Neutronenphysikalische Berechnungen zur Umstellbarkeit von Forschungsreaktoren auf niedrig angereichertes Uran

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Hintergrund

Forschungsreaktoren, allgemein

IAEA Datenbank: ca. 550 Reaktoren in mehr als 60 Ländern, heute ca. 280 in Betrieb

Besondere Bedeutung in der Grundlagenforschung: Neutronenstreuung

Hochangereichertes Uran und Proliferationsrisiko

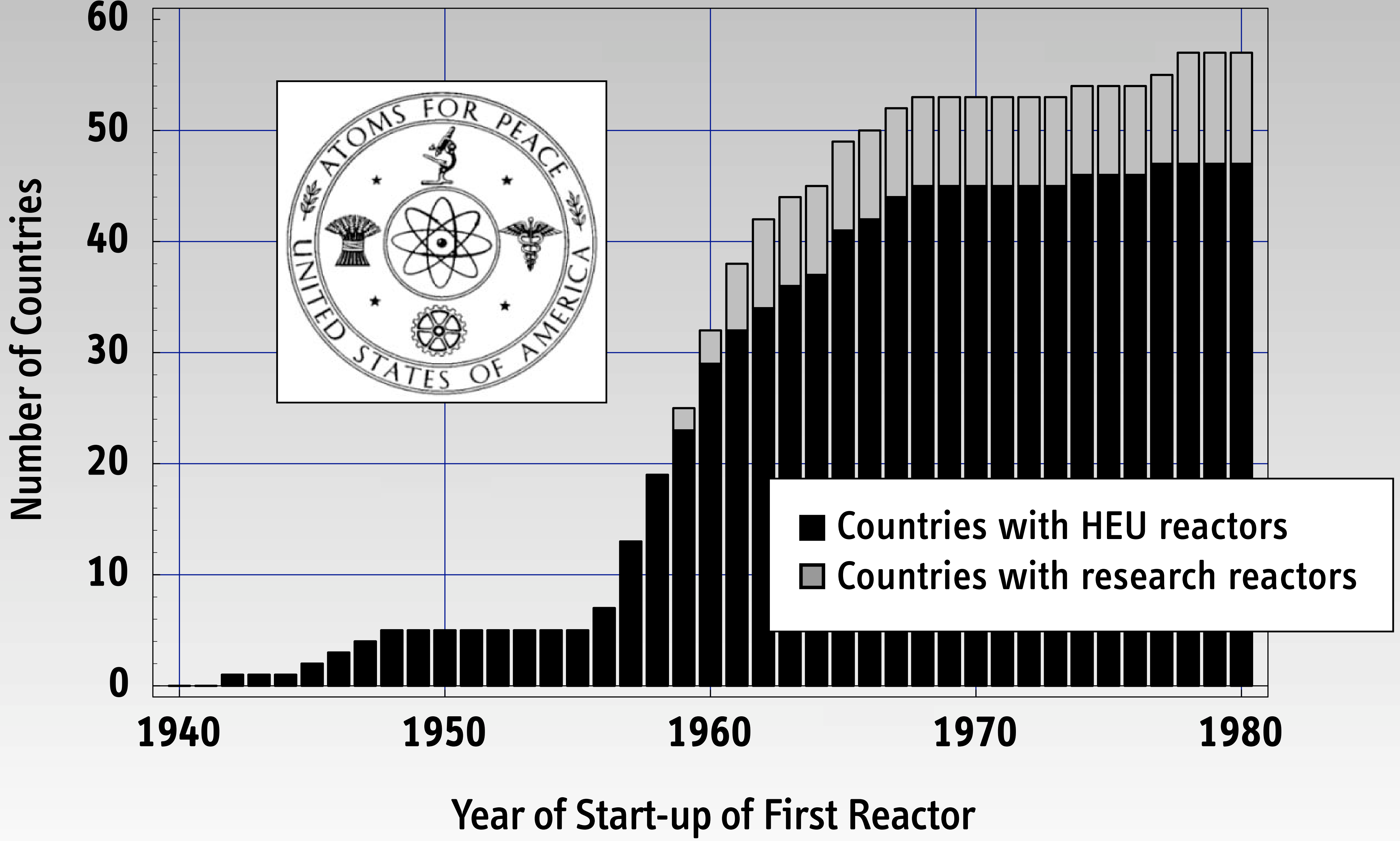
HEU ist (neben Plutonium) für Kernwaffen geeignetes Material

ca. 50 Reaktoren (mit mind. 1 MW) weltweit nutzen hochangereichertes Uran

Umstellung von Reaktoren auf niedrig angereichertes Uran

Problemstellung: Wie kann dies ohne wesentliche Einbussen
in der Nutzbarkeit der Anlagen geschehen?

Number of Countries with Research Reactors



Research Reactor Applications

Application	Reactors
1. Neutron activation analysis	71
2. Teaching	68
3. Training	63
4. Materials or fuel tests	53
5. Isotope production	48

Application	Reactors
6. Material structure studies	34
7. Neutron radiography	32
8. Transmutation	21
9. Geochronology	14
10. Neutron capture therapy	9
Other uses	47

Data based upon a survey among operators
Table adapted from Dodd et al., Physica B (311), 2002

High-Flux-Reactor Grenoble

Institut-Laue-Langevin, 1972

Thermal power: 58 MW, max. thermal neutron flux: ca. $1.5\ 10^{15}\ n/cm^2s$

HEU-Fueled Research Reactors

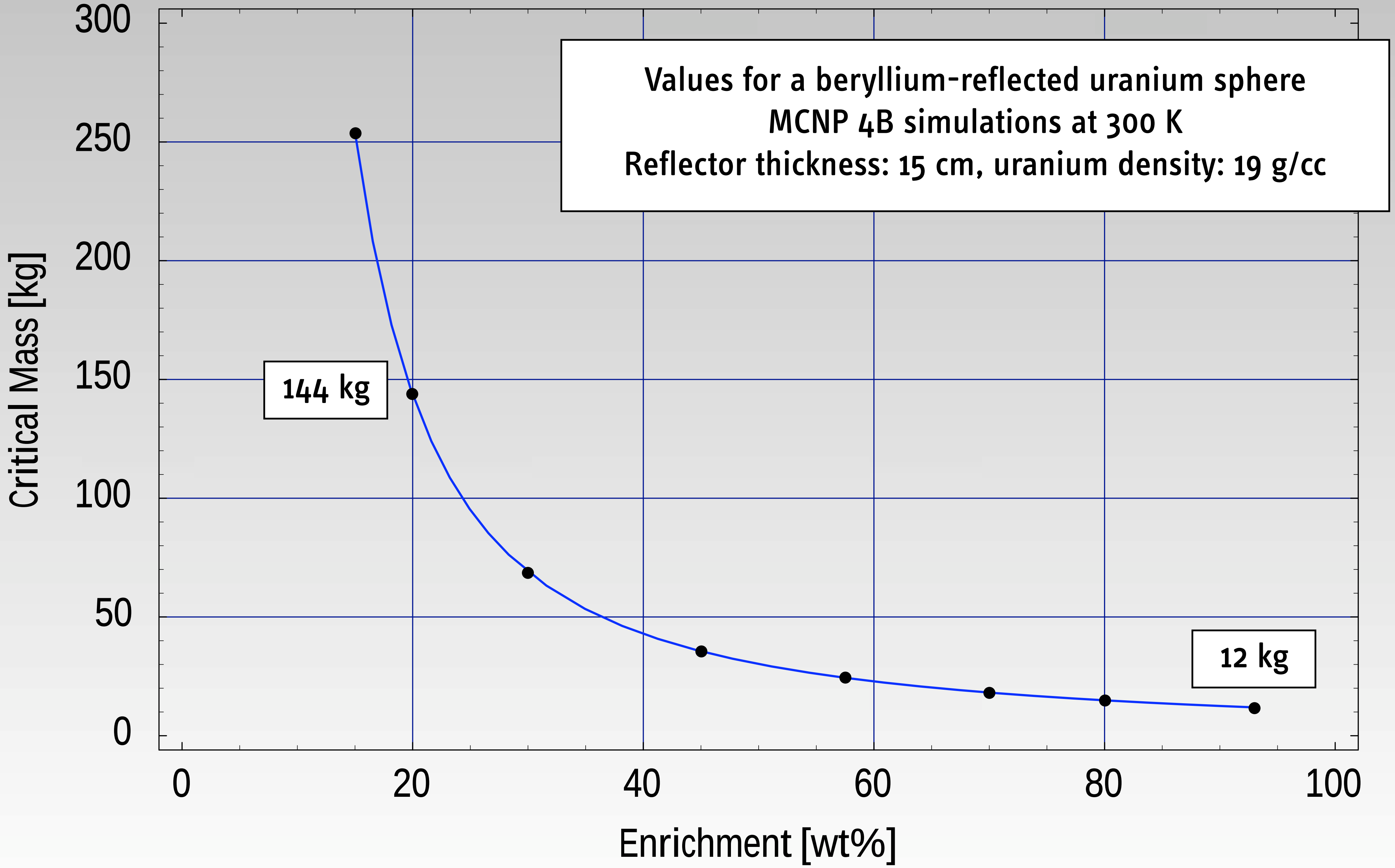
(Highest Relevance Group, 2004)

Country	IAEA Code	Name	Criticality	Power	Enrichment	HEU Demand
USA	US-0070	ATR	1967/07	250 MW	93%	120–175 kg/yr
USA	US-0137	HFIR	1965/08	85–100 MW	93%	91–150 kg/yr
Russia	RU-0024	SM-2	1961/10	100 MW	90%	43–110 kg/yr
China	CN-0004	HFETR	1979/12	125 MW	90%	75 kg/yr
Russia	RU-0013	MIR-M1	1966/12	100 MW	90%	62.2 kg/yr
Kazakhstan	KZ-0003	EWG-1	1972/01	60 MW	90%	?
France	FR-0017	HFR	1971/07	58.3 MW	93%	54.8 kg/yr
Germany	DE-0051	FRM-II	2004/03	20 MW	93%	40.5 kg/yr
Netherland	NL-0004	HFR	1961/11	45 MW	93%	38.3 kg/yr
Belgium	BE-0002	BR-2	1961/06	80–100 MW	74–93%	29 kg/yr
USA	US-0204	MURR	1966/10	10 MW	93%	23.5 kg/yr
Germany	DE-0006	FRJ-2	1962/11	23 MW	80–93%	19.2 kg/yr
Poland	PL-0004	MARIA	1974/12	17–30 MW	36–80%	?
France	FR-0022	ORPHEE	1980/12	14 MW	93%	15.8 kg/yr
Russia	RU-0008	WWR-M	1959/12	18 MW	90%	3.7–14.4 kg/yr
USA	US-0126	NBSR	1967/12	20 MW	93%	13 kg/yr
South Africa	ZA-0001	SAFARI	1965/03	20 MW	87–93%	12.6 kg/yr
USA	US-0120	MITR-2	1958/07	4.9–10 MW	93%	1.6–12 kg/yr
Romania	RO-0002	TRIGA-2	1979/11	14 MW	20–93%	11.8 kg/yr
Russia	RU-0010	IVV-2M	1966/04	15 MW	90%	3.5–9 kg/yr
Kazakhstan	KZ-0002	IGR	1961/01	10 MW	36–90%	?
Australia	AU-0001	HIFAR	1958/01	10 MW	60%	8.1 kg/yr
Russia	RU-0014	IRT-T	1967/07	6 MW	90%	5.6 kg/yr

Hochangereichertes Uran und Proliferationsrisiko

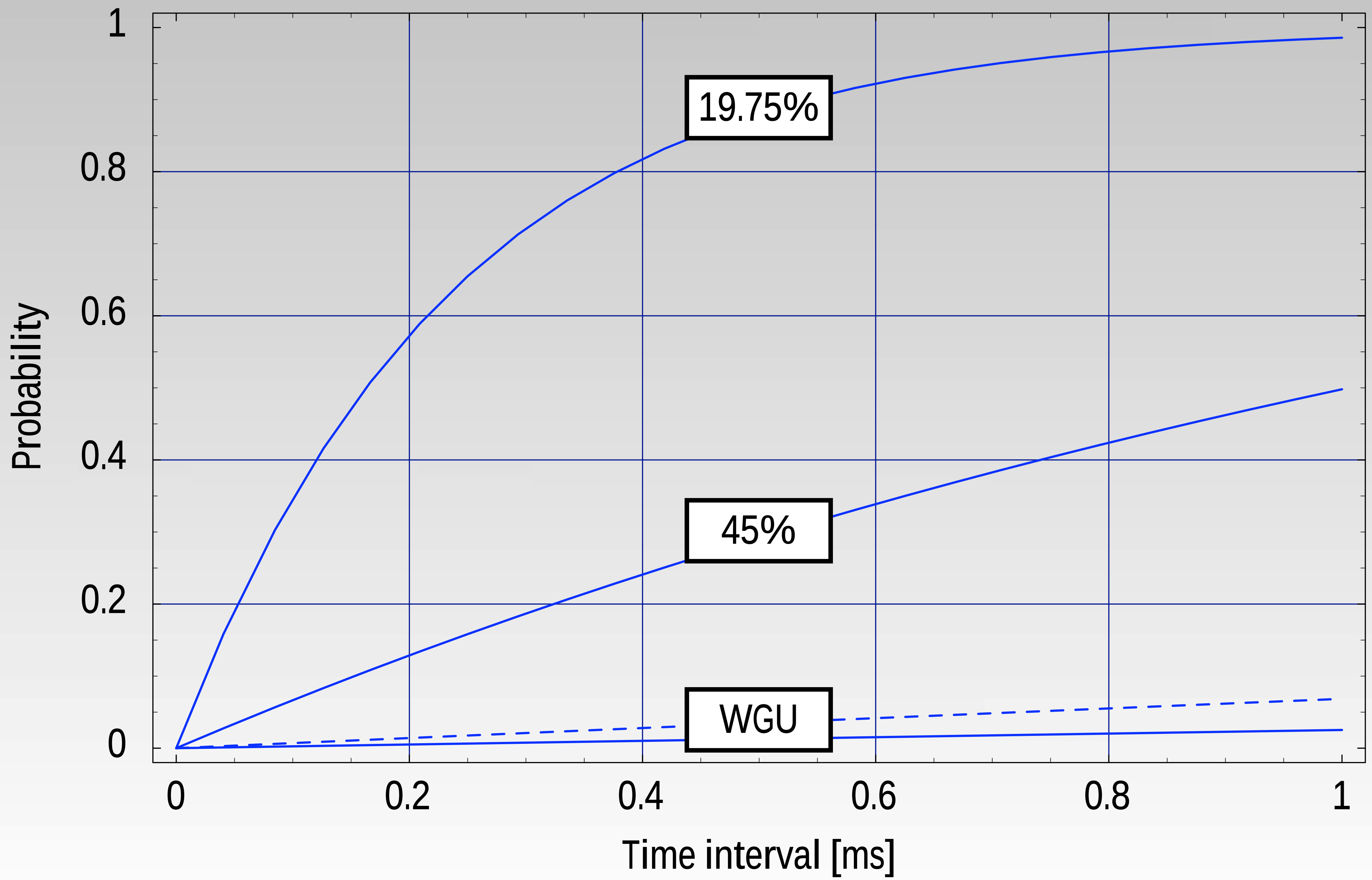
(Waffentauglichkeit, Mengen und geographische Verbreitung)

Critical Mass of Uranium



Spontaneous Fission in Uranium

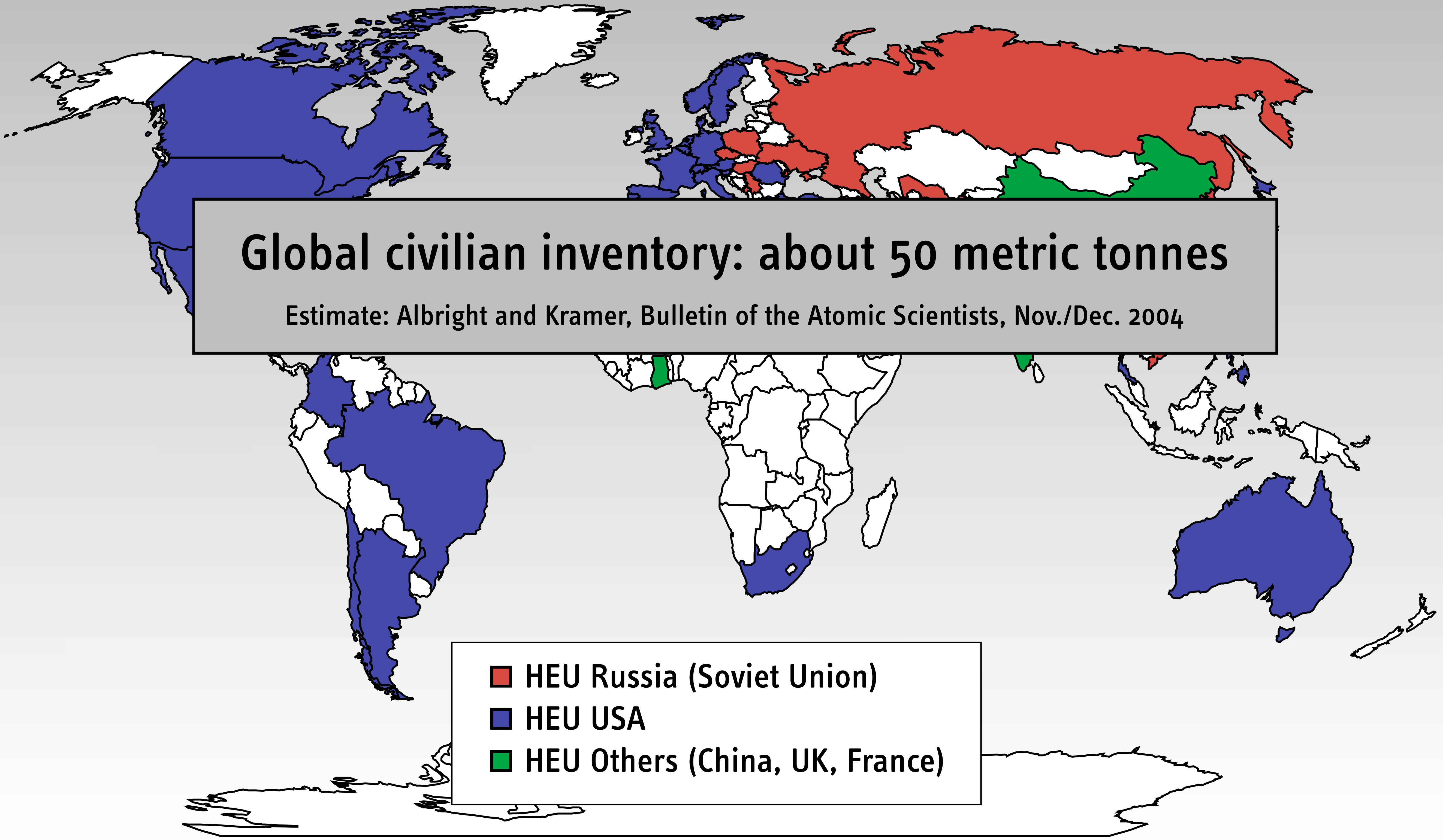
Probability for at least one SF event in one bare critical mass



“With modern weapons-grade uranium, the background neutron rate is so low that terrorists, if they had such material, would have a good chance of setting off a high-yield explosion simply by dropping one half of the material onto the other half. Most people seem unaware that if separated U-235 is at hand it's a trivial job to set off a nuclear explosion ...”

Luis Alvarez, Adventures of a Physicist, Basic Books, 1987, p. 125

Geographical Distribution of Highly Enriched Uranium



Global civilian inventory: about 50 metric tonnes

Estimate: Albright and Kramer, Bulletin of the Atomic Scientists, Nov./Dec. 2004

- 🟥 HEU Russia (Soviet Union)
- 🟦 HEU USA
- 🟩 HEU Others (China, UK, France)

Umstellung von Forschungsreaktoren auf niedrig angereichertes Uran

(und die Entwicklung hochdichter Brennstoffe)

Internationaler Kontext

RERTR Programm (seit 1978) und Unterstützungsprogramme

(Reduced Enrichment for Research Reactor Test Reactors)

Kooperation zwischen dem U.S. RERTR Programm und dem entsprechenden russischen Programm seit 1996

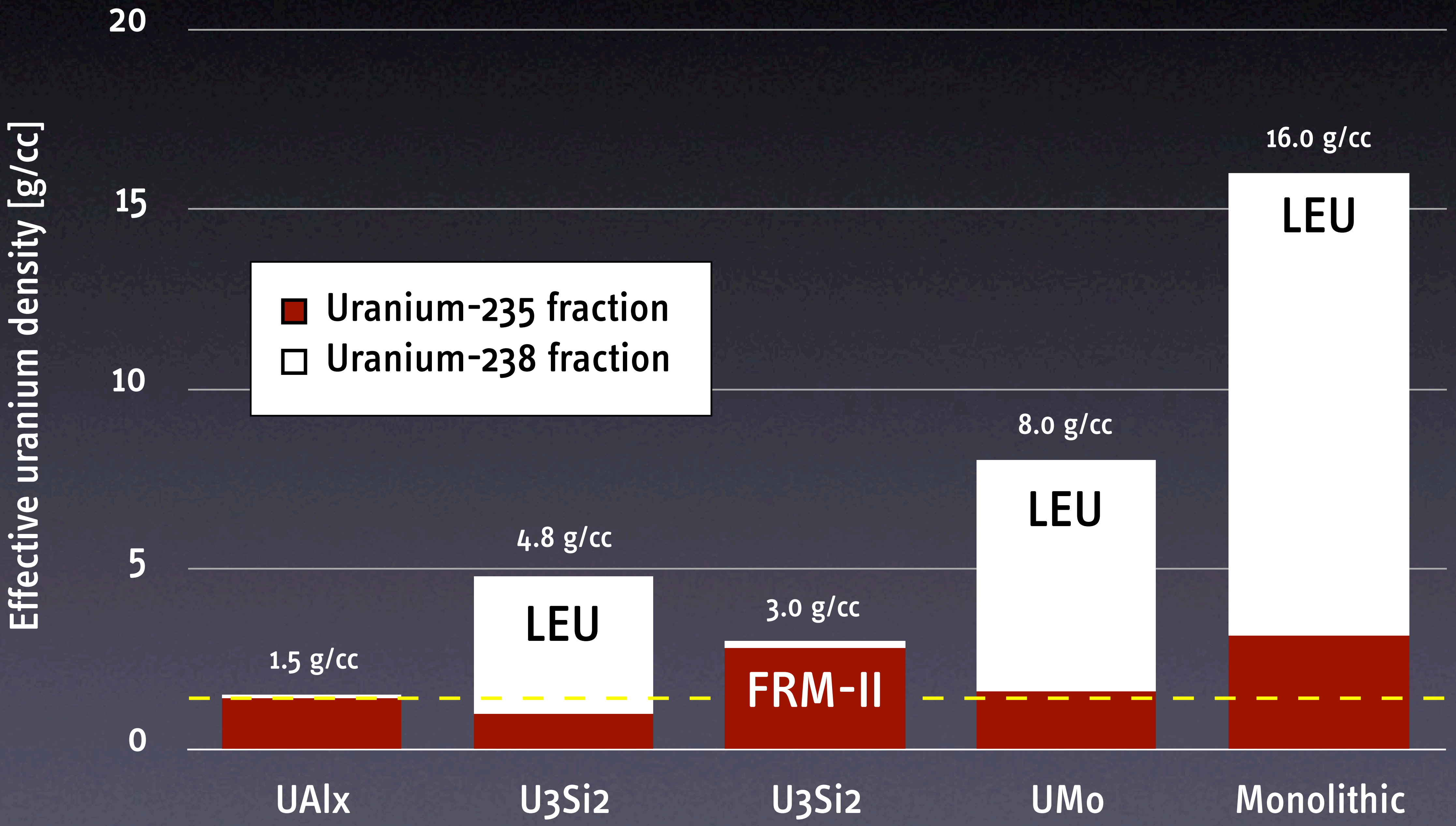
INFCE Konferenz (1978-1980)

Deutsches AF Programm (1979-1989)

51.5 Millionen DM zur Umstellung aller deutschen Reaktoren

Entscheidendes Element: Brennstoffentwicklung

Effective Uranium Densities in Research Reactor Fuels



Neutronics Calculations for Single Element Reactors

(Steady state and burnup calculations)

Methodik und Ziele

Entwicklung von Mathematica-Modulen zur Erzeugung von detaillierten 3D-Modellen von Forschungsreaktorgeometrien (zur Analyse mit Monte Carlo Neutronentransportcodes)

Entwicklung des Programmsystems “M^3O” für neutronenphysikalische Berechnungen basierend auf diesen 3D-Modellen (Mathematica, MCODE, MCNP, ORIGEN)

Bestimmung wesentlicher Leistungsmerkmale von Forschungsreaktoren

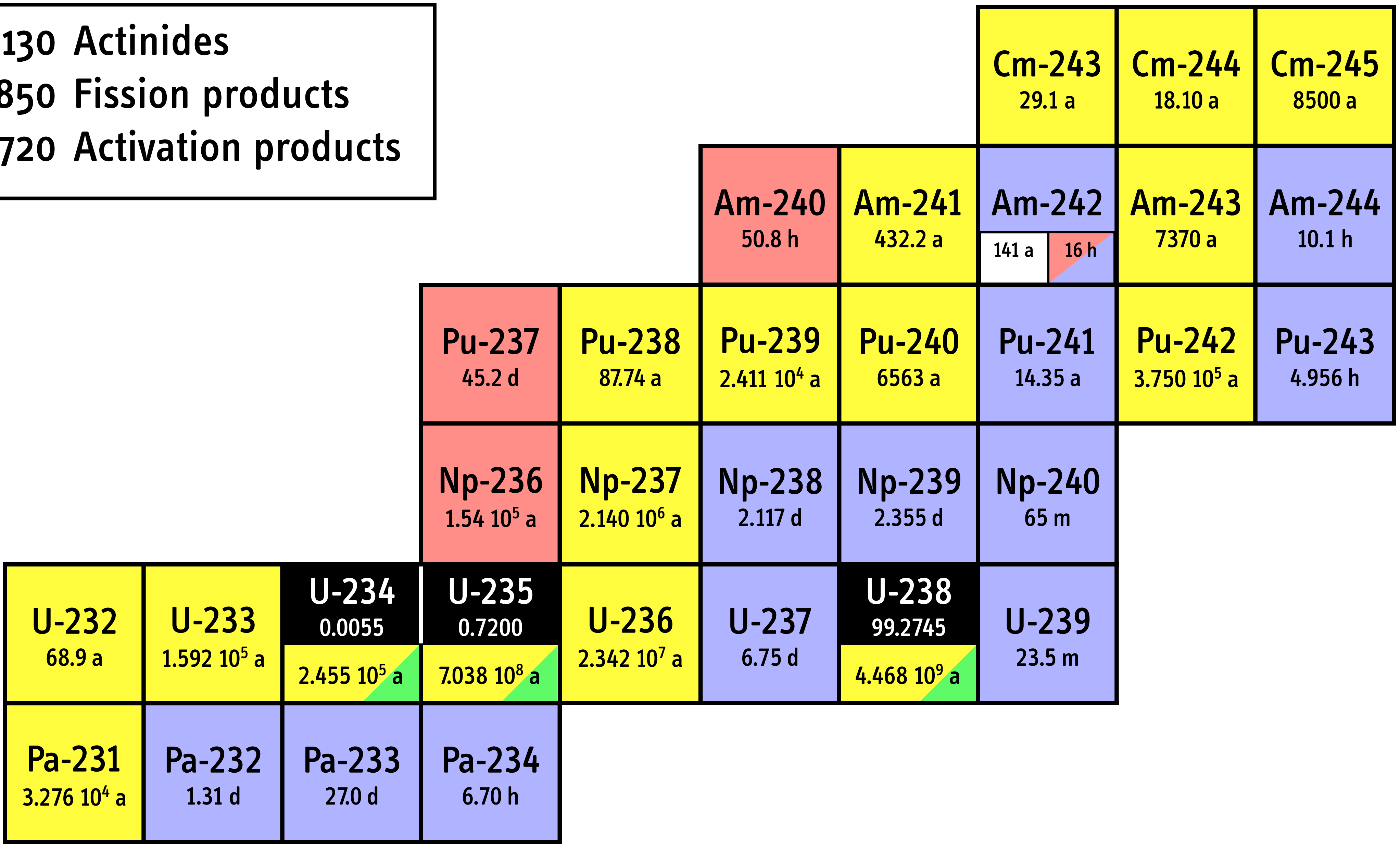
Anwendungsbeispiele:
“Generic Single Element Reactor” (GSER) und FRM-II

Implementierung eines Algorithmus zur neutronenphysikalischen Optimierung von Forschungsreaktorgeometrien

Beurteilung der wissenschaftlichen Nutzbarkeit von Neutronenquellen

Nuclides in Burnup Calculations

130 Actinides
850 Fission products
720 Activation products



							Cm-243 29.1 a	Cm-244 18.10 a	Cm-245 8500 a
					Am-240 50.8 h	Am-241 432.2 a	Am-242 141 a 16 h	Am-243 7370 a	Am-244 10.1 h
			Pu-237 45.2 d	Pu-238 87.74 a	Pu-239 2.411 10^4 a	Pu-240 6563 a	Pu-241 14.35 a	Pu-242 3.750 10^5 a	Pu-243 4.956 h
			Np-236 1.54 10^5 a	Np-237 2.140 10^6 a	Np-238 2.117 d	Np-239 2.355 d	Np-240 65 m		
U-232 68.9 a	U-233 1.592 10^5 a	U-234 0.0055 2.455 10^5 a	U-235 0.7200 7.038 10^8 a	U-236 2.342 10^7 a	U-237 6.75 d	U-238 99.2745 4.468 10^9 a	U-239 23.5 m		
Pa-231 3.276 10^4 a	Pa-232 1.31 d	Pa-233 27.0 d	Pa-234 6.70 h						

Burnup Equations I

$$\frac{d}{dt}N_i(\vec{r},t) = -\left[\int_0^\infty dE\,\sigma_a^i(E)\,\phi(E,\vec{r},t) + \lambda_i\right] N_i(\vec{r},t)$$

$$+\sum_{j\neq i}\left[\int_0^\infty dE\,f_{j\to i}\,\sigma_a^j(E)\,\phi(E,\vec{r},t) + l_{j\to i}\,\lambda_j\right] N_j(\vec{r},t)$$

$\phi(E,\vec{r},t)$ itself is a function of $N(\vec{r},t)$

Complex structure of $\phi(E,\vec{r},t)$
due to spatial and spectral resonance-self-shielding

Burnup Equations II

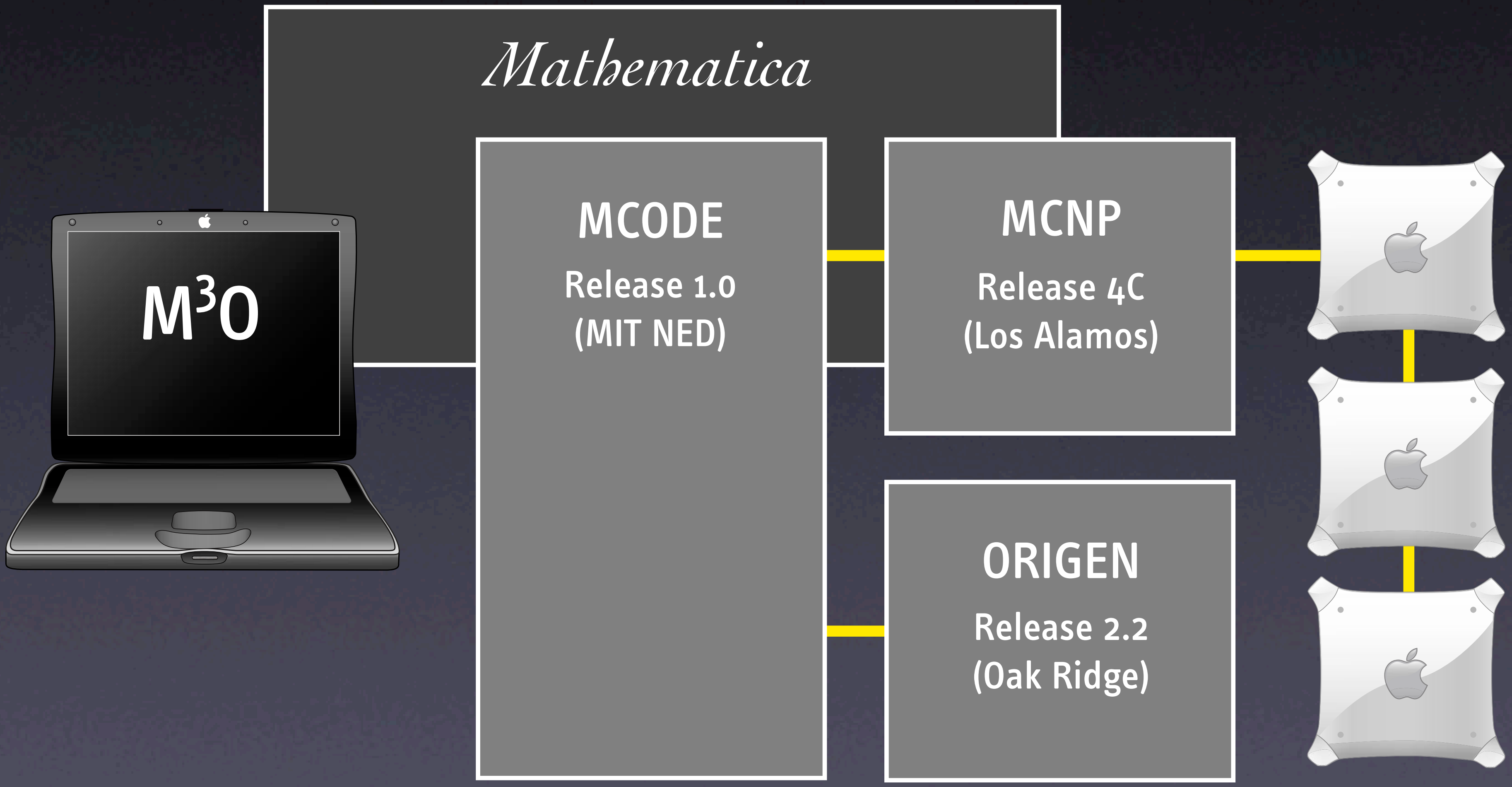
$$\phi_{\text{tot}}(\vec{r},t) = \int_0^\infty dE\,\phi(E,\vec{r},t) \qquad \sigma(\vec{r},t) = \frac{\int_0^\infty dE\,\sigma(E)\,\phi(E,\vec{r},t)}{\int_0^\infty dE\,\phi(E,\vec{r},t)}$$

Total neutron flux and spectrum-averaged cross-sections

$$\frac{d}{dt}N_i(t) = -\left[\sigma_a^i(t)\,\phi_{\text{tot}}(t) + \lambda_i\right] N_i(t) + \sum_{j\neq i}\left[f_{j\to i}(t)\,\sigma_a^j(t)\,\phi_{\text{tot}}(t) + l_{j\to i}\,\lambda_j\right] N_j(t)$$

Burnup equations for point-depletion (cell burnup equations)

Computational System for Research Reactor Analysis



M^3O

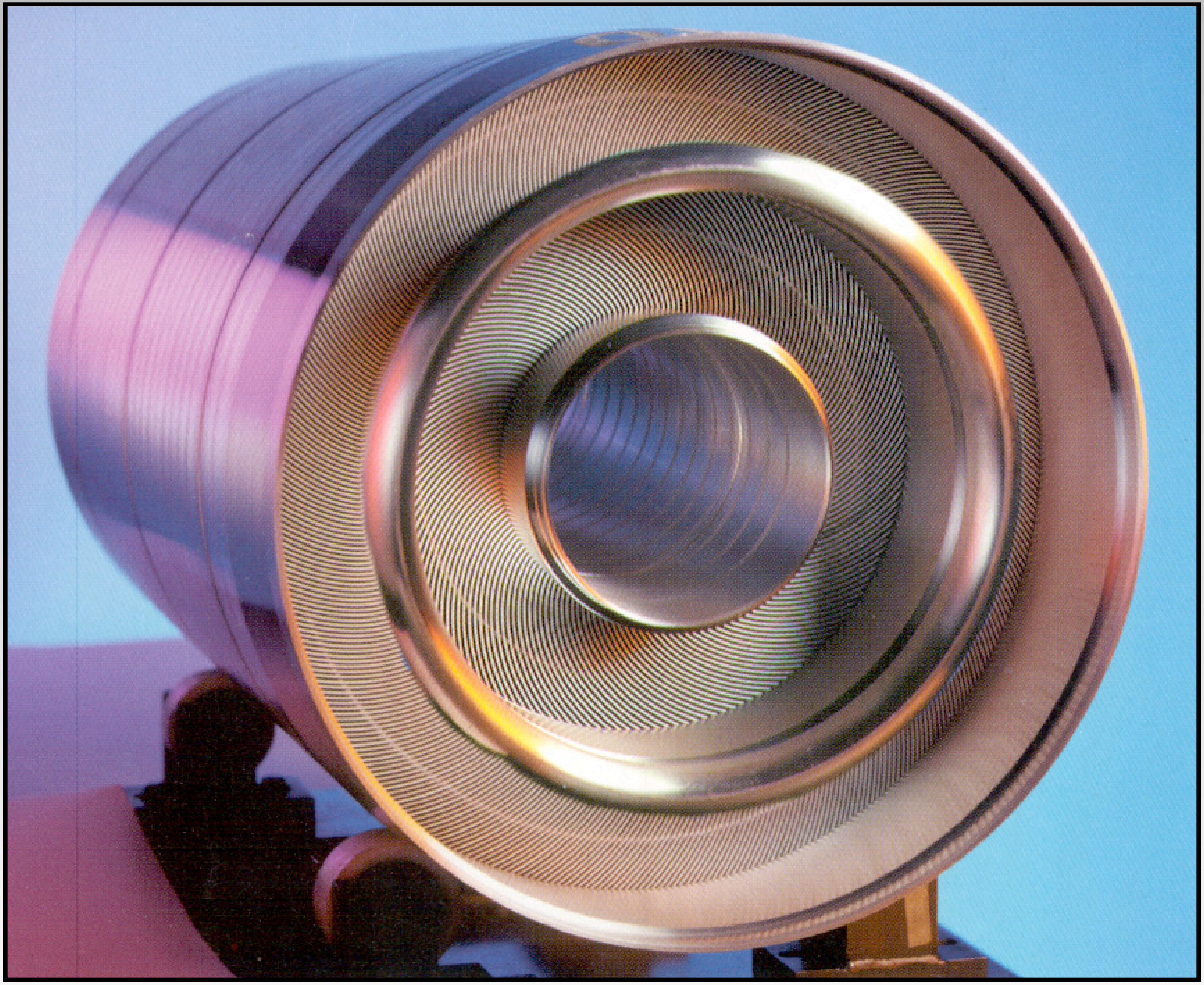
Mathematica

MCODE
Release 1.0
(MIT NED)

MCNP
Release 4C
(Los Alamos)

ORIGEN
Release 2.2
(Oak Ridge)

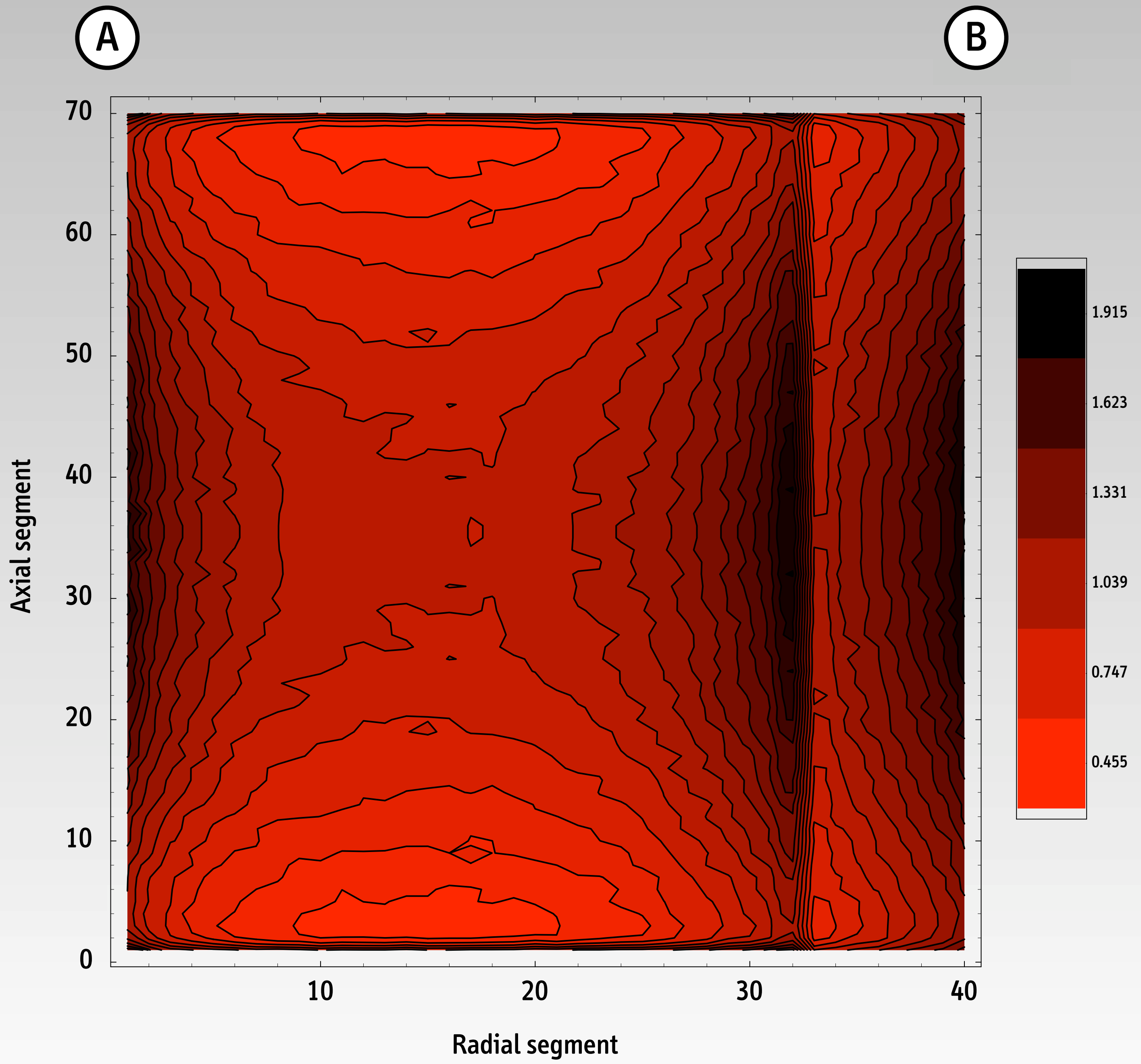
Fuel Element of HFIR

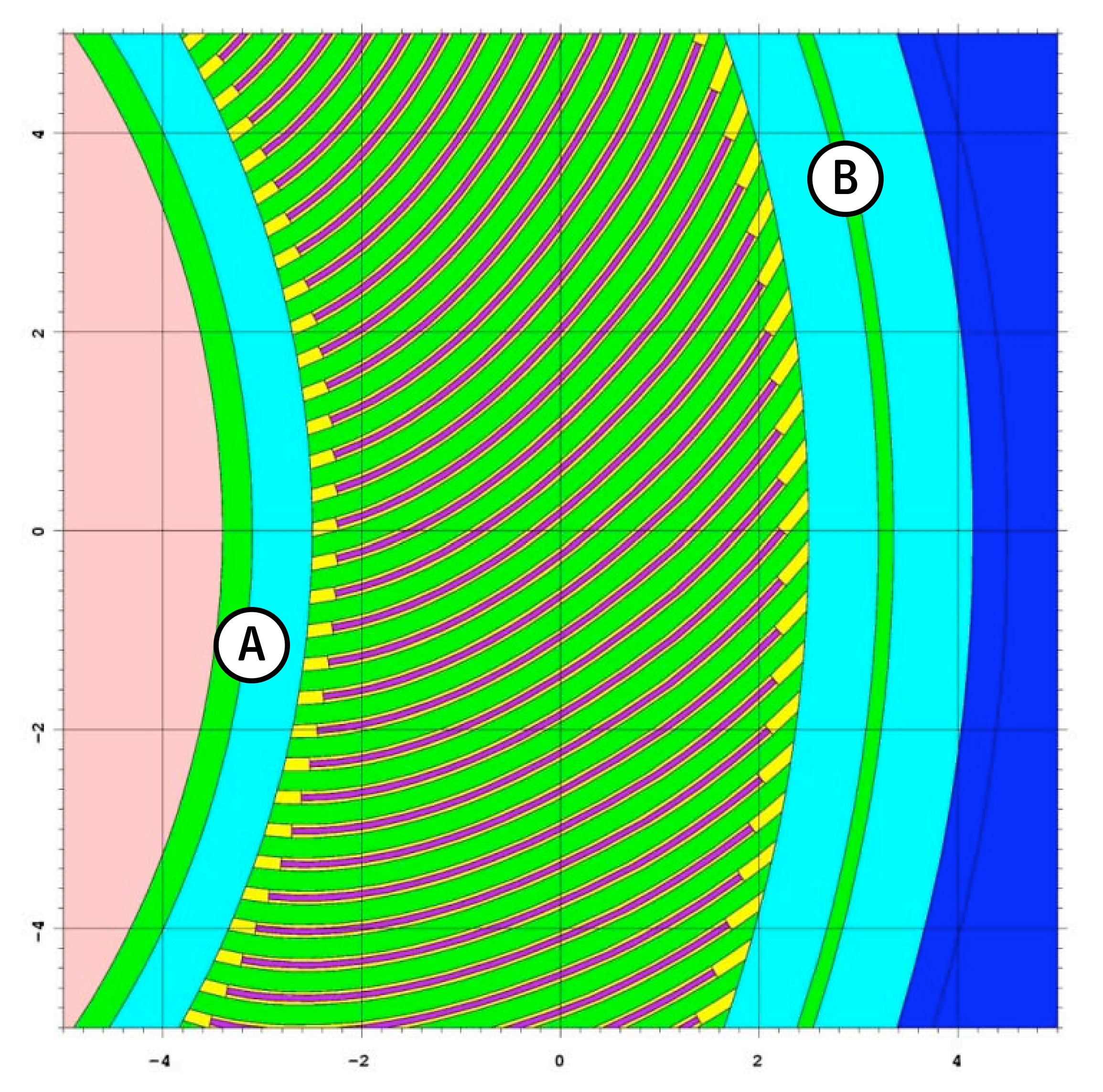


Source: BWXT

Adaptive Cell Structure for FRM-II

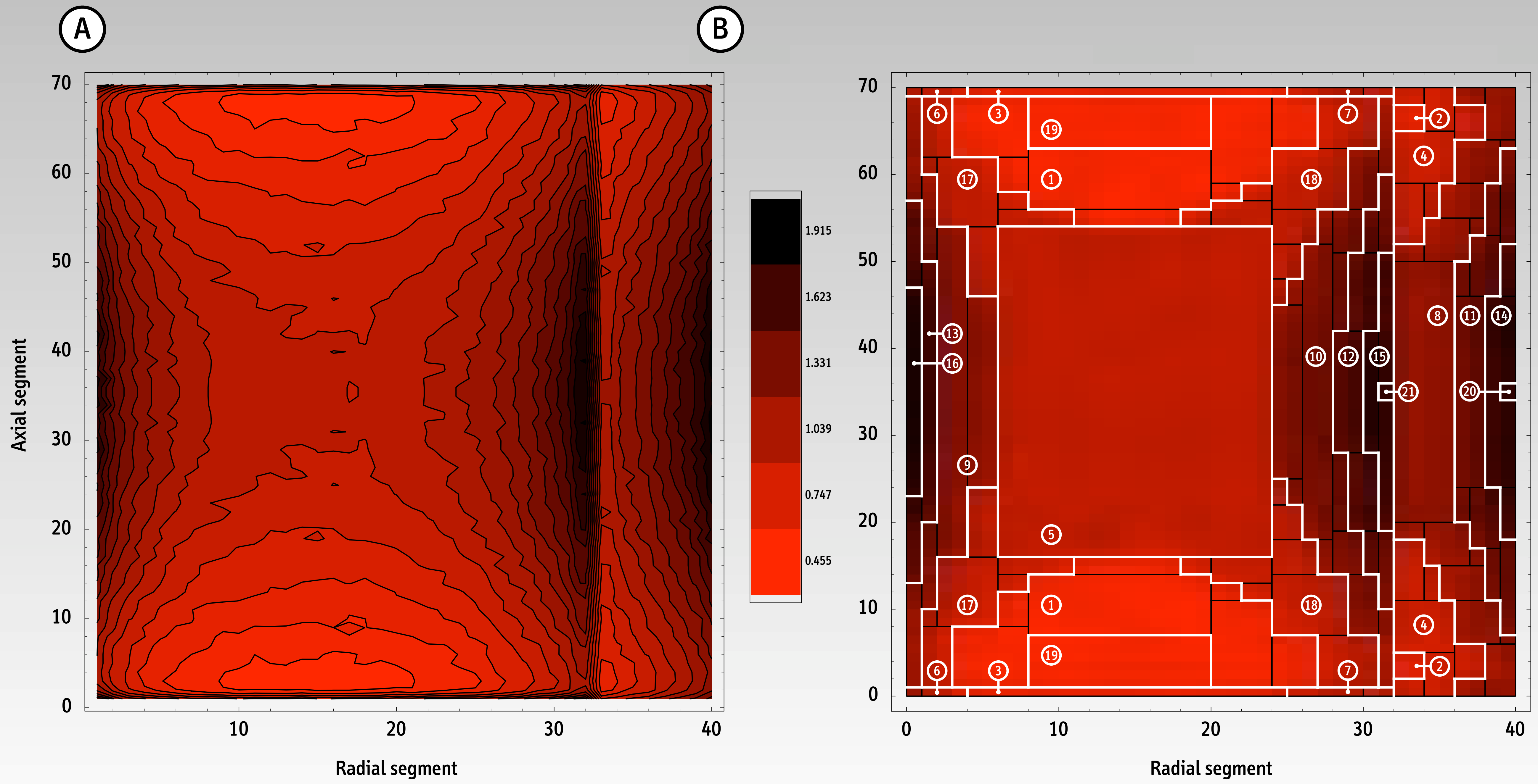
for Burnup Calculations





Adaptive Cell Structure for FRM-II

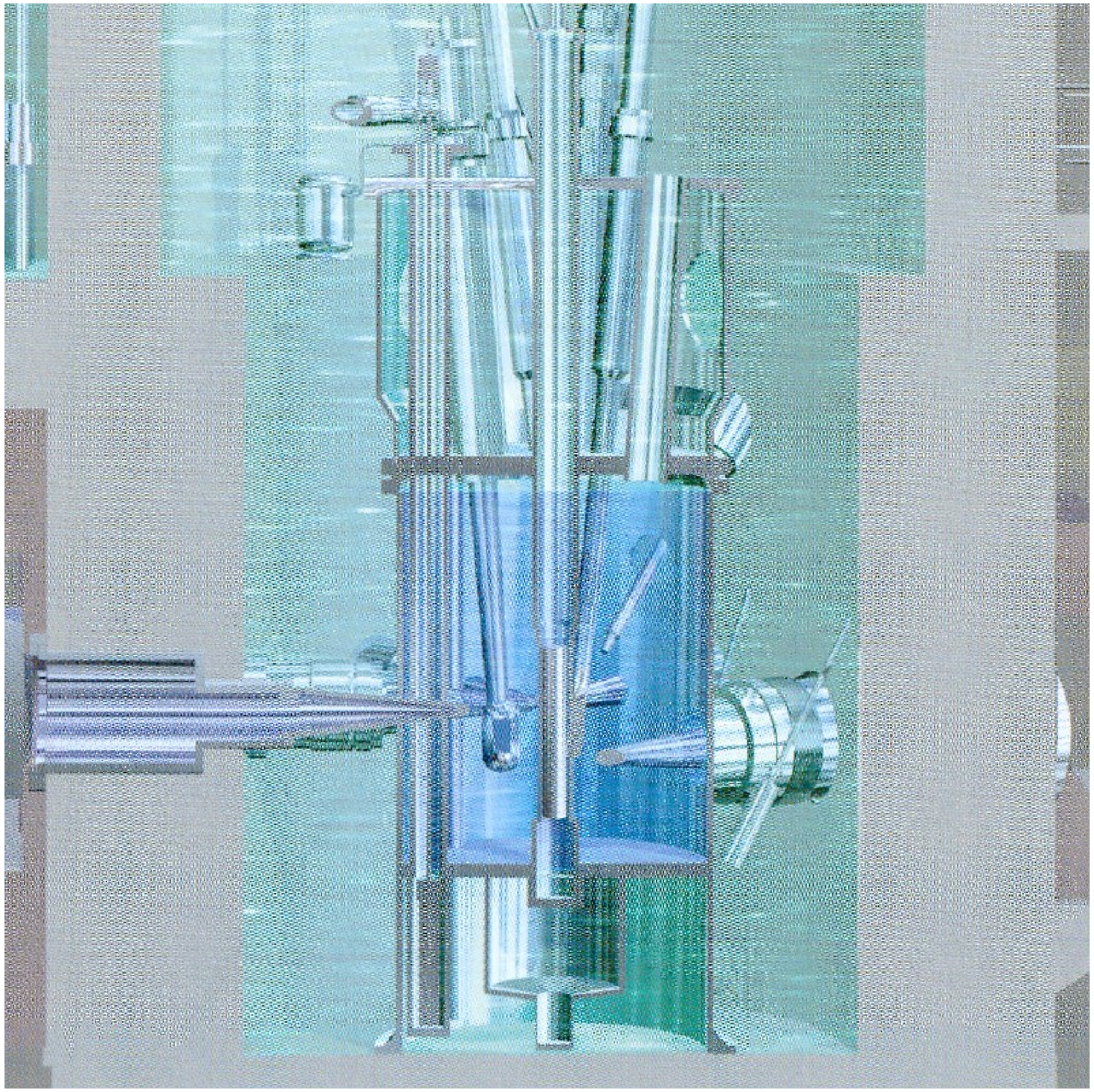
for Burnup Calculations



Fallbeispiel FRM-II

Forschungsreaktor München II (FRM-II), 2004

Technische Daten FRM-II



Thermische Leistung: 20 MW
Kühlmittel: H_2O, Moderator: D_2O
Brennstoffinventar: 8.1 kg Uran (93% U-235)

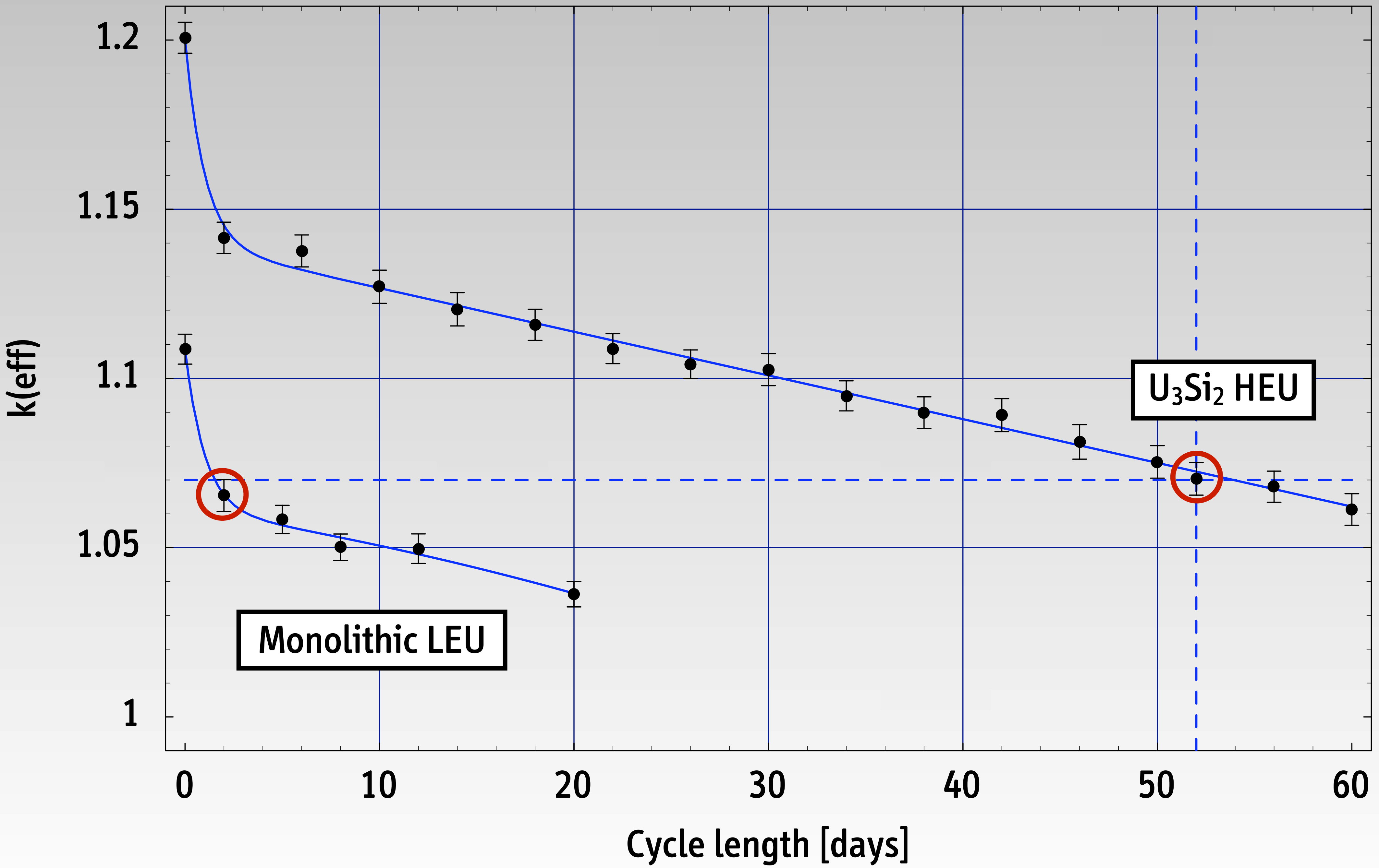
Durchmesser des Reaktorkerns: 24.3 cm
Höhe des Reaktorkerns: 70.0 cm

Wesentliche Kenndaten:

Zykluslänge: 52 Tage
Maximaler th. Neutronenfluss: $8.0 \; 10^{14} n/cm^2s$

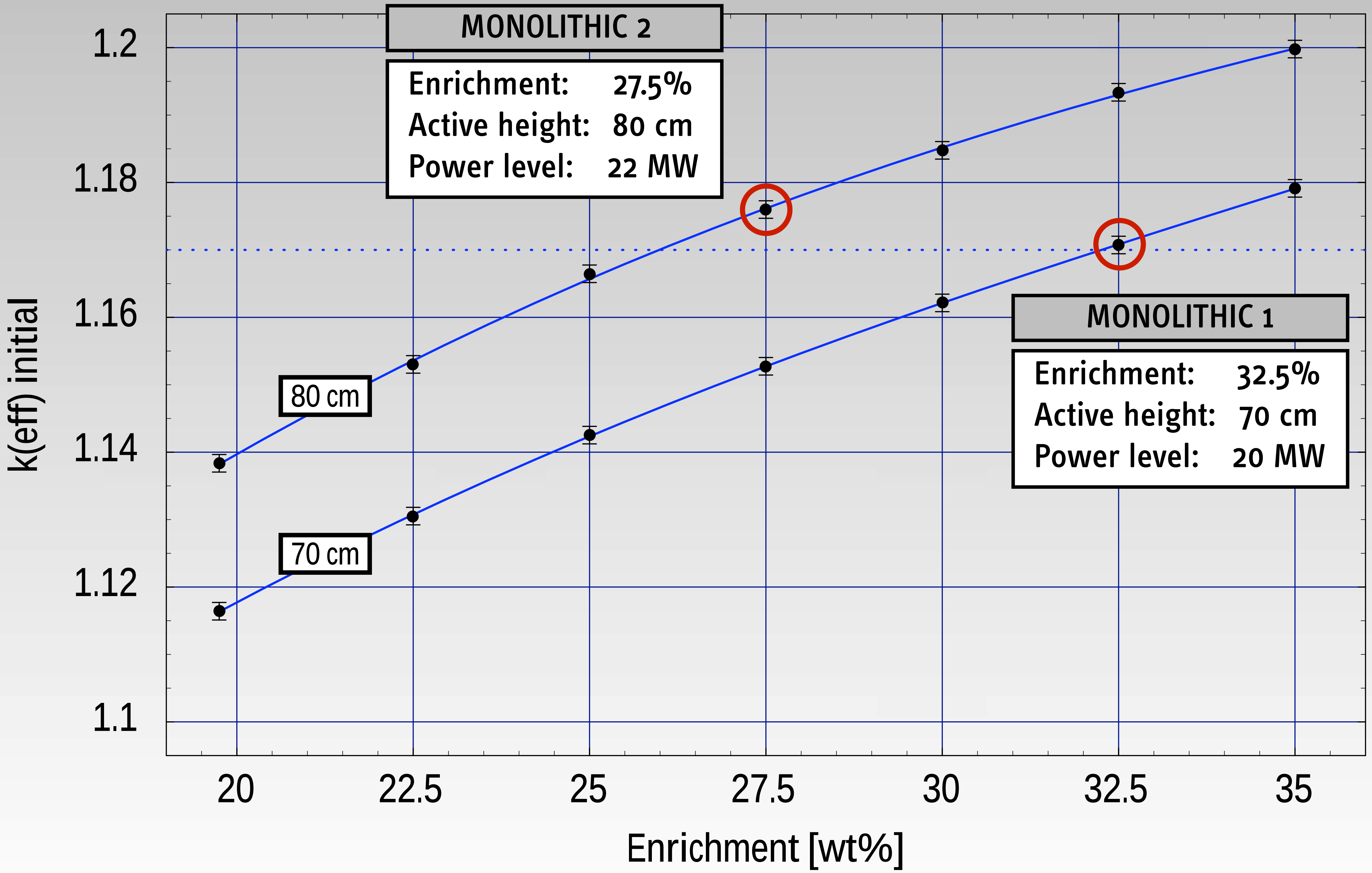
FRM-II Cycle Length

Standard HEU fuel (93%) vs monolithic LEU in original geometry



Initial k(eff) versus Enrichment

Modification: Height of fuel element



MONOLITHIC 2

Enrichment: 27.5%
Active height: 80 cm
Power level: 22 MW

MONOLITHIC 1

Enrichment: 32.5%
Active height: 70 cm
Power level: 20 MW

Optimization of Single Element Reactor Performance Using the Linear Programming Technique

Linear Programming Technique

(n independent variables and m constraints)

maximize $$\sum_{j=1}^{n} c_j \, x_j$$

subject to $$\sum_{j=1}^{n} a_{ij} \, x_j \leq b_i \qquad (i = 1, 2, \ldots, m)$$

$$x_j \geq 0 \qquad (j = 1, 2, \ldots, n)$$

First suggested for research reactor optimization by S.C. Mo, RERTR 1991

Solution with Simplex algorithm

Design Variables and Constraints

x1 : Meat thickness
x2 : Cladding thickness
x3 : Coolant channel width
x4 : Inner core radius
x5 : Outer core radius
x6 : Active height of fuel plate
x7 : Fuel enrichment
x8 : Transition radius
x9 : Discontinuity factor

ϕ : Max. thermal neutron flux

C1 : Cycle length
C2 : Average power density
C3 : Average heat flux
C4 : Power peaking factor 1
C5 : Power peaking factor 2

Objective Function and Constraints

$$\phi(\vec{x}) = \phi(\vec{x}^{\,0}) + \sum_{i=1}^{n} \frac{\partial \phi}{\partial x_i}(x_i - x_i^0)$$

Linearization of thermal neutron flux (objective function)

$$C_j(\vec{x}) = C_j(\vec{x}^{\,0}) + \sum_{i=1}^{n} \frac{\partial C_j}{\partial x_i}(x_i - x_i^0)$$

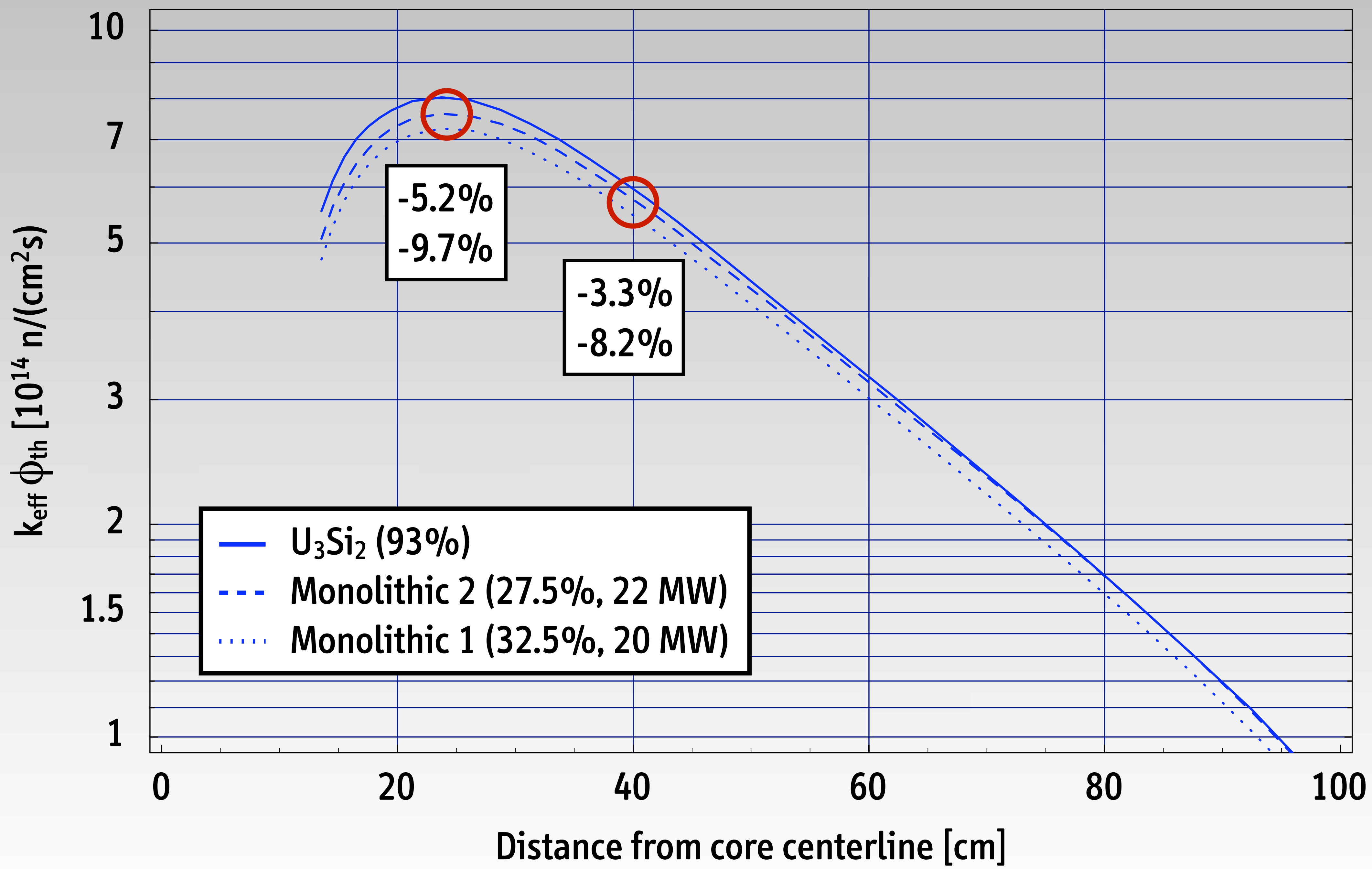
Linearization of constraints

Partial derivatives determined with MCNP (or exactly)

Main Results for Option 2

	FRM-II Monolithic 2		
	Enrichment: 27.5 wt% Active core height: 80 cm; Power level: 22 MW		
	Start	LP Solution	Verification
x_1	0.60 mm	0.60 mm	
x_3	2.20 mm	2.70 mm	
x_8	10.56 cm	10.48 cm	
x_9	0.50	0.49	
Plates	113	100	
k(eff)	1.174 ± 0.001	1.182	1.180 ± 0.001
ϕ	7.56E14 n/cm^{2}s	7.57E14 n/cm^{2}s	7.62E14 n/cm^{2}s
C_1	52 days	52 days	52 days
C_2	985 kW/cc	985 kW/cc	985kW/cc
C_3	175 W/cm^2	200 W/cm^2	200 W/cm^2
C_4	1.73	1.67	1.66
C_5	2.08	2.00	1.99

Thermal Neutron Flux



Wissenschaftliche Nutzbarkeit

Fallbeispiel FRM-II

Relative Acquisition Time

Signal-to-noise ratio: $f = \frac{N_{\mathrm{sig}}}{N_{\mathrm{noi}}} = \frac{\phi_{\mathrm{th}}}{C + \phi_{\mathrm{fast}}}$

Proposed by Axmann et al., TUM, 1999

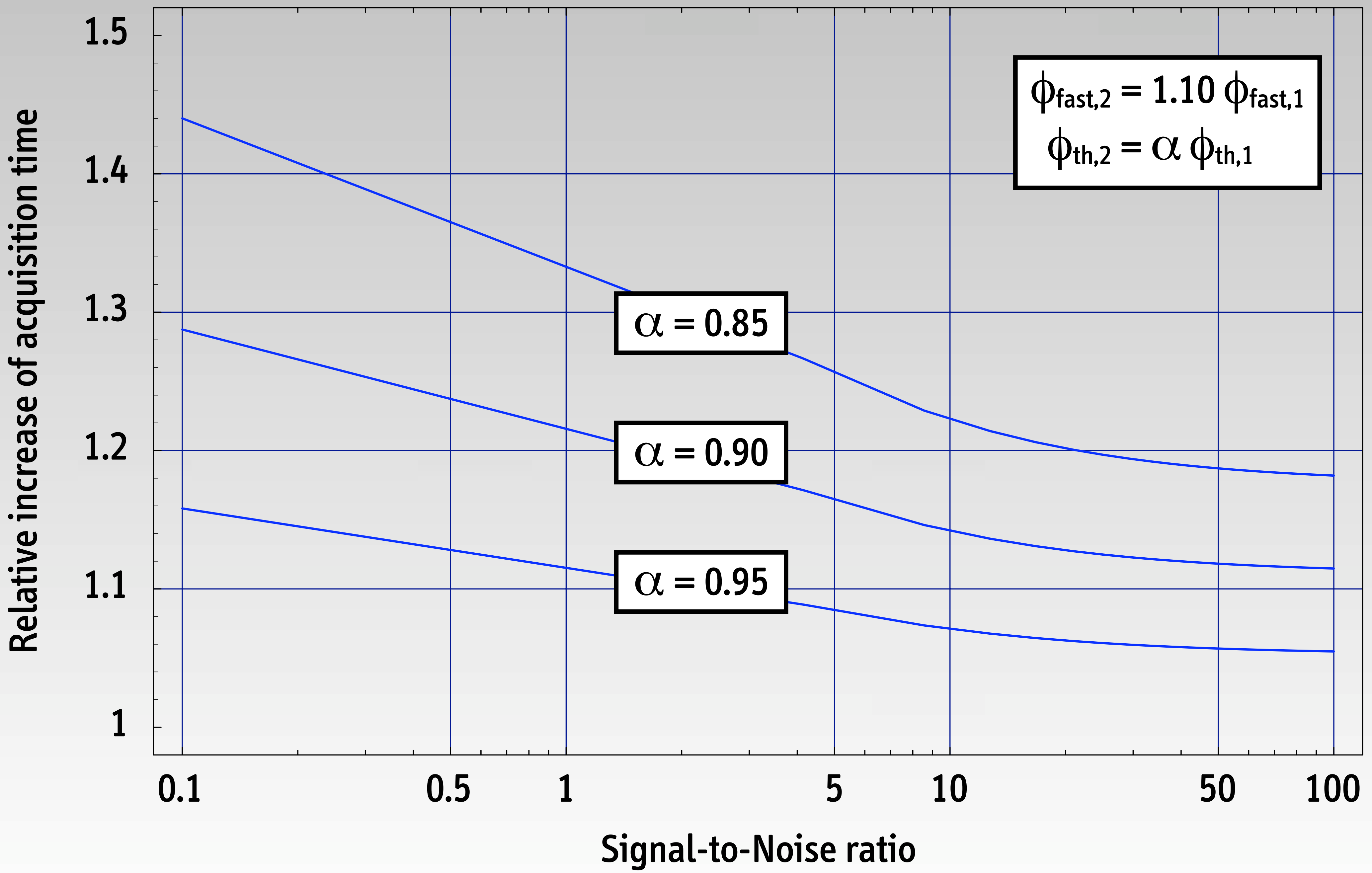
$\phi_{\mathrm{th},2} = \alpha\, \phi_{\mathrm{th},1}$ **and** $\phi_{\mathrm{fast},2} = \beta\, \phi_{\mathrm{fast},1}$

$$\frac{t_2}{t_1} = \frac{1}{\alpha}\left[1 + \left(\frac{1+\beta}{\alpha\, f}\right)\right] \cdot \left[1 + \left(\frac{2}{f}\right)\right]^{-1}$$

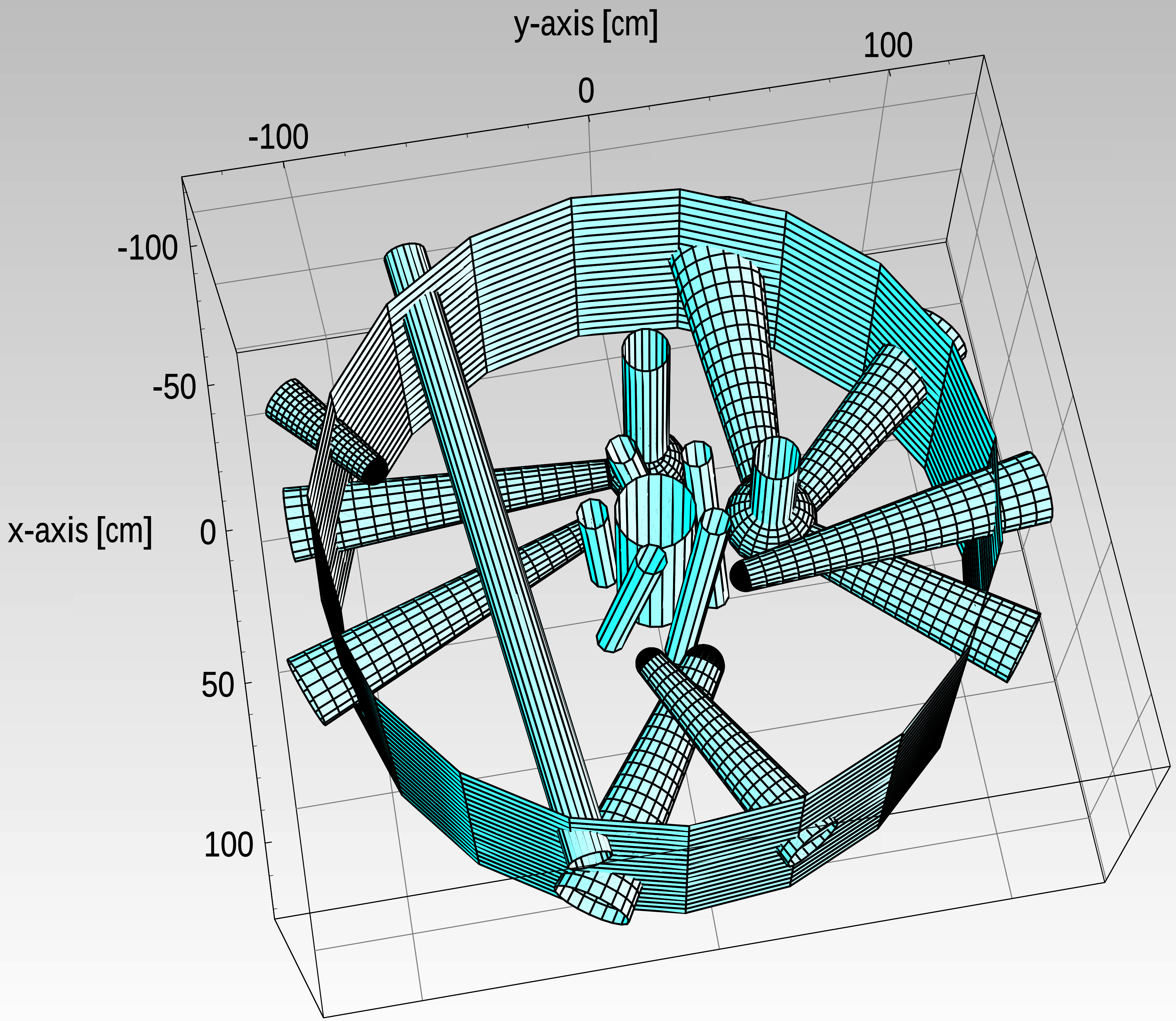
Relative acquisition time to achieve the same relative error of data

Increase of Required Beam Time

for constant relative error, exemplary data

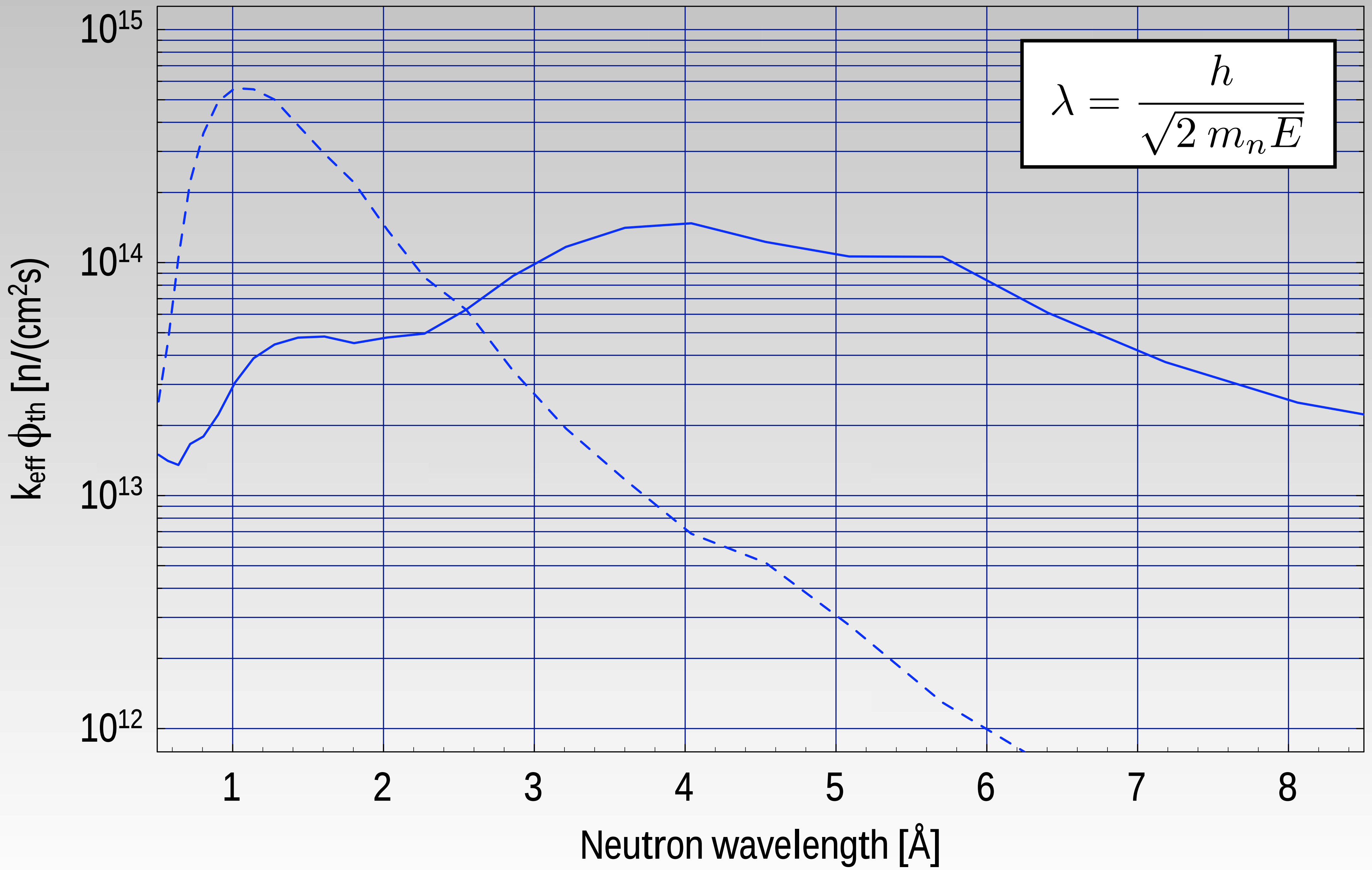


MCNP Model of FRM-II Tank



Neutron Wavelength in CNS

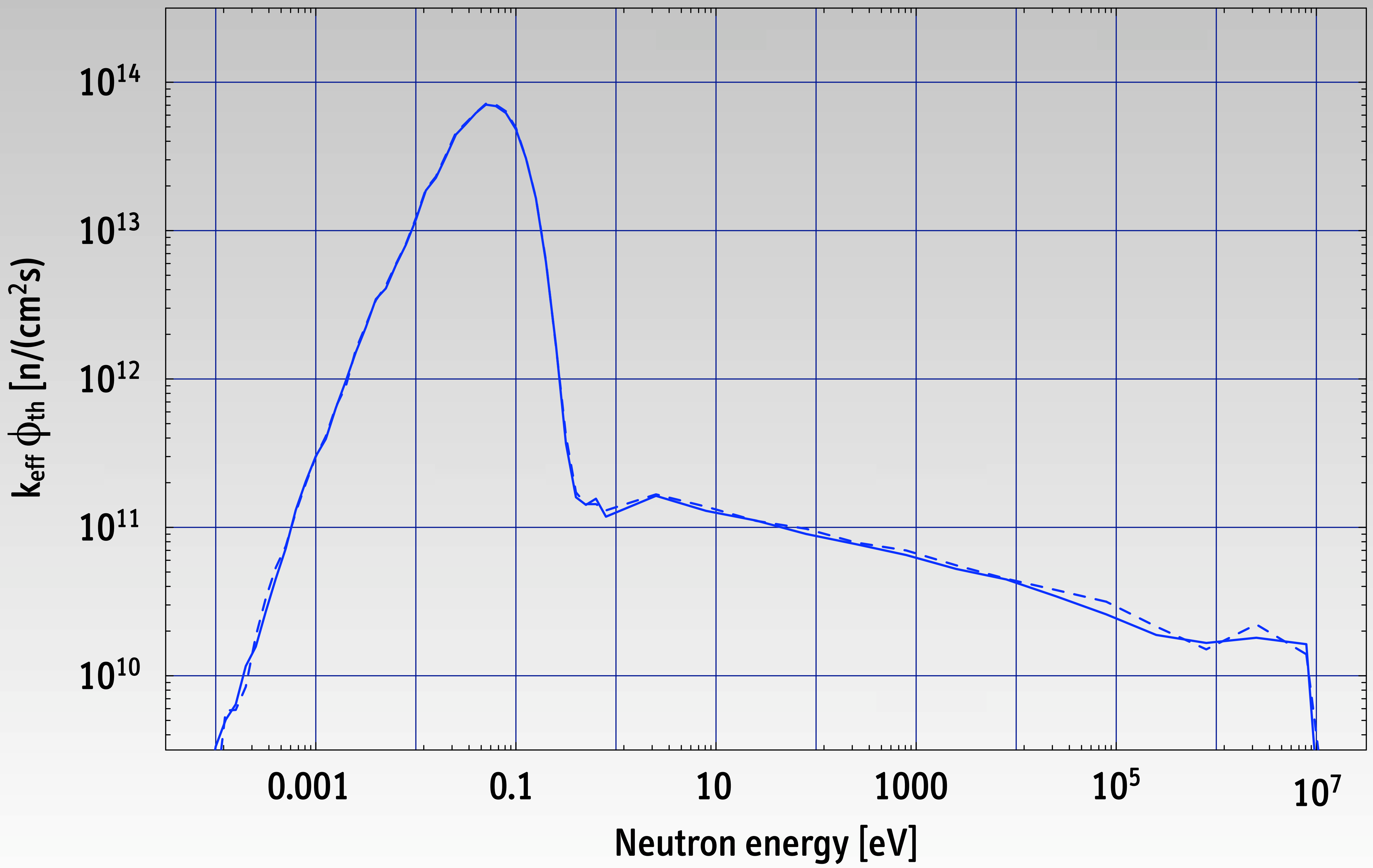
HEU design of FRM-II, liquid deuterium at 20 K



$$\lambda = \frac{h}{\sqrt{2\, m_n E}}$$

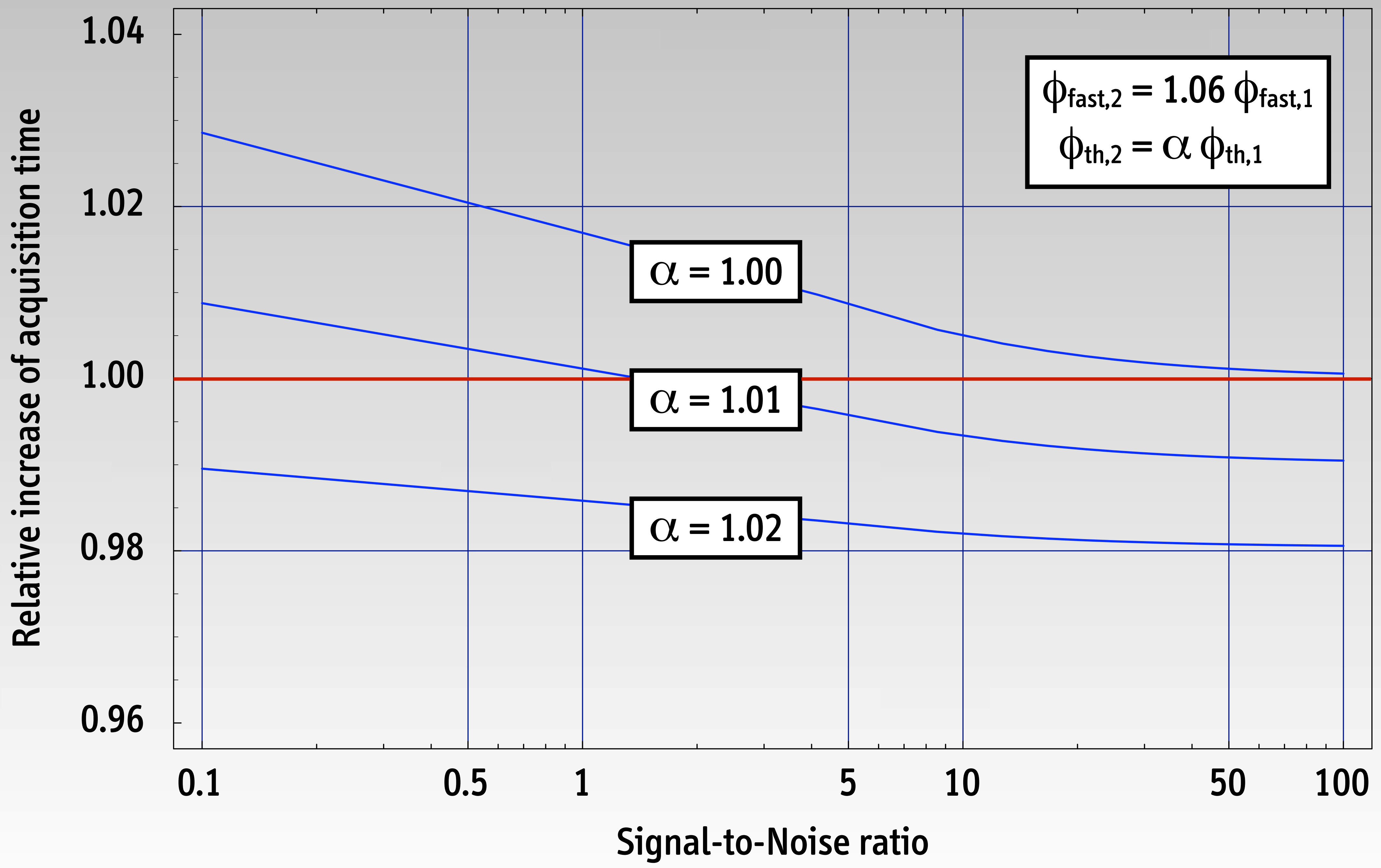
Neutron Spectrum in Beam Tube 1

(measured at -70 cm in beam direction, preliminary data)



Increase of Required Beam Time

for constant relative error, HEU vs Monolithic 2 in FRM-II



Schlussfolgerungen und Ausblick

Monolithische Brennstoffe würden enormes Potential zur Umstellung von Forschungsreaktoren bieten

FRM-II stellt die grösste Herausforderung bezüglich Anreicherungsreduktion dar, allerdings wäre Einsatz von monolithischem Brennstoff mit < 30% möglich

(Alle anderen HFR's sollten auf LEU umstellbar sein)

Typische Probleme bei der Umstellung auf monolithischen Brennstoff: Anfangsreaktivität und Power Peaking

Methoden der Linearen Programmierung kombiniert mit Monte Carlo "Störungsrechnungen" können mit zunehmender Rechnerleistung (weiter) an Bedeutung gewinnen