NKS-R and NKS-B Joint Summary Seminar Armémuseum, Stockholm, 26th - 27th March 2009

IACIP: NKS_R_2008_61:

Improving accuracy of the calculation of in-core power distributions for light water reactors

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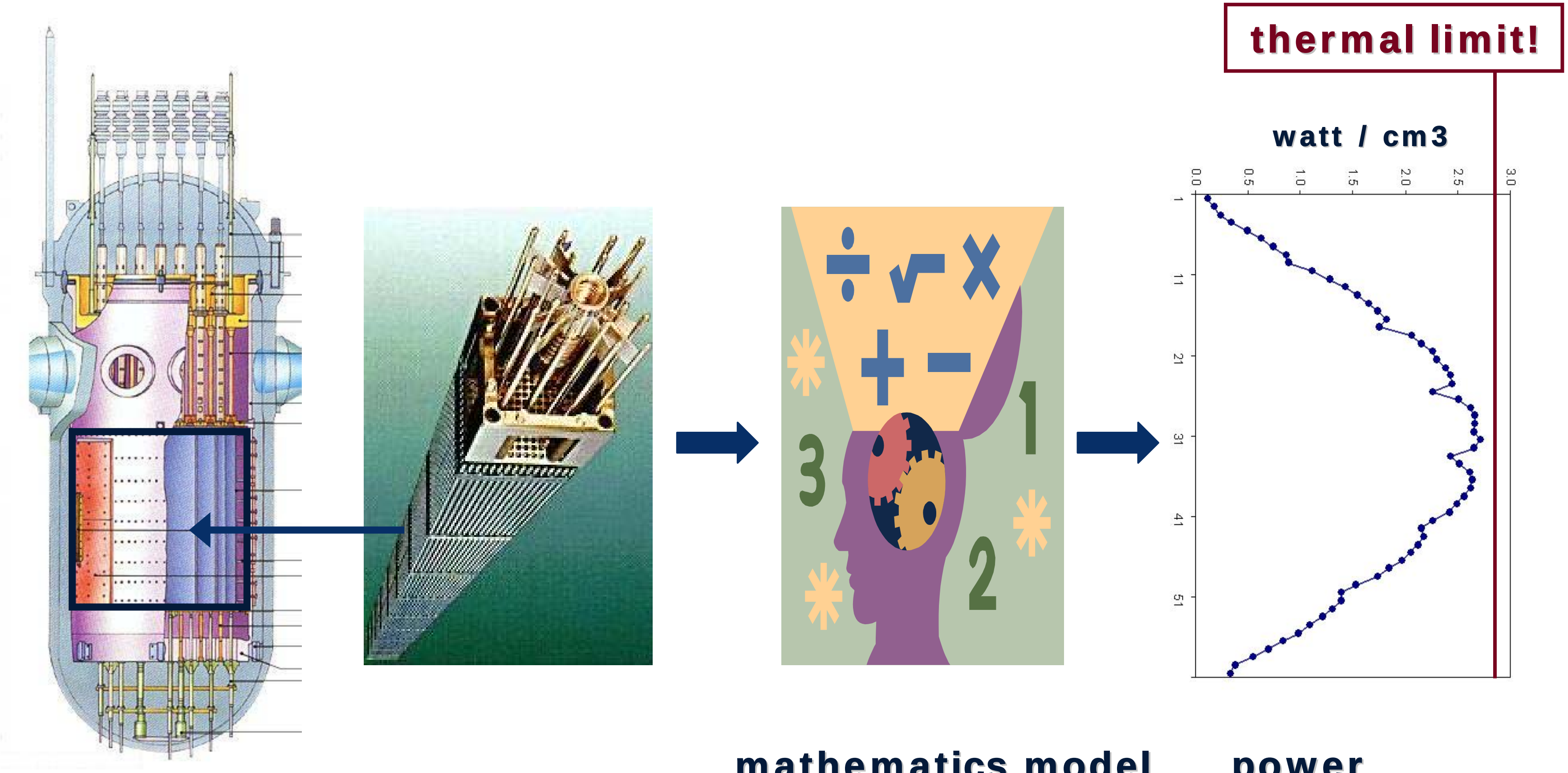
IFE, OECD Halden Reactor Project

LWR core neutronics calculation



core / fuel composition, geometry

mathematics model on neutrons behavior

power distribution, reactivity

purpose

increase accuracy of power distribution calculations

less safety margin requirements

more economy oriented core operation

e.g., less fresh fuel
higher fuel burnup
less high level wastes

more accurate transient analysis

safer design of fuel and core

basic equations

static multigroup neutron transport equations

$$\Omega\cdot\nabla\Phi_g(\mathbf{r},\Omega) + \Sigma_g(\mathbf{r})\,\Phi_g(\mathbf{r},\Omega) = Q_g(\mathbf{r})$$

$$\equiv \quad \int_{4\pi} d\Omega' \, \Sigma_{g'} \, \Sigma^s(\mathbf{r}; g, \Omega \leftarrow g', \Omega')\,\Phi_{g'}(\mathbf{r},\Omega')$$

$$+ \quad (\chi_g / 4\pi / \mathrm{keff}\,) \int_{4\pi} d\Omega' \, \Sigma_{g'} \, \nu\Sigma_{f,\,g'}(\mathbf{r})\,\Phi_{g'}(\mathbf{r},\Omega')$$

$\Phi_g(\mathbf{r},\Omega)$: **neutron angular flux (unknown function)**

keff : **effective multiplication factor (unknown)**

$\mathbf{r}$: **spatial position**

Ω : **direction of neutron motion**

g : **kinetic energy of neutrons**

$\Phi_g(\mathbf{r},\Omega) = v\, n(\mathbf{r},\Omega)$ [cm / sec][neutrons / cm^3]

solution

power density distribution (energy / volume / time):

$$P(\mathbf{r}) = c \int_{4\pi} d\Omega \sum_g \Sigma_{f,\,g}(\mathbf{r})\, \Phi_g(\mathbf{r}, \Omega)$$

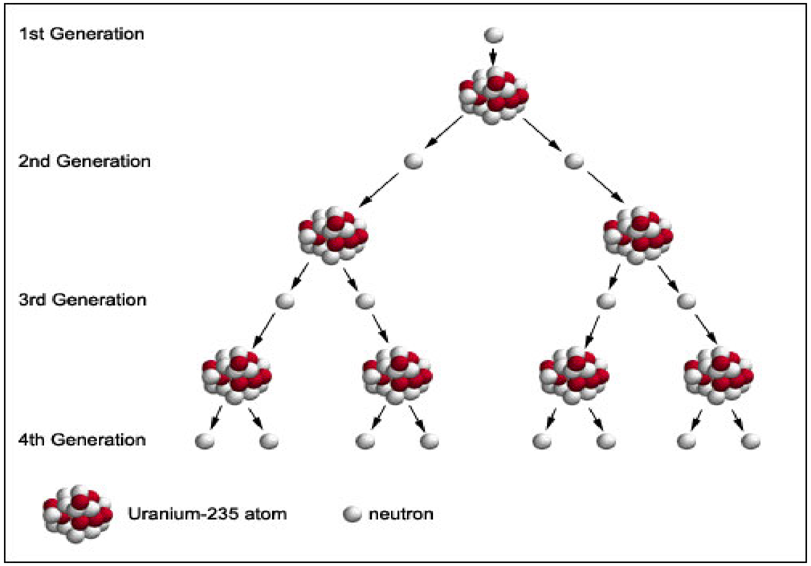
c : energy release per fission

keff: core criticality

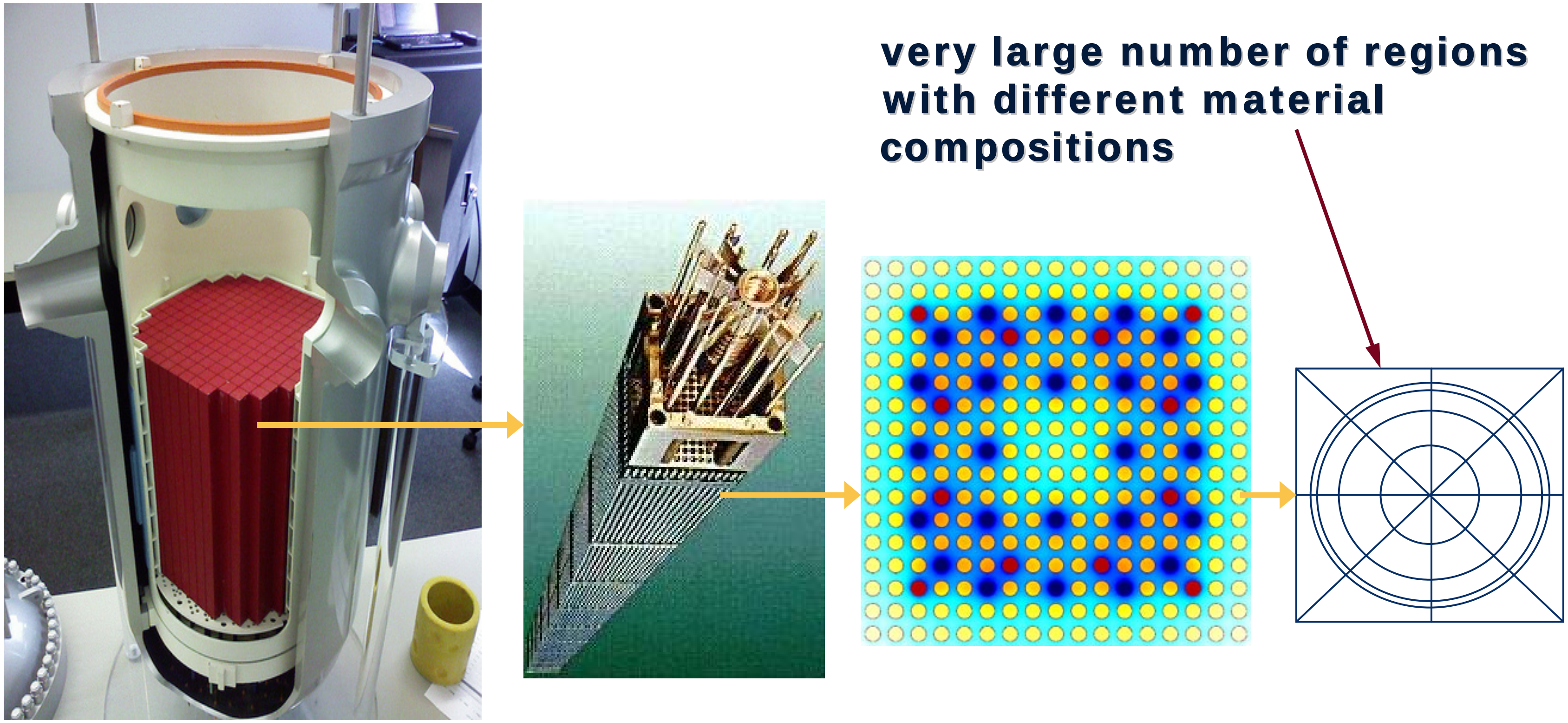
keff > 1: supercritical

keff = 1: critical

keff < 1: subcritical



difficulty (1) in space



very large number of regions with different material compositions

reactor core

fuel assembly

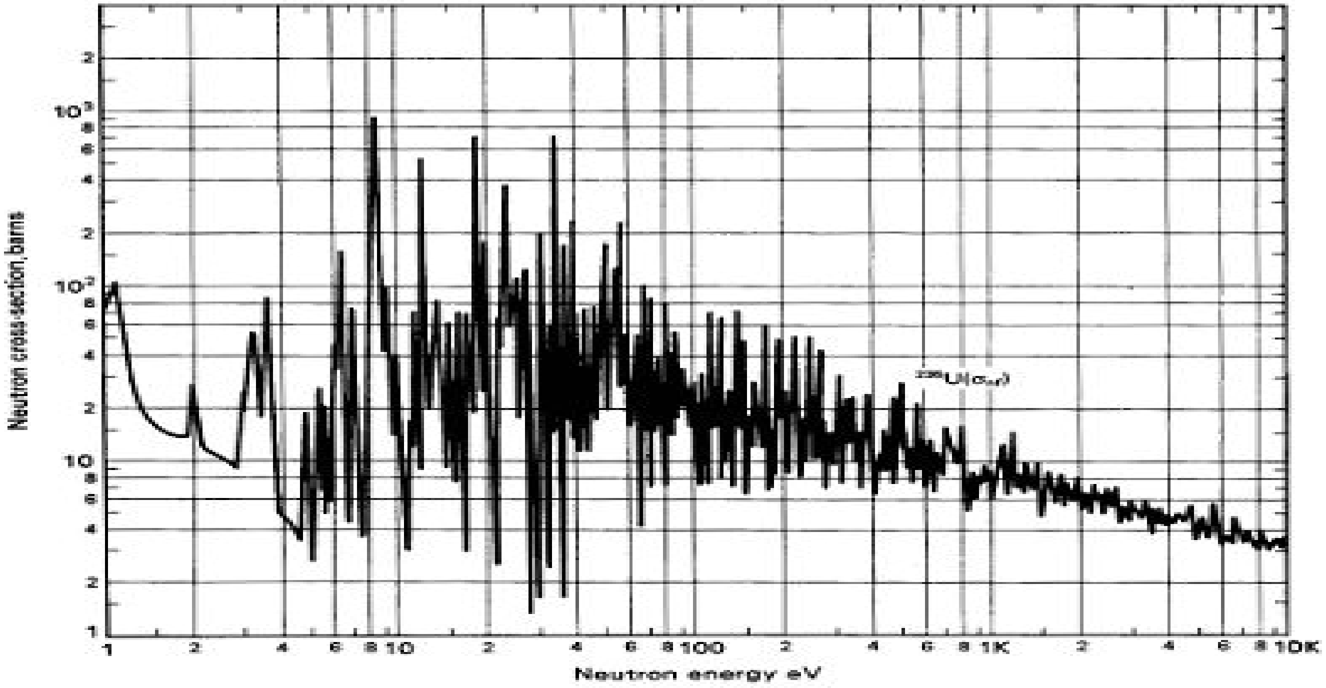
fuel rods

fuel cell

difficulty (2) in neutron energy

very complicated energy dependence of neutron cross sections

σ **f, g(U235)**



g

conventional "nodal diffusion" methods

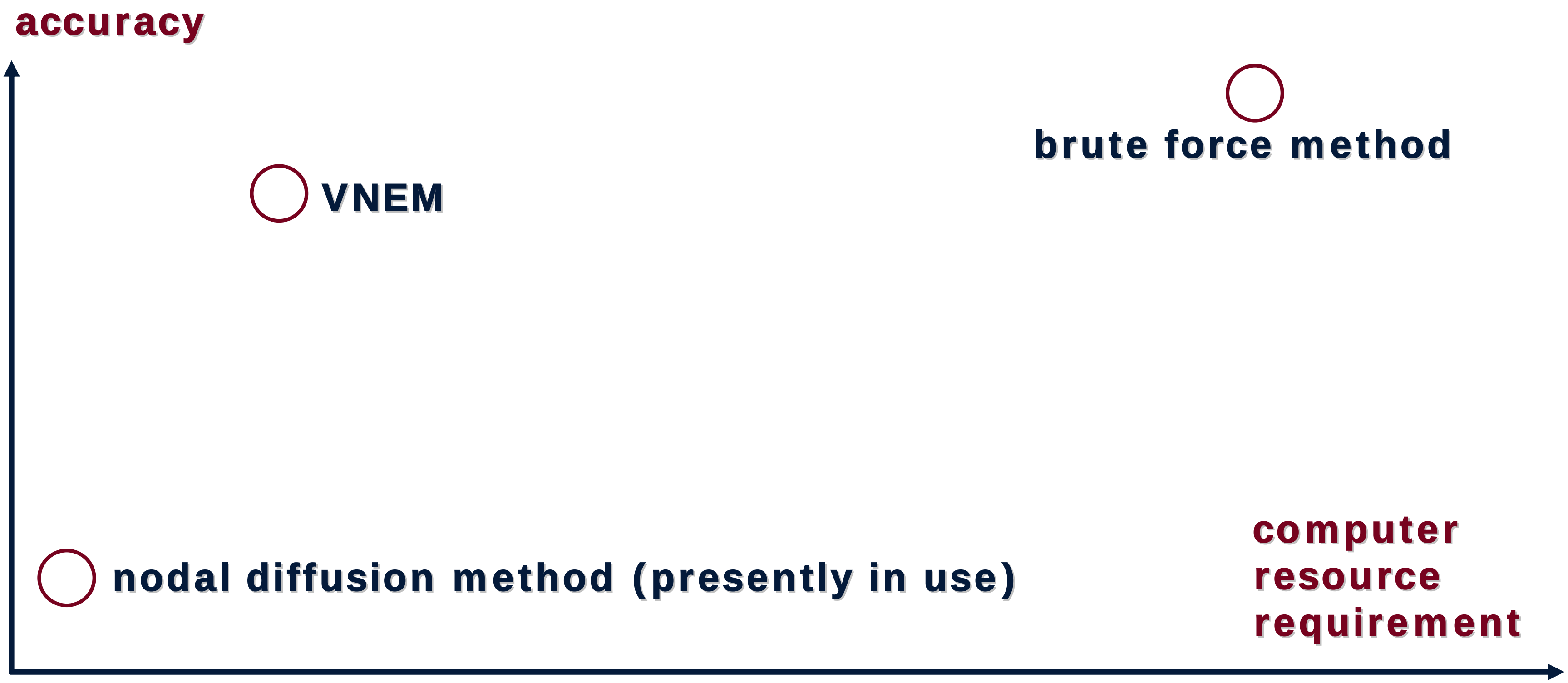
- 2 stages method: separate into assembly and full core

? diffusion approximation: Ω-dependence almost ignored

? assembly homogenization: heterogeneity of intra-assembly structure

- energy group condensation

our target



accuracy

brute force method

VNEM

nodal diffusion method (presently in use)

computer resource requirement

VNEM* solution

higher accuracy :

solve rigorous equation

use even / odd PL ***transport theory***

reduced computing resource :

- nodal expansion method
- variational (Ritz) method

*Variational Nodal Expansion Method

NEACRP PWR MOX benchmark

participating transport codes

organization	code	method
CEN-MOL	DOT4.3	SN
ECN-PETTEN	DORT	SN
NFI	TWODANT	SN
PSI	BOXER	TPM
JAERI	TWOTRAN II	SN
	GMVP	MC
IKE	ICM2D	J+-
ANL	VIM	MC
AEC / AEK	RED-1	BC
	RED-2	BC
IFE	*FCM2D*	*CM*
	VNEM2D	*VNEM*

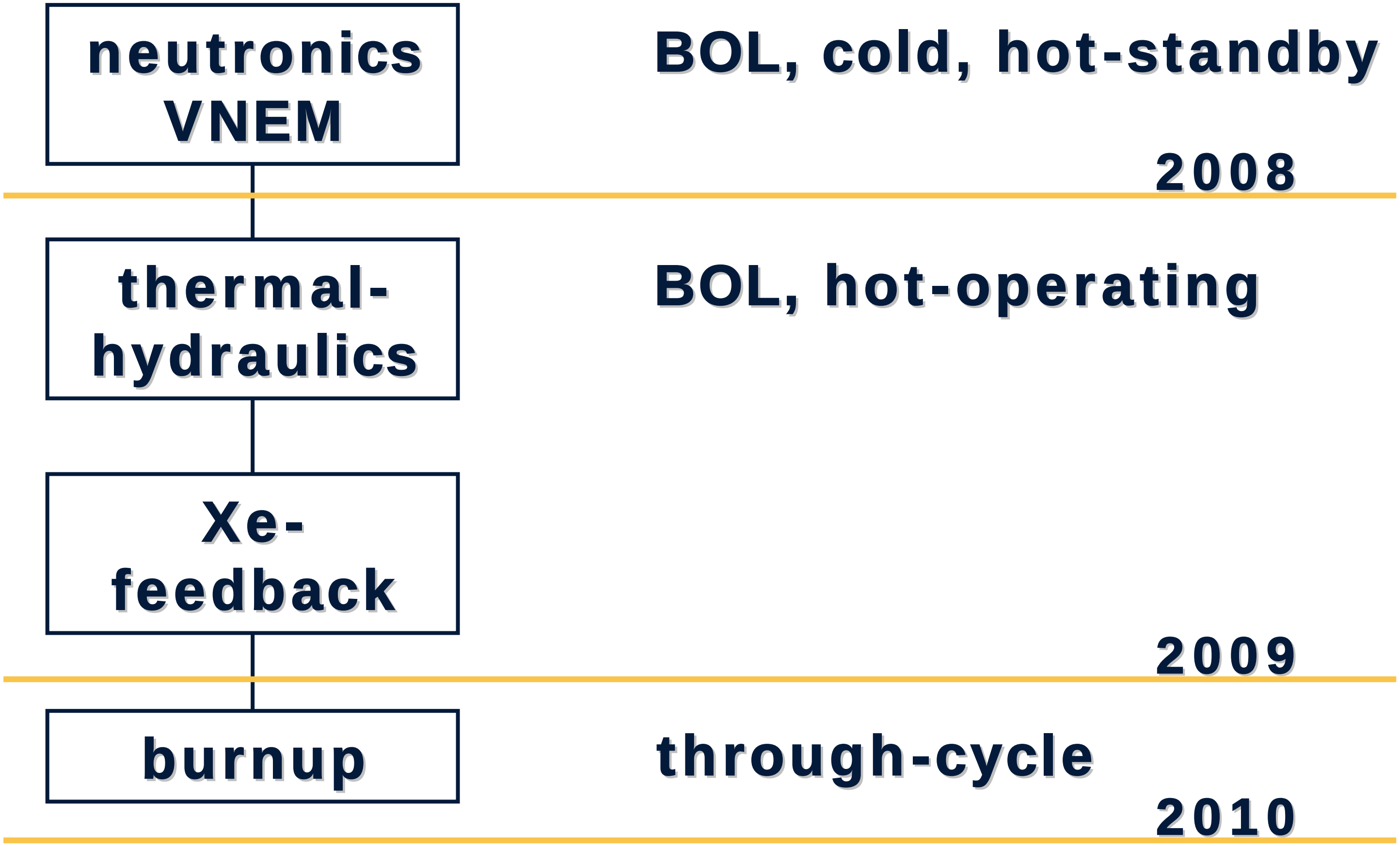
keff comparison, case C3 (inner core)

organization	code	error pcm
CEN-MOL	DOT4.3	-101
ECN-PETTEN	DORT	-68
NFI	TWODANT	-121
PSI	BOXER	-112
JAERI	TWOTRAN II	-63
	GMVP	-111
IKE	ICM2D	-89
ANL	VIM	-136
AEC/AEK	RED-1	-90
	RED-2	-109
IFE	*FCM2D*	*1*
	VNEM2D	*-30*

keff comparison, case C5 (peripheral)

organization	code	error pcm
CEN-MOL	DOT4.3	-138
ECN-PETTEN	DORT	42
NFI	TWODANT	-8
PSI	BOXER	1
JAERI	TWOTRAN II	70
	GMVP	-60
IKE	ICM2D	-196
ANL	VIM	-90
AEC/AEK	RED-1	4588
	RED-2	4111
IFE	*FCM2D*	*43*
	VNEM2D	*-39*

verification plan for actual plants



neutronics VNEM

BOL, cold, hot-standby

2008

thermal-hydraulics

BOL, hot-operating

Xe-feedback

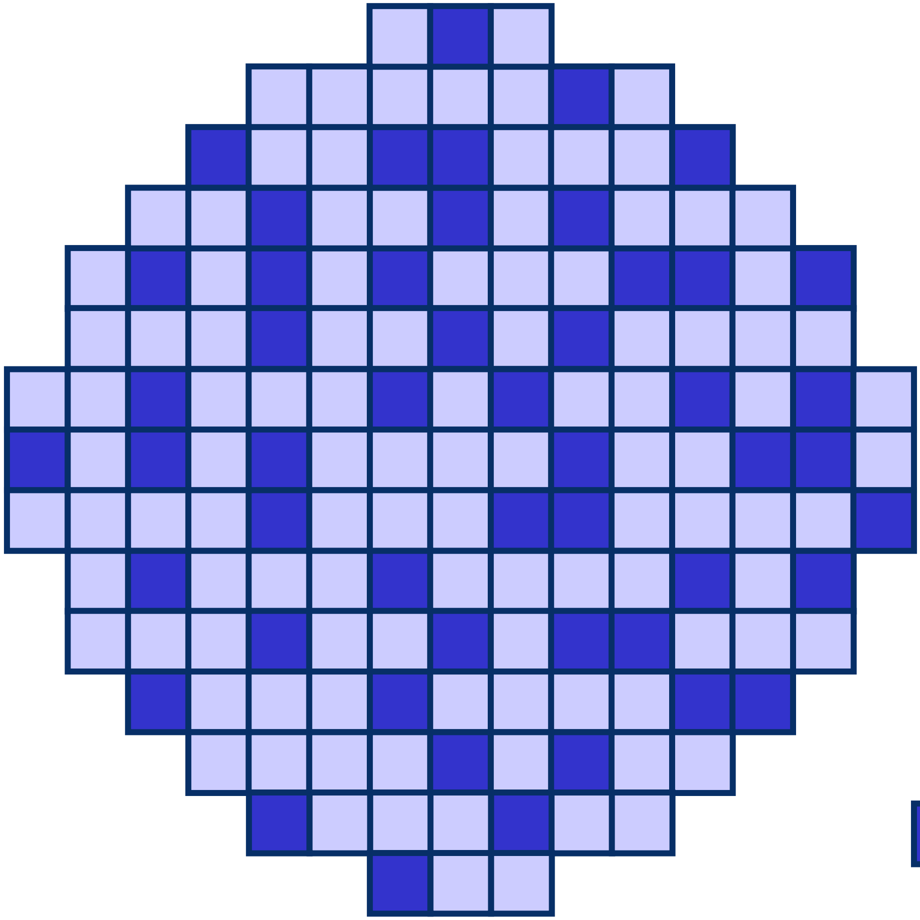
2009

burnup

through-cycle

2010

Ringhals-3, case 1



B bank : 228steps

C bank : 228steps

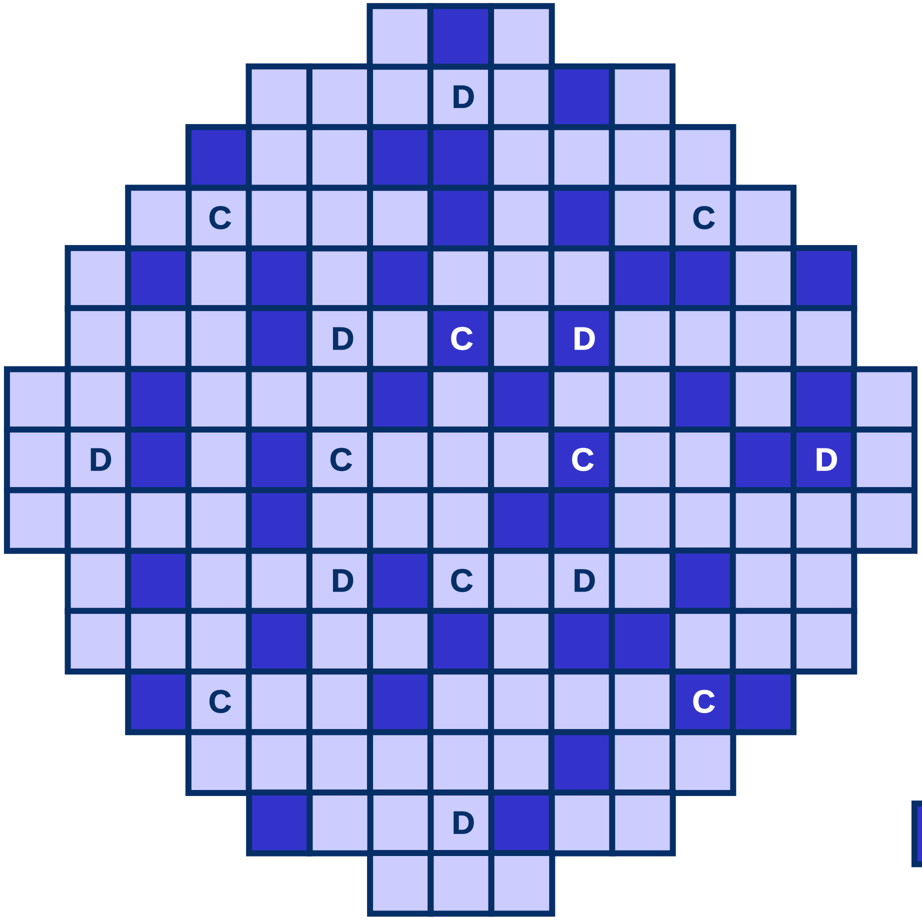
D bank : 228steps

boron : 1315ppm

power : 4 %

■ : measured assembly

Ringhals-3, case 2



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		□	C	□	□	□	■	□	■	□	C	□		
	□	■	□	■	□	■	□	□	□	■	■	□	■	
	□	□	□	■	D	□	■ C	□	■ D	□	□	□	□	
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	□	■	□	□	D	■	C	□	D	□	■	□	□	
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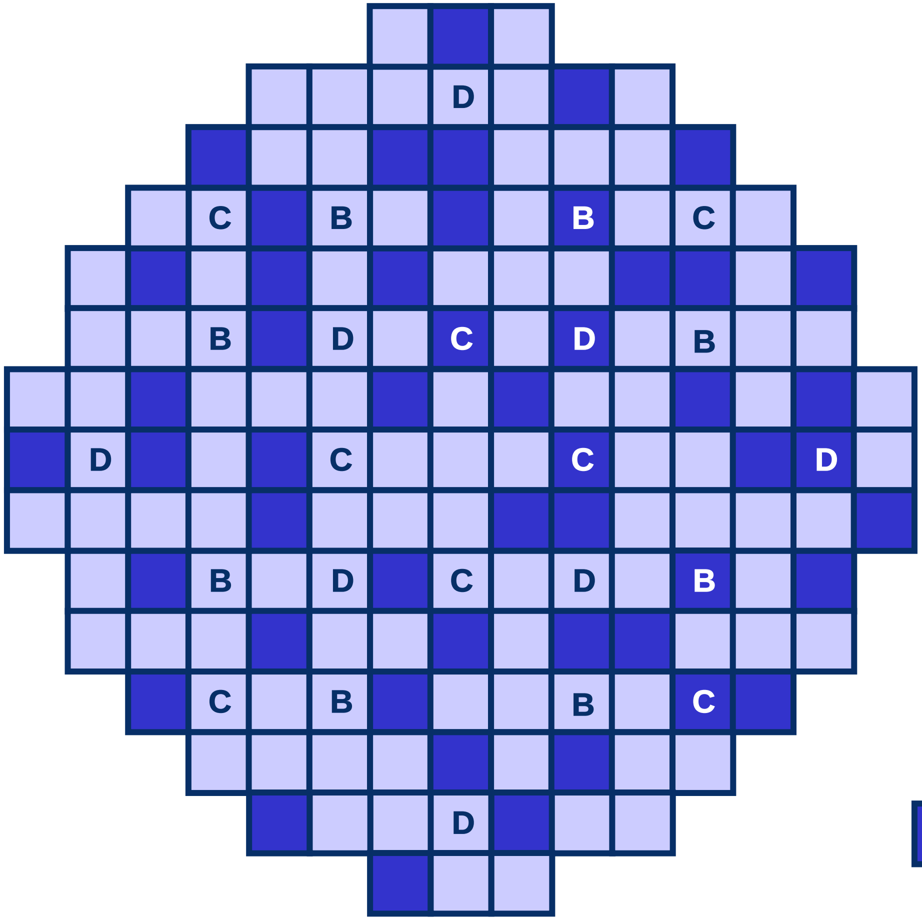
		■	C	□	□	■	□	□	□	□	■ C	■		
			□	□	□	□	□	□	■	□	□			
				■	□	□	D	■	□	□				
						□	□	□						

B bank : 228steps
C bank : 111steps
D bank : 0steps
boron : 1131ppm
power : 4 %

■ **: measured assembly**

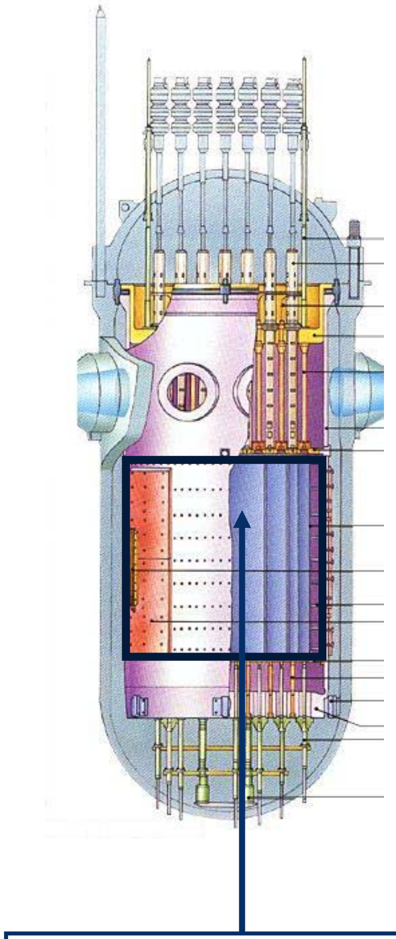
Ringhals-3, case 3



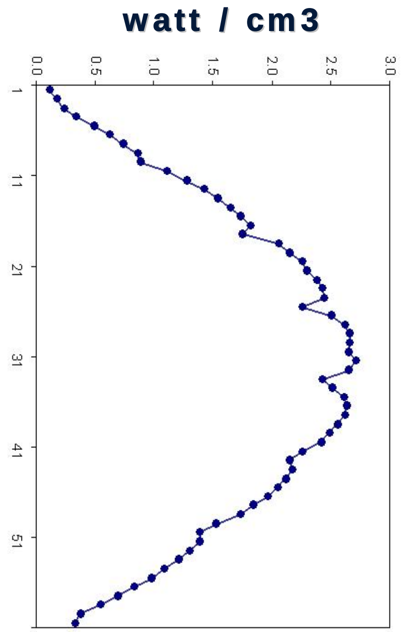
B bank : 217 steps
C bank : 0 steps
D bank : 0 steps
boron : 1060 ppm
power : 4 %

🟦 : measured assembly

measured data from plant



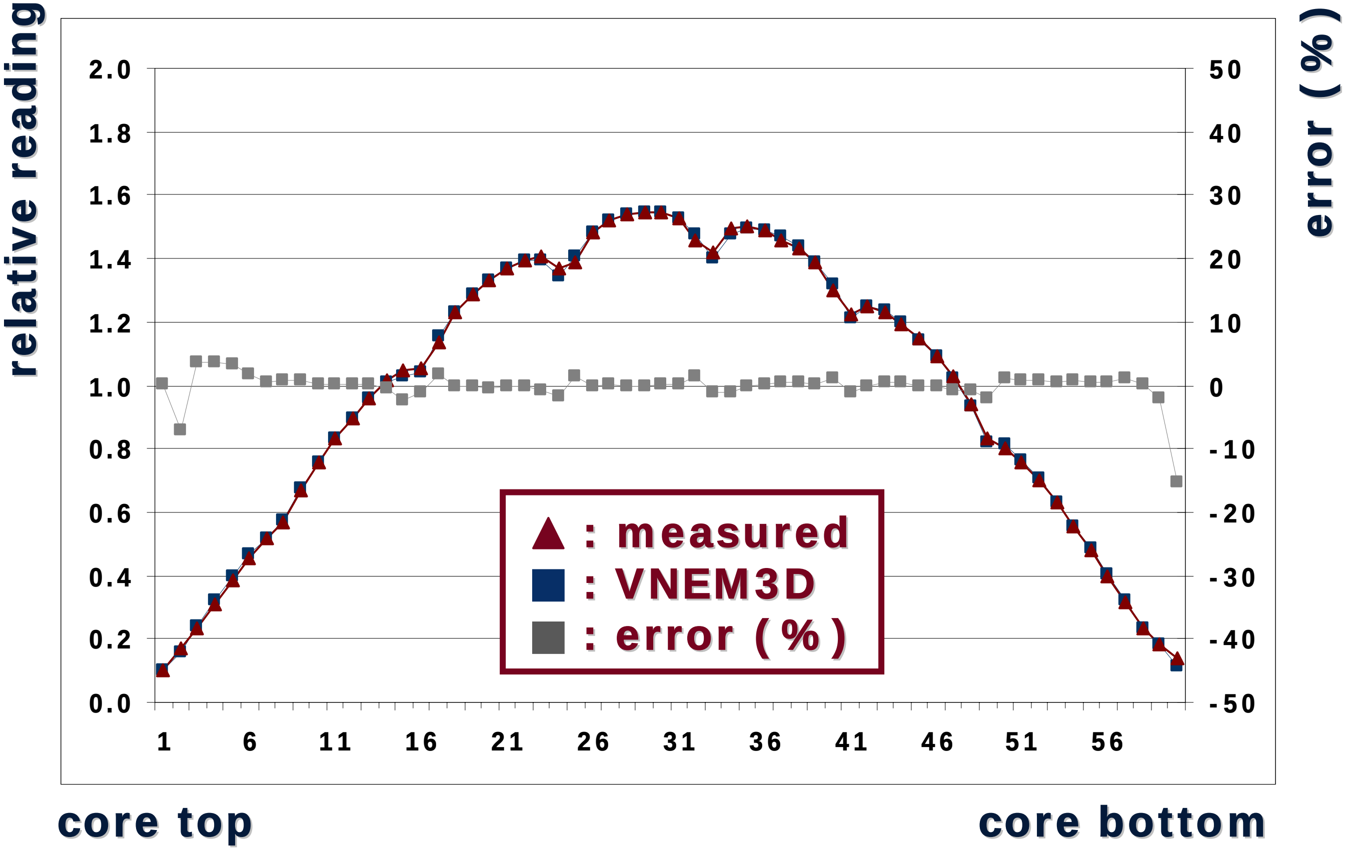
movable detector



detector readings

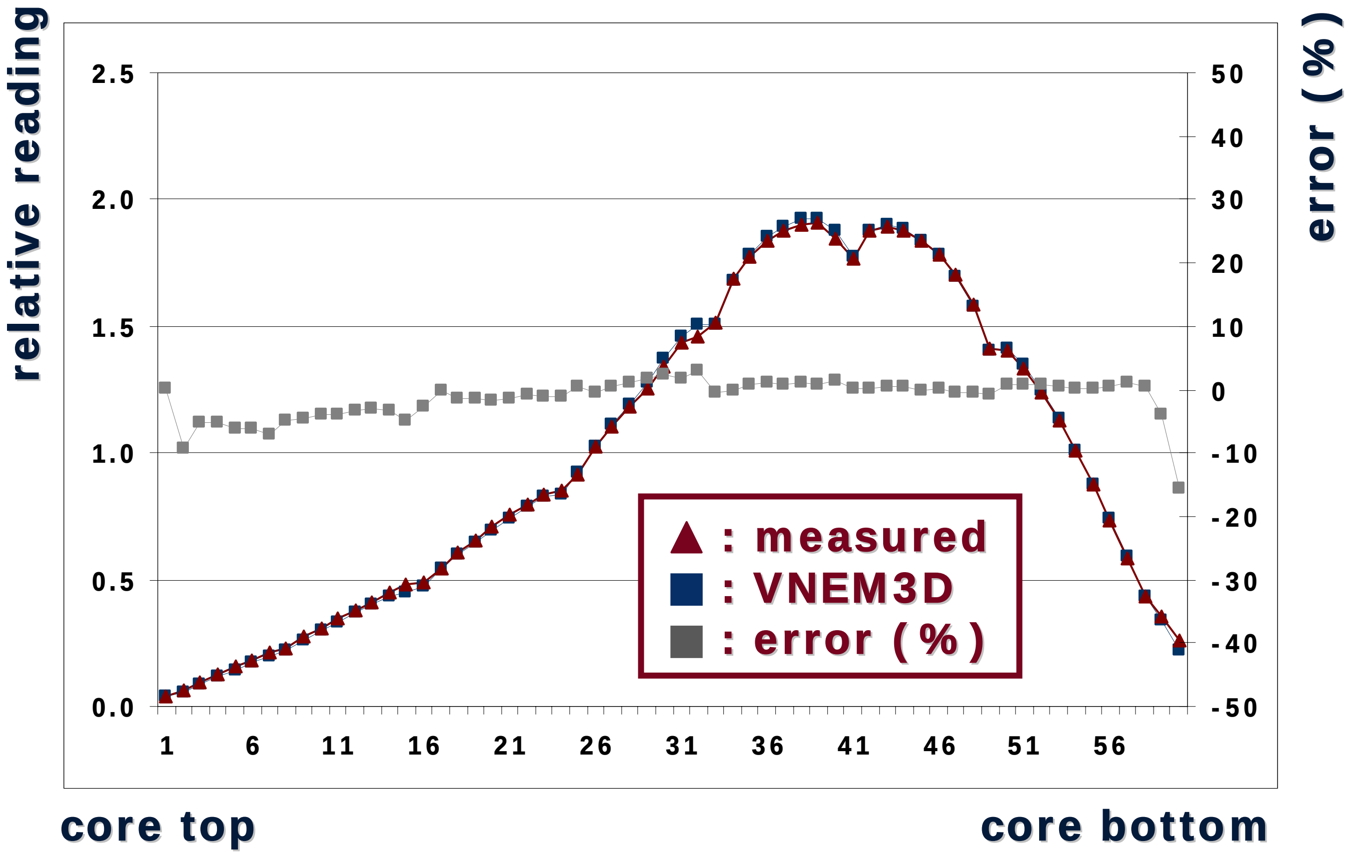
core average axial detector readings

(average = 1.0), case 1



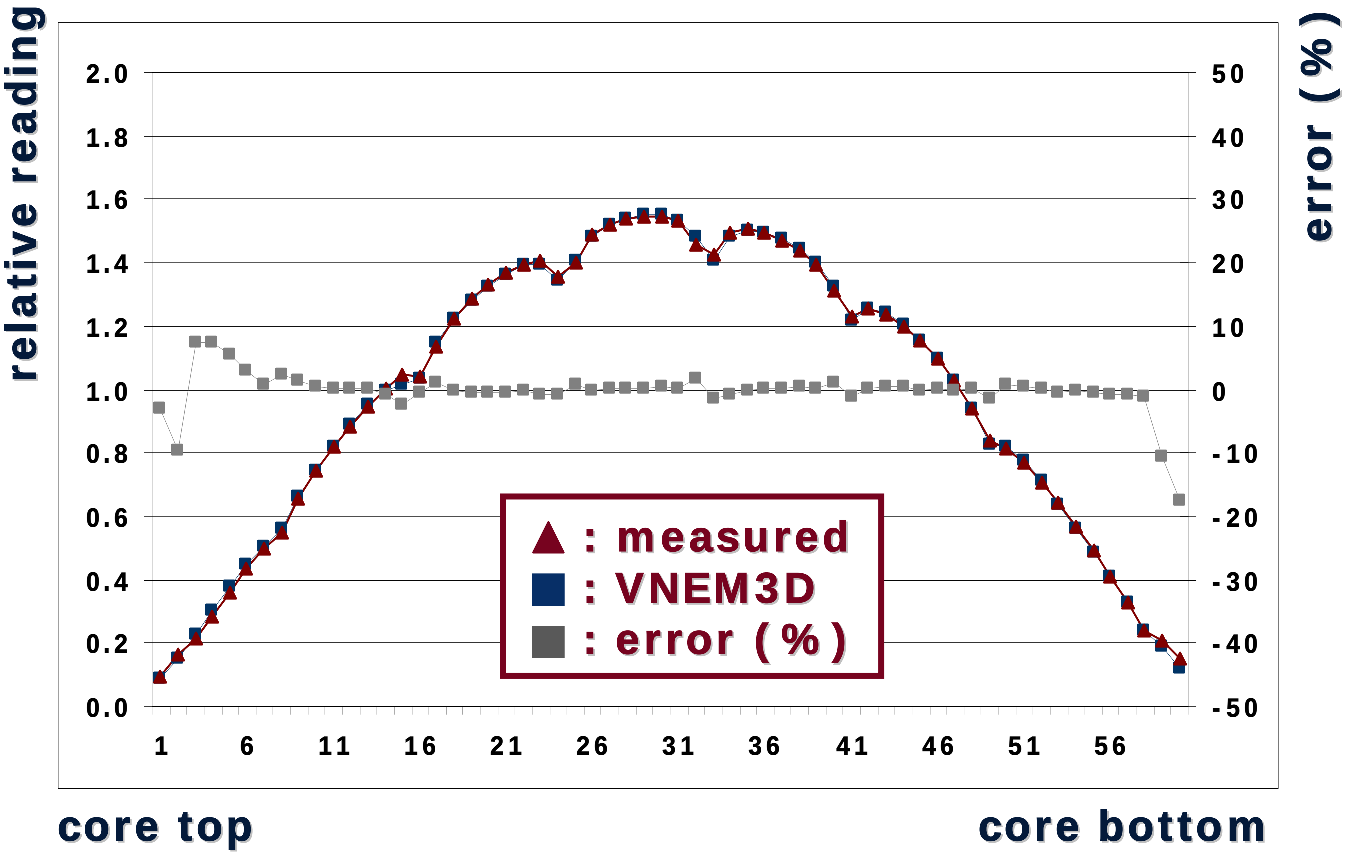
core average axial detector readings

(average = 1.0), case 2



core average axial detector readings

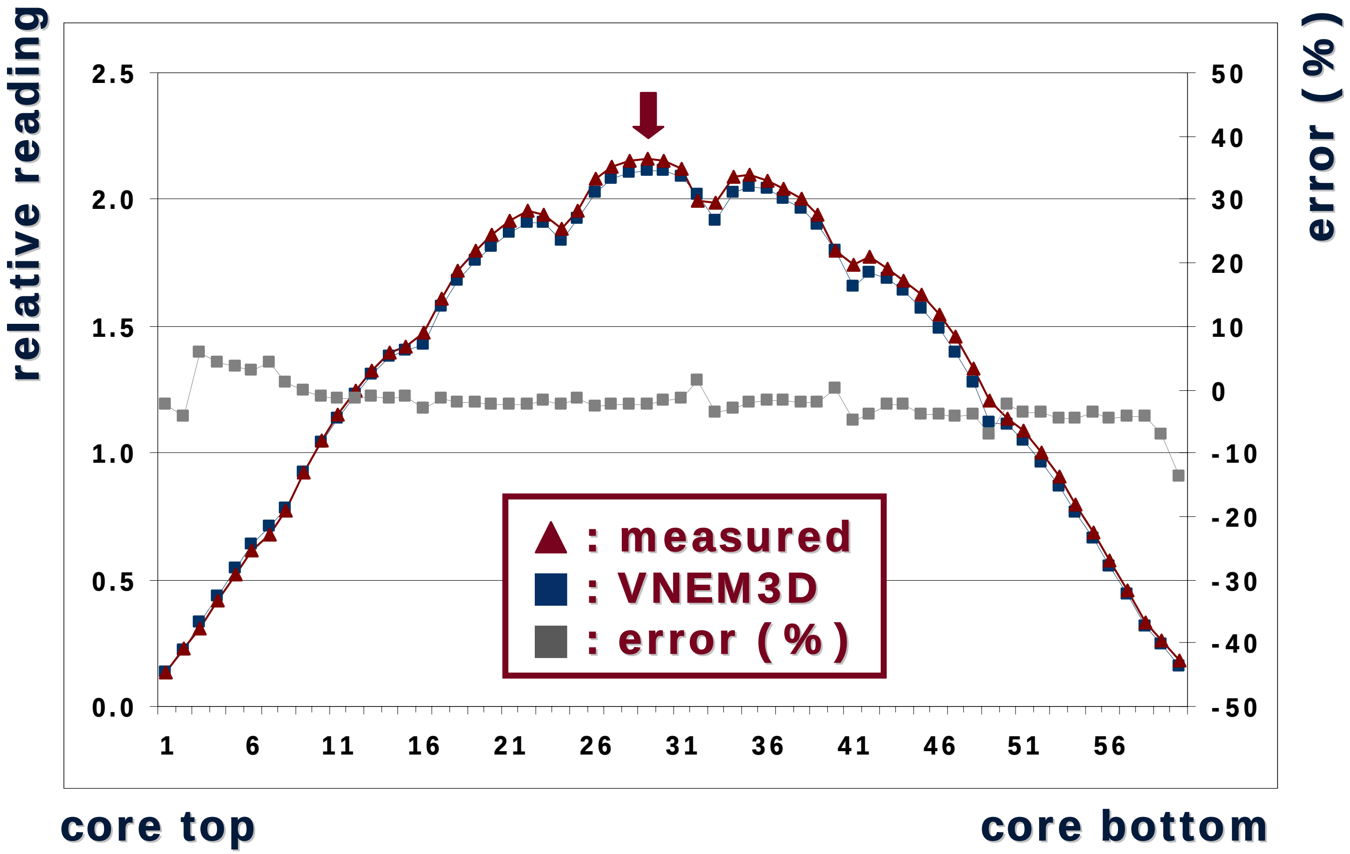
(average = 1.0), case 3



(c) 2009 by IFE

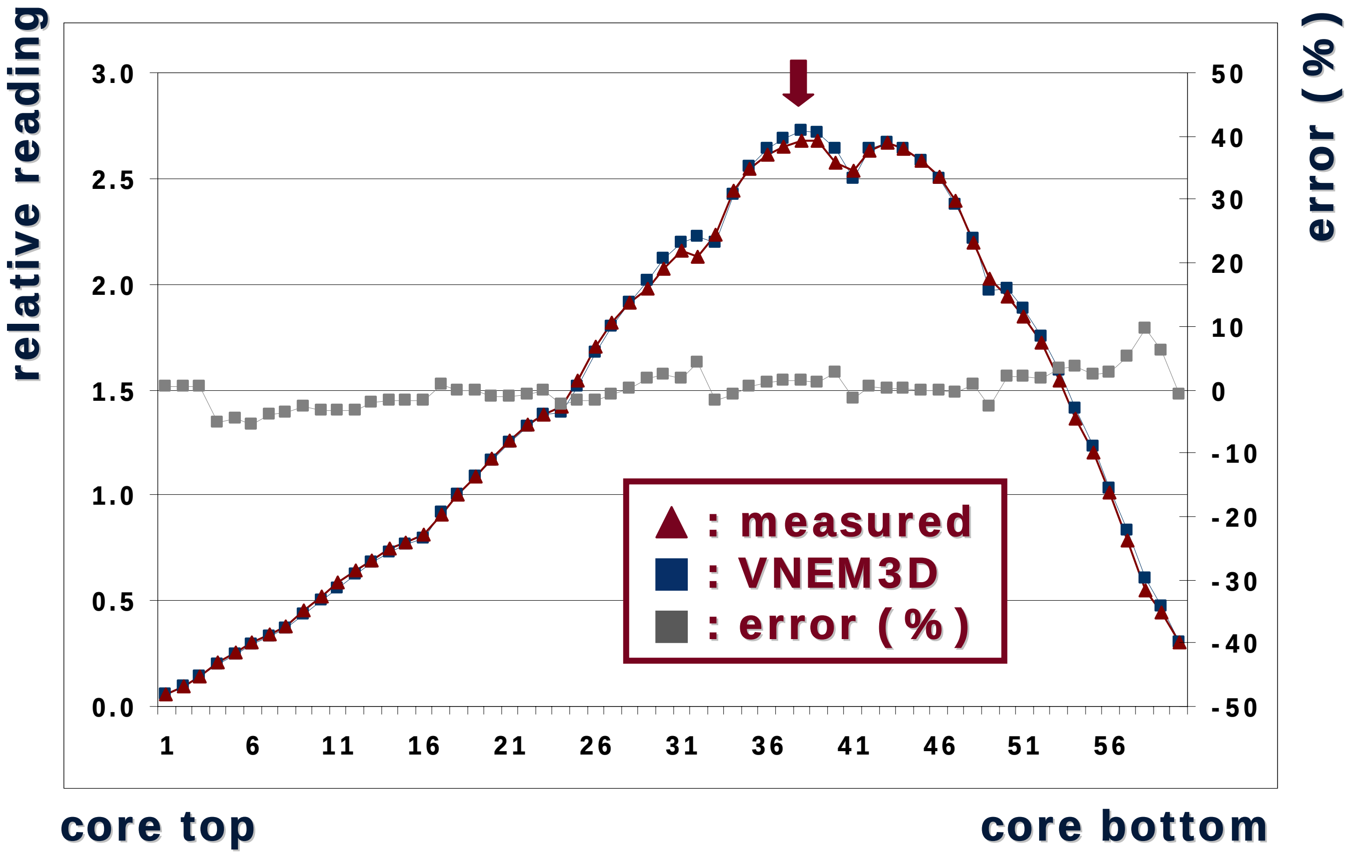
core maximum detector reading

(relative to core average), case 1



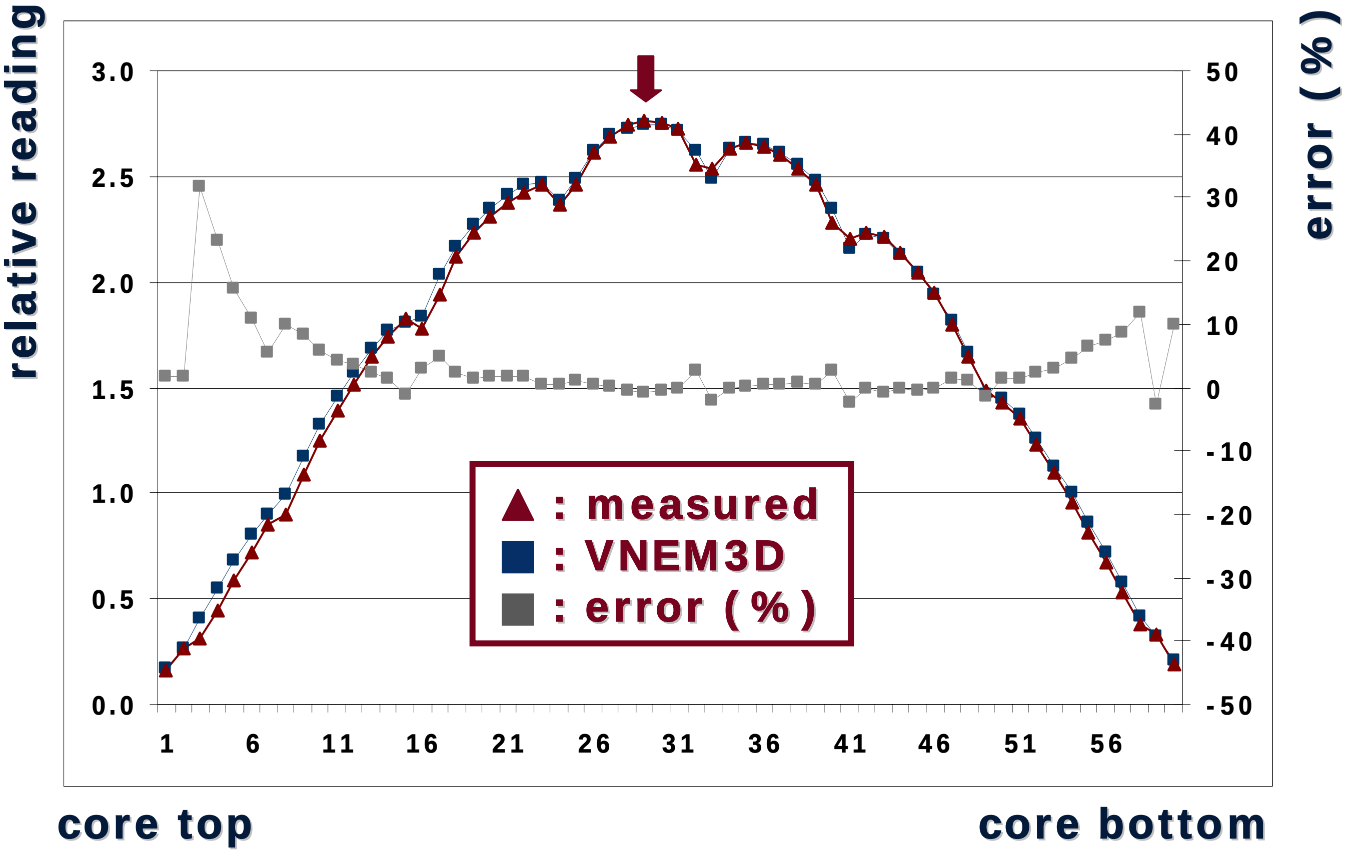
core maximum detector reading

(relative to core average), case 2



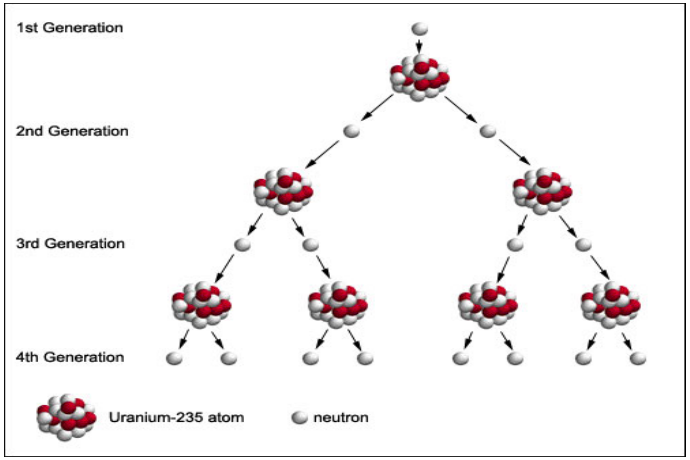
core maximum detector reading

(relative to core average), case 3



neutron multiplication factor

case	keff	error(%)
1	0.9983	-0.17
2	0.9998	-0.02
3	0.9996	-0.04



conclusion

1. excellent agreement of power distribution and effective multiplication factor
2. transport effect (P1:P3) is significant
3. large sensitivity on number of groups
4. computing time = 10min./case

cooperation

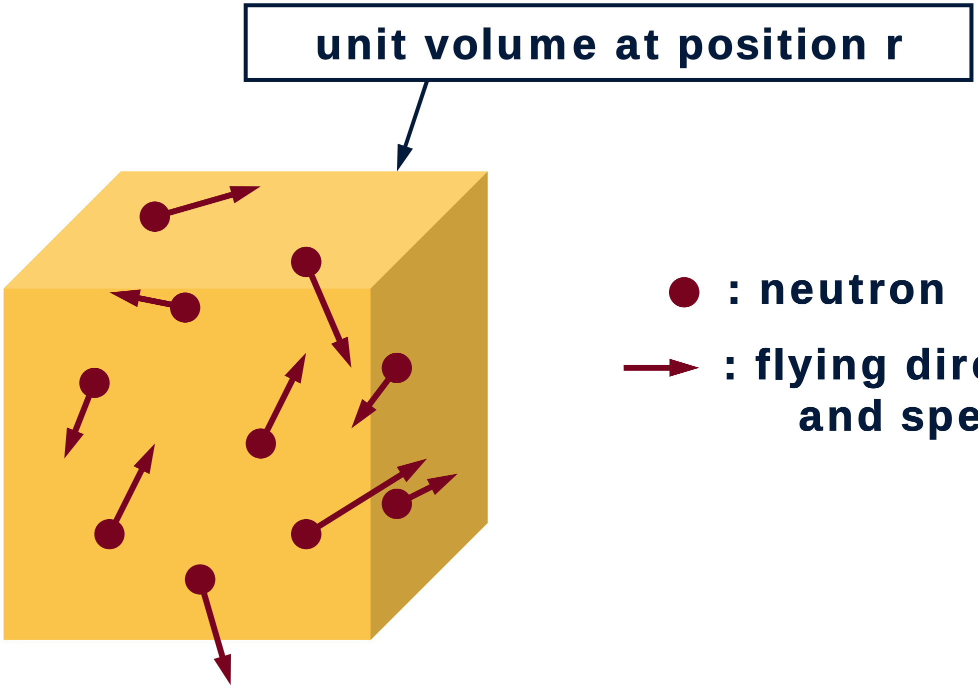
- Rinhgals NPP - Sweden
- SEPCO - Japan
- TEPSYS (TEPCO) - Japan

- NTNU - Norway (master student)
- VTT - Finland

work in 2009, 2010

1. Develop VNEM coefficient generator: VCOEF code
2. Develop VNEM coefficients tabulator: VTABLE code
3. Burnup-tilt model development
4. Make VNEM module faster
5. Built in VNEM module into CYGNUS code
6. verification

conservation law of neutrons flying in unit volume in core



unit volume at position r

● : neutron

→ : flying direction and speed

count number of neutrons in unit volume at position r, speed (energy) g, direction $\underline{\Omega}$

energy group condensation

energy-condensed angular flux:

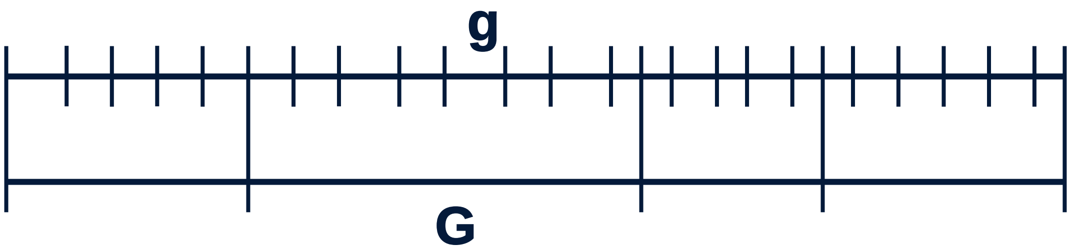
$$\Phi_G (\mathbf{r}, \Omega) \equiv \sum_{g \in G} \Phi_g (\mathbf{r}, \Omega) \, \Delta E_g$$

energy-condensed neutron cross section:

$$\Sigma_G(\mathbf{r}) \equiv \sum_{g \in G} \Sigma_g (\mathbf{r}) \, \Phi_g (\mathbf{r}) \, \Delta Eg \, / \, \Phi_G (\mathbf{r})$$

scalar neutron flux:

$$\Phi_g (\mathbf{r}) \equiv \int_{4\pi} d\Omega \, \Phi_g (\mathbf{r}, \Omega)$$



fine group

broad group

homogenization (VNEM)

PL method for angular dependence:

$$\Phi_G(\mathbf{r}, \Omega) \equiv \sum_{l,\, m} \phi_{G,\, l,\, m}(\mathbf{r})\, Y_{l,\, m}(\Omega)$$

← **spherical harmonics**

spatial expansion of moments:

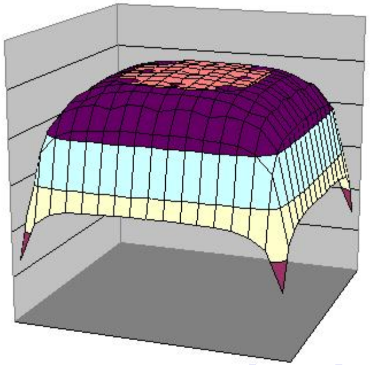
calculate in stage 1

$$\begin{aligned}\phi_{G,\, l,\, m}(\mathbf{r}) = & \sum_{nr} F^{S}_{G,\, nr}\, \Psi^{S}_{G,\, nr,\, l,\, m}(\mathbf{r}) \\ & + \sum_{pp,\, lmcq} F^{CB}_{G,\, pp,\, lmcq}\, \Psi^{CB}_{G,\, pp,\, lmcq,\, l,\, m}(\mathbf{r}) \\ & + \sum_{pp,\, lmsq} F^{SB}_{G,\, pp,\, lmsq}\, \Psi^{SB}_{G,\, pp,\, lmsq,\, l,\, m}(\mathbf{r})\end{aligned}$$

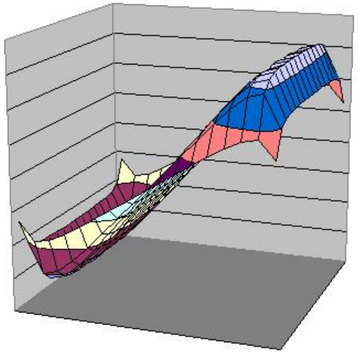
reduce the size of the problem (Ritz method):

solve $\Phi_g(\mathbf{r}, \Omega)$ **to solve** $F^{S}_{G,\, nr}$, $F^{CB}_{G,\, pp,\, lmcq}$, $F^{SB}_{G,\, pp,\, lmsq}$

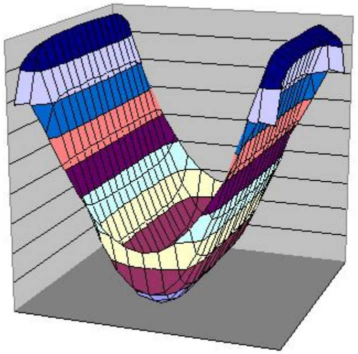
flux moment nodal expansion



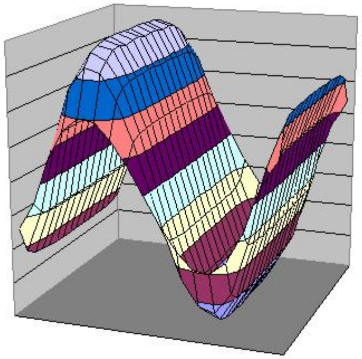
$S_{n=0,g=1}(x,y)$



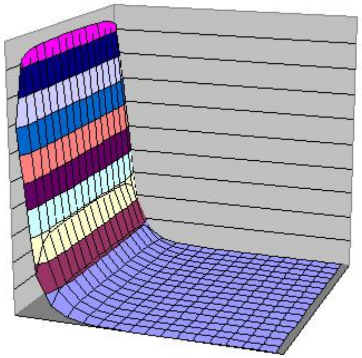
$S_{n=1,g=1}(x,y)$



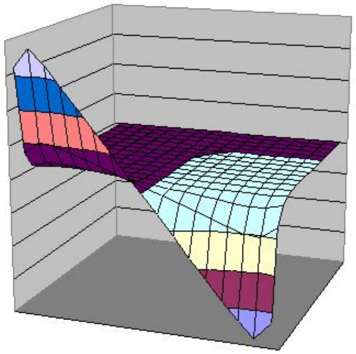
$S_{n=2,g=1}(x,y)$



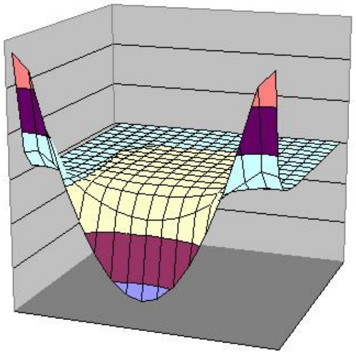
$S_{n=3,g=1}(x,y)$



$B_{m=0,g=1}(x,y)$



$B_{m=1,g=1}(x,y)$



$B_{m=2,g=1}(x,y)$

number of energy groups, PL-order

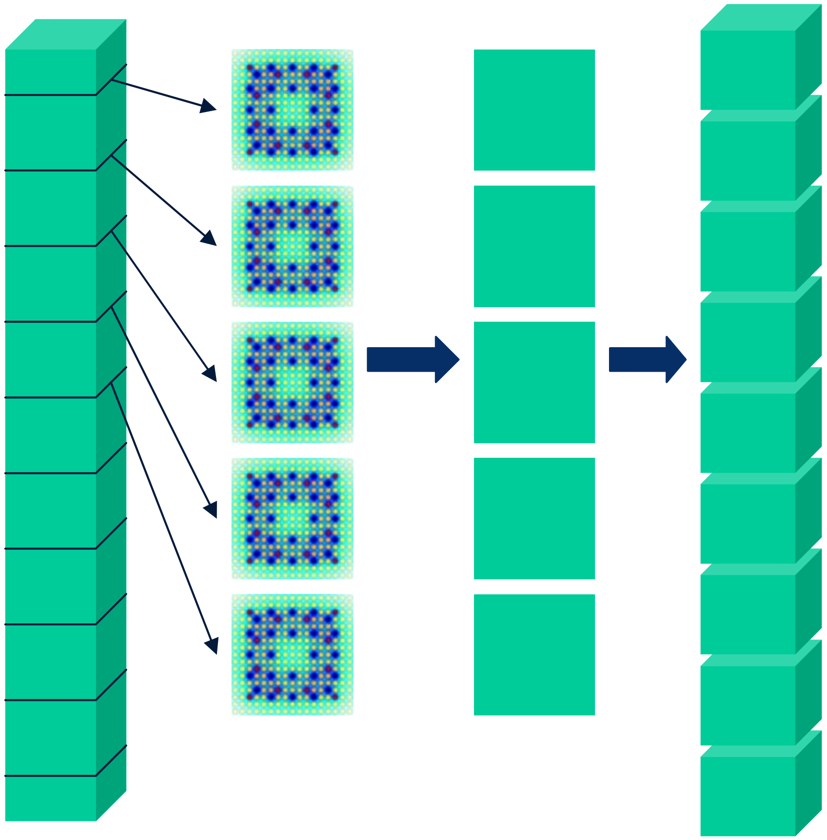
Case 2

	dkeff (%)	rms (%) overall	axial	radial
7G	reference	3.1	1.5	2.0
5G	0.04	3.1	1.5	2.0
4GA	0.17	4.6	1.6	3.4
4GB	0.46	9.9	2.6	7.7
3G	1.02	21.8	3.3	17.8
(7GP1	0.04	4.6	1.6	3.5)

Case 1

	dkeff (%)	rms (%) overall	axial	radial
7G	reference	3.4	2.7	1.4
5G	–0.01	3.5	2.8	1.5
(7GP1	-0.01	4.1	2.7	2.6)

method – stage 1 of 2



2D cross sectional calculation, infinite-lattice assumption

"homogenized" node and assembly

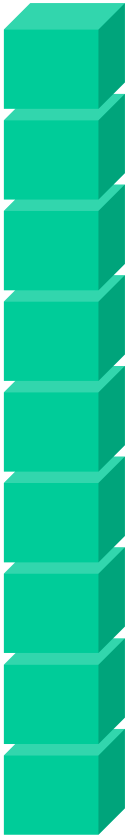
- solve 2D transport equations
- detailed geometry
- with sufficiently large no. of energy groups
- assuming reflective boundary condition

↓

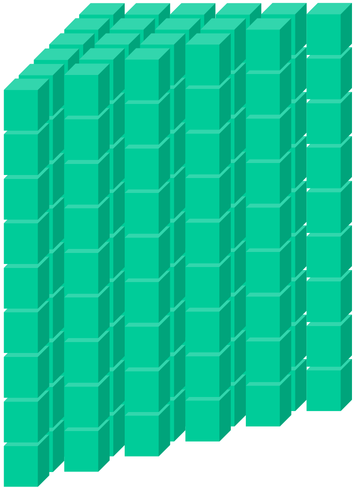
- homogenization of cross sectional area
- energy group condensation

method – stage 2 of 2

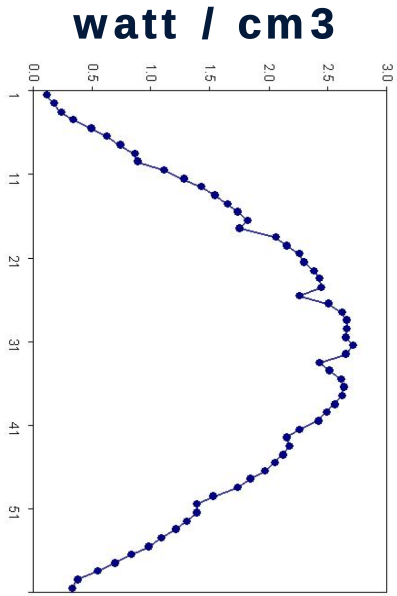
- results of stage 1 are tabulated
- solve 3D (homogenized) nodal transport equations
- including feedback effects



"homogenized" node and assembly



"nodal" core model



power distribution, keff