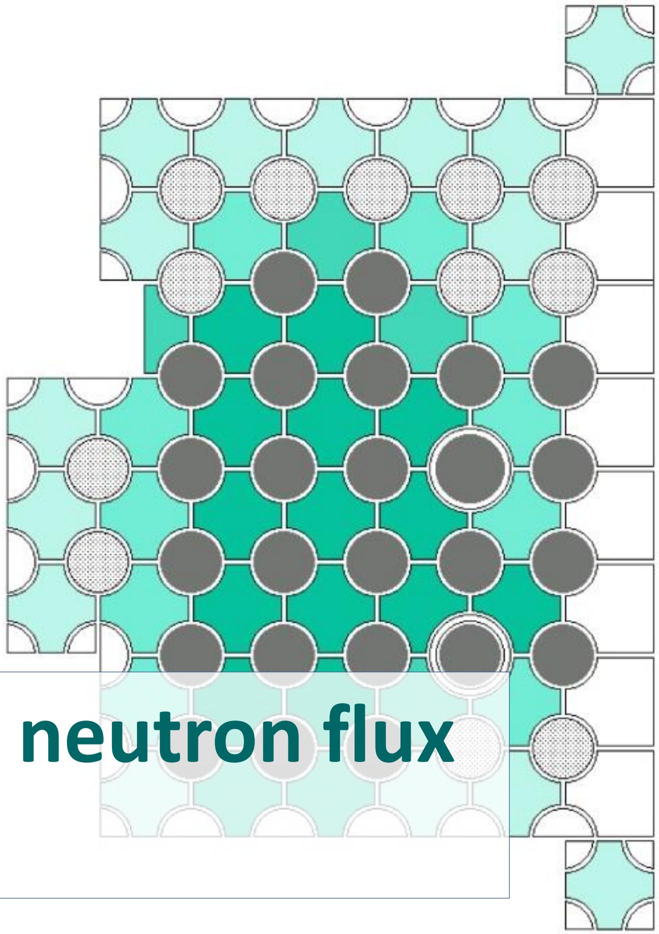
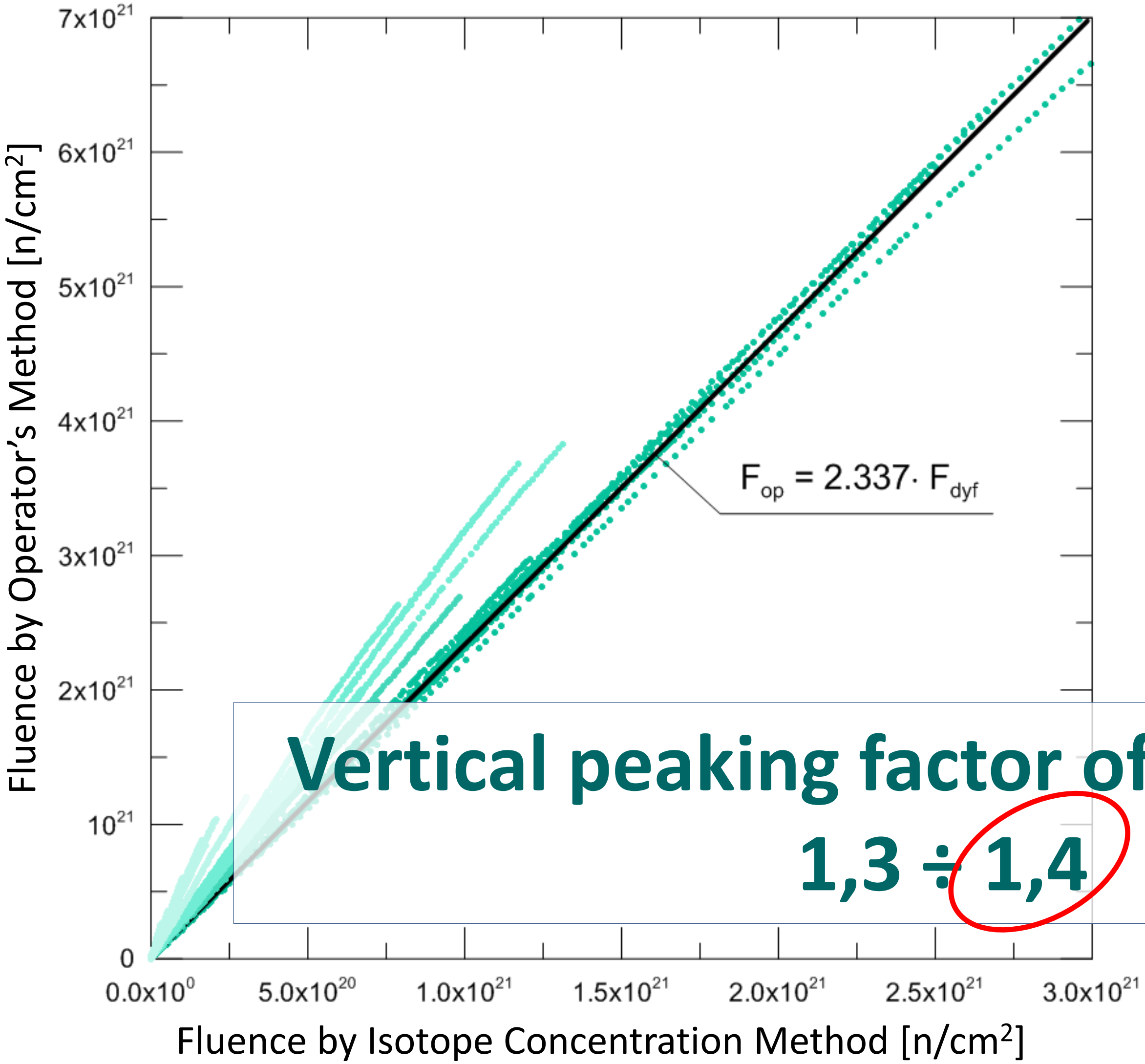


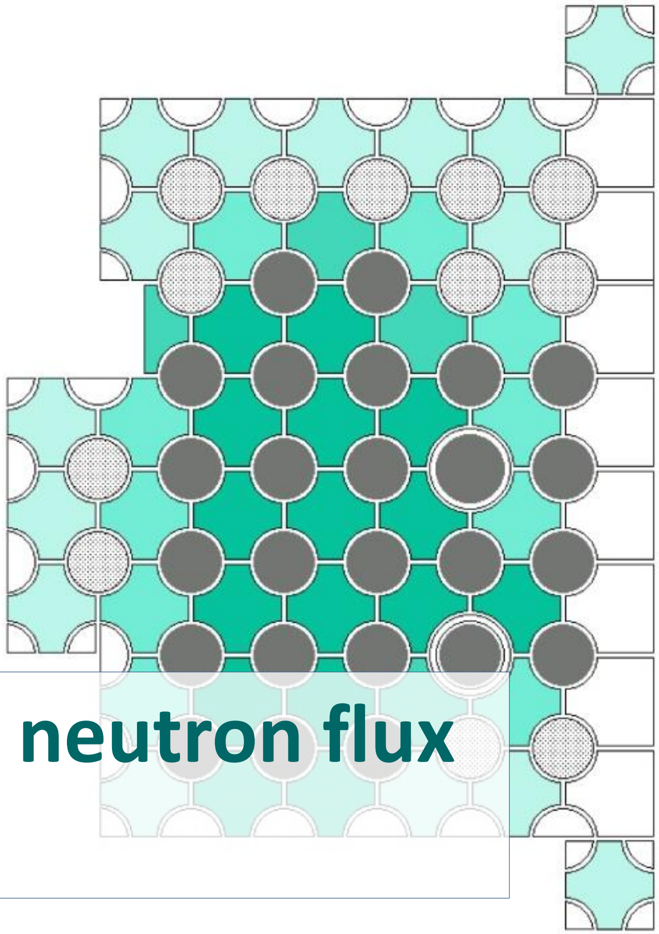


Vertical peaking factor of neutron flux

1,3 ÷ 1,4

COMPARISON OF METHODS





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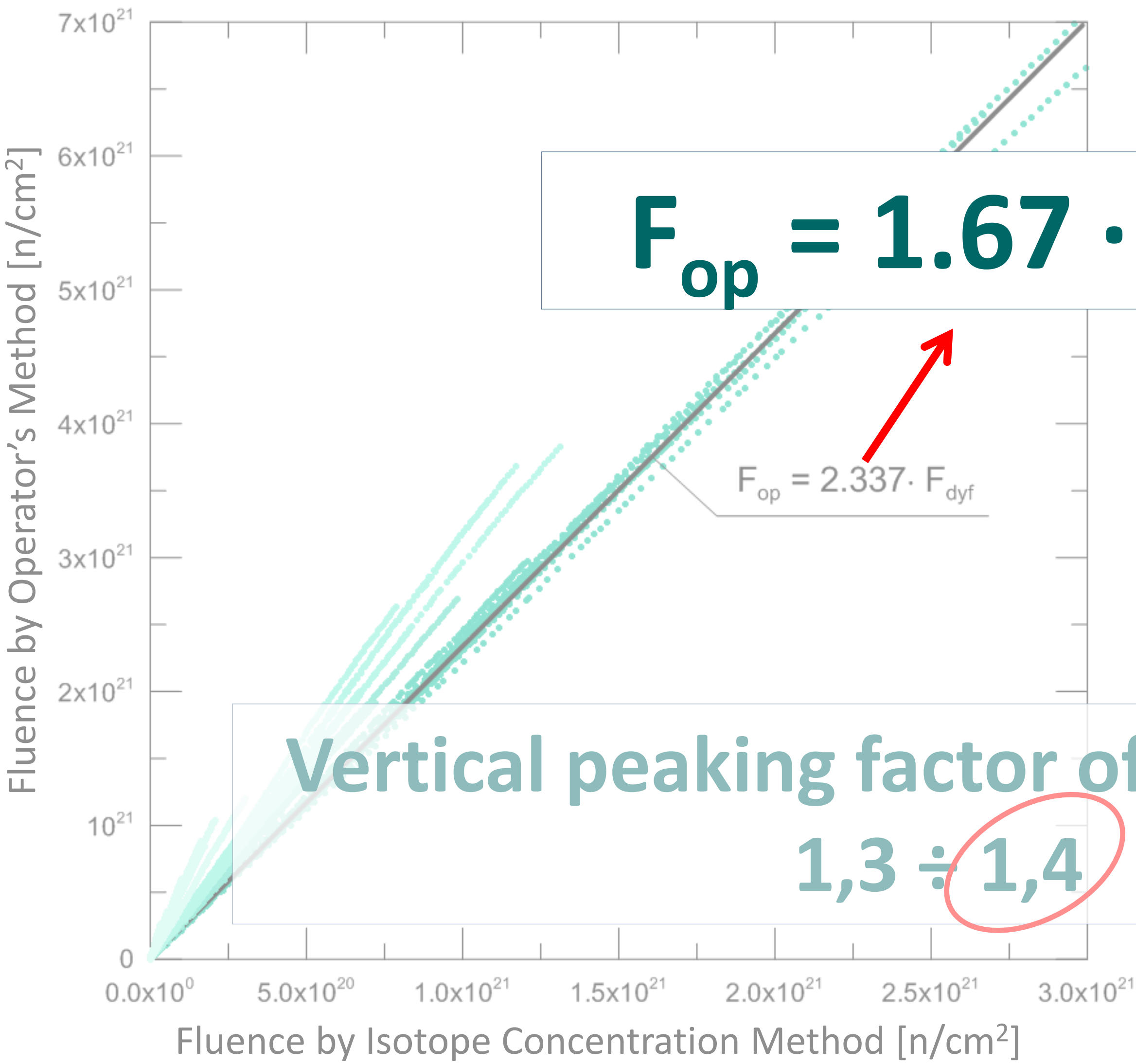
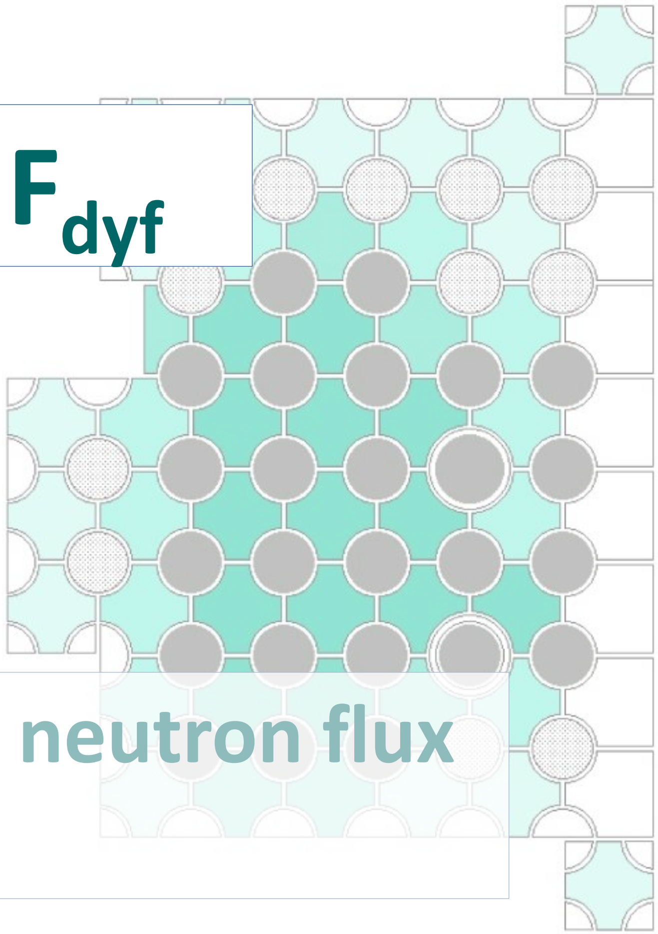




$$F_{op} = 1.67 \cdot F_{dyf}$$

Vertical peaking factor of neutron flux

1,3 ÷ 1,4

COMPARISON OF METHODS

BERYLLIUM MATRIX AT 21.08.2013

	IV	V	VI	VII	VIII	IX	X
M							20 1.93E+19 0.10%
L		23 1.81E+20 0.90%	14 4.41E+21 22.05%	13 3.62E+20 1.81%	ST4 7.46E+21 37.29%	16 1.76E+20 0.88%	
K		26 9.91E+20 4.96%	9 2.46E+21 12.30%	ST7 8.32E+21 41.59%	15 1.52E+21 7.58%	1 1.17E+22 58.49%	
J		1/2 5.45E+21 27.20%	ST8 7.63E+21 38.16%	ST6 1.11E+22 55.34%	ST5 6.58E+21 32.88%	21 2.73E+21 13.63%	
I	18 2.25E+21 11.23%	11 3.96E+21 19.82%	ST9 1.07E+22 53.29%	29 6.20E+21 31.01%	ST10 6.54E+21 32.71%	ST19 4.34E+21 21.68%	
H	2 1.08E+22 53.87%	8 8.02E+21 40.14%	28 9.68E+21 48.38%	27 7.27E+21 36.34%	24 9.85E+19 0.49%	POCZTA 0.00%	
G	10 6.34E+20 3.17%	17 6.61E+21 33.01%	6-kanałowy 1.45E+21 7.27%	ST11 1.16E+22 58.24%	ST22 9.80E+21 48.99%	ST16 8.66E+21 43.28%	
F		12 7.04E+21 35.24%	7 8.01E+21 40.07%	5 8.23E+21 41.14%	ST3 7.85E+21 39.25%	ST15 8.57E+21 32.86%	
E		25 9.34E+20 4.68%	22 2.16E+20 1.08%	19 POCZTA 1.52E+21 7.60%	4 1.12E+22 56.15%	6 4.43E+20 2.22%	
D							3 1.19E+22 59.63%

Fluence by Isotope Concentration Method

	IV	V	VI	VII	VIII	IX	X
M							20 1.54E+20 0.77%
L		23 7.30E+20 3.65%	14 8.76E+21 43.78%	13 1.28E+21 5.42%	ST4 1.55E+22 77.70%	16 ST19 5.21E+20 2.61%	
K		26 2.89E+21 14.46%	9 4.92E+21 24.60%	ST7 1.86E+22 92.85%	15 4.26E+21 21.30%	1 1.97E+22 98.28%	
J		1/2 8.96E+21 44.79%	ST8 1.30E+22 65.02%	ST6 1.79E+22 89.65%	ST5 1.33E+22 66.33%	21 5.45E+21 27.24%	
I	18 6.28E+21 31.42%	11 8.98E+21 44.95%	ST9 1.77E+22 88.42%	29 1.08E+22 53.86%	ST10 1.22E+22 60.97%	ST19 9.34E+21 46.70%	
H	2 3.15E+21 15.74%	8 1.62E+22 80.90%	28 1.55E+22 77.39%	27 1.09E+22 54.71%	24 3.61E+20 1.80%	POCZTA	
G	10 2.52E+21 12.62%	17 1.42E+22 71.20%	6-kanałowy 3.01E+21 15.07%	ST11 1.78E+22 88.81%	ST22 1.70E+22 85.23%	ST16 1.68E+22 83.80%	
F		12 1.10E+22 55.13%	7 1.43E+22 71.42%	5 1.36E+22 68.15%	ST3 1.49E+22 74.50%	ST15 1.42E+22 71.00%	
E		25 3.06E+21 15.30%	22 6.99E+20 3.50%	19 POCZTA 4.90E+21 24.50%	4 1.60E+22 80.05%	6 1.06E+21 5.30%	
D							3 1.94E+22 97.06%

Fluence by Operator’s Method

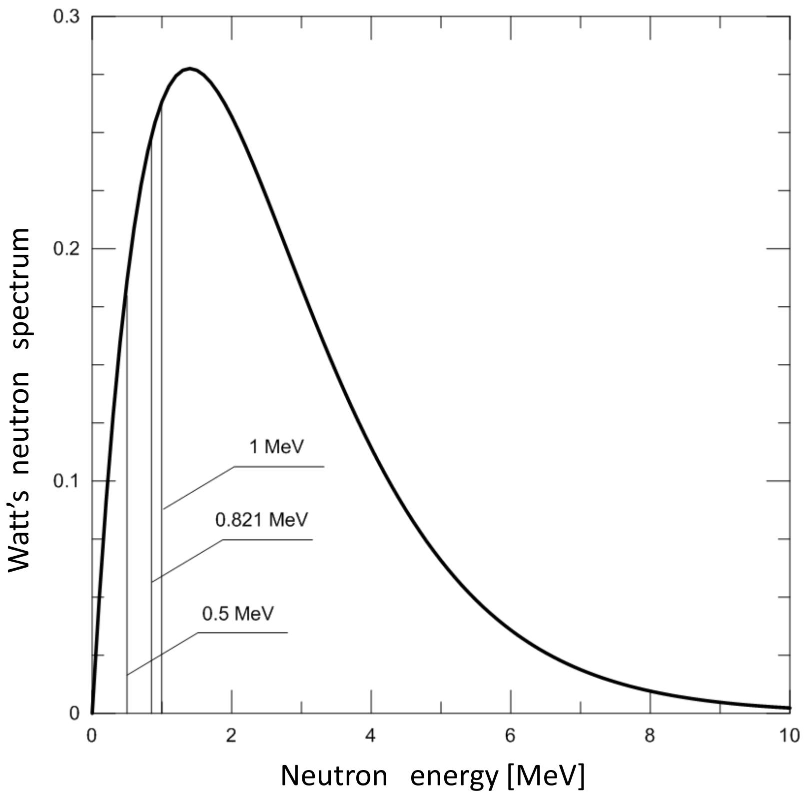
CONCLUSIONS

- The Sum of Concentration Method allows to determine the fluence instantly, without taking into account whole operational history of considered beryllium block. The fluence is obtained from the results of diffusion model calculations. Those follow-up calculations are carried out to date for each real core configuration, so access to data is instantaneous. The only required information is concentration of ^{6}Li, ^{3}H and ^{3}He in considered beryllium block.

- The SIMS (Secondary Ion Mass Spectrometry) measurements of concentrations of ^{6}Li, ^{3}H or ^{3}He in Be samples (coupons) irradiated in several locations of MARIA core are considered as an alternative tool for verification of Isotope Concentration Method.

Thank you for your attention

CONCLUSIONS



Because of the cross section behaviour for the reaction $^{9}Be(n,\alpha)^{6}He$ it is proposed to redefine fast neutron group, as a neutrons with energy above 1 MeV (this is an energy treshold widely accepted in the literature).

Then the limit specified in The Operational Safety Report of MARIA Reactor shall be:

„Maximum of fast neutron fluence (En > 1 MeV) in beryllium blocks can not exceed $1.75 \cdot 10^{22}$ n/cm^2".

BATEMAN'S EQUATIONS

By adding all four Bateman's equations, one obtains:

$$\frac{d}{dt}(N_b + N_l + N_h + N_t) = 0$$

The sum of beryllium, litium, tritium and helium concentrations is constant and thus equal to initial concentration of beryllium in considered beryllium material.