International Workshop on Applications of Advanced Monte Carlo Simulations in Neutron Scattering
October 3-4, 2006, Paul Scherrer Institute (PSI), Switzerland

The Role of Neutron Scattering Simulations in Identifying Optimum Strategies to Convert Research Reactors to Low-Enriched Fuel

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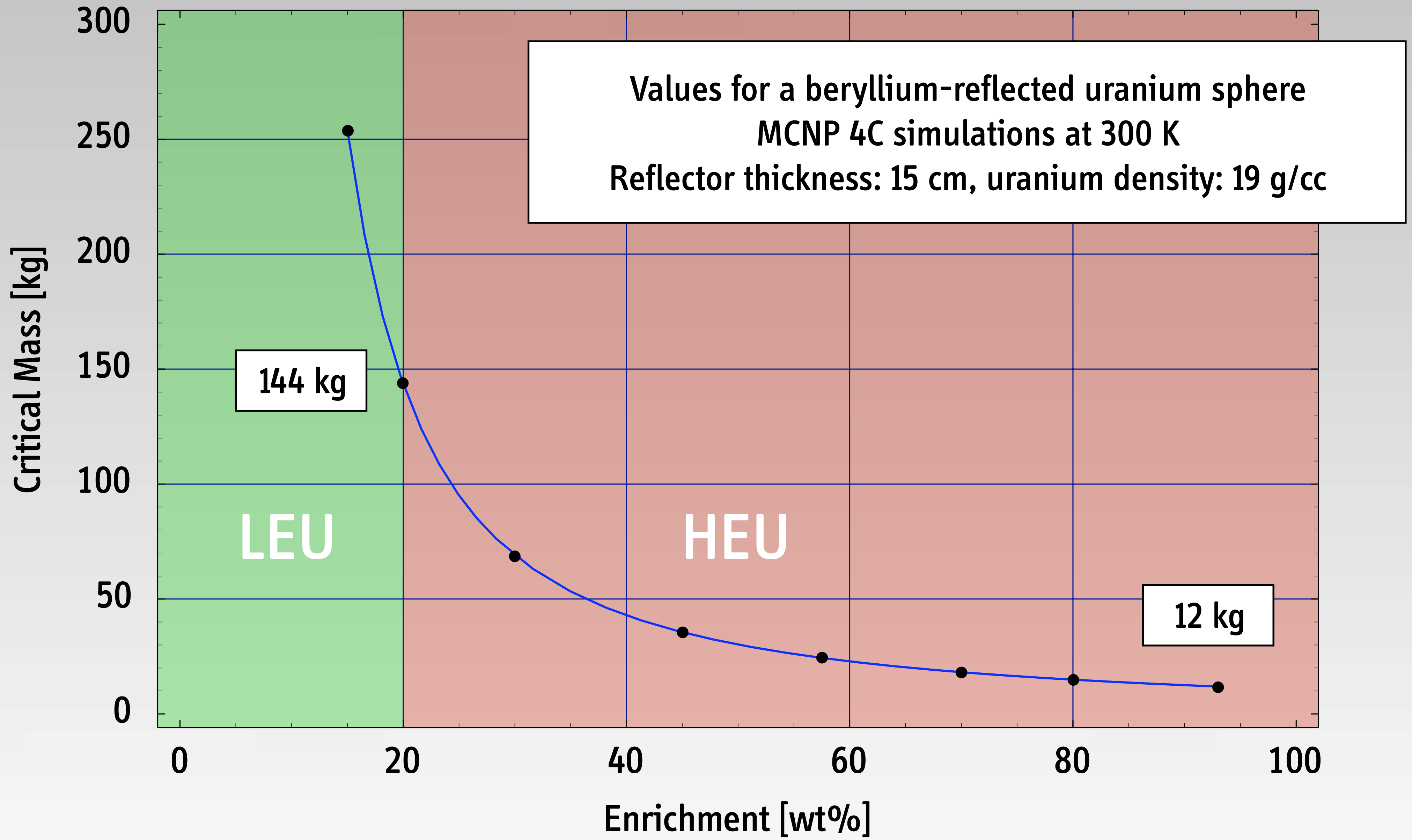
Revision 9

Critical Mass of Uranium

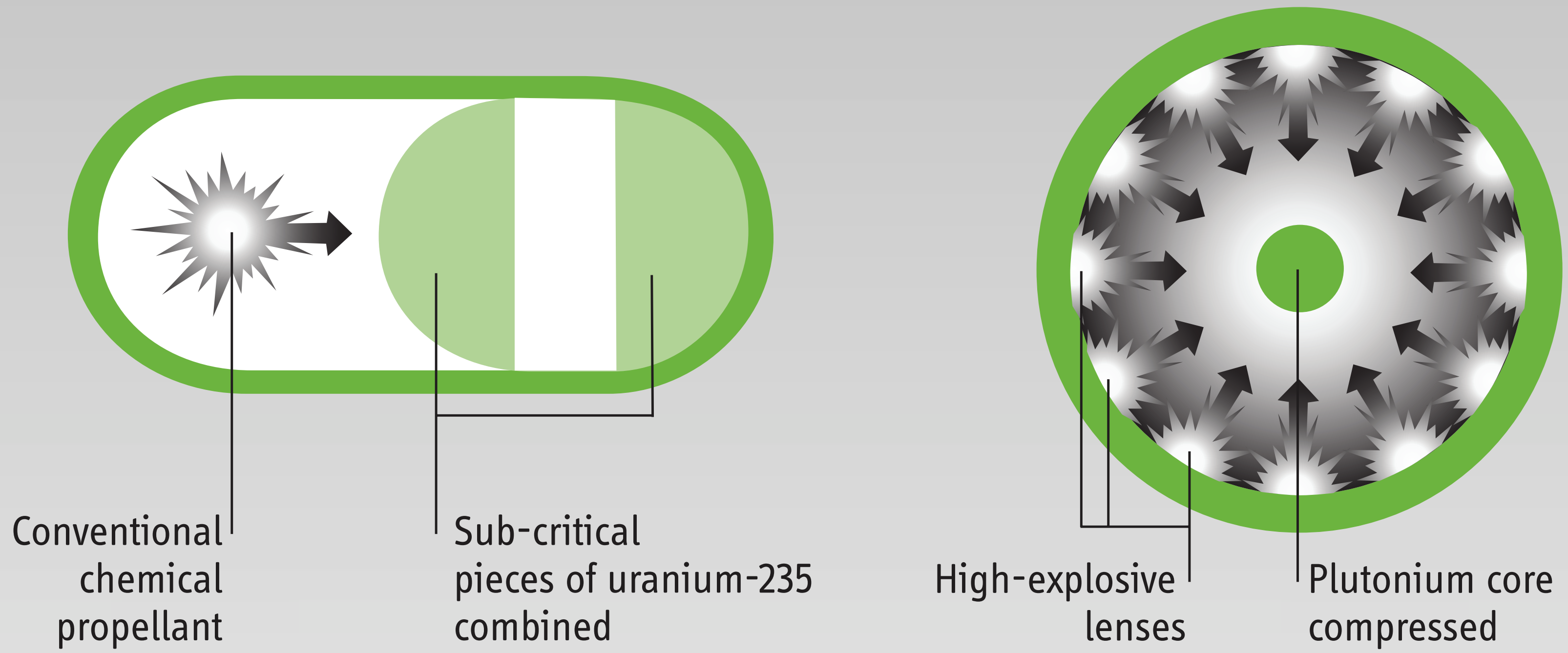


Characteristics of Highly Enriched Uranium

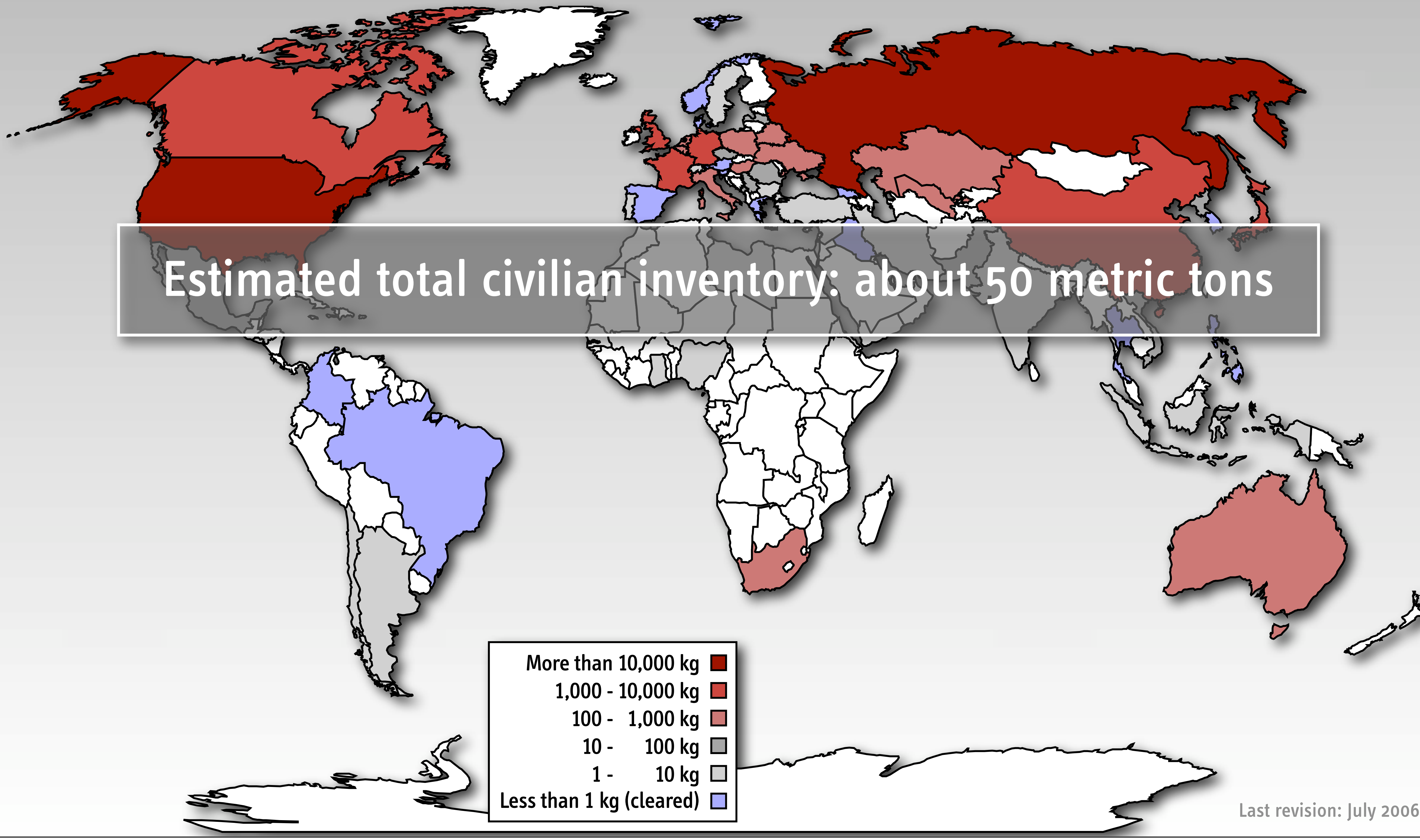
Easy to handle

Easy to use in nuclear weapon or nuclear explosive device

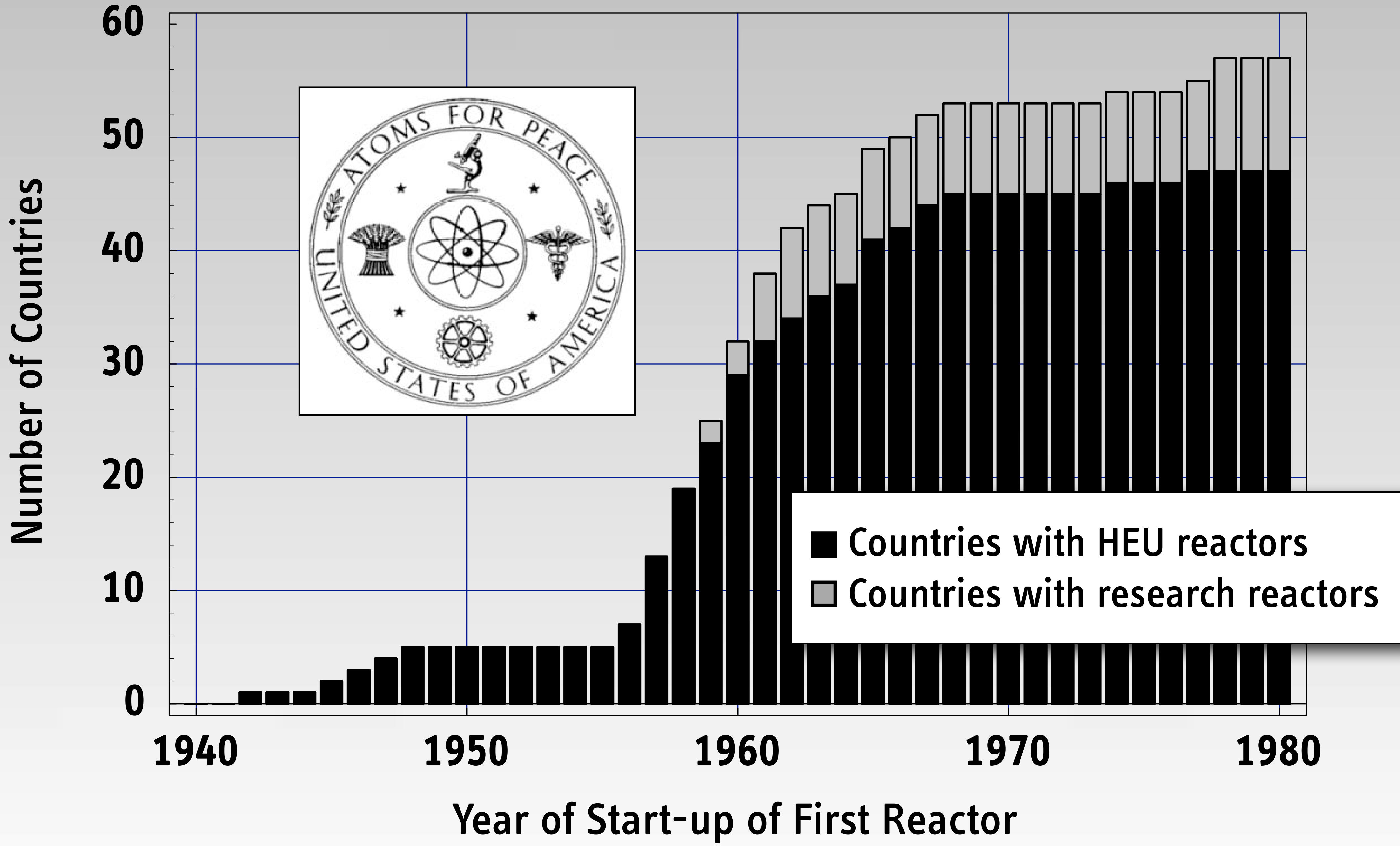
Difficult/impossible to detect remotely



Global Distribution of Civilian HEU



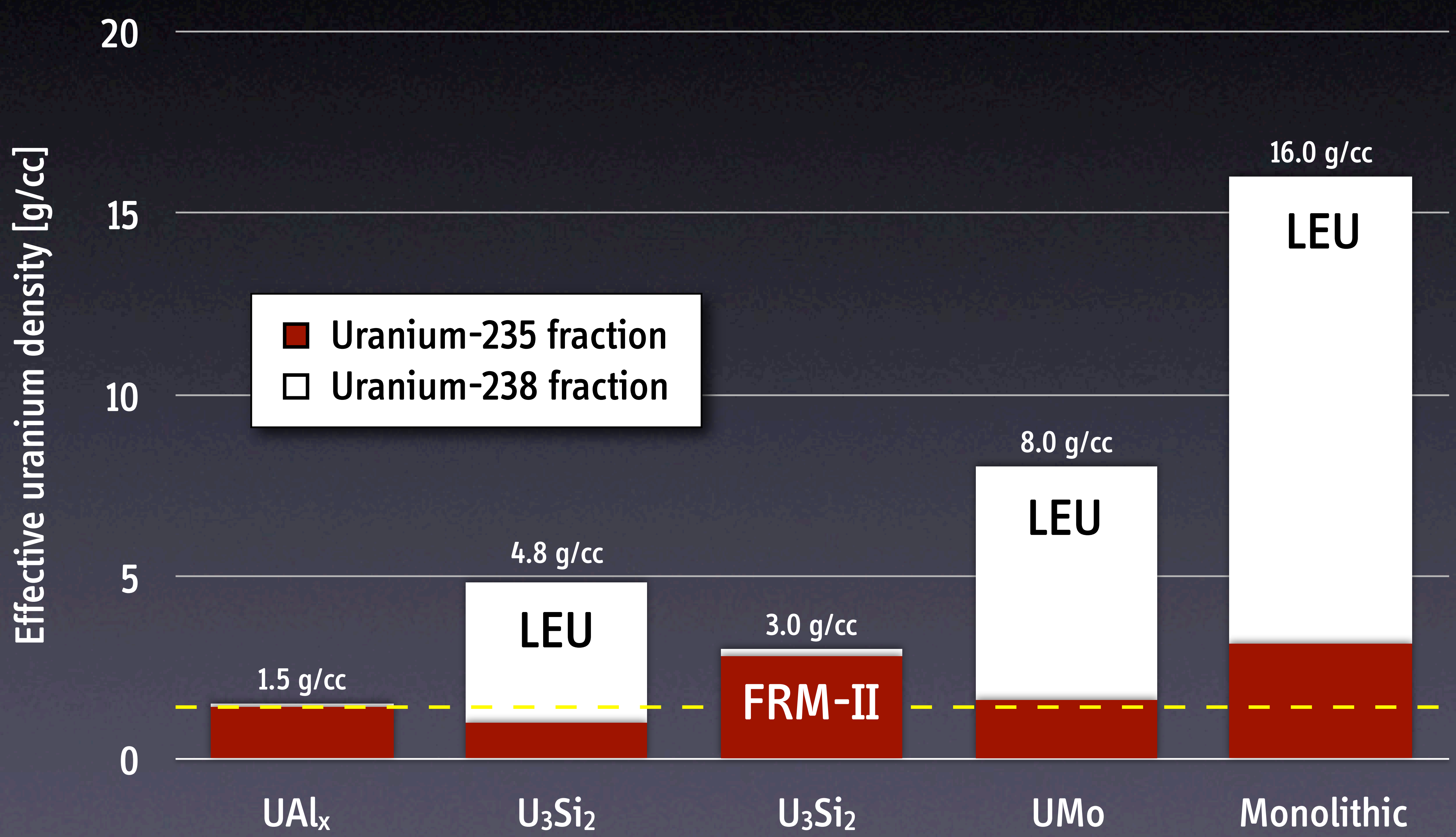
Number of Countries with Research Reactors



The Conversion of Research Reactors to Low-Enriched Fuel

Fundamental element: development of high-density fuels

Effective Uranium Densities in Research Reactor Fuels



HEU-Fueled Research Reactors

🔴 Neutron scattering, primary use
🟡 Some neutron scattering

(Highest Relevance Group, 2006)

	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
converted	~~Netherlands~~	~~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
shutdown	~~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
🟡	Ukraine	UA-0001	WWR-M	1960/12	10 MW	36–90%	13.9 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	5–10 MW	93%	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
🔴	Russia	RU-0004	IR-8	1981/08	8 MW	90%	2.2 kg/yr

Footnote: *Pulsed Reactors

Pulsed reactors do not require regular supply of fresh fuel

(often: life-time core, virtually no burnup of uranium fuel)

Most of them are used for military research

but some also for civilian research using
neutron scattering techniques

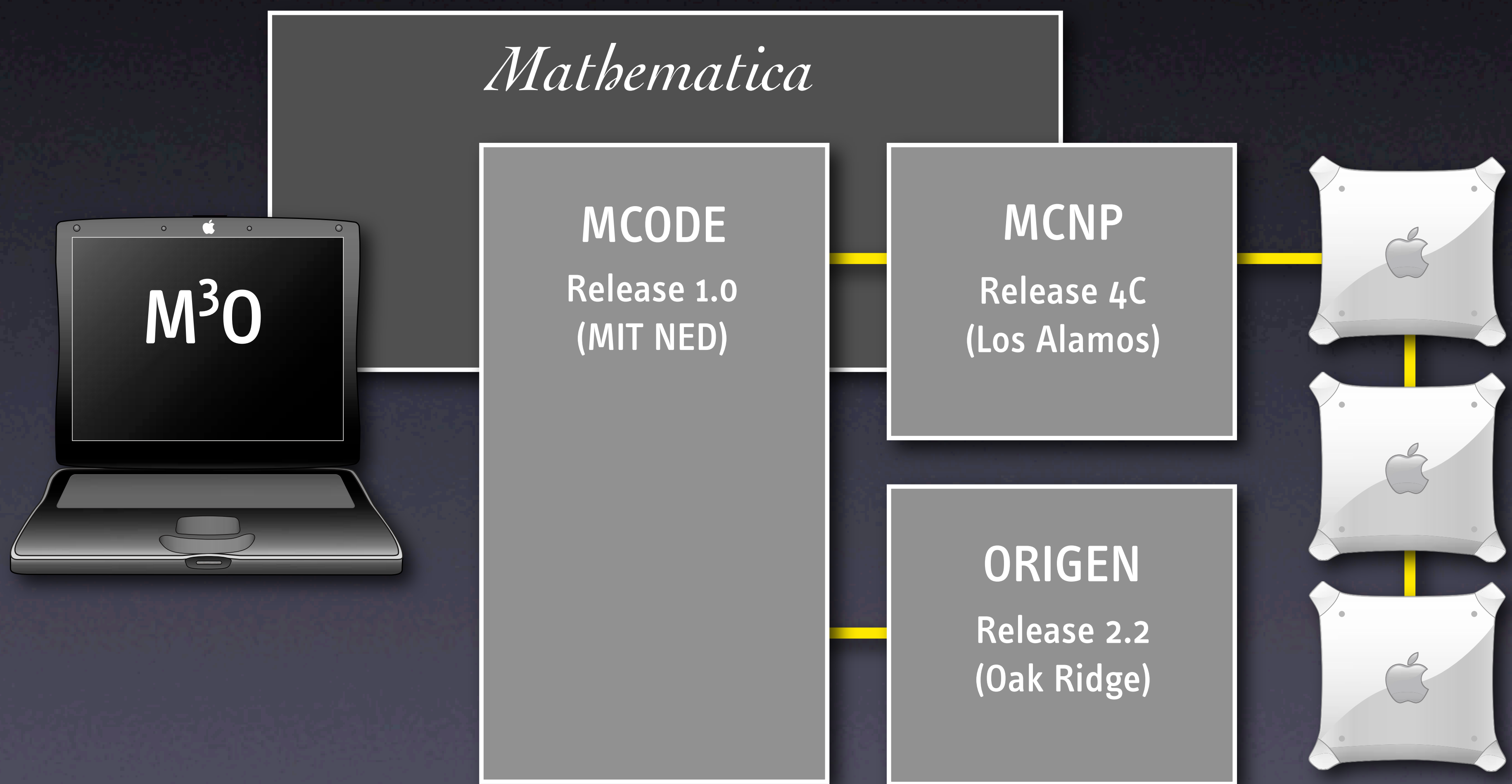
Example: IBR-2 in Dubna, Russia (TOF, 20 instruments)

Core inventory: 82.5 kg enriched to 98%

Identifying Optimum Conversion Strategies

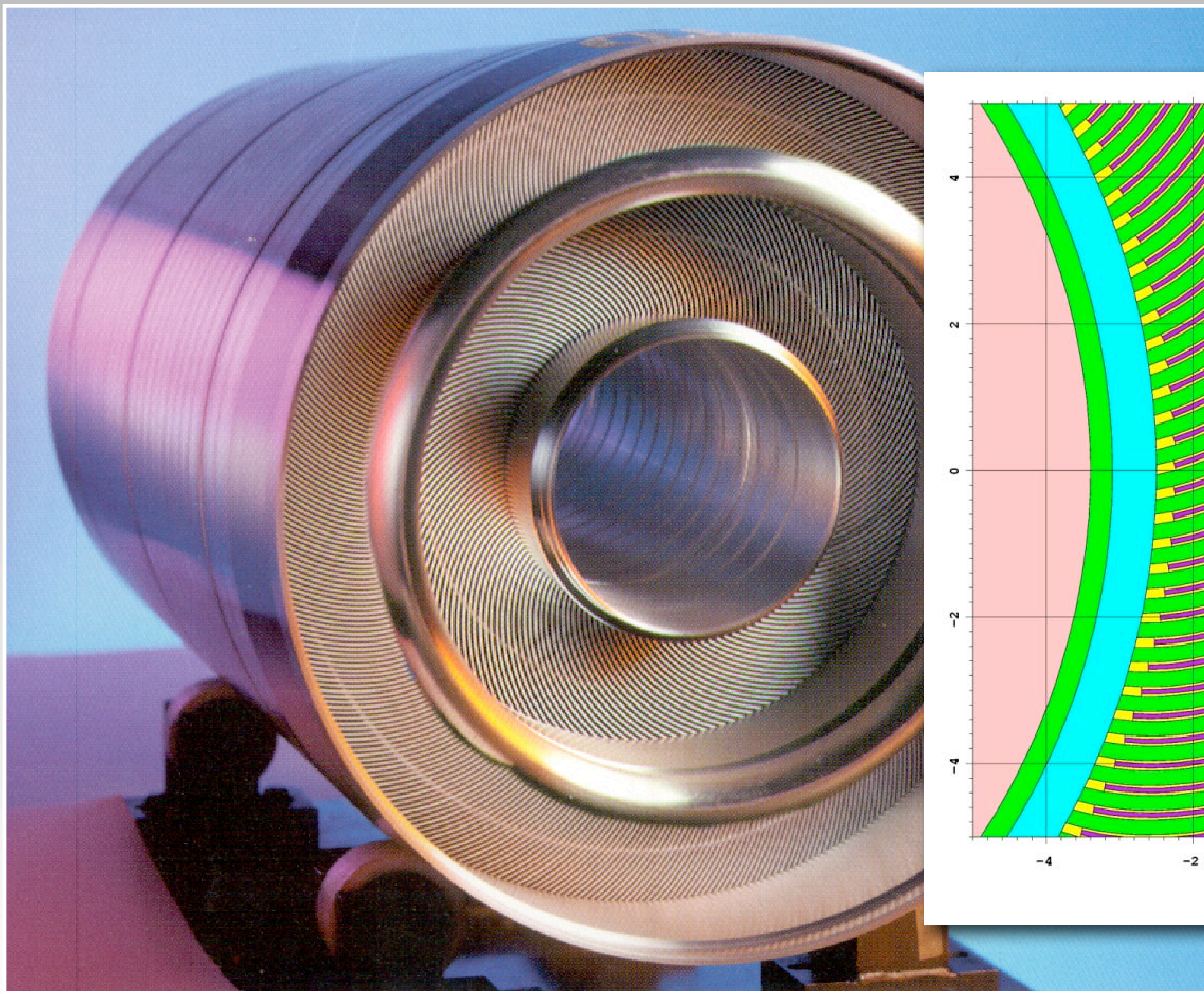
How to use low-enriched fuel without compromising the scientific usability of a research reactor

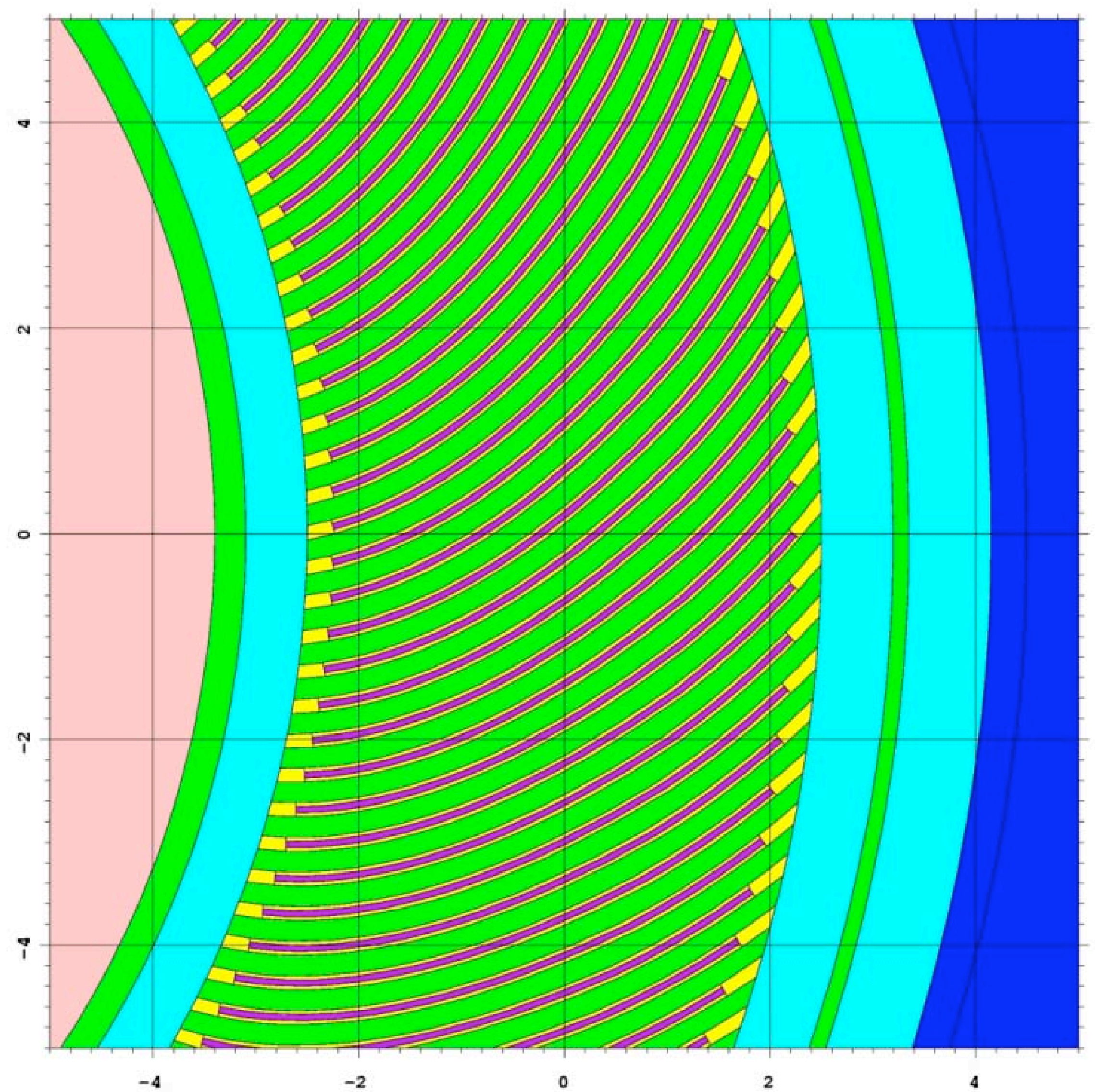
Computational System for Research Reactor Analysis



Source: A. Glaser, Ph.D. thesis, Darmstadt University of Technology, April 2005

High-Flux Reactor Fuel Elements

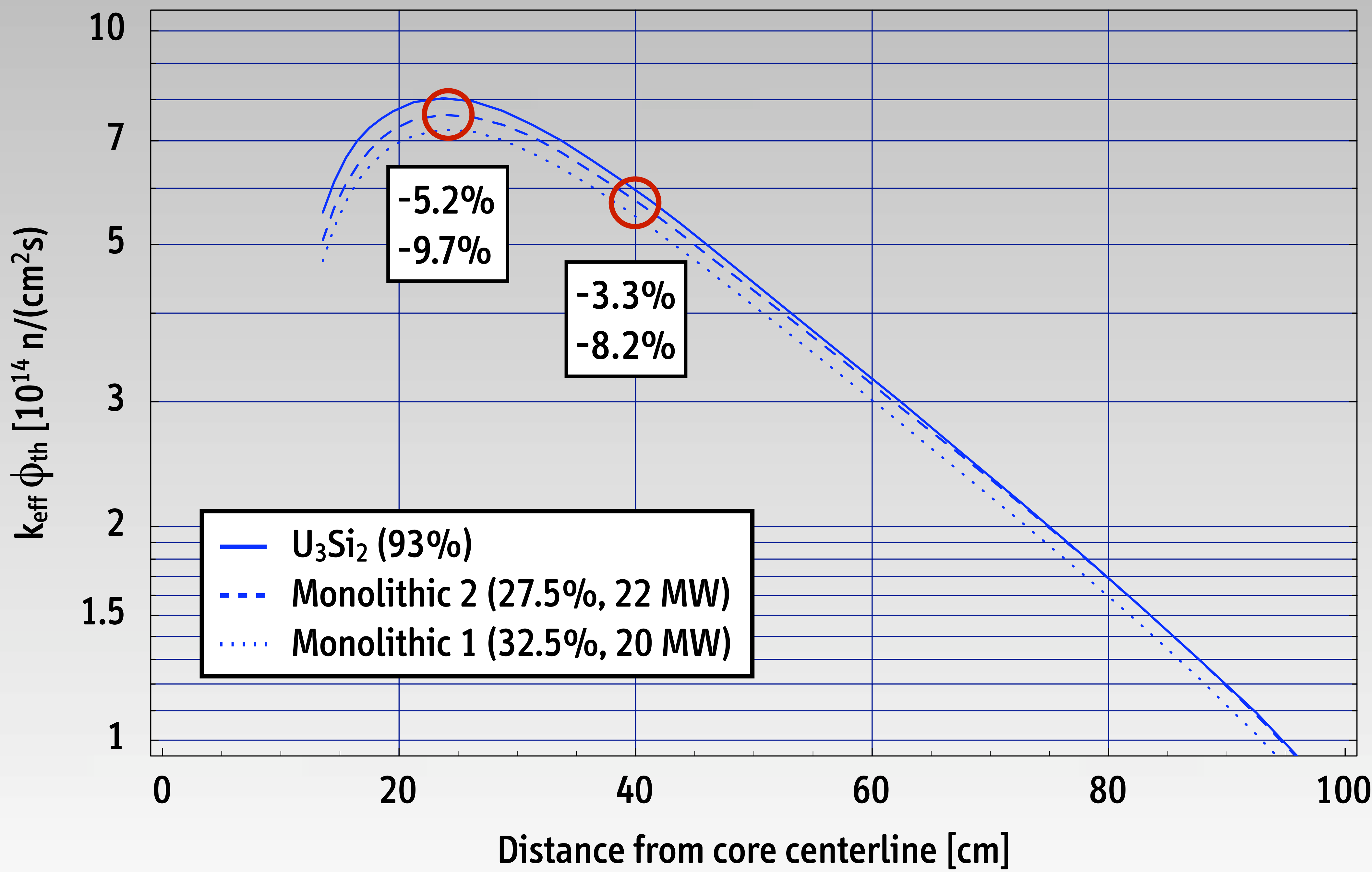




MCNP model of FRM-II core

HFIR fuel element (Source: BWXT)

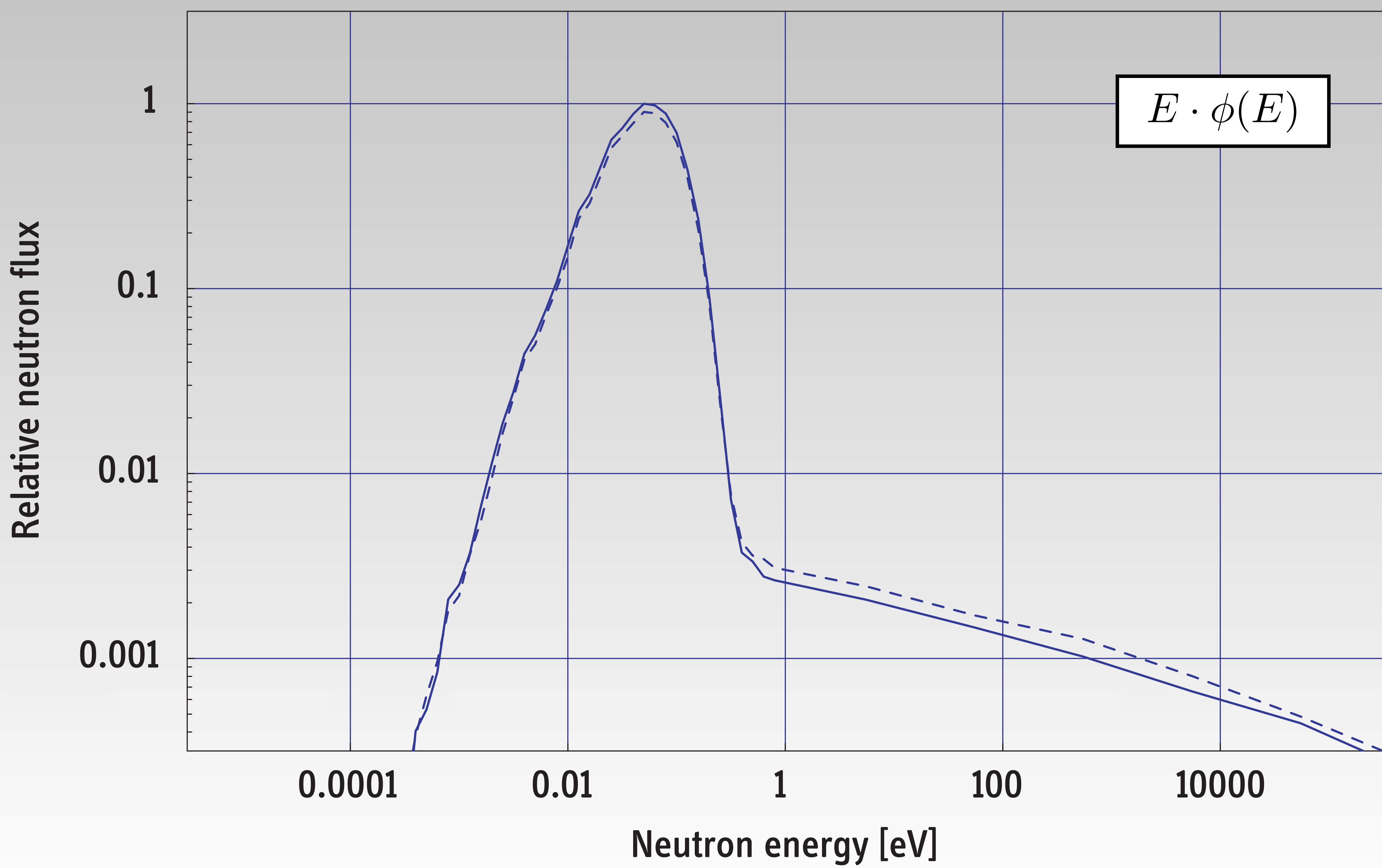
Thermal Neutron Flux of FRM-II



Source: A. Glaser, Ph.D. thesis, Darmstadt University of Technology, April 2005

Neutron Spectrum in Beam Tube

Illustrative data for a 1999 FRM-II conversion option



Scientific Usability

What is a “marginal loss” in reactor performance?

International Nuclear Fuel Cycle Evaluation (INFCE), 1978-80

"In assessing the practical feasibility of utilizing lower enriched fuel in existing research reactors, the agreed criteria are that the safety margins and fuel reliability should not be lower than those for the current design based on highly enriched uranium, and that neither any loss in the overall reactor performance (e.g. flux per unit power) nor any increase in operation costs should be more than marginal."

A Crude Method to Quantify Scientific Usability

(It's not good enough)

“Figure of Merit”

to quantify the scientific usability of neutron sources

$$\mathrm{FOM} = n\, 2^{\log \phi^\star} \quad \textbf{with} \quad \phi^\star = \phi \cdot 10^{-13}\, \left(\mathrm{n/cm^2 s}\right)^{-1}$$

$$\phi = 10^{13}\, \left(\mathrm{n/cm^2 s}\right) \rightarrow \mathrm{FOM} = n$$

$$\phi = 10^{14}\, \left(\mathrm{n/cm^2 s}\right) \rightarrow \mathrm{FOM} = 2\, n$$

Inherent shortcoming of approach: all instruments are weighed equally

D. Richter and T. Springer
A twenty year forward look at neutron scattering facilities in the OECD countries and Russia
Technical Report, European Science Foundation, November 1998

“Figure of Merit”

(of existing neutron sources operated in continuous mode)

Country	Facility	Weight Factor	Scattering Instruments	Figure of Merit
Australia	HIFAR	2.2	7	15.4
Canada	NRU	2.8	6	16.8
~~Denmark~~	~~DR3~~	~~2.3~~	~~8~~	~~18.4~~
France	HFR	4.2	32	134.4
France	Orphée	2.8	25	70.0
Germany	BER-II	2.5	16	40.0
~~Germany~~	~~FRJ-2~~	~~2.5~~	~~16~~	~~40.0~~
Germany	FRG	1.9	8	15.2
Germany	FRM-II	3.6	17	61.2
Hungary	BNC	2.3	7	16.1
Japan	JRR-3M	2.5	23	57.5

Country	Facility	Weight Factor	Scattering Instruments	Figure of Merit
South Korea	Hanaro	1.7	6	16.2
Netherlands	HOR	1.2	5	6.0
Norway	JEEP II	1.3	5	6.5
Russia	IR-8	2.3	4	9.2
Russia	IVV-2M	2.0	7	14.0
Russia	WWR-M	2.2	12	26.4
~~Denmark~~	~~R-2~~	~~2.0~~	~~5~~	~~10.0~~
Switzerland	SINQ	2.5	13	32.5
~~USA~~	~~HFBR~~	~~3.0~~	~~14~~	~~42.0~~
USA	HFIR	4.2	9	37.8
USA	NBSR	2.5	17	42.5

Data and methodology based on Richter and Springer, 1998   HEU   LEU

Quantitative Upgrades

Example: HFIR at ORNL

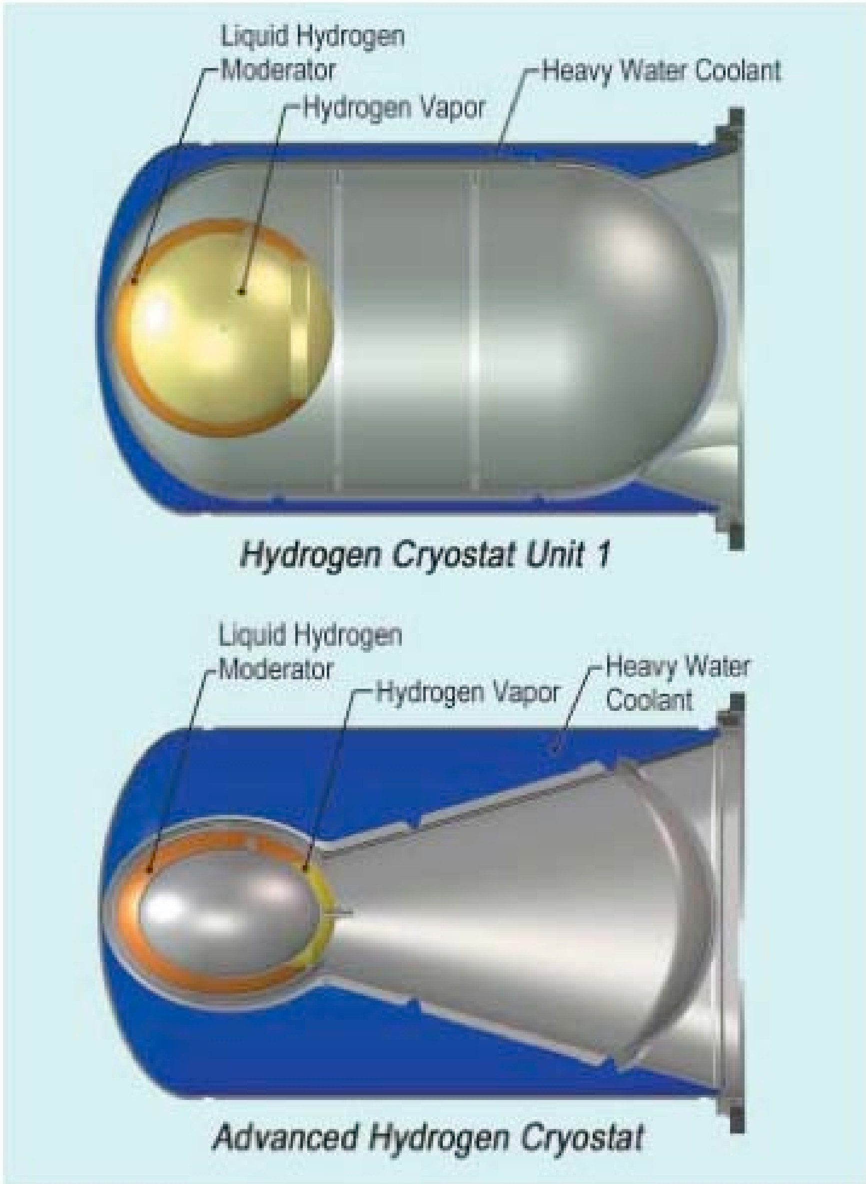
	Country	Facility	Weight Factor	Scattering Instruments	Figure of Merit	
	USA	HFIR	4.2	9	37.8	Status in 1998
	USA	HFIR upgrade 1	4.2	12	50.4	
	USA	HFIR upgrade 2	4.2	15	63.0	Status in 2006
Assuming 20% loss of thermal flux	USA	HFIR	3.95	15	59.3	
Assuming 10% loss of thermal flux	USA	HFIR	4.10	15	61.5	

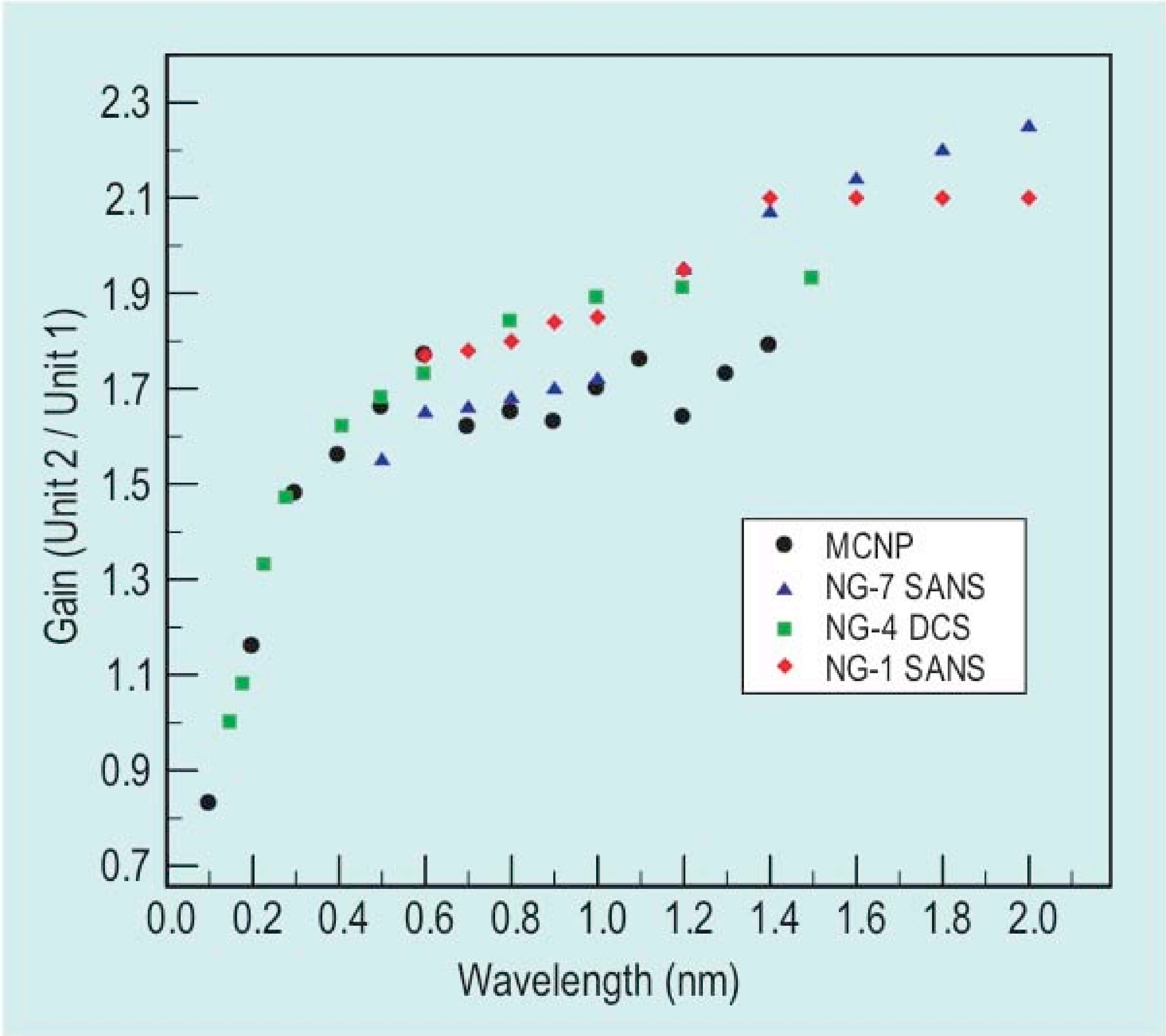
Preliminary conversion studies for HFIR

R. T. Primm III, R. J. Ellis, J. C. Gehin
Design Study for a Low Enriched Uranium (LEU) Core for the High Flux Isotope Reactor (HFIR)
ORNL/TM-2006/80 (Preliminary Report), April 20, 2006

Qualitative Upgrades

Example: NBSR at NIST, new cold neutron source (2002)





Source: NIST Center for Neutron Research, Annual Report 2002

Qualitative Upgrades

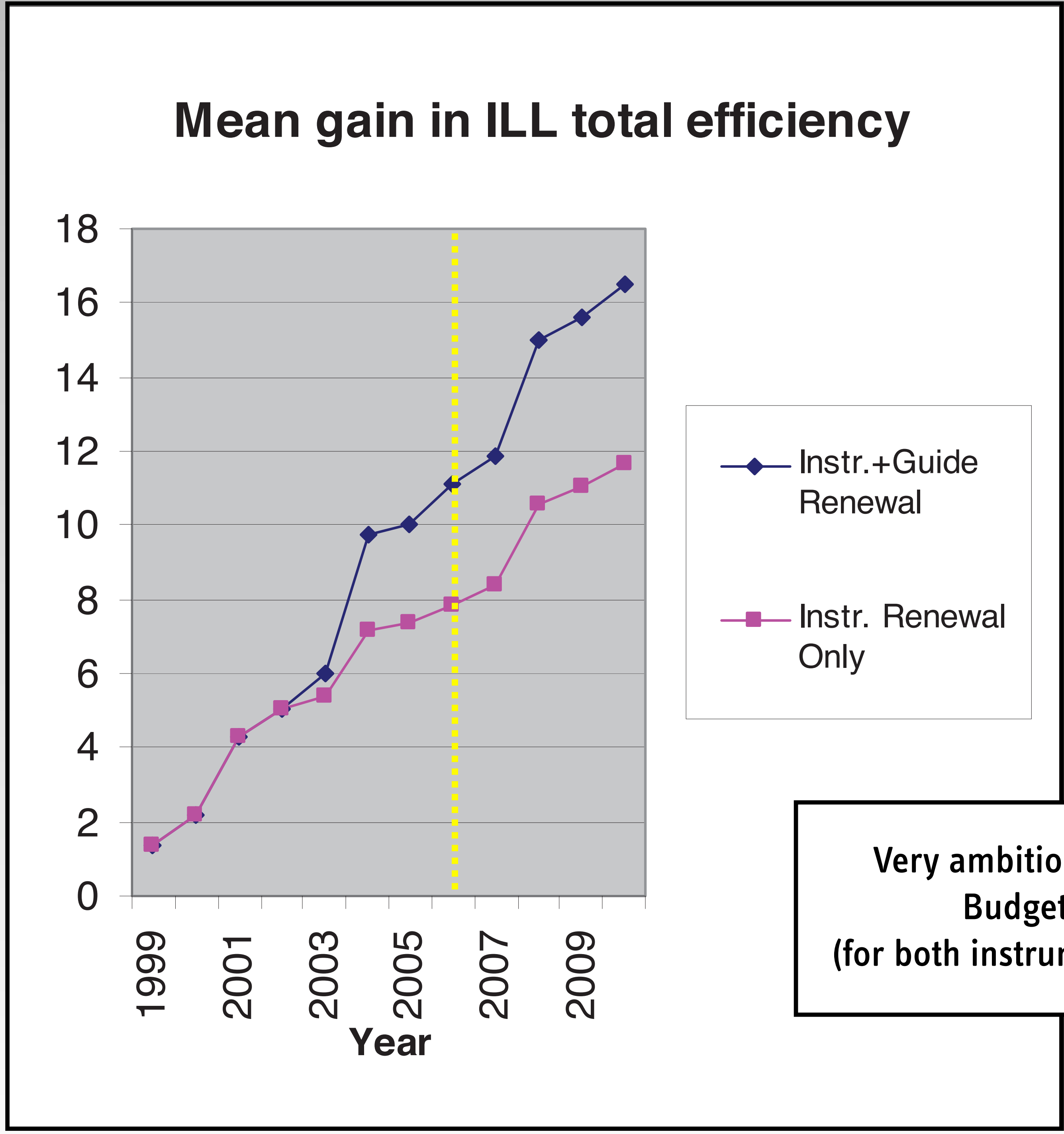
Example: HFR at ILL, Millennium Program (2000-2015)

	Country	Facility	Weight Factor	Scattering Instruments	Figure of Merit	
	France	HFR	4.2	32	134.4	Status in 1998
Millennium Program underway	France	HFR	4.2	(32)	?	Status in 2006

Richter and Springer methodology not applicable

but ILL reports a 10-fold increase of total efficiency (as of 2006) due to instrument upgrades and guide renewals

ILL Millennium Program



Very ambitious long-term program
Budget in 2006: €5.8M
(for both instruments and infrastructure)

Source: D. Dubbers, The Institute Laue-Langevin and its role in Neutron Science, Millennium Symposium, April 27-29, 2006

Qualitative Upgrades

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	France	HFR	4.2	32	134.4	Status in 1998
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due to instrument upgrades and guide renewals

	Country	Facility	Weight Factor	Scattering Instruments	Figure of Merit	
Assuming 20% loss of thermal flux	France	HFR	3.95	(32)	126.4	based on pre-MP FOM
Assuming 10% loss of thermal flux	France	HFIR	4.10	(32)	131.2	

Instrument upgrades and guide renewals very effective in increasing the scientific usability of neutron sources

Conclusion and Outlook

Since 2002, broad international support to end the use of highly enriched uranium in the civilian nuclear fuel cycle

("Global Cleanout of HEU")

Example: U.S. support for these initiatives

Global Threat Reduction Initiative, since 2004: $107M in FY2007 (+10% vs 2006)

includes funding for RERTR Program: $32M in FY2007 (+30% vs 2006, +430% vs 2003)

Why Does That Matter to the Neutron Scattering Community?

Performance gains due to instrument upgrades and/or neutron guide renewals dwarf potential neutron flux losses after conversion to low-enriched fuel

Opportunity to develop a “package for the system”

Coordination of projects to upgrade instruments and renew guides
with efforts to convert HFRs to LEU fuel

Identification of conversion/upgrade strategies that optimize the performance of integral system

A Win-Win Situation!?

Process is likely to develop momentum/support for upgrade more effectively
(given the broad international support to end the use of HEU from the civilian nuclear fuel cycle)