Workshop on Nuclear Data Needs and Capabilities for Applications
May 27-29, 2015, Lawrence Berkeley National Laboratory

Several Illustrative Examples of Nuclear Data Needs for Nuclear Energy Systems

Jasmina Vujic
Nuclear Science and Security Consortium (NSSC
University of California, Berkeley

May 27, 2015

Nuclear Science and Security Consortium

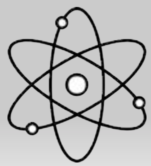
- **Research Project Title:** Nuclear Science and Security Consortium
- **Award Institution:** DOE NNSA
- **Lead Organization:** University of California, Berkeley
- **Participating Universities:** MSU, UCD, UCI, UCSD-IGCC, UNLV, WUSTL
- **Participating Laboratories:** LBNL, LANL, LLNL, SNL
- **Lead PI:** Prof. Jasmina Vujic, University of California, Berkeley
- **Executive Director:** Prof. Karl van Bibber, University of California, Berkeley
- **Deputy Executive Director:** Prof. Brad Sherrill, Michigan State University
- **External Advisory Board Chair:** Dr. Jay Davis, President of the Hertz Foundations
- **Award Amount:** $25 million for 5 years (2011 – 2016) +$1.5M for MSI
- **Lab Mentorship for NSSC Students:** $125 k/per year/per lab

National Nuclear Security Administration

Nuclear Science and Security Consortium Goals

- **Support multiyear research projects which are of a basic or fundamental nature that do not necessarily align with programmatic missions of DOE/NNSA but are critical to maintaining the discipline of nuclear science and security.**
- **Enable collaborative research relationships between universities, the national laboratories, and other government agencies.**
- **Transition technology from universities to national laboratories.**
- **Motivate talented researchers toward careers in nuclear security applications.**
- **Recruit broadly, focusing on disciplinary excellence, not necessarily immediate relevance to specific NA-22 problems**
- **Select those who combine (i) broad perspective, (ii) solid science & engineering foundation, (iii) highly developed specialization.**

Nuclear Science and Security Consortium

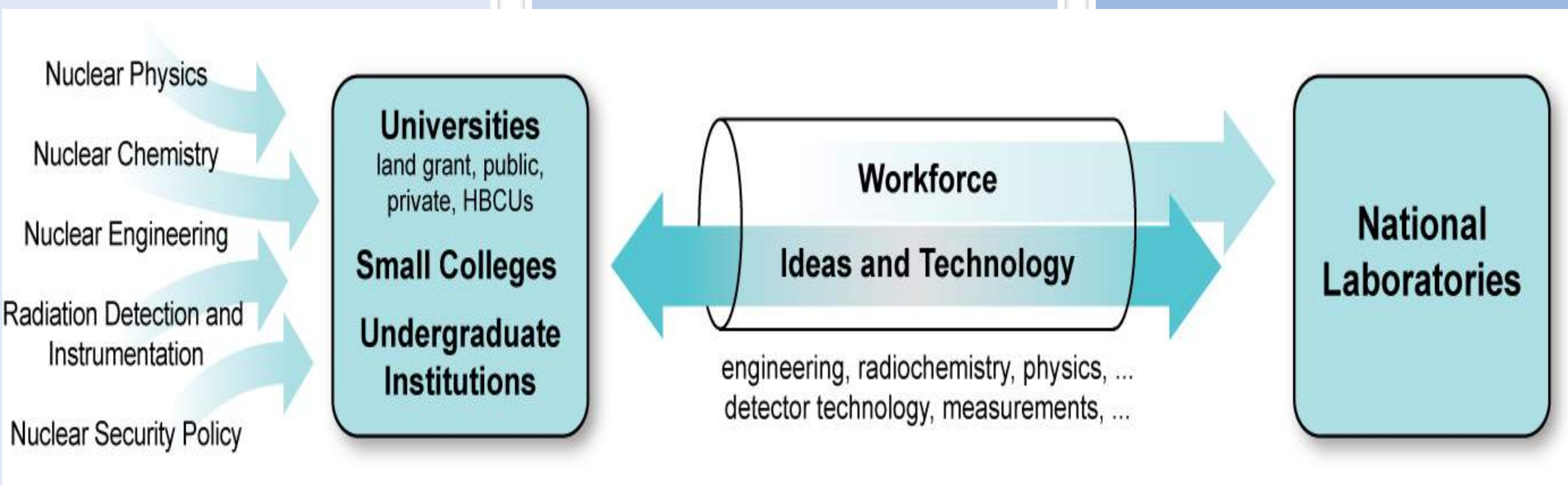


Science

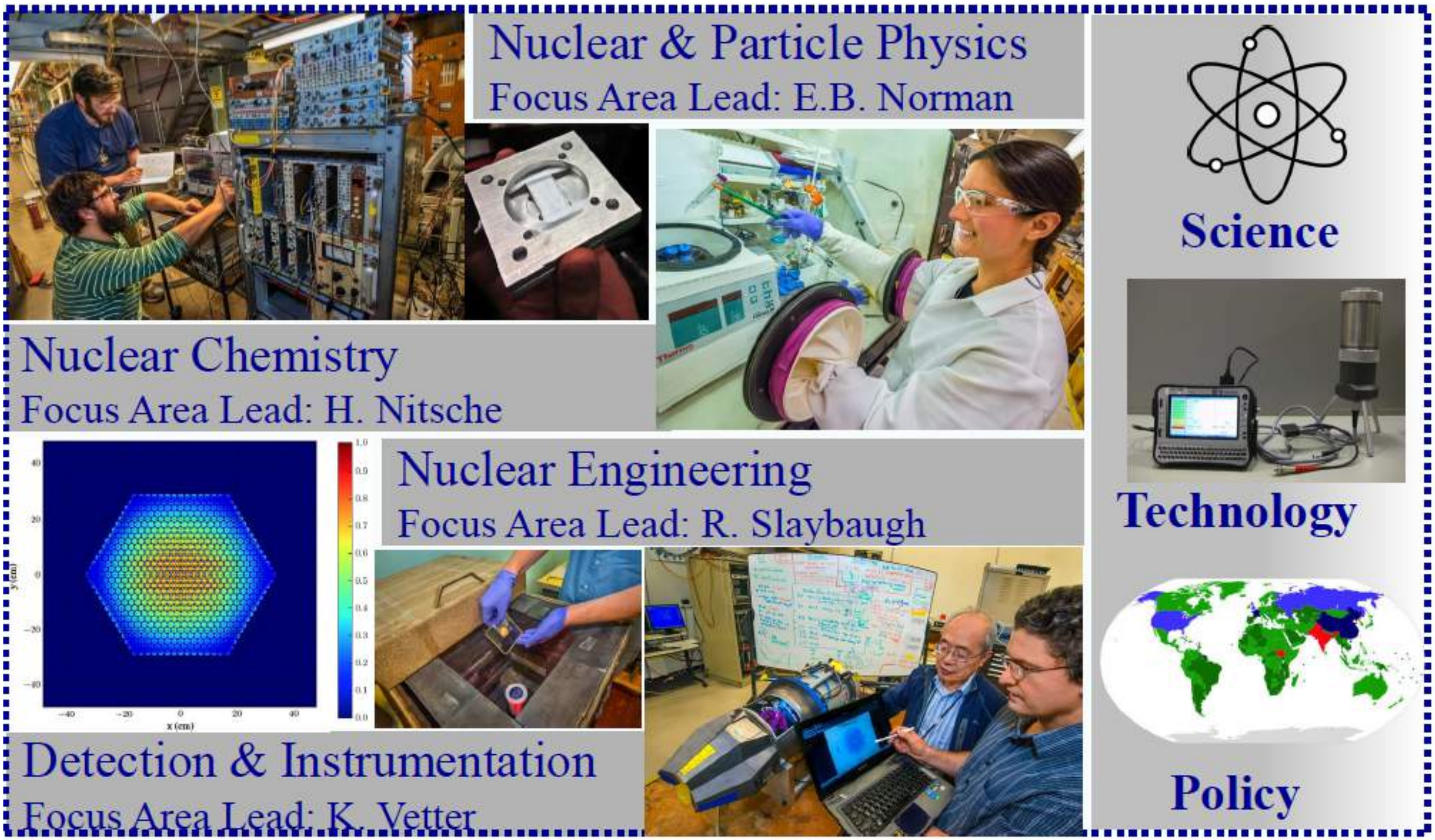
Technology

Policy

PI:	Jasmina Vujic (UCB)
Assoc. Dir.:	Bethany Goldblum (UCB)
Exec. Dir.:	Karl van Bibber (UCB)
Deputy ED:	Brad Sherrill (MSU)
Dir. For Labs:	Ed Hartouni (LLNL)
NNSA Liaison:	Kai Vetter (UCB-LBNL)



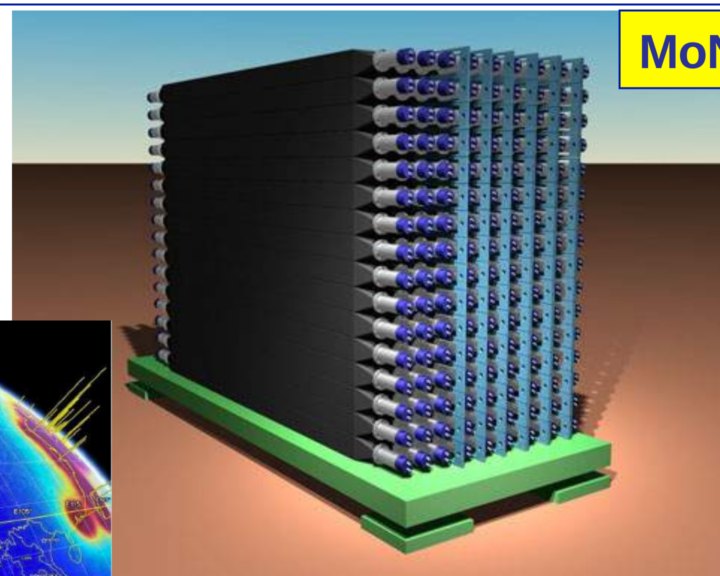
A Science-Technology-Policy Interface



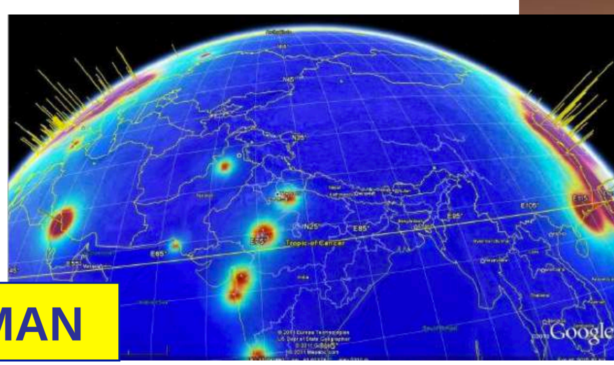
Nuclear Physics Focus Area

- Basic Nuclear Structure Physics with GRETINA
- Neutron Physics using a Modular Neutron Array (MoNa)
- Beta-Delayed Neutron Studies
- CUORE Double Beta Decay
- Anti-Neutrino Reactor Monitoring
- Low Background Measurements
- Nuclear Data

Eric Norman
Dept. Nuclear Engineering
UC Berkeley
Focus Area Lead



MoNA



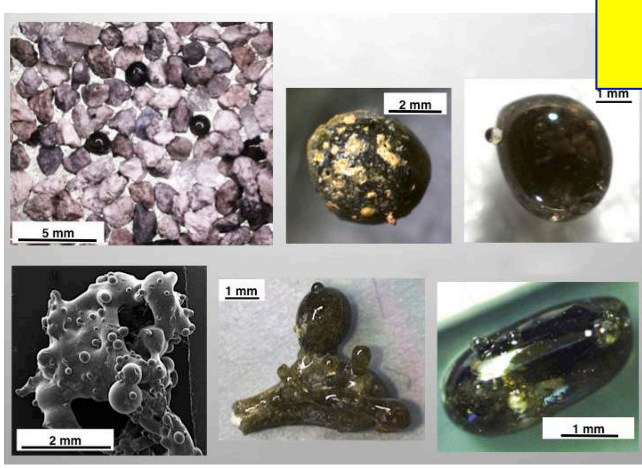
WATCHMAN

GRETINA

Radiochemistry Focus Area

Ken Czerwinski
Dept. of Chemistry
University of Nevada, Las Vegas
Focus Area Lead

- isotope ratio measurements
- actinides in soil samples
- radiochemical separations
- fallout sample characterization
- heavy and superheavy elements
- molecular nuclear forensics



Nuclear Fallout Forms

Radiochemical Separations

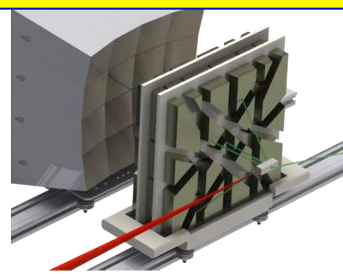
NSSC 7
NUCLEAR SCIENCE and SECURITY CONSORTIUM

Radiation Detection & Instrumentation Focus Area

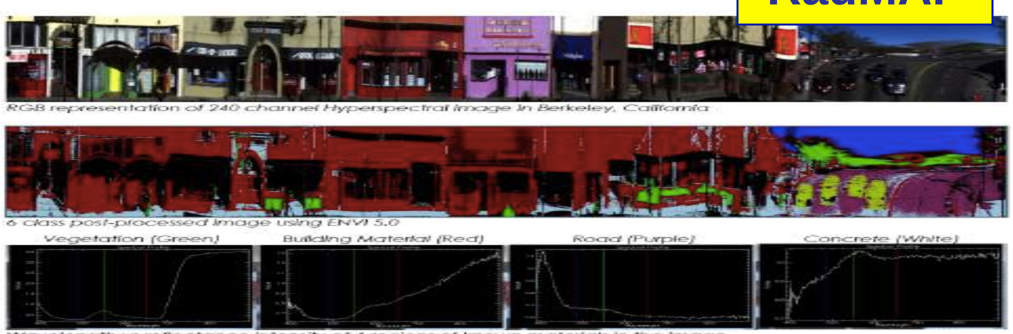
Kai Vetter
Dept. Nuclear Engineering
UC Berkeley
Focus Area Lead

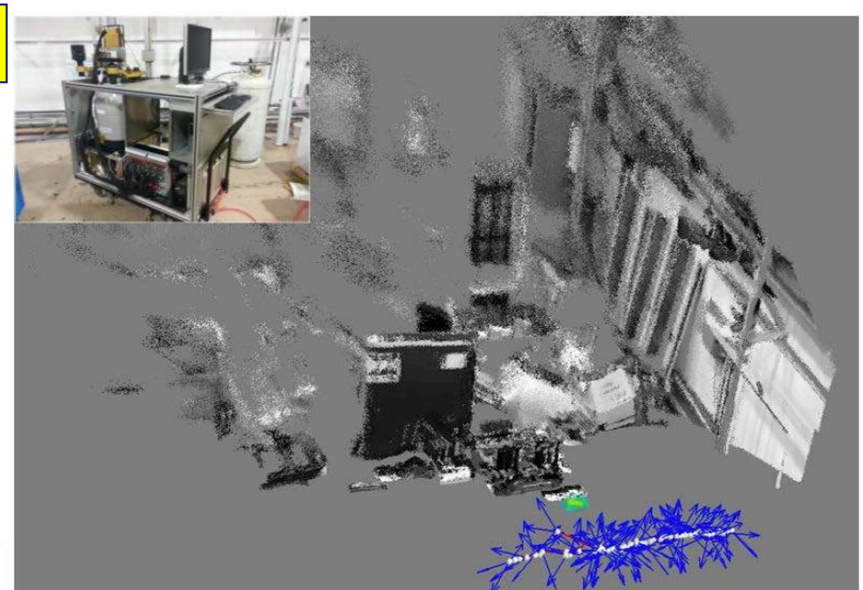
- gamma-ray imaging systems
- position sensitive HPGe detectors
- image reconstruction and 3D data fusion
- coherent elastic neutrino-nucleus scattering with Ge
- background characterization with RadWatch and RadMap

Gamma-Ray Imaging



RadMAP

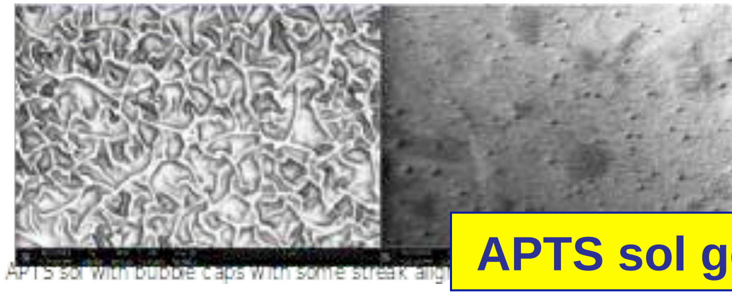




Scene Fusion Gamma-Ray Imaging

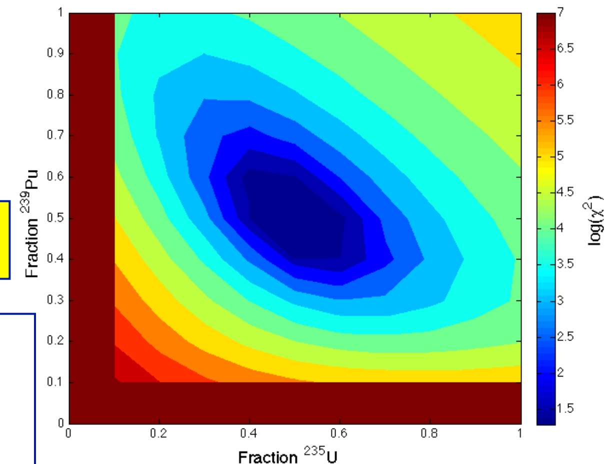
Nuclear Engineering Focus Area

Rachel Slaybaugh
Dept. Nuclear Engineering
UC Berkeley
Focus Area Lead

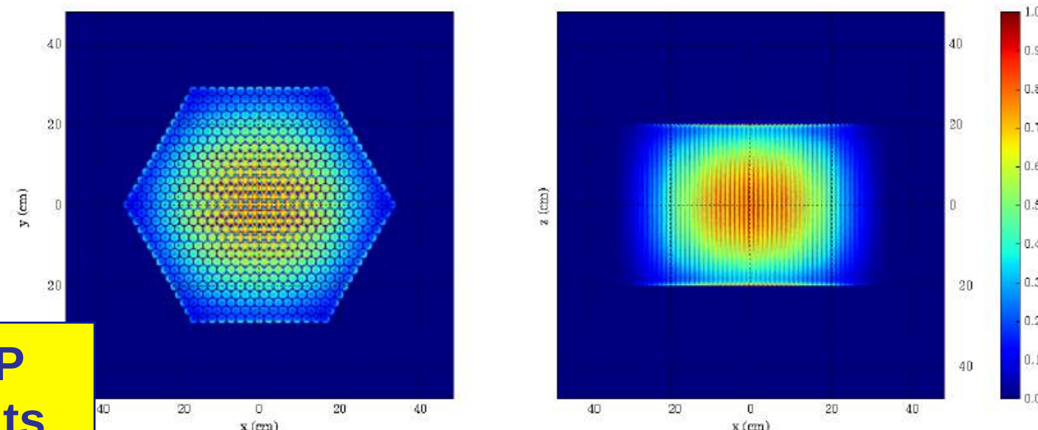


APTS sol gel

- modeling and simulation
- high performance computing
- detector material characterization
- beta-delayed gamma ray analysis
- novel scintillators



Inverse Analysis of Delayed Gamma Spectra



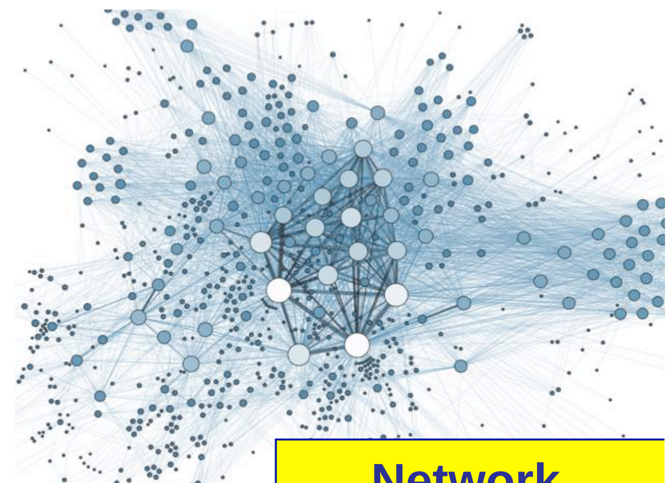
WARP Results

Nuclear Security Policy Focus Area

Michael Nacht
Public Policy
UC Berkeley
Focus Area Lead

- cross domain deterrence
- international cooperation on nuclear security
- network science for nonproliferation
- advanced detectors for international safeguards
- Nuclear Policy Working Group (NPWG) – New Chapters!

Cross Domain Deterrence



Network Science

Nuclear Policy Working Group

NSSC Lifetime Support

	Undergrad	Grad	Postdoc	Faculty	Specialist	Total
UCB	38	25	8	9	12	92
UCD	14	12	4	2	0	32
UCI	0	9	0	2	0	11
UNLV	10	12	2	3	0	27
MSU	0	14	7	0	0	21
WUSTL	6	3	1	1	0	11
IGCC	0	8	0	4	0	12
Total*	68	83	22	21	12	206

***To date (4.28.15). Final Year 4 numbers pending.**

Affiliate Involvement/Impact

	Undergrad	Grad	Postdoc	Total
UCB	31	38	5	74
UCD	2	8	1	12
UCI	13	22	2	37
UNLV	6	9	3	18
MSU	11	7	1	19
WUSTL	1	2	3	5
IGCC	0	0	0	0
Total*	64	86	15	165

***Numbers include Year 4 to date (5.15.15)**

NSSC Lifetime Metrics Overview*

Oral Presentations	Posters	Awards & Honors
309	200	44

Peer-Reviewed Publications	Non-Peer-Reviewed Publications	Conference Proceedings
77	11	21

***To date: 5.15.15. Year 4 numbers pending.**

NSSC Fellows & Affiliates hired at National Laboratories

	LBNL	SNL	LANL	LLNL	Other	Total
UCB	5	1	1	5	2	13
UCD	1	0	0	0	0	1
UCI	0	0	0	0	0	0
UNLV	0	0	4	1	0	5
MSU	1	0	0	0	4	5
WUSTL	0	0	0	0	0	0
Total*	7	1	5	6	6	25★

***Includes both postdoctoral and staff positions at the labs for NSSC fellows and affiliates; Year 4 data included to date (5.13.15)**

★ 7 affiliates

NSSC Status - Summary

- **NSSC is running successfully at "full load" for four years**
- **More than 370 people engaged in NSSC supported research and activities**
- **25 NSSC fellows hired at national laboratories to date**
- **NSSC undergraduate students are transitioning to NSSC graduate students**
- **Strong relationships between national laboratory scientists and students and post-docs working at national laboratories**
  - NSSC PIs and students are collaborating with over 60 national laboratory scientists
- **Successful summer schools held for three years in a row**
  - 19 total summer schools delivered from 2012 - 2015
  - 6 NSSC supported summer schools planned for Summer 2015
- **MSI process executed**
  - 18 summer internship and scholarships for MSI students awarded to date
  - 29 research proposals received and reviewed
  - 5 MSI research proposals awarded

Nuclear Reactor Design and Analysis

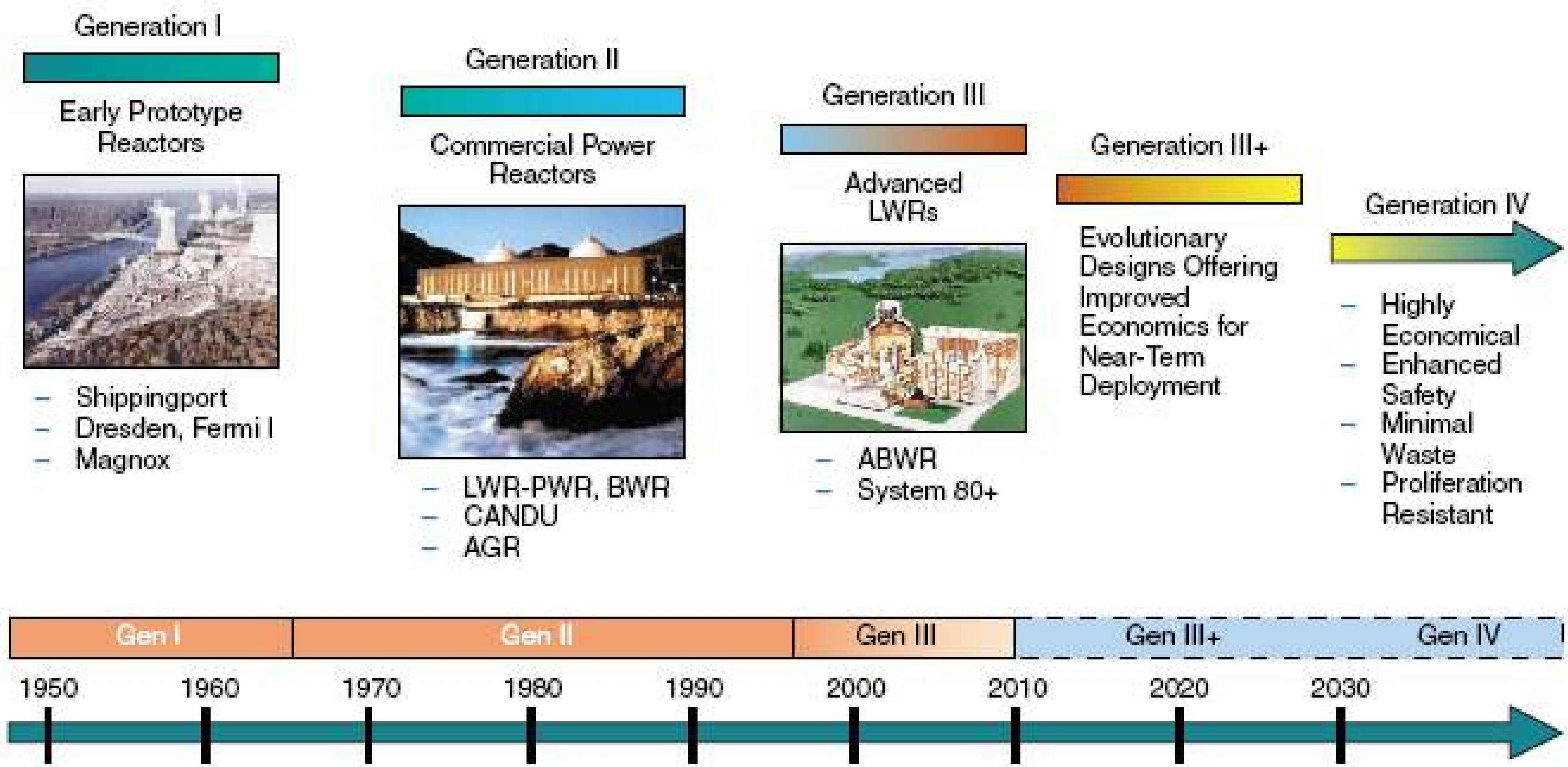
- **Variety of nuclear reactor designs:**
  - Based on fast, epithermal, thermal neutron spectra
  - Nuclear fuel materials, and structural materials
  - Various coolants and moderators
  - Various operating temperatures
- **Generation IV and Beyond – very different issues**
- **Nuclear Physics is typically incorporated into reactor simulation codes through nuclear data libraries**
- **There are a variety of Nuclear Data Libraries:**
  - ENDF (USA), JENDL (Japan), JEFF (Europe), BRONDL (Russia)
- **Regardless of many decades invested in the cross section library development, all those libraries contain approximations, inaccuracies, and produce discrepancies when compared.**
- **Nuclear data libraries could be further improved with improvements in nuclear theory and relevant experiments**

What Parts of Fuel Cycle are Affected by Uncertainties in Nuclear Data?

- Reactor Core and Fuel Design
- Safety and safety margins
- Criticality safety
- Shielding
- Radiation damage in fuel and structural materials
- Decay heat produced in reactor shut-down
- Decay heat produced in the repository
- Long term spent nuclear fuel analysis
- Spent nuclear fuel reprocessing and recycling options
- Nuclear Materials detection

Uncertainties in nuclear data libraries propagate to uncertainties in calculated integral quantities, increasing safety margins and increasing costs in advanced nuclear reactor designs

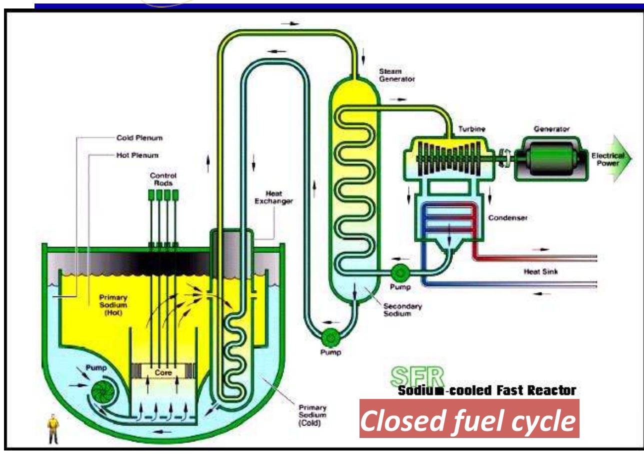
Generations of Nuclear Reactor Designs



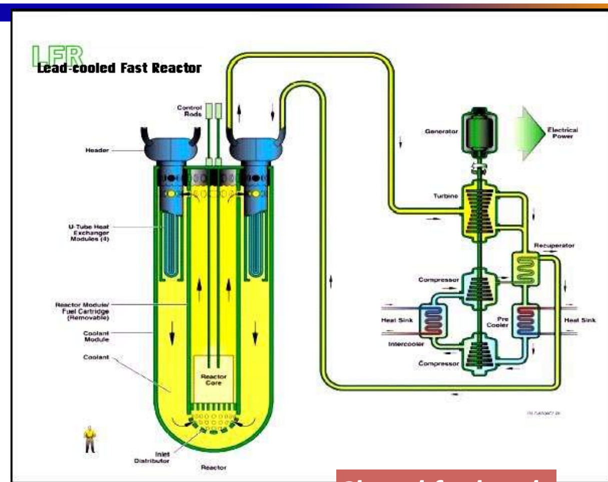
Existing Commercial Nuclear Reactors

Врста	Опис	У раду	У изградњи	Угашени	У плану
PWR	**P**ressurized **W**ater **R**eactor (light water cooled and moderated) и ВВЭР	270	53	38	101
BWR	**B**oiling **W**ater **R**eactor (light water cooled and moderated)	84	4	31	10
PHWR	**P**ressurized **H**eavy **W**ater moderated and cooled **R**eactor	47	5	9	
GCR	**G**as **C**ooled **R**eactor (graphite moderated)	17		35	
LWGR	**L**ight **W**ater cooled, **G**raphite moderated **R**eactor (РБМК)	15	1	9	
HTGR	**H**igh **T**emperature **G**as-cooled **R**eactor (graphite moderated)			4	1
HWGCR	**H**eavy **W**ater moderated, **G**as **C**ooled **R**eactor			4	
HWLWR	**H**eavy **W**ater moderated, boiling **L**ight **W**ater cooled **R**eactor			2	
SGHWR	**S**team **G**enerating **H**eavy **W**ater **R**eactor			1	
FBR	**F**ast **B**reeder **R**eactor (sodium cooled)	2	2	8	2
X	**Other**			2	
Укупно		435	65	143	114

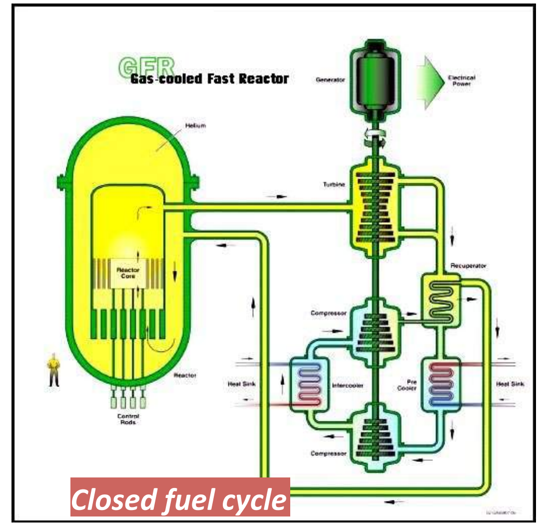
Proposed Generation IV Nuclear Reactors



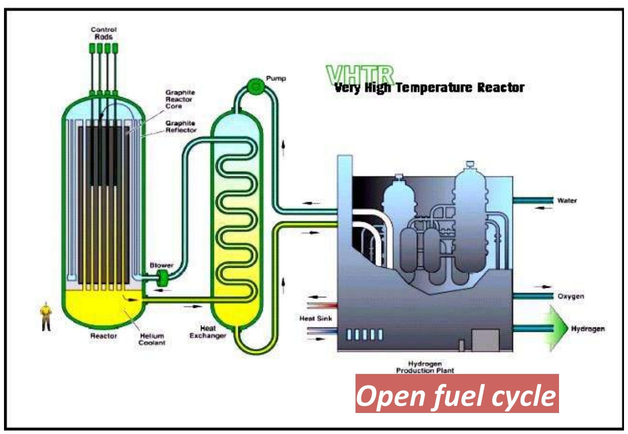
Sodium Fast Reactor



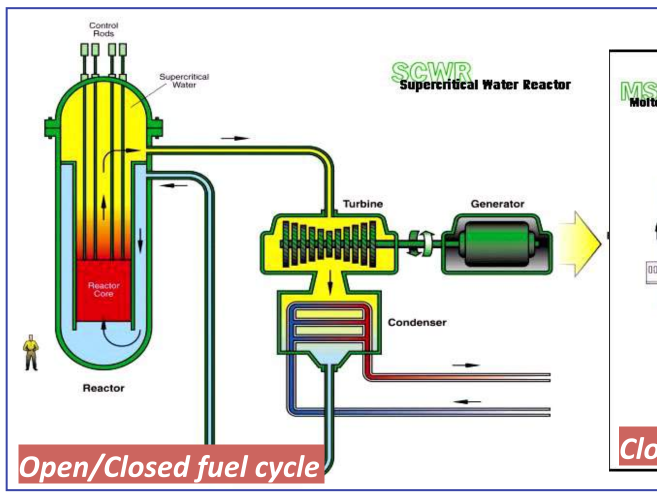
Lead Fast Reactor



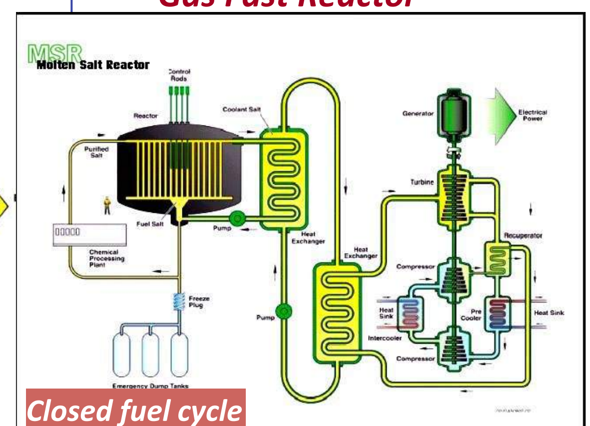
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

The recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissil regeneration) and waste minimization (minor actinide burning)

Proposed Generation IV Nuclear Reactors

	Neutron Spectra//Coolant/ Fuel	*Inlet/Outlet Coolant Temp/ Pressure*	*Fuel Cycle*	*Size/Power MWth*	*Applications*	*Research and Development*
Sodium-cooled Fast Reactor (SFR)	Fast Sodium Metal Alloy or Oxide	550°C outlet 1 atm	Closed	Med to Large 1000-5000	Electricity, Actinide Mgmt. (AM)	Advanced Recycle
Lead-alloy Fast Reactor (LFR)	Fast Pb-Bi Metal alloy/ Nitride	550-800°C outlet 1 atm	Closed	Small to Large 125-3600	Electricity, Hydrogen Production	Fuels, Materials compatibility
Gas-Cooled Fast Reactor (GFR)	Fast Helium UPuC/SiC (70/30%)	490°C inlet 850°C outlet 90 bar	Closed	Med 600	Electricity, Hydrogen, AM	Fuels, Materials, Safety
Very High Temp. Gas Reactor (VHTR)	Thermal Helium ZrC coated particles	640°C inlet 1000°C outlet high	Open	Med 600	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Supercritical Water Reactor (SCWR)	Thermal, Fast Water	280°C inlet 510-550°C outlet 25 MPa	Open, Closed	Large 1700MWe	Electricity	Materials, Safety
Molten Salt Reactor (MSR)	Thermal Fluoride salts UF	565°C inlet 700-850°C outlet	Closed	Large 1000MWe	Electricity, Hydrogen, AM	Fuel, Fuel treatment, Materials, Safety and Reliability

Some Studies Performed

- **Nuclear Data needs for Gen-IV and other advanced reactor systems**
- **Sensitivity study for parameters affected the most by nuclear data uncertainties: Multiplication factor, Power peak, Burnup $\Delta k/k$, Coolant void reactivity coefficient, Doppler reactivity coefficient, Nuclide density at the end of cycle (transmutation potential), Neutron source at fuel fabrication, and Dose in a repository.**
- **M. Salvatores et al., "Nuclear Data Needs for Advanced Reactor Systems. A NEA Nuclear Science Committee Initiative," Int. Conf. on Nuclear Data for Science and Technology, 2007 (BNL-78164-2007-CP)**
- **G. Aliberti et al., "Nuclear data sensitivity, uncertainty and target accuracy assessment for future nuclear systems," Annals of Nuclear Energy 33, 700-733, 2006**

Salvatores et al. Results

Table 1. Fast Neutron Systems: Total Uncertainties (%).

Reactor		k_{eff}	Power Peak	Doppler	Void	Burnup [pcm]	Decay Heat	Dose	Neutronic Source
ABTR	PEC [(a)]	1.96	0.6	6.4	12.5	97	0.1	0.1	0.5
	BOLNA [(b)]	0.92	0.3	4.4	6.0	52	0.2	0.1	0.5
SFR	PEC	1.66	0.5	6.0	23.4	234	0.3	0.2	0.9
	BOLNA	1.82	0.4	5.6	17.1	272	0.4	0.3	1.0
EFR	PEC	1.57	1.1	5.1	12.1	989	2.3	1.7	6.0
	BOLNA	1.18	1.2	3.8	7.8	871	2.4	1.2	6.6
GFR	PEC	1.90	1.8	5.5	7.1	384	0.5	0.6	1.8
	BOLNA	1.88	1.7	5.5	7.7	381	0.4	0.5	1.4
LFR	PEC	2.26	1.0	7.8	20.6	258	0.5	0.5	1.1
	BOLNA	1.43	0.6	4.3	7.2	198	0.6	0.4	1.1

[(a)] Partial Energy Correlation as used in ref. [1]
[(b)] BNL_ORNL_LANL_NRG_ANL

Salvatores et al. Results

- The contribution of the fission product uncertainty (due to "lumped" FPs) to the overall burnup reactivity is significant only in the case of a fast reactor with an extended burnup.

Table 4. $\Delta\rho$ Burnup Uncertainty Breakdown into Components [pcm].

System → ↓ $\Delta\rho$ component	SFR	EFR	GFR	LFR	VHTR	PWR
Actinides	±272	±871	±381	±198	±530	±851
Fission Products	±73	±755	±130	±76	±215	±244
Total	±282	±1153	±402	±212	±572	±885

Fuel Cycle Options*

Base cases in red italics

Once Through:

Build ALWR/ Current Burnup (50 MWD/kg)

Limited Thermal Reactor Recycle:

PUREX-based one time recycling of U-Pu as mixed oxides (MOX) to LWRs

Fast Reactor Recycle of all transuranics, TRU(metallic fueled reactors studied by ANL and GE):

TRU to self-sustaining FR (Conversion Ratio =1)

TRU recycle in fast burner ABR (with low CR = 0.75)

TRU recycle in fast breeder FBR (with CR = 1.23)

*M. Kazimi, MIT, 2010

Many measurements have been identified in the fast reactor sensitivity calculations

- **Fission Cross Section Measurements**
  - Np237, Pu238, Pu239, Pu240, Pu241, Pu242, Am241, Am242m, Am243, Cm244, Cm245
- **Capture Cross Section Measurements**
  - Si28, Fe56, B10
  - Np237, U238, Pu239, Pu240, Pu242, Am241, Am242, Am243, Cm242, Cm244, Cm245
- **Inelastic Cross Section Measurements**
  - Na23, U238, Fe56
- **fission neutron spectrum and multiplicity**
  - Pu238, Pu239, Pu240

Previously completed

Completed 2007

Completed 2008

In progress 2009

The measurements and required accuracies are EXTREMELY challenging

C. Lombardi et al. / Progress in Nuclear Energy 50 (2008) 944–953

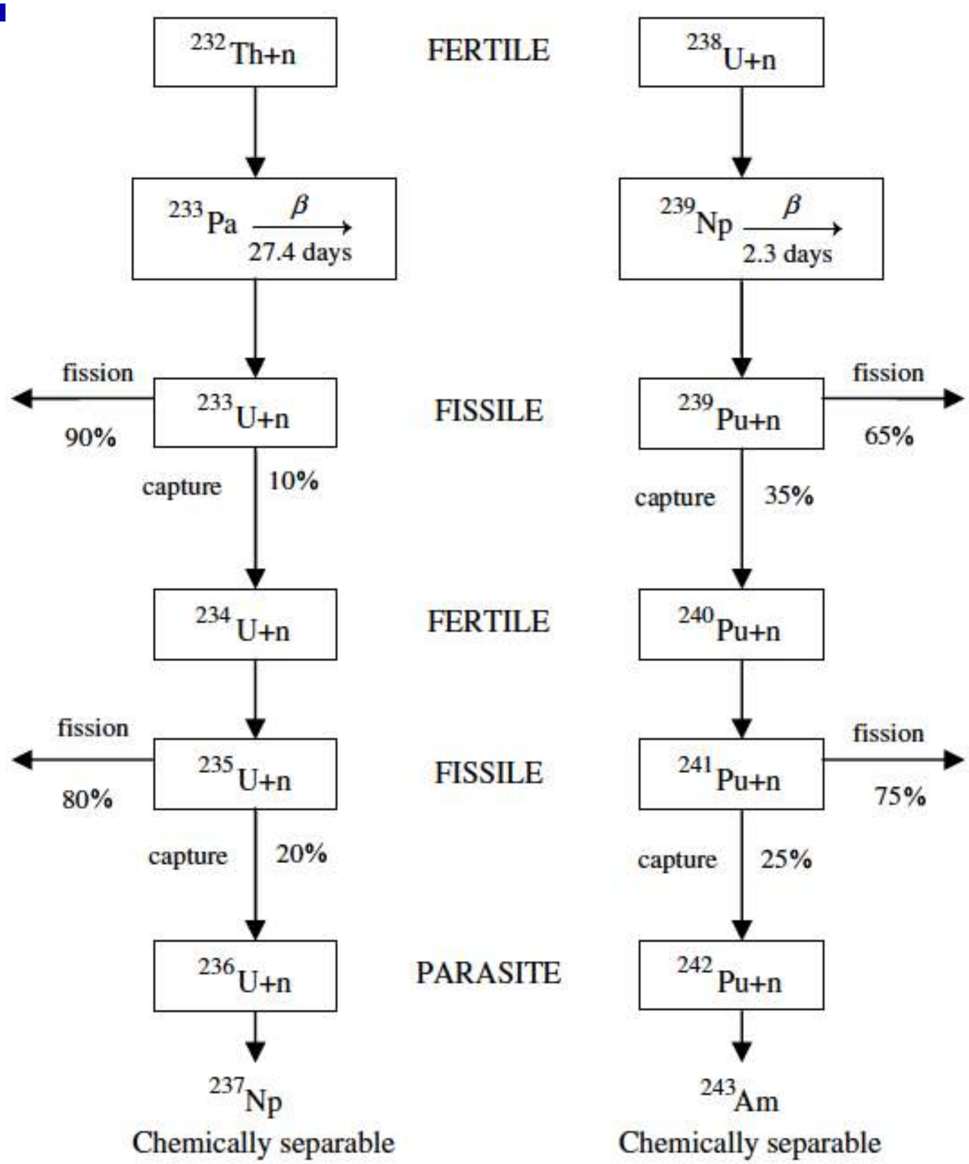


Fig. 1. Analogy in thorium and uranium fertilization.

Thorium-Based Fuel Cycle – Experience*

Country	Reactor	Capacity	Fuel composition	Time
Germany	HTGR (Pebble bed)	15 MW(e)	Th + ^{235}U, Coated Oxide & carbides	1967–1988
Germany	The same	300 MW(e)	The same	1985–1989
Germany	BWR	60 MW(e)	Fuel (Th,Pu)O_2 pellets	1968–1973
UK, Sweden	HTGR (Pin-in-Block Design)	20 MW(t)	Th + ^{235}U Driver, Coated fuel particles, Oxide & Dicarbides	1966–1973
USA	HTGR (Prismatic Block)	40 MW(e)	The same	1966–1972
USA		330 MW(e)		1976–1989
USA	MSBR	7.5 MWt	^{233}U Molten Fluorides	1964–1969
USA	BWR (Pins)	24 MW(e)	Th + ^{235}U Fuel Oxide	1963–1968
USA	*LWBR PWR (Pins)*	*100 MW(e)*	*Th + ^{233}U Driver Fuel, Oxide Pellets*	*1977–1982*
USA	The same	285 MW(e)	The same	1962–1980
Canada	MTR (Pins)	20-200 MW	Th + ^{235}U, Test Fuel	1947–1957
India	MTR Thermal	40 MW(t); 100 MW(t)	Al + ^{233}U Driver Fuel, Th & ThO_2	1960–2010
India	PHWR (Pins)	220 MW(e)	ThO_2 Pellets	1980–pres.
India	LMFBR (Pins)	40 MW(t)	ThO_2 blanket	1985–pres.

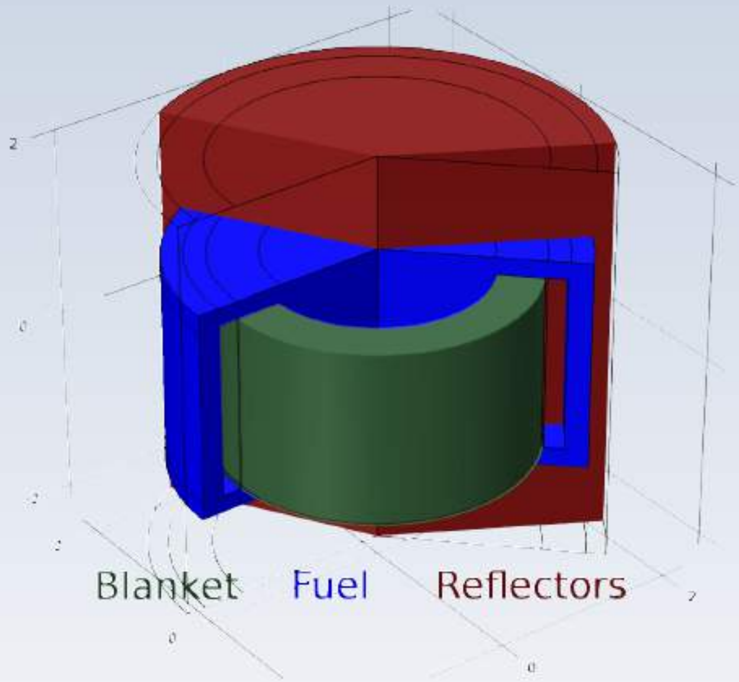
*IAEA TECDOC-1450

Example from the 2012 Serpent User Group Meeting in Madrid

- **Presentation by Manuele Aufiero, Politecnico di Milano**
- **Work on modifications of the Serpent Monte Carlo code to study the fuel isotopic evolution of molten salt reactors designed for continuous reprocessing**
- **Needed to determine conversion ratios (CR)**
- **Noticed a big discrepancy in the capture cross section for U-233 between JEFF 3.1 and ENDF/B 7.x**
- **Noticed also a discrepancy in the capture cross section for Pa-233 between JEFF 3.1 and ENDF/B 7.x above a few keV**
- **Both discrepancies lead to higher CRs when JEFF 3.1 is used as compared to the ENDF/B 7.x results**

Example from the 2012 Serpent User Group Meeting in Madrid

MSFR modelling in SERPENT



Thermal power: 3 GW

- Fuel salt initial composition:
  $LiF - ThF_4 - UF_4$ or
  $LiF - ThF_4 - (Pu - MA)F_3$
- Blanket salt initial composition: $LiF - ThF_4$
- *Ni-based* alloy for vessel and reflectors
- Gaseous & insoluble *FPs* extraction with time constants ∼ tens of seconds (30*s* in the reference scenario)
- Few liters of salt reprocessed each day (40*l* in the reference scenario)

– – –

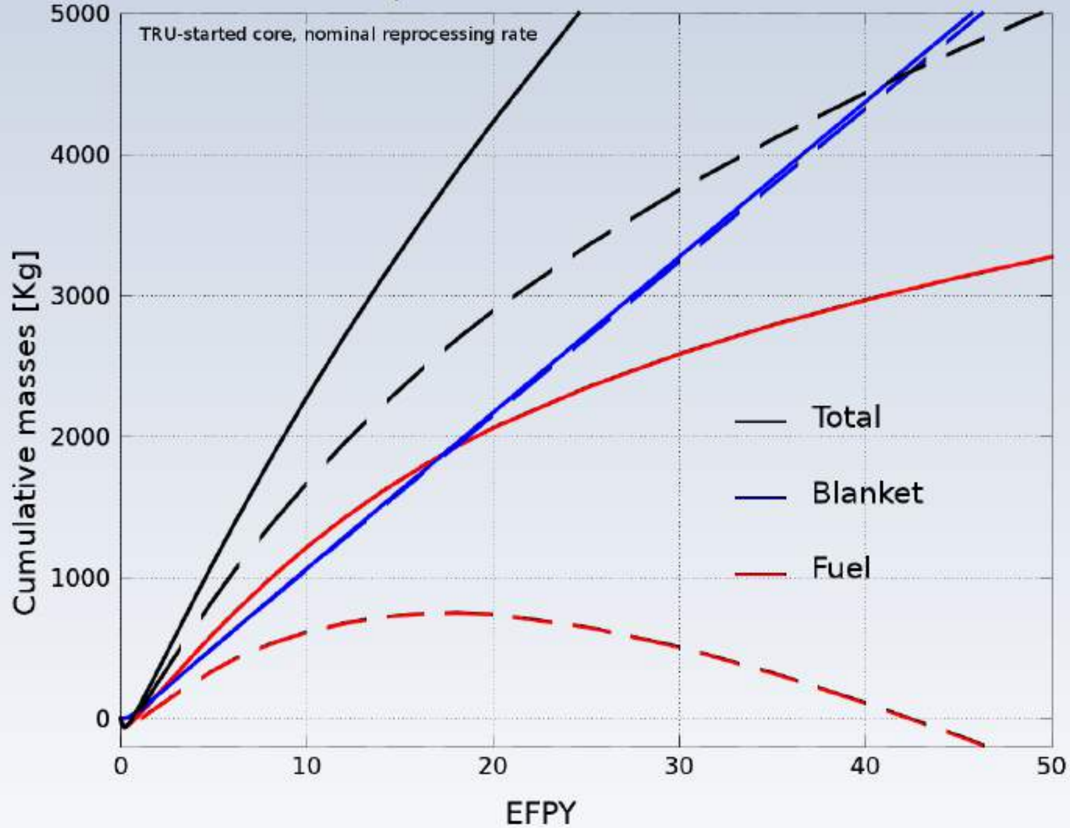
- $50 \cdot 10^6$ neutron histories for equilibrium calc.
- $10 \cdot 10^6$ neutron histories for transient calc.
- MPI = 6, OMP = 5, 1000+100 cycles
- *URES* activated only for main isotopes
- *opti* mode = 3

Example from the 2012 Serpent User Group Meeting in Madrid

JEFF vs ENDF: ^{233}U production

Huge difference in the fuel cycle prediction between JEFF-3.1 and ENDF/B-VII.

Solid lines: JEFF-3.1 – Dashed line: ENDF/B-VII

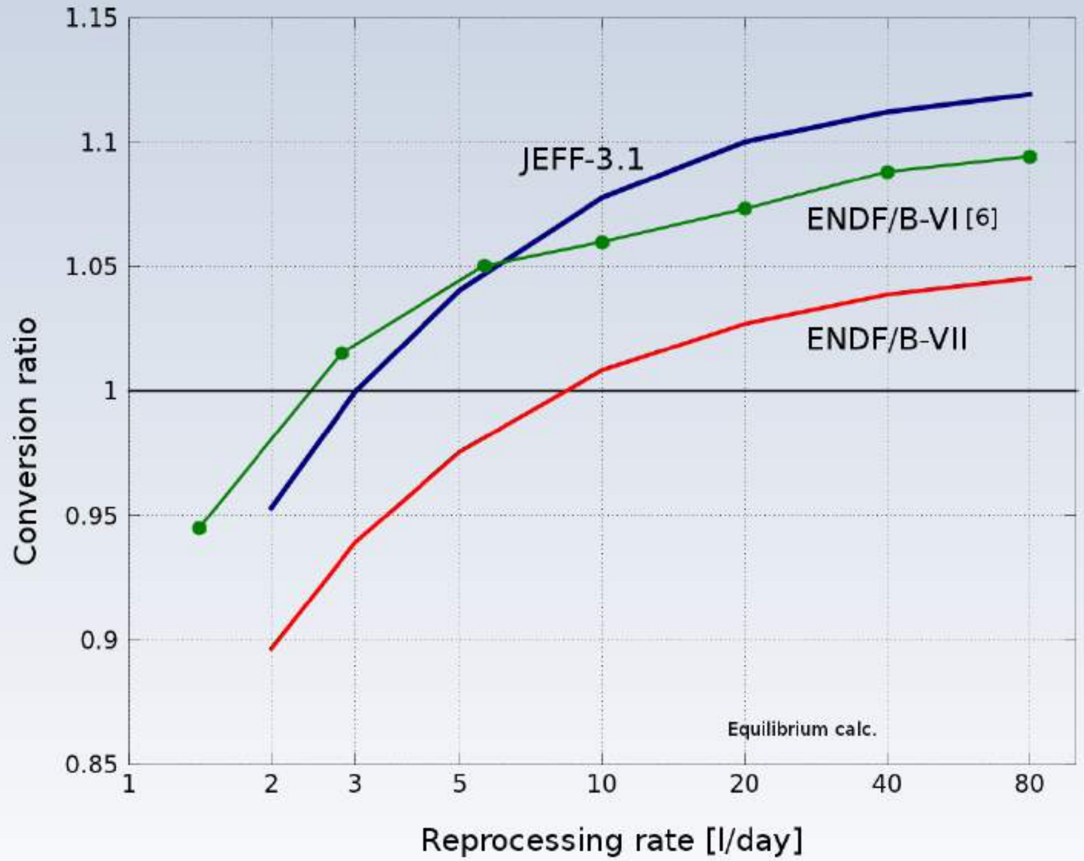


Good agreement for the Uranium production only in the blanket.

Example from the 2012 Serpent User Group Meeting in Madrid

JEFF vs ENDF: equilibrium *CR*

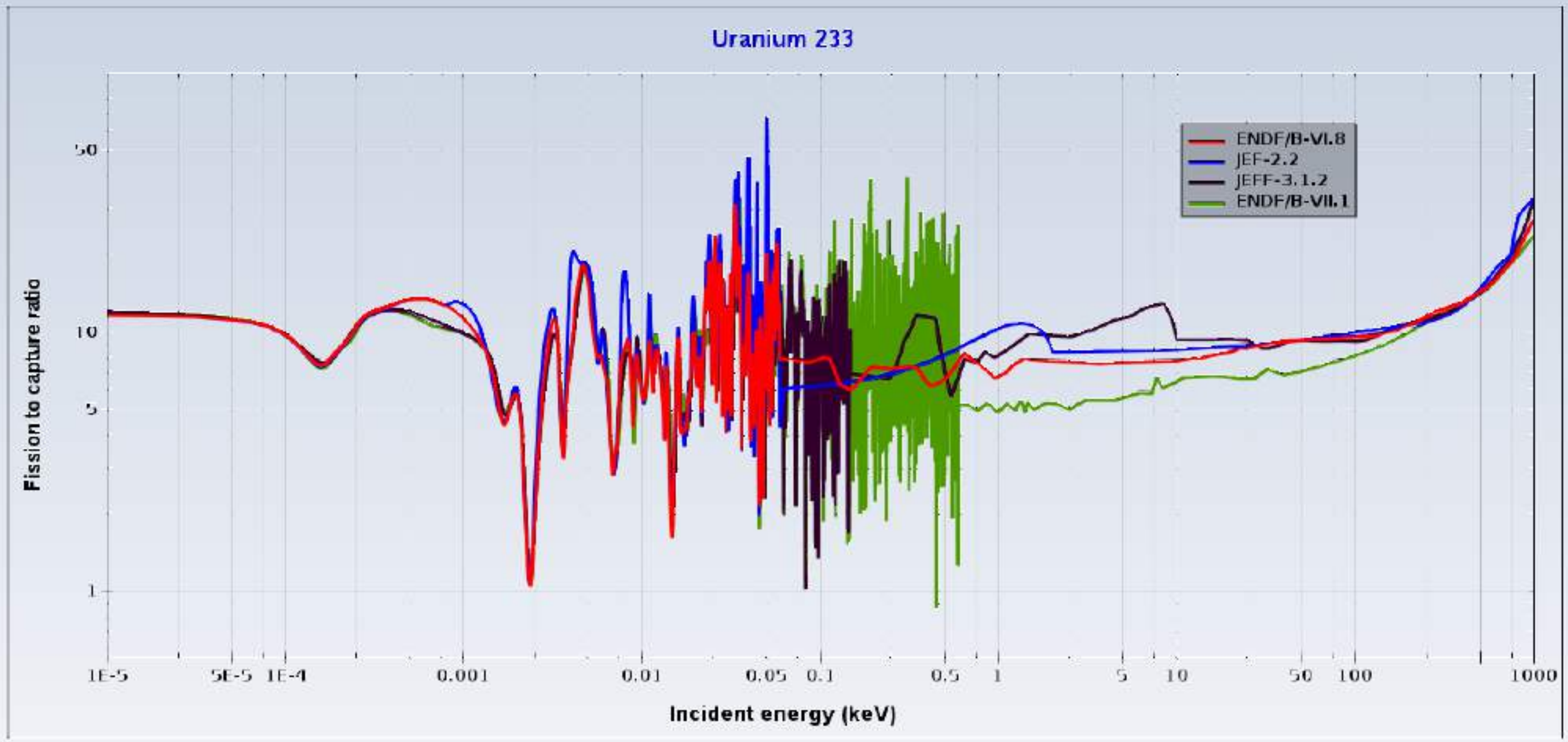
From JEFF-3.1 to ENDF/B-VII, break-even reprocessing rate prediction doubles.



[6] X. Doligez, Influence du retraitement physico-chimique du sel combustible sur le comportement du MSFR et sur le dimensionnement de son unité de retraitement, 2010.

Example from the 2012 Serpent User Group Meeting in Madrid

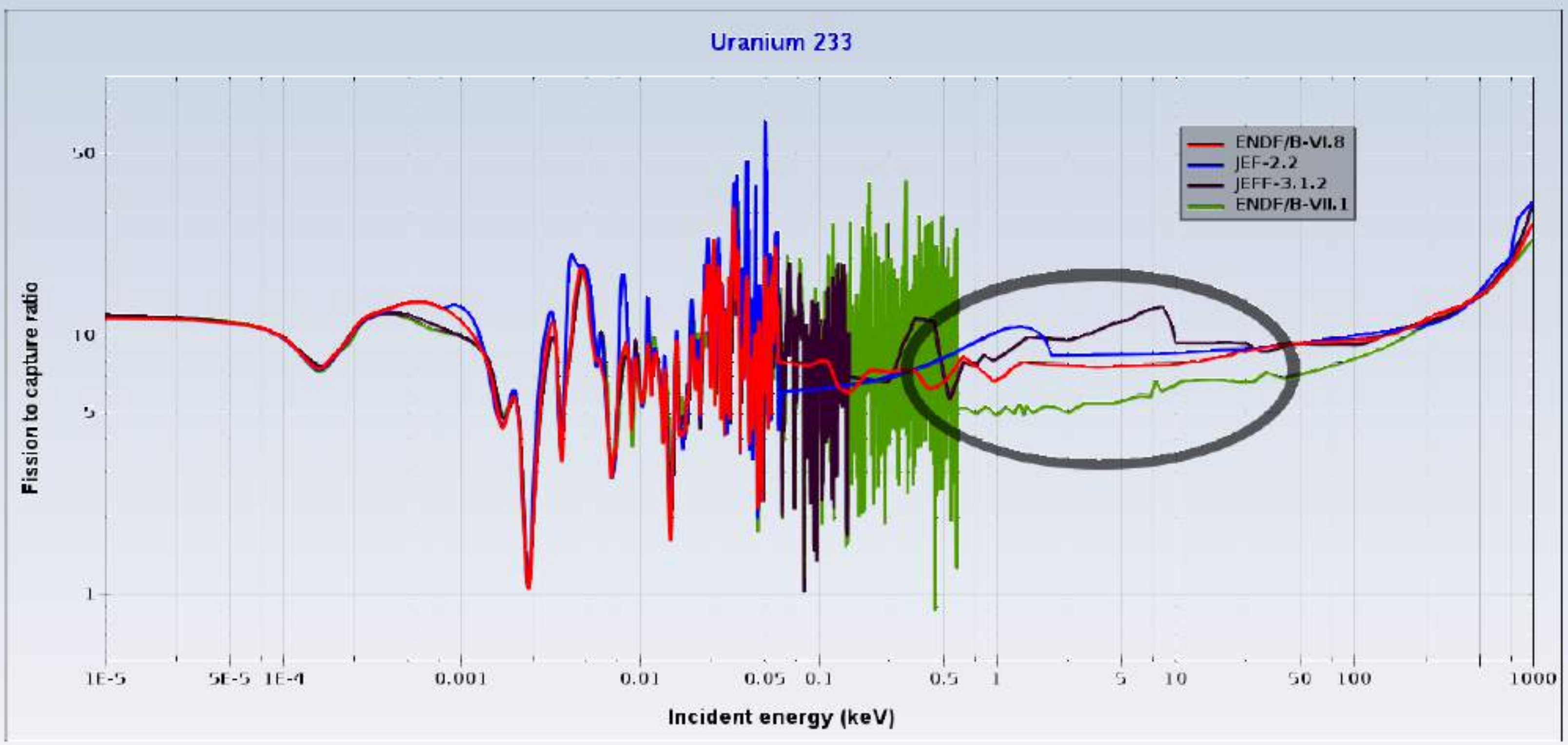
^{233}U Fission to capture ratio



Good agreement between the libraries almost everywhere...

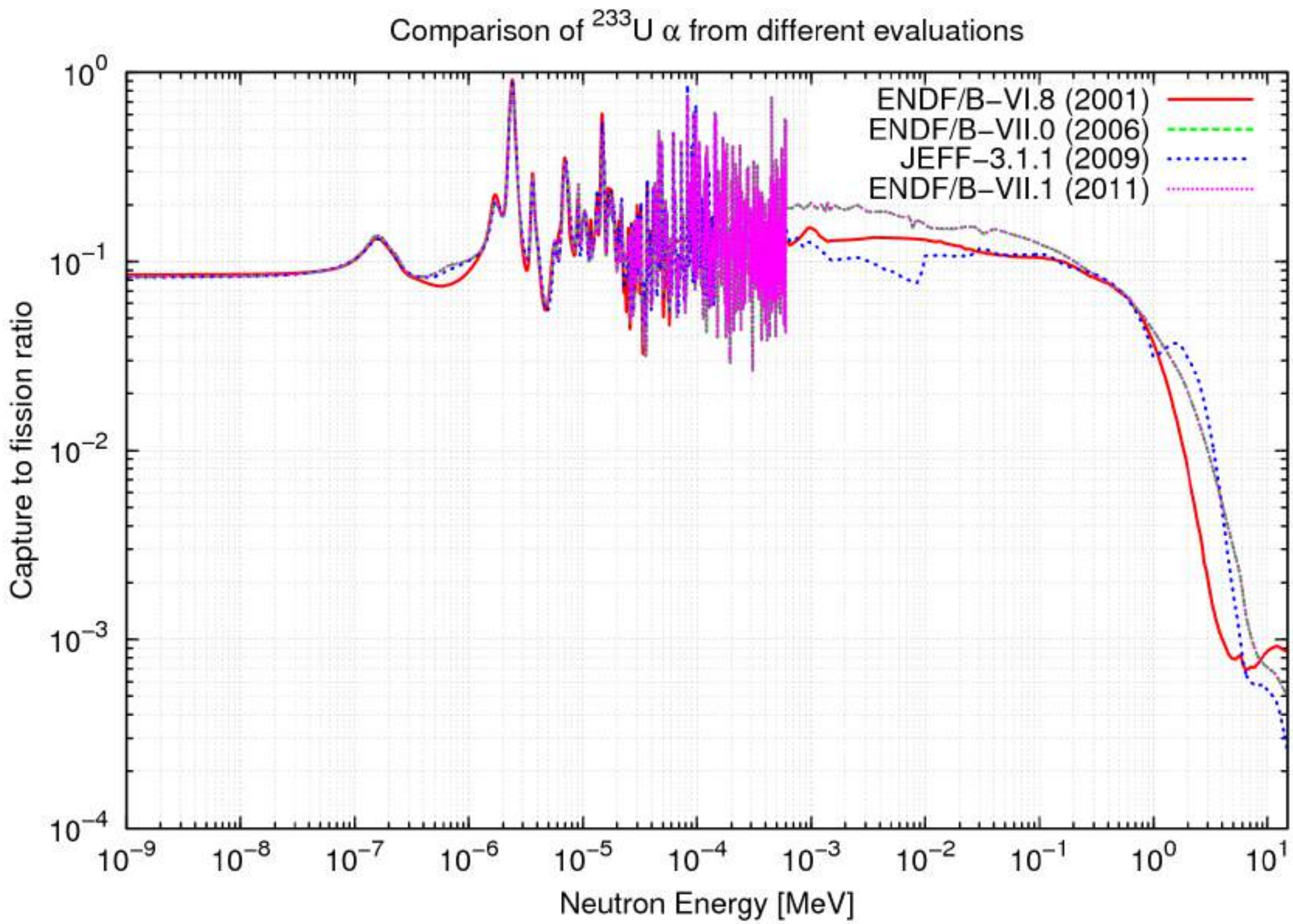
Example from the 2012 Serpent User Group Meeting in Madrid

^{233}U Fission to capture ratio



...NOT in the MSFR energy spectrum region.

ENDF/B and JEFF disagree on U-233



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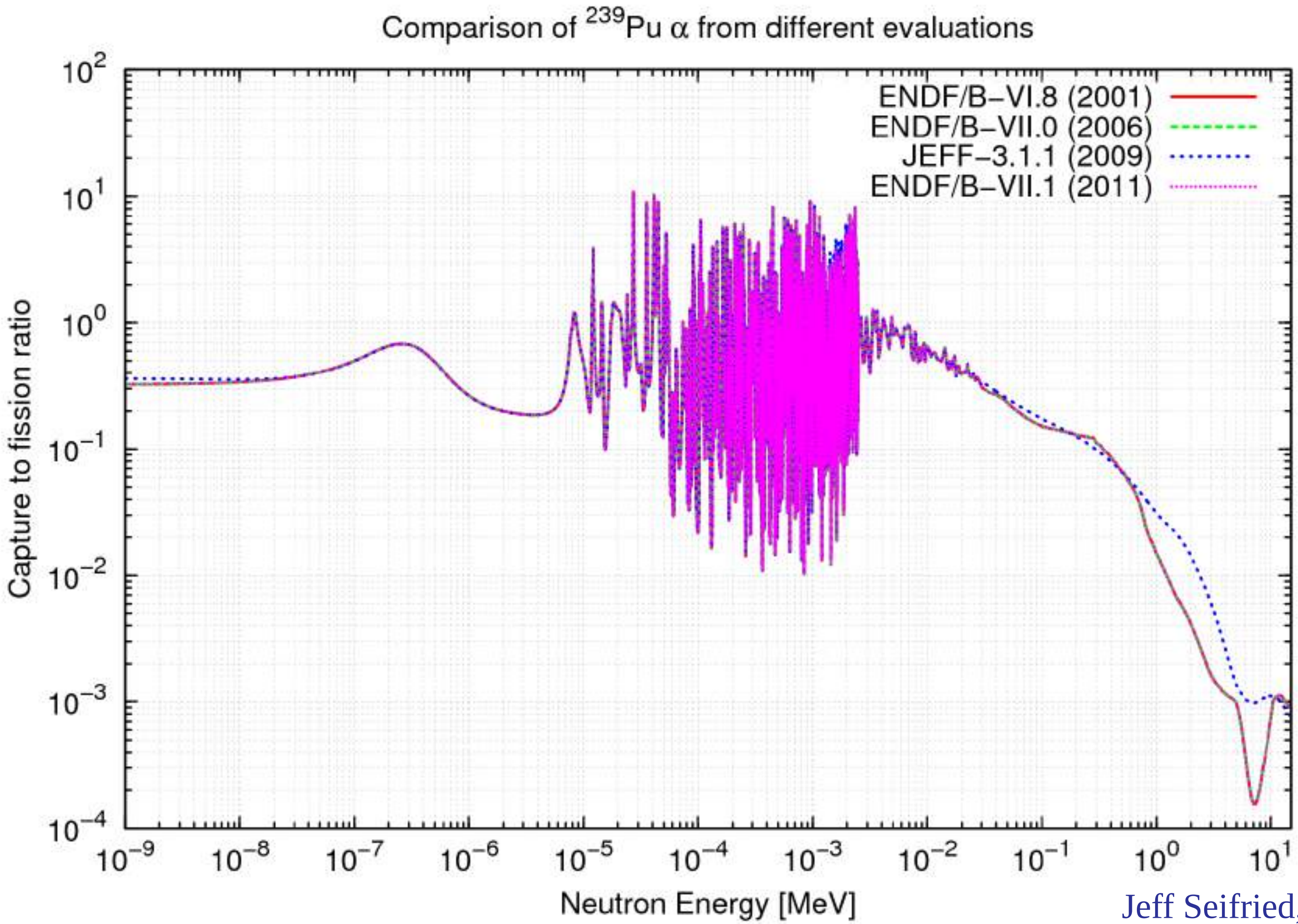
Disagreement for Pu-239



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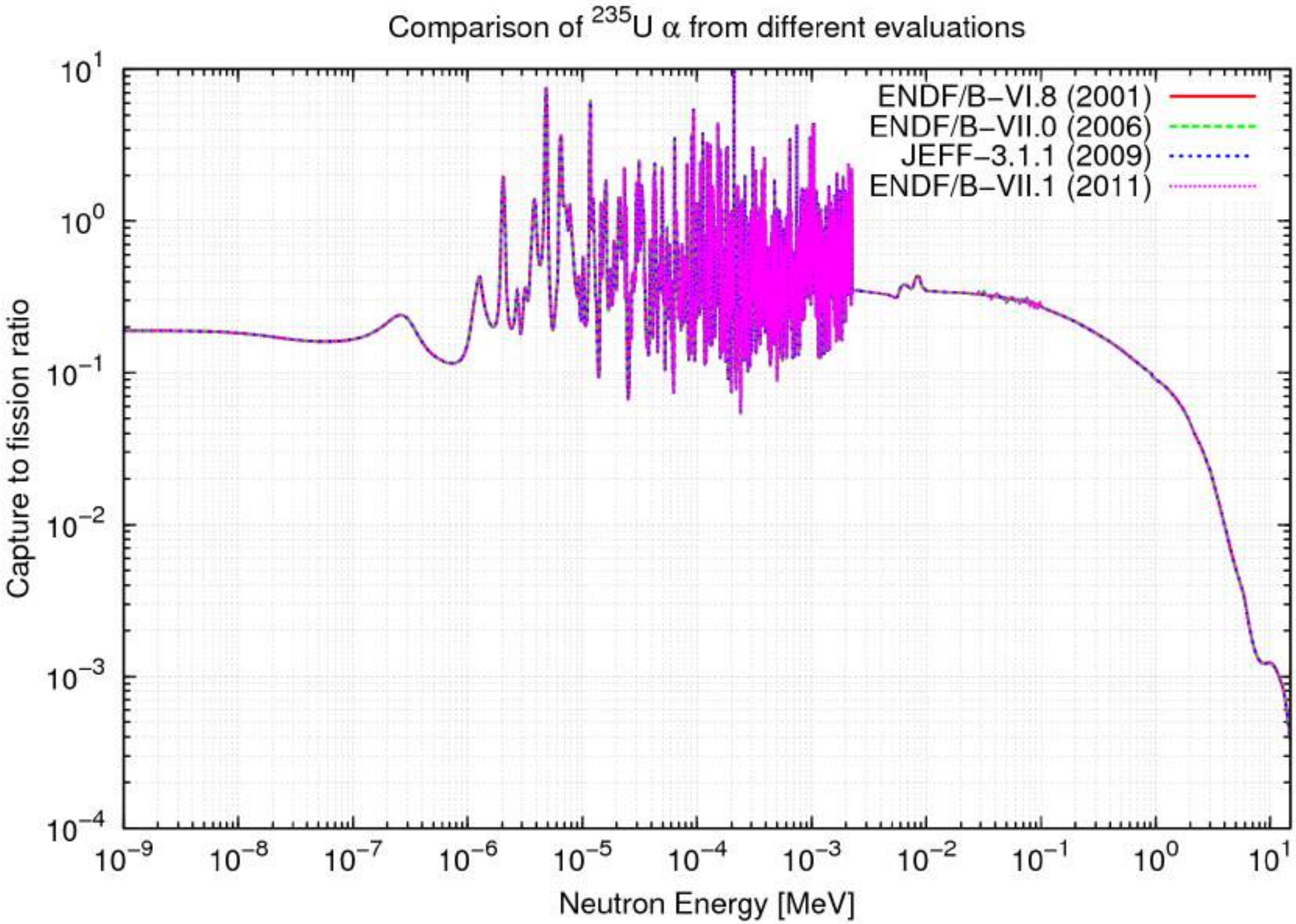
No Disagreement for U-235



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UCB NE Advanced Reactor Design Projects - Current

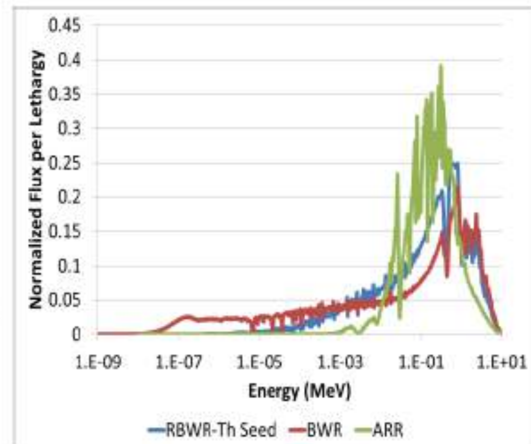
- **Collaborating Faulty: Ehud Greenspan, Max Fratoni, Jasmina Vujic**

Project	Researchers (no longer with project)
1. NEUP: Thorium-based Fuel-self-sustaining RBWR & TRU transmuting RBWR	Phillip Gorman, PhD Sandra Bogetic, PhD George Zhang, PhD Jeff Seifried, Post Doc Christopher Varela, MSc
2. NEUP: Seed-and-Blanket Liquid-Metal Reactors (S&B SFR)	George Zhang, PhD Staffan Qvist, Post Doc Christian DiSanzo, PhD Alejandra Jolodosky, MSc
3. NEUP: 3-D fuel shuffling in Breed and Burn (B&B) reactors (Pebble-bed B&B cores)	Phillip Gorman, MSc and NE-265 project team Jason Hou, Post Doc Staffan Qvist, Post Doc
4. Synergism between B&B, S&B and LWR fuel cycles 5. → 2-Tier and 3-Tier fuel cycles	Christian DiSanzo, PhD (Graduated)
6. Autonomous Reactivity Control (ARC) system for fast reactors (NEUP 2015?)	Staffan Qvist, Post Doc Meg Suvdantsetseg, PhD visiting from[1] KTH

Concerns about Hitachi RBWR Design

Concerns:

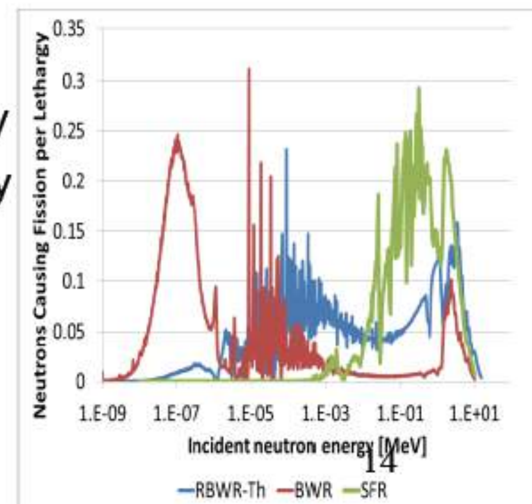
- Positive void coefficient (turned out to be negative)
- Very high LHGR – too low safety margins
- Axial power instabilities
- Very high peak burnup and high fast neutron fluence



Our (NEUP) Approach:

- Use thorium instead of depleted uranium as the primary fertile fuel
    - Greatly reduce positive spectral component of void reactivity
    - Do not have to rely on enhanced neutron leakage probability
- Use longer seeds and eliminate internal blanket

Collaborators: UoM (Downar), MIT (Kazimi), BNL (Todosow)



Sensitivity and uncertainty analysis for nuclear energy systems

Jeffrey Seifried

Postdoctoral Researcher
Department of Nuclear Engineering
University of California, Berkeley

Sather workshop on the thorium fuel cycle and nuclear data

November 20, 2013

Three Parts to Sensitivity and Uncertainty Analisys

1. **Quantify the sensitivity of results (R) to nuclear data (p)**

$$S_{R,p} \equiv \frac{\partial R}{\partial p}\frac{p}{R} \approx \frac{\delta R}{R}\frac{p}{\delta p}$$

2. **Estimate the covariance of those nuclear data (cov[p])**

ENDF6 MF=33

3. **Collapse to estimate result uncertainty**

$$\mathrm{var}\left[R\right] = \sum_{p} \left\langle S_{R,p}\right| \mathrm{cov}\left[p\right] \left|S_{R,p}\right\rangle$$

Direct sampling is the obvious, but expensive approach

- Its procedure is straightforward …
  1. Directly perturb an input (-5%, 0%, +5%)
  2. Perform an entire perturbed simulation (depletion)
  3. Extract perturbed results
  4. Quantify result sensitivities

- … but it is extremely expensive
12	[isotopes]
× 8	[reactions/isotope]
× 50	[energy regions/reaction]
= ~5,000	[uncertainty inputs]
= ~5,000	[depletion calculations] !
  - Monte Carlo counting uncertainties must not swamp nuclear data defects

Two tools for adjoint-based S/U analysis

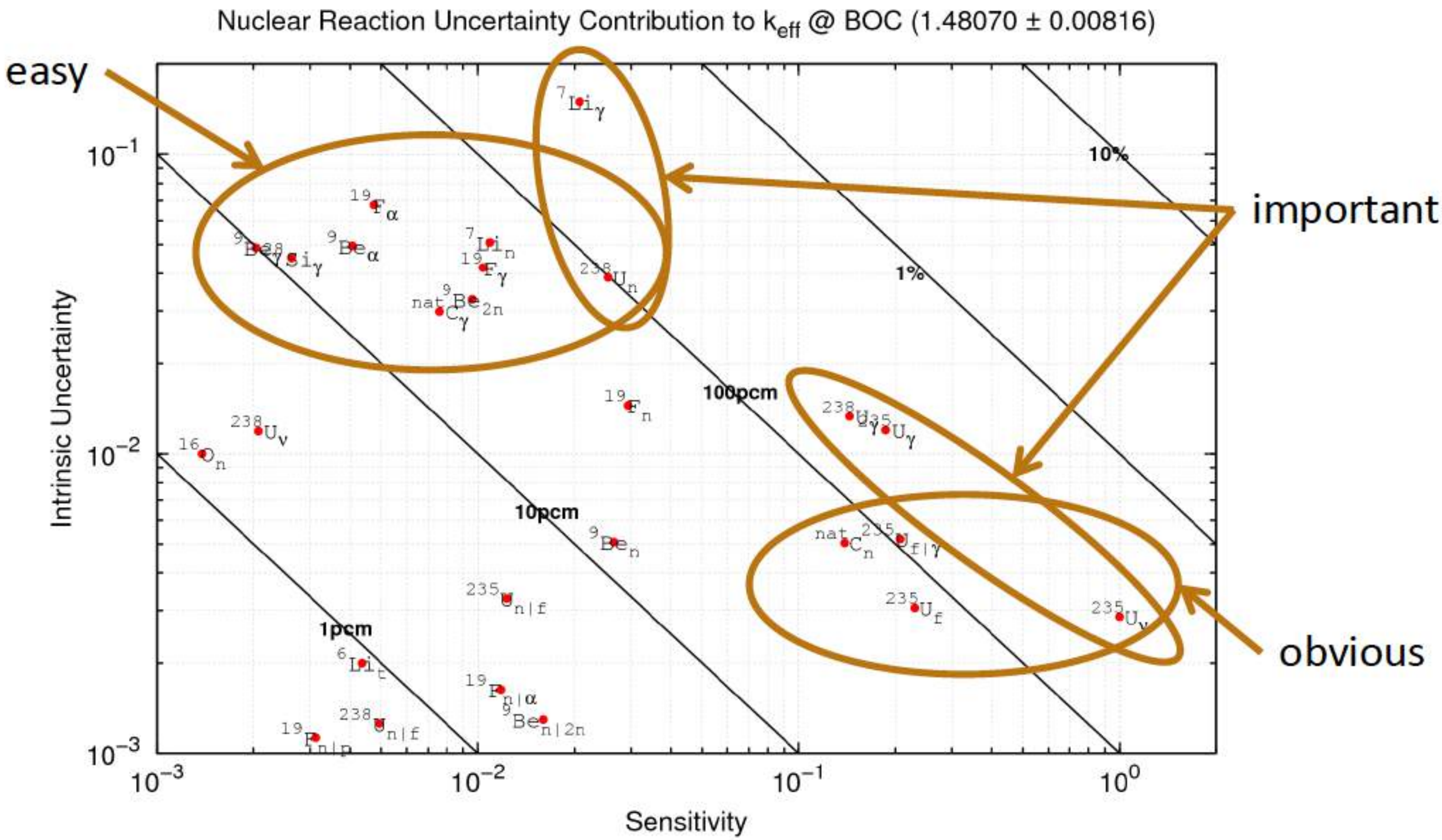
- SCALE/TSUNAMI is more convenient and mature
  - Built-in covariance libraries
  - Automated inner products
  - Many extraneous tools for analysis
  - Dancoff factors
  - Multi-group Monte Carlo (forward and adjoint) transport
  - Very slow!

- MCNP6/KSEN is much faster (but still slow)
  - Continuous-energy Monte Carlo (forward only) transport
  - Efficient forward estimator for the adjoint distribution
  - Parallelized transport
  - Matrix operations must be done by hand

The S/U analysis example for static multiplication factors for the PBFHR

- … for a single pebble unit cell …
  - TRISO pebble fuel
  - 20% enriched ^{235}U oxy-carbide
  - Immersed in ^{7}Li-enriched flibe
  - Infinitely hexagonal lattice
- … on my work desktop …
  - Intel i7-2600 @ 3.4 GHz
  - 4 GB RAM
- … took 1 week !

Results


Nuclear Reaction Uncertainty Contribution to k_{eff} @ BOC (1.48070 ± 0.00816)
easy
important
obvious
Intrinsic Uncertainty
Sensitivity
10%
1%
100pcm
10pcm
1pcm
10^{-1}
10^{-2}
10^{-3}
10^{0}
$^{7}Li_{\gamma}$
$^{19}F_{\alpha}$
$^{9}Be_{\alpha}$
$^{7}Li_{n}$
$^{19}F_{\gamma}$
$^{238}U_{n}$
$^{9}Be_{2n}$
$^{nat}C_{\gamma}$
$^{19}F_{n}$
$^{238}U_{\nu}$
$^{16}O_{n}$
$^{238}U_{\gamma}$
$^{235}U_{\gamma}$
$^{nat}C_{n}$
$^{235}U_{f|\gamma}$
$^{9}Be_{n}$
$^{235}U_{n|f}$
$^{235}U_{f}$
$^{235}U_{\nu}$
$^{6}Li_{t}$
$^{19}F_{n|\alpha}$
$^{9}Be_{n|2n}$
$^{238}U_{n|f}$
$^{19}F_{n|p}$

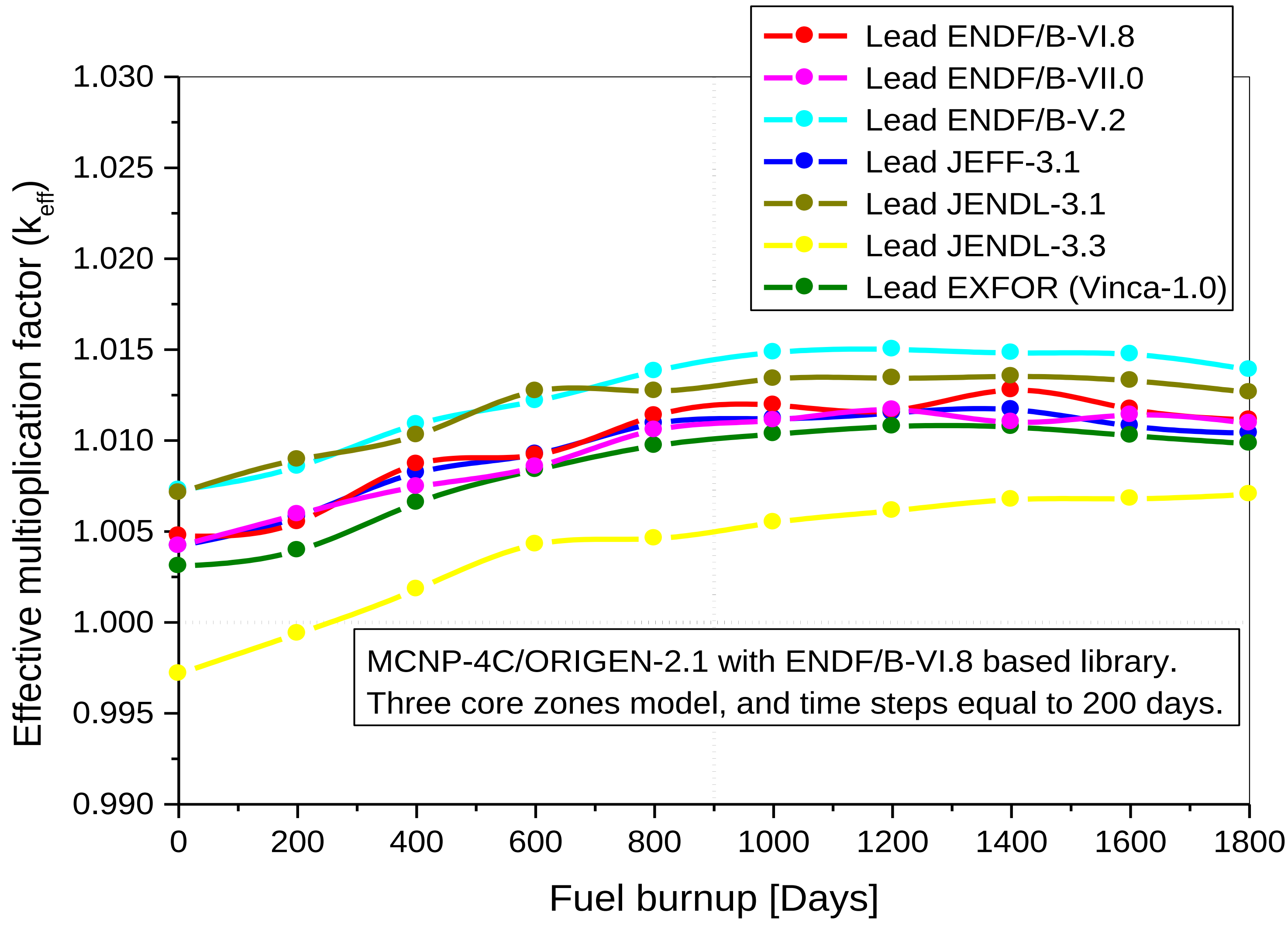
Issues with Lead Cross Sections

- UCB NE worked on the design of two lead-bismuth cooled reactors:
- The Encapsulated Nuclear Heat Source (ENHS) is a new conceptual designs of small lead-bismuth or lead cooled reactors with natural circulation.
- The International Atomic Energy Agency (IAEA) proposed a Co-ordinated Research Programme (CRP) on ″Development of Small Reactors without On-site Refuelling″. The RBEC-M lead-bismuth cooled fast reactor benchmark is suggested for this purpose.
- The depletion benchmark problem was prepared based on the RBEC-M core, which is a 900 MW(th) lead-bismuth cooled fast reactor conceptual design developed by the Russian Research Centre, ″Kurchatov Institute″ (RRC KI).

The RBEC-M core benchmark

- The MCNP and ORIGEN2.1 utility codes interfaced by the MOCUP driver were used.
- The continuous energy MCNP library based on the ENDF/B-VI.8, ENDF/B-VII.0, JEFF-3.1 and JENDL-3.3 evaluations was prepared for all lead nuclides.
- The largest differences between various evaluations were observed for ^{208}Pb cross section data. For other lead nuclides (^{204}Pb, ^{206}Pb and ^{207}Pb) the modern evaluations converge to the JEFF-3.1 evaluation.
- It was also found our hat ENDF/B-VI did not have data for Pb-204.
- M. Milosevic, E. Greenspan, and J. Vujic, “Effects of Lead Cross Section Uncertainties on the RBEC-M Fast Reactor Benchmark Results,” *Int. Conf. on Reactor Physics, Nuclear Power: A Sustainable Resource*, Interlaken, Switzerland, September 14-19, 2008

Comparison for Lead

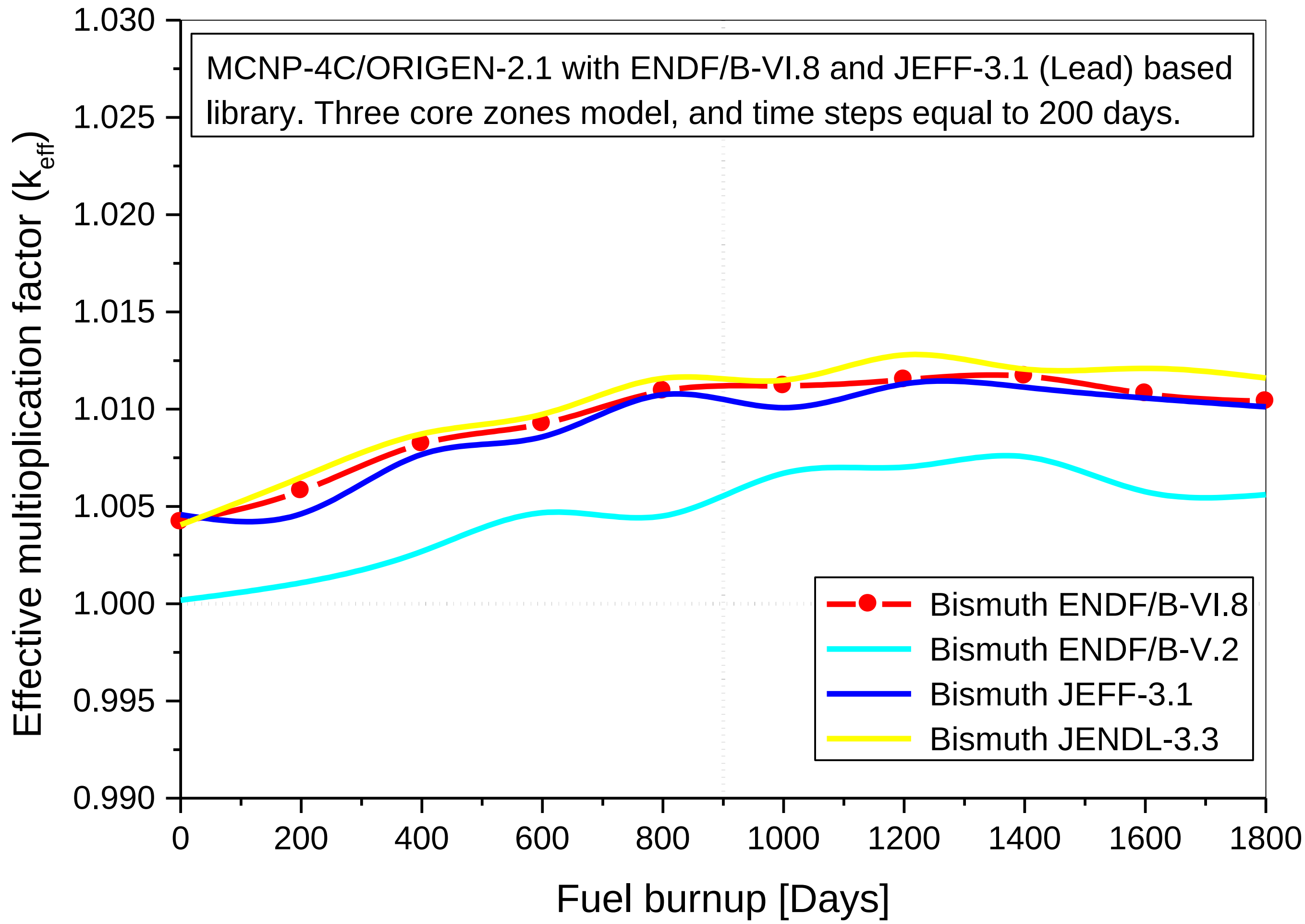


NUCLEAR SCIENCE and SECURITY CONSORTIUM

Results of this analysis, given in Figure 5 show:

- a good agreement between calculations based on the ENDF/B-VI.8, ENDF/B-VII.0, JEFF-3.1 and evaluation [13] founded on the EXFOR data for lead;
- a notable difference (about -600 pcm) between calculations based on the ENDF/B-VI.8 and older evaluated cross section data for lead (ENDF/B-V.2 and JENDL-3.1); and
- a notable difference (about 1000 pcm) between calculations based on the ENDF/B-VI.8 and JENDL-3.3 evaluated cross section data for lead (due to slightly higher values of ^{207}Pb elastic cross section data in the JENDL-3.3 evaluation in comparison with the ENDF/B-VI.8, ENDF/B-VII.0 and JEFF-3.1 evaluation).

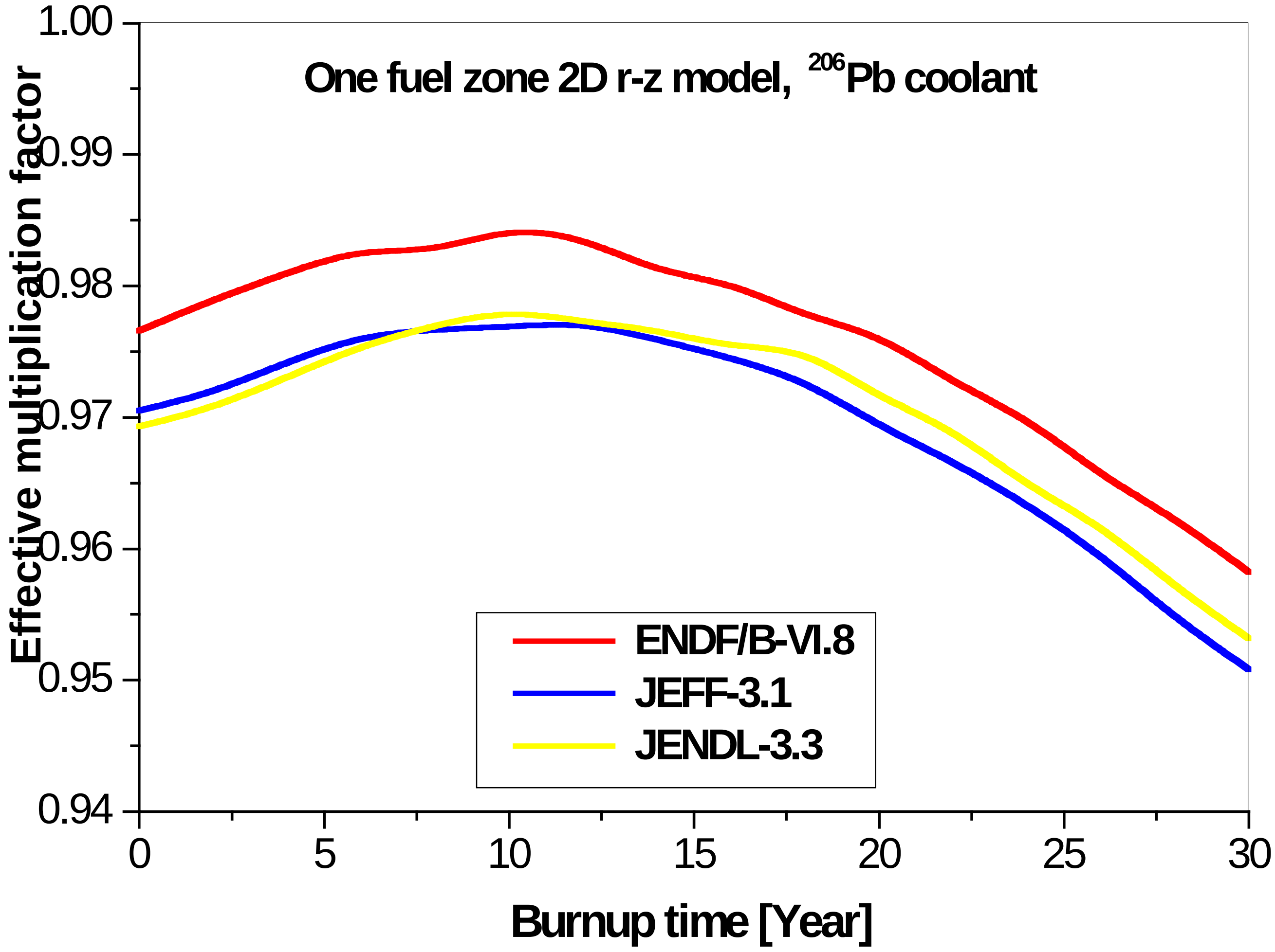
Comparison for Bismuth



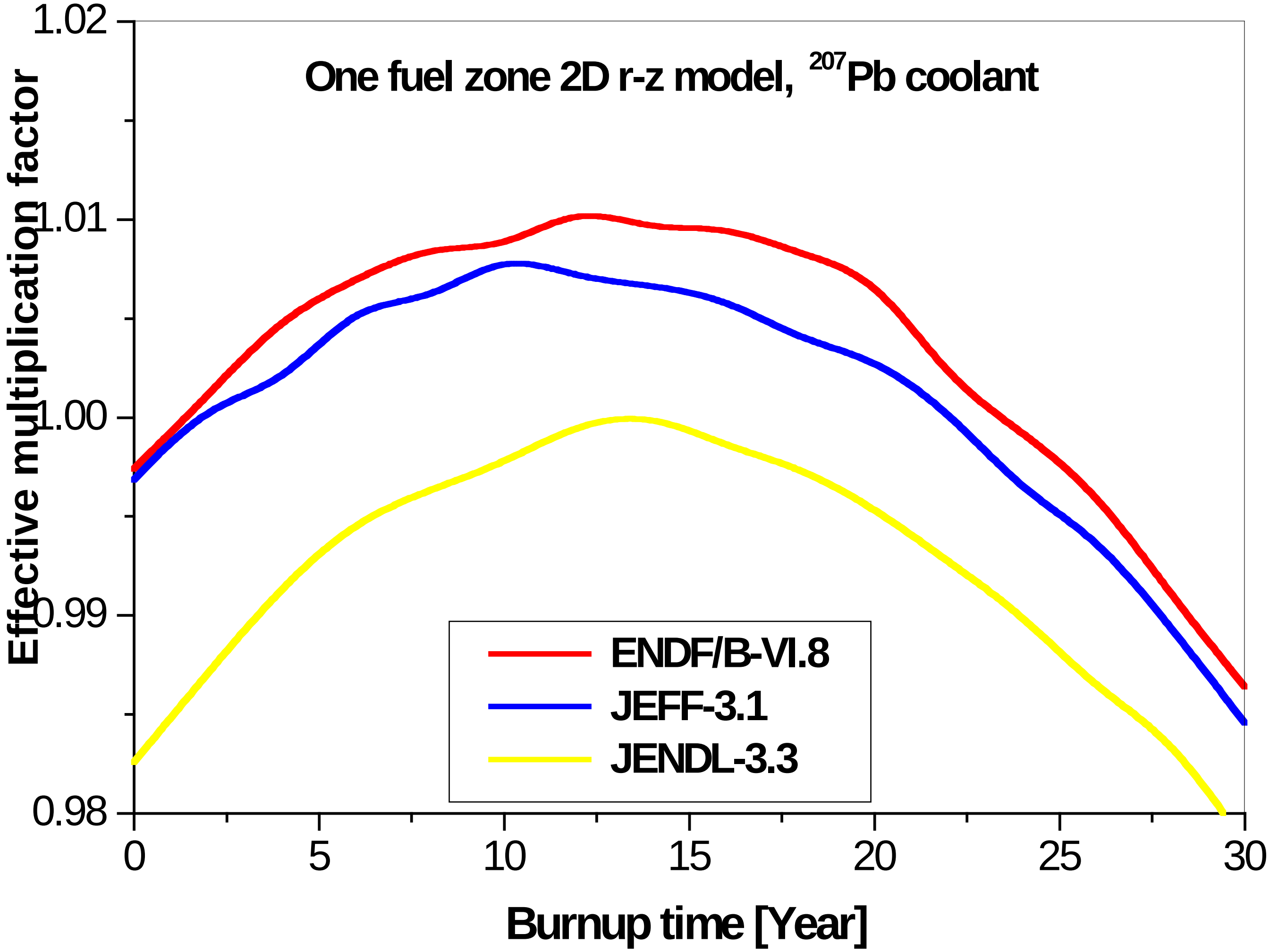
The ENHS Benchmark

- M. Milosevic, E. Greenspan, and J. Vujic, "Uncertainties in Monte Carlo Analysis of Innovative Lead-Cooled Fast Reactors," Advances in Nuclear Analysis and Simulation, PHYSOR 2006, Vancouver, BC, Canada, September 10 - 14, 2006
- The ENHS is a lead-bismuth or lead cooled novel reactor concept that is fuelled with metallic alloy of Pu, U and Zr, and is designed to operate for 20 effective full power years without refuelling and with very small burnup reactivity swing.
- A significant difference (about 1500 pcm) was found in k-eff between the ENDF/B-VI.8 and JENDL-3.3 evaluations due to a slightly higher values in JENDL-3.3 evaluation for elastic cross section of ^{207}Pb.

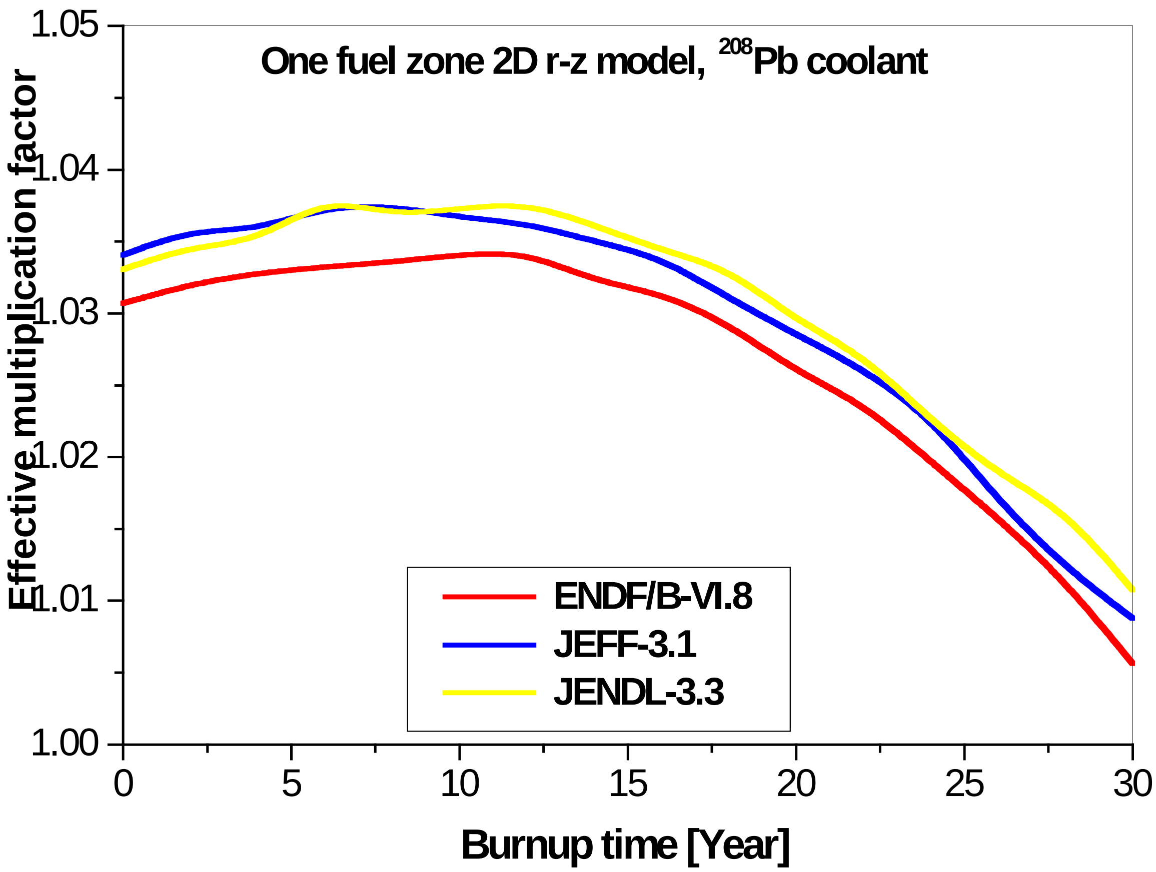
The ENHS Benchmark –Pb-206



The ENHS Benchmark –Pb-207

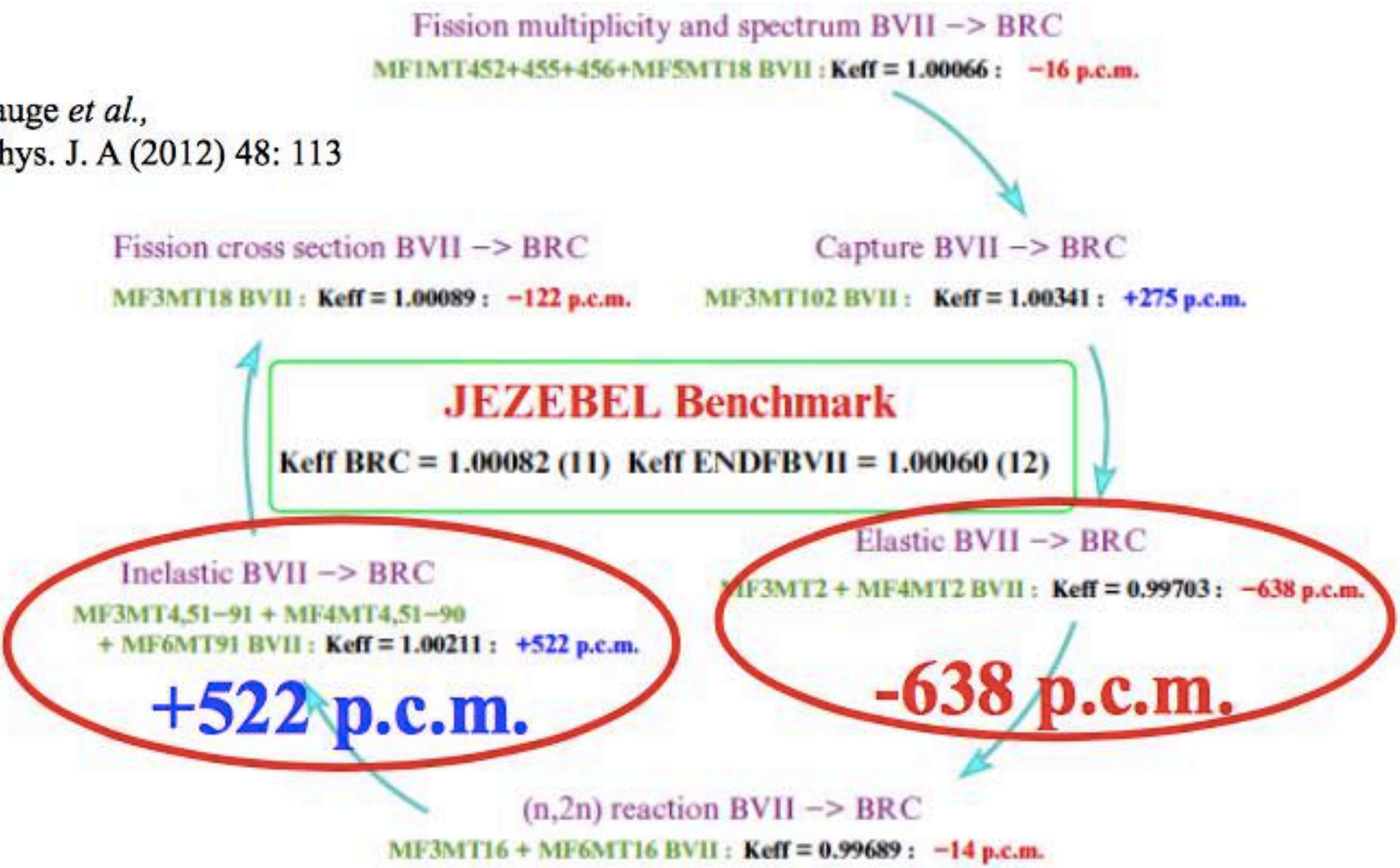


The ENHS Benchmark –Pb-207



Bauge* highlighted the uncertainty in reaction databases for (n,n$_{el}$) and (n,n’) in a prompt fission neutron spectrum

*E. Bauge *et al.*,
Eur. Phys. J. A (2012) 48: 113



SUMMARY

- **Although the quality of the main evaluated data libraries mentioned in this presentation is high, there is still a lot of work to be done.**
- **There examples (particularly in nuclear criticality experiments) that good results are obtained mainly due to compensation of errors, as shown in recently presented uncertainty analysis of Jezebel criticality experiment.**
- **The CIELO paper (Chadwick et al., Nuclear Data Sheets 118, 1-24, 2014), lists and analyses some important nuclides**
  - Light elements (H-1, O-16),
  - Structural materials (Fe-56), inelastic scatering, (n,xn), (N,xp), (n,alpha)
  - U-235, Pu-239
  - U-238
- **Thorium and it isotopes also very important**

Acknowledgement

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