

Nuclear data analyses for improving the safety of advanced lead-cooled reactors

P. Romojaro¹, F. Álvarez-Velarde¹, N. García-Herranz²

(1)Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)

(2)Universidad Politécnica de Madrid (UPM)

pablo.romojaro@ciemat.es



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- Nuclear data are one of the key elements in the neutronics and safety assessment
- Uncertainty in nuclear data is one of the most important sources of uncertainty
- **Significant gaps between current uncertainties and target accuracies have been shown in the past**

Target accuracy for fast reactors $k_{\text{eff}} = 300 \text{ pcm}^*$

Target accuracy for fast reactors $\beta_{\text{eff}} = 3\%^{}$**

- **Objectives:**
 1. UQ analysis and target accuracy assessment with state-of-the-art ND for LFR reactor concept
 2. Data assimilation (DA) for uncertainty reduction if target accuracies are not met
- **MYRRHA** (Multi-purpose hYbrid Research Reactor for High-tech Applications)

* OECD/NEA WPEC SG-26 final report (2008)

** Rudstan et al.; 2002; D'Angelo and Rowlands, 2002



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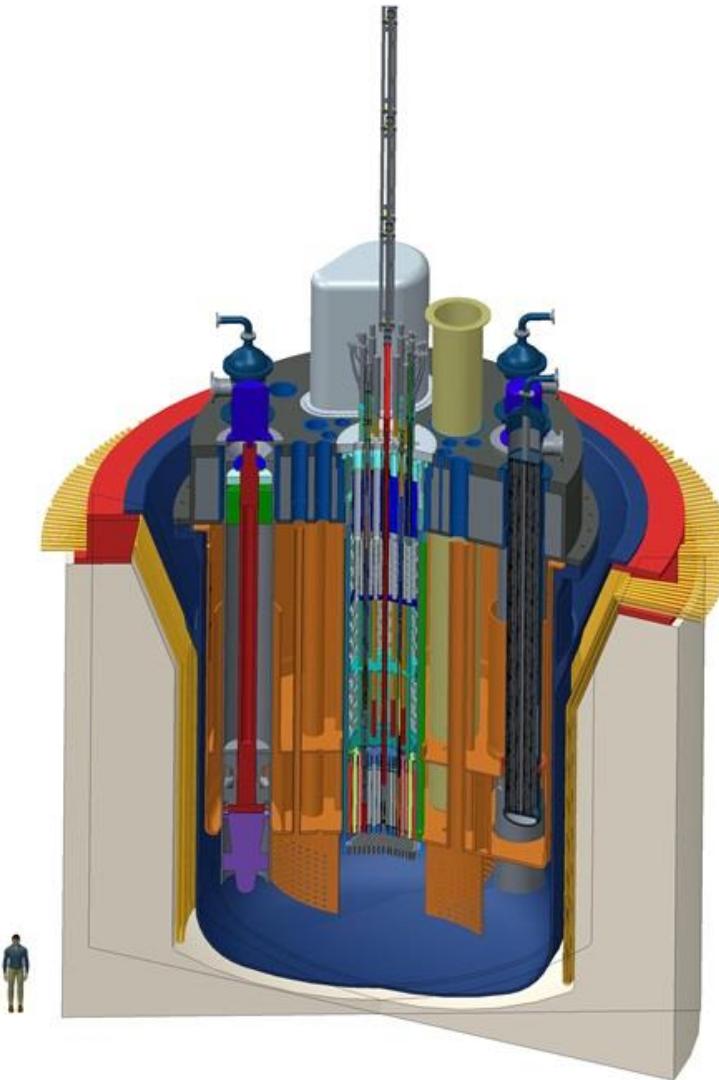
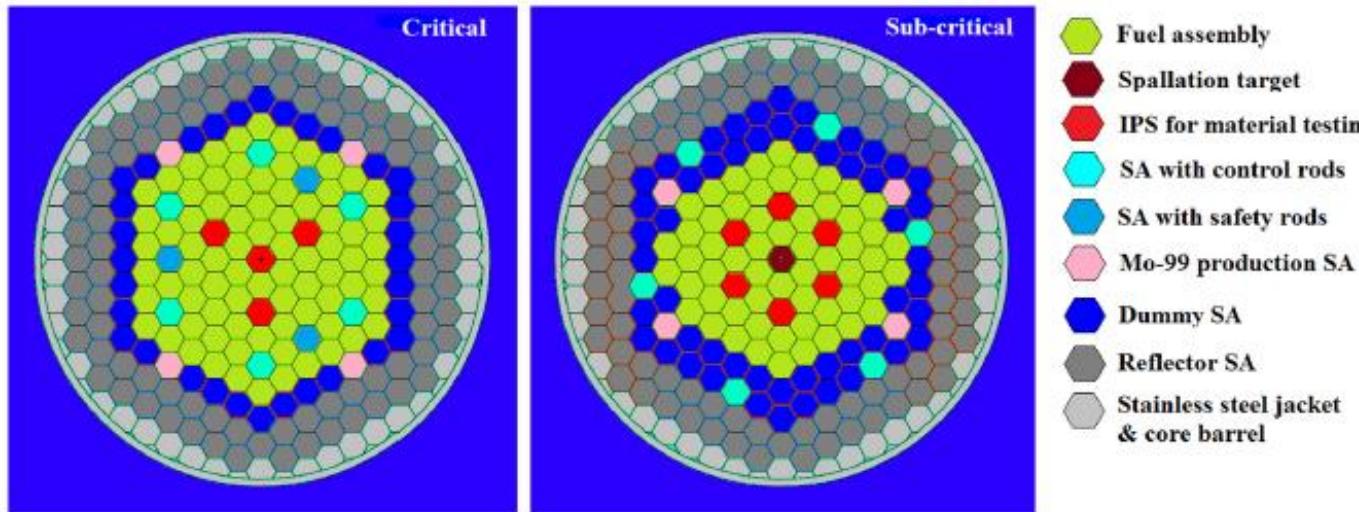
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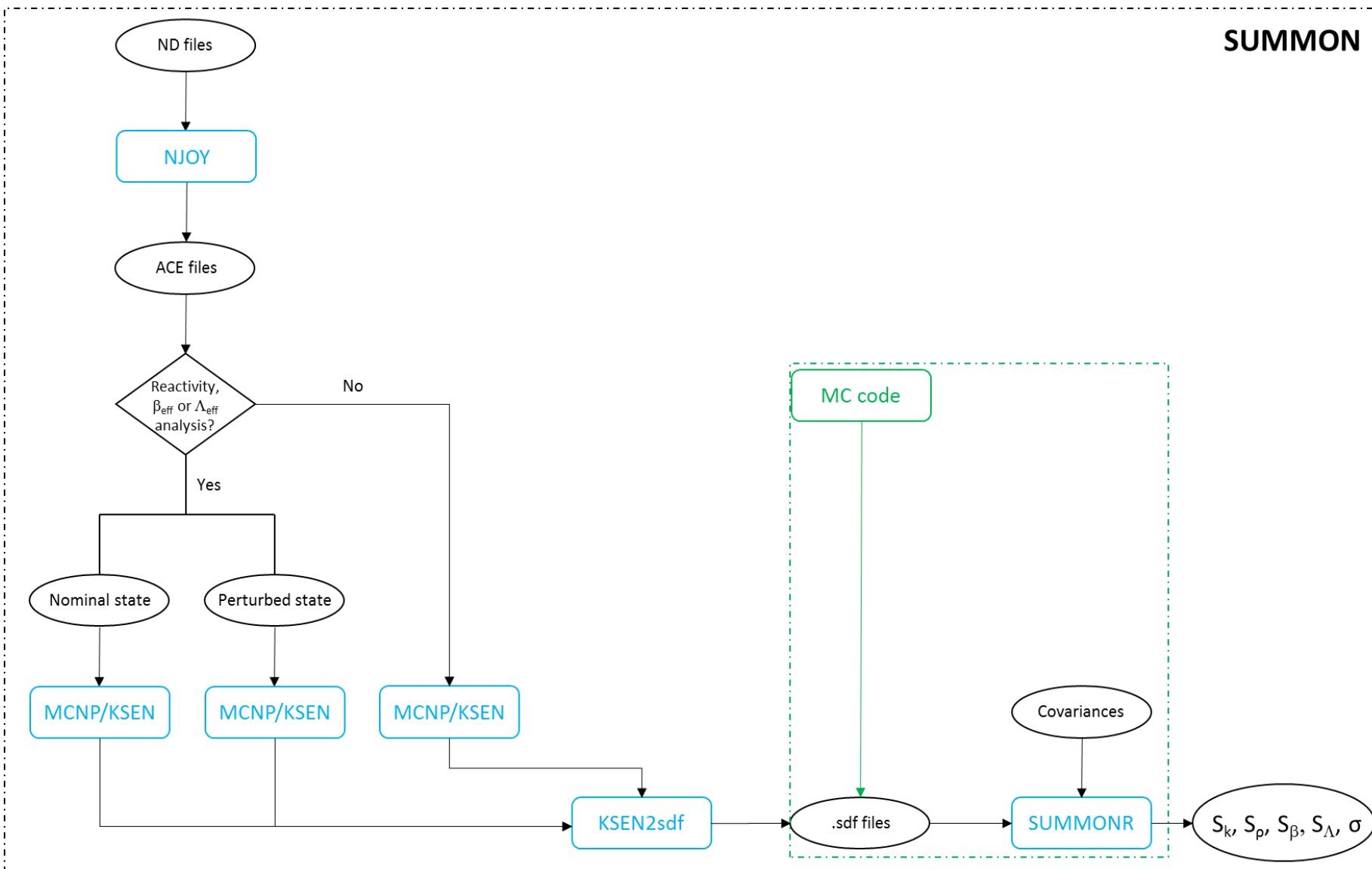
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MYRRHA

- 50 – 100 MWth
- Flexible fast spectrum irradiation facility
- Pool type reactor
- **Cooled by lead-bismuth** liquid metal
- **Critical and sub-critical (ADS) modes**
- Highly enriched **MOX fuel**
- Start-up core can be UO_2 fuel



- **JEFF-3.3 and ENDF/B-VIII.0** processed with **NJOY2016.27** for **sensitivity analyses**
- **JEFF-3.3, ENDF/B-VIII.0 and JENDL-4.0u2** processed with **NJOY2016.40** for **UQ**
- **JEFF-3.3** processed with **NJOY2016.40** for **DA**
- **MCNP6.1.1beta** for **sensitivity** calculations
- **SUMMONR** for **UQ**
- **DAWN** for **DA**
- MYRRHA homogenized critical core configuration in nominal conditions at Beginning of Life



- Based on the GLS technique:

$$\chi^2 = \left(\frac{\sigma' - \sigma}{\sigma} \right)^T M_{\sigma}^{-1} \left(\frac{\sigma' - \sigma}{\sigma} \right) + \left(\frac{E - C}{C} \right)^T M_{EC}^{-1} \left(\frac{E - C}{C} \right)$$

- Cross section modifications that minimize the χ^2 thanks to the adjustment:

$$\left(\frac{\sigma' - \sigma}{\sigma} \right) = M_{\sigma} S^T G^{-1} \left(\frac{E - C}{C} \right)$$

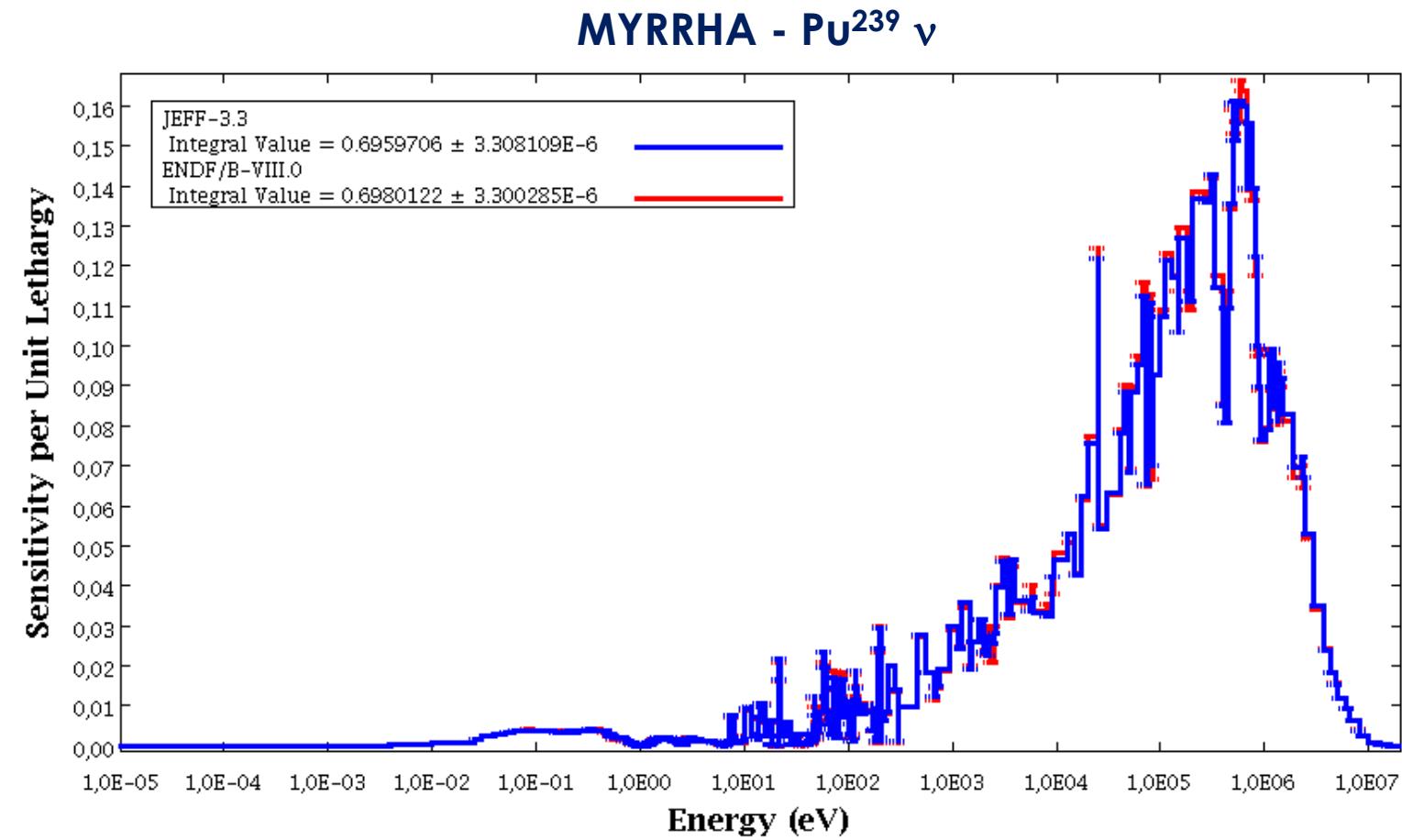
- A posteriori covariance matrix:

$$M'_{\sigma} = M_{\sigma} - M_{\sigma} S^T G^{-1} S M_{\sigma} = M_{\sigma} (I - S^T G^{-1} S M_{\sigma})$$

Sensitivity calculations

MYRRHA – ISC (%%)

Quantity	JEFF-3.3	ENDF/B-VIII.0
^{239}Pu ν	0.696	0.698
^{239}Pu (n,f)	0.482	0.486
^{238}U (n,γ)	-0.112	-0.115
^{240}Pu ν	0.081	0.080
^{239}Pu (n,γ)	-0.053	-0.056



JEFF-3.3

Quantity		$\Delta k_{eff}/k_{eff}(\%)$
^{240}Pu	(n,f)	0.543
^{240}Pu	(n,f)	-0.420
^{239}Pu	ν	0.321
^{239}Pu	(n,f)	0.295
^{239}Pu	χ	0.267
^{240}Pu	(n, γ)	0.197
^{239}Pu	(n,f)	0.174
^{238}U	(n, γ)	0.167
^{239}Pu	(n, γ)	0.151
^{238}U	(n,inel.)	-0.138
Uncertainty in k_{eff}		0.694

ENDF/B-VIII.0

Quantity		$\Delta k_{eff}/k_{eff}(\%)$
^{239}Pu	(n,f)	0.550
^{239}Pu	(n, γ)	0.227
^{209}Bi	(n,inel.)	0.222
^{239}Pu	ν_p	0.187
^{238}U	(n, γ)	0.139
^{239}Pu	χ	0.128
^{238}U	(n,inel.)	-0.095
^{240}Pu	(n, γ)	0.091
^{238}U	ν_p	0.087
^{238}U	(n,inel.)	0.081
Uncertainty in k_{eff}		0.698

JENDL-4.0u2

Quantity		$\Delta k_{eff}/k_{eff}(\%)$
^{239}Pu	(n,f)	0.251
^{239}Pu	χ	0.195
^{238}U	(n,inel.)	0.188
^{238}U	(n, γ)	0.180
^{239}Pu	(n, γ)	0.171
^{56}Fe	(n,inel.)	0.136
^{239}Pu	ν_p	0.112
^{240}Pu	(n, γ)	0.104
^{56}Fe	(n, γ)	0.084
^{241}Pu	χ	0.084
Uncertainty in k_{eff}		0.506

JEFF-3.3

				$\Delta\beta_{eff}/\beta_{eff}(\%)$
^{241}Pu	ν_d	^{241}Pu	ν_d	0.653
^{238}U	(n,f)	^{238}U	(n,f)	0.440
^{238}U	(n,inel.)	^{238}U	(n,f)	-0.321
^{241}Pu	χ	^{241}Pu	χ	0.283
^{240}Pu	(n,f)	^{240}Pu	(n,f)	0.277
^{239}Pu	ν_p	^{239}Pu	ν_p	0.270
^{238}U	(n,inel.)	^{238}U	(n,inel.)	0.197
^{238}U	(n,el.)	^{238}U	(n,f)	0.130
^{238}U	(n,inel.)	^{238}U	(n, γ)	0.129
^{238}U	ν_p	^{238}U	ν_p	0.125
Uncertainty in β_{eff}		0.913		

ENDF/B-VIII.0

				$\Delta\beta_{eff}/\beta_{eff}(\%)$
^{238}U	ν_d	^{238}U	ν_d	0.385
^{239}Pu	χ	^{239}Pu	χ	0.351
^{242}Pu	ν_d	^{242}Pu	ν_d	0.251
^{240}Pu	χ	^{240}Pu	χ	0.244
^{238}U	(n,inel.)	^{238}U	(n,f)	-0.228
^{238}U	ν	^{238}U	ν	0.221
^{238}U	(n,f)	^{238}U	(n,f)	0.220
^{239}Pu	(n,f)	^{239}Pu	(n,f)	0.199
^{238}U	χ	^{238}U	χ	0.177
^{239}Pu	ν_p	^{239}Pu	ν_p	0.161
Uncertainty in β_{eff}		0.733		

JENDL-4.0u2

				$\Delta\beta_{eff}/\beta_{eff}(\%)$
^{239}Pu	ν_d	^{239}Pu	ν_d	1.709
^{238}U	ν_d	^{238}U	ν_d	1.002
^{241}Pu	ν_d	^{241}Pu	ν_d	0.653
^{239}Pu	χ	^{239}Pu	χ	0.543
^{238}U	(n,inel.)	^{238}U	(n,inel.)	0.341
^{240}Pu	ν_d	^{240}Pu	ν_d	0.308
^{241}Pu	χ	^{241}Pu	χ	0.283
^{56}Fe	(n,inel.)	^{56}Fe	(n,inel.)	0.262
^{242}Pu	ν_d	^{242}Pu	ν_d	0.251
^{238}U	χ	^{238}U	χ	0.173
Uncertainty in β_{eff}		2.259		

- JEFF-3.3 and ENDF/B-VII.0 yield similar ISC and sensitivity profiles
- Good agreement between JEFF-3.3 and ENDF/B-VIII.0 for k_{eff} uncertainty
- Differences between JEFF-3.3, ENDF/B-VIII.0 and JENDL-4.0u2 for β_{eff}
- Very different magnitude and contributors to the uncertainty
- k_{eff} target accuracy is exceeded approximately by a factor of two for all considered ND evaluations
- β_{eff} target accuracy for all considered ND evaluations is met

- **Data assimilation** for main contributors to k_{eff} uncertainty: ^{240}Pu , ^{239}Pu and ^{238}U
- **JEFF-3.3** nuclear data library
- Two selection methods:
 1. **Rank similar** with DICE*: cosine similarity
 2. **Representativity factor:**

$$f_{RE} = \frac{S_R^T M_\sigma S_E}{\sqrt{(S_R^T M_\sigma S_R)(S_E^T M_\sigma S_E)}}$$

* OECD/NEA. DICE: User's Manual. NEA/NSC/DOC(95)03/II

Rank similar

Case ID	Sensitivity Ranking
MIX-COMP-FAST-006-001	0.9586370
MIX-COMP-FAST-001-001	0.9496865
MIX-COMP-FAST-005-001	0.9466432
MIX-MISC-FAST-002-001	0.9275238
MIX-MISC-FAST-003-001	0.8876426
MIX-MET-INTER-004-001	0.8518469
MIX-MET-INTER-003-001	0.8109334
MIX-MET-FAST-011-001	0.7942846
PU-MET-FAST-033-001	0.7705911
PU-MET-INTER-002-001	0.7109429

MIX-COMP-FAST-001-001

Original JEFF-3.3

		Quantity		$\Delta k_{eff}/k_{eff} (\%)$
^{240}Pu	(n,f)	^{240}Pu	(n,f)	0.543
^{240}Pu	(n,f)	^{240}Pu	(n, γ)	-0.420
^{239}Pu	ν	^{239}Pu	ν	0.321
^{239}Pu	(n,f)	^{239}Pu	(n,f)	0.295
^{239}Pu	χ	^{239}Pu	χ	0.267
^{240}Pu	(n, γ)	^{240}Pu	(n, γ)	0.197
^{239}Pu	(n,f)	^{239}Pu	(n, γ)	0.174
^{238}U	(n, γ)	^{238}U	(n, γ)	0.167
^{239}Pu	(n, γ)	^{239}Pu	(n, γ)	0.151
^{238}U	(n,inel.)	^{238}U	(n,f)	-0.138
MYRRHA uncertainty in k_{eff}		0.694		

Adjusted JEFF-3.3 with MCF001

		Quantity		$\Delta k_{eff}/k_{eff} (\%)$
^{240}Pu	(n,f)	^{240}Pu	(n,f)	0.534
^{240}Pu	(n,f)	^{240}Pu	(n, γ)	-0.422
^{239}Pu	ν	^{239}Pu	ν	0.321
^{239}Pu	(n,f)	^{239}Pu	(n,f)	0.263
^{239}Pu	χ	^{239}Pu	χ	0.231
^{240}Pu	(n, γ)	^{240}Pu	(n, γ)	0.196
^{239}Pu	(n,f)	^{239}Pu	(n, γ)	0.171
^{238}U	(n, γ)	^{238}U	(n, γ)	0.154
^{239}Pu	(n, γ)	^{239}Pu	(n, γ)	0.146
^{238}U	(n,inel.)	^{238}U	(n,f)	-0.141
MYRRHA uncertainty in k_{eff}		0.652		

Representativity factor

- Benchmarks with **high sensitivity, few isotopes and simple configuration**
- 3 integral experiments from ICSBEP:
 - **JEZEBEL** : bare sphere of ^{239}Pu metal
 - **$^{240}\text{Pu JEZEBEL}$** : bare sphere of ^{239}Pu metal with 20.1 at% ^{240}Pu
 - **PU-MET-FAST-006-001**: plutonium sphere reflected by uranium

f_{re}	MYRRHA	JEZEBEL	$^{240}\text{Pu JEZEBEL}$	PFM006
MYRRHA	1.00	0.71	0.88	0.52
JEZEBEL	0.71	1.00	0.78	0.98
$^{240}\text{Pu JEZEBEL}$	0.88	0.78	1.00	0.75
PFM006	0.52	0.98	0.75	1.00

Results

Adjusted JEFF-3.3 with JEZEBEL

	Quantity	$\Delta k_{eff}/k_{eff}(\%)$
^{240}Pu	(n,f)	0.527
^{240}Pu	(n,f)	-0.421
^{239}Pu	(n,f)	0.286
^{239}Pu	v	0.269
^{239}Pu	χ	0.205
^{240}Pu	(n, γ)	0.197
^{239}Pu	(n,f)	0.173
^{238}U	(n, γ)	0.167
^{239}Pu	(n, γ)	0.151
^{238}U	(n,inel.)	-0.138
Uncertainty in k_{eff}		0.630

Adjusted JEFF-3.3 with ^{240}Pu JEZEBEL

	Quantity	$\Delta k_{eff}/k_{eff}(\%)$
^{240}Pu	(n,f)	-0.428
^{240}Pu	(n,f)	0.346
^{239}Pu	v	0.305
^{239}Pu	(n,f)	0.292
^{239}Pu	χ	0.241
^{240}Pu	(n, γ)	0.196
^{239}Pu	(n,f)	0.173
^{238}U	(n, γ)	0.167
^{239}Pu	(n, γ)	0.151
^{238}U	(n,inel.)	-0.138
Uncertainty in k_{eff}		0.522

Adjusted JEFF-3.3 with PMF006

	Quantity	$\Delta k_{eff}/k_{eff}(\%)$
^{240}Pu	(n,f)	0.536
^{240}Pu	(n,f)	-0.420
^{239}Pu	v	0.294
^{239}Pu	(n,f)	0.289
^{239}Pu	χ	0.221
^{240}Pu	(n, γ)	0.197
^{239}Pu	(n,f)	0.173
^{238}U	(n, γ)	0.167
^{239}Pu	(n, γ)	0.151
^{238}U	(n,inel.)	-0.135
Uncertainty in k_{eff}		0.656



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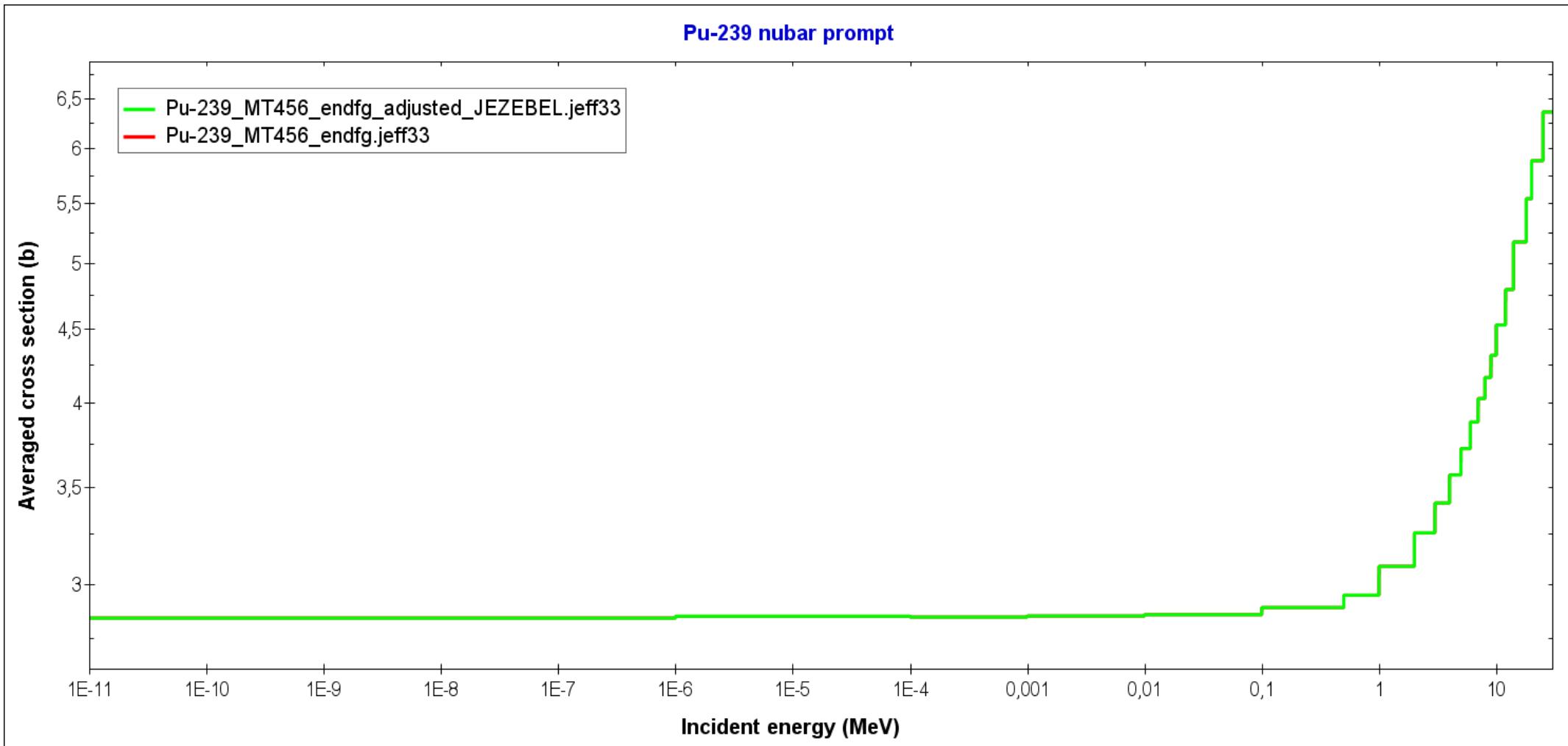


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Data assimilation

JEZEBEL

Pu-239 nubar prompt





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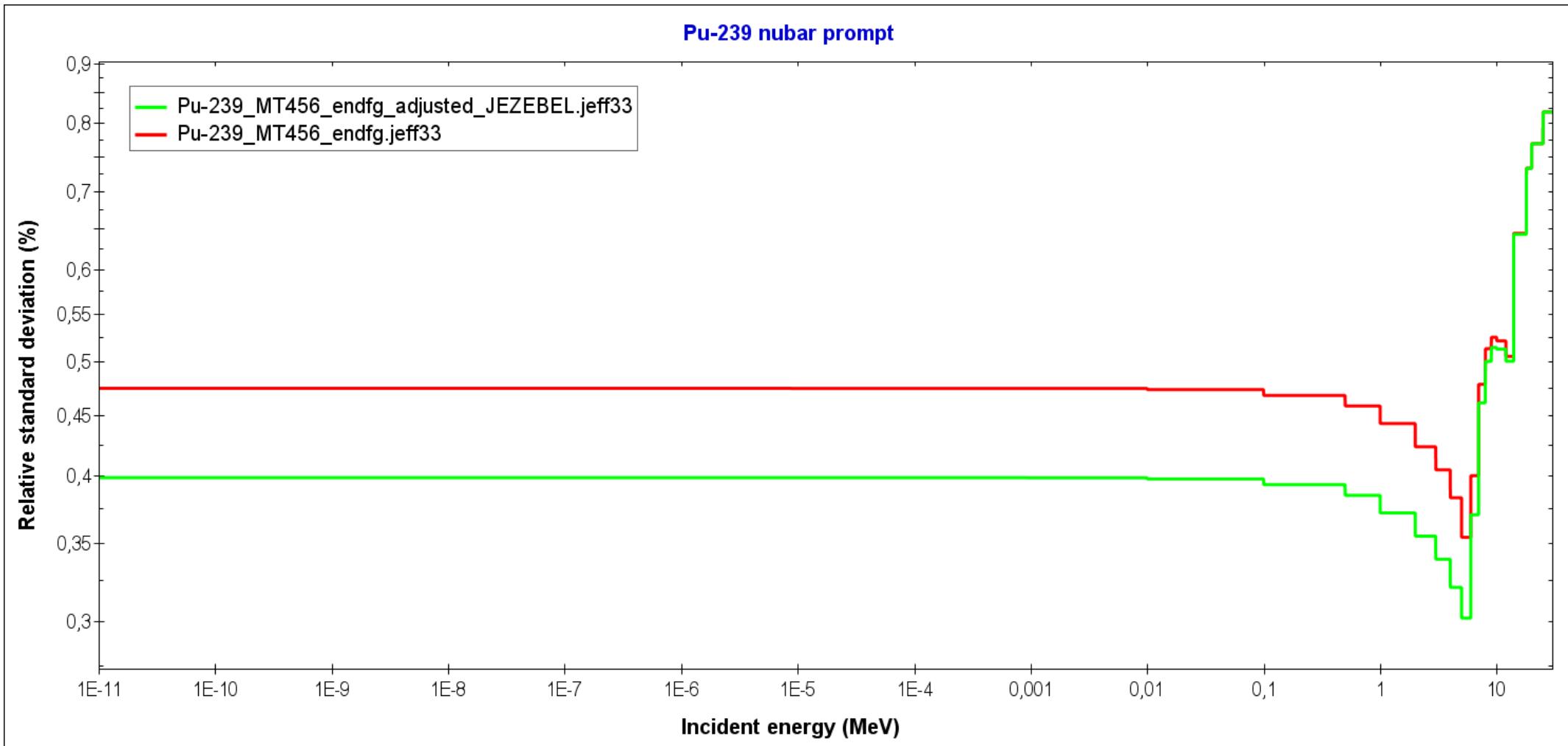


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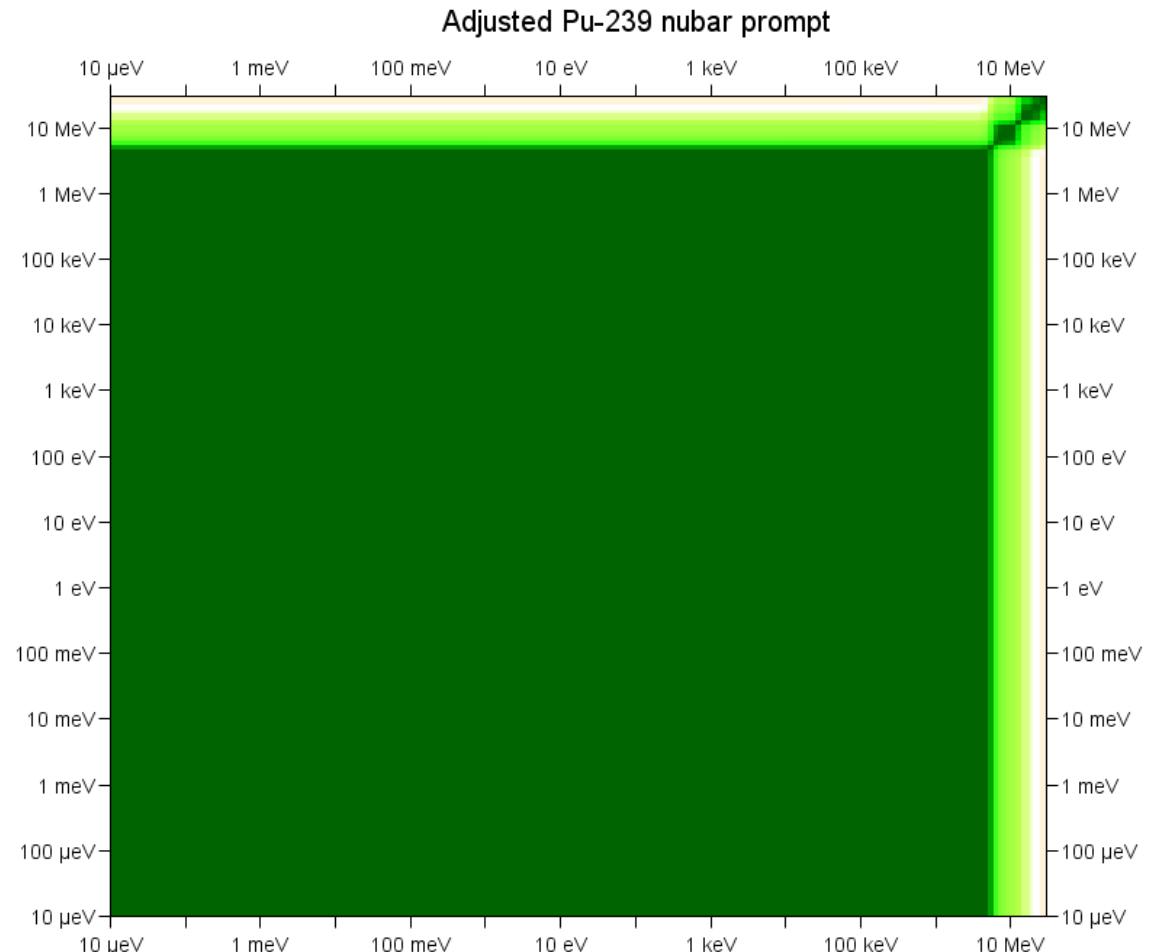
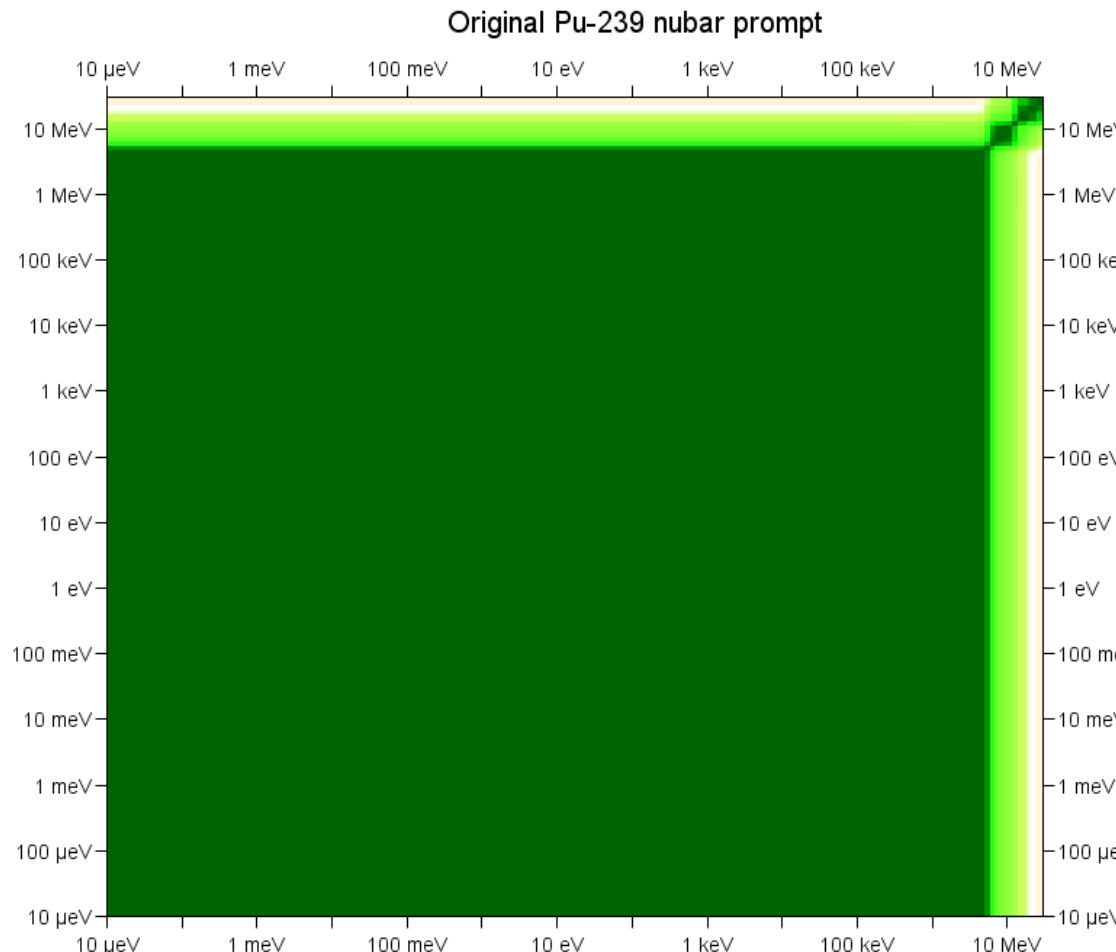
Data assimilation

JEZEBEL

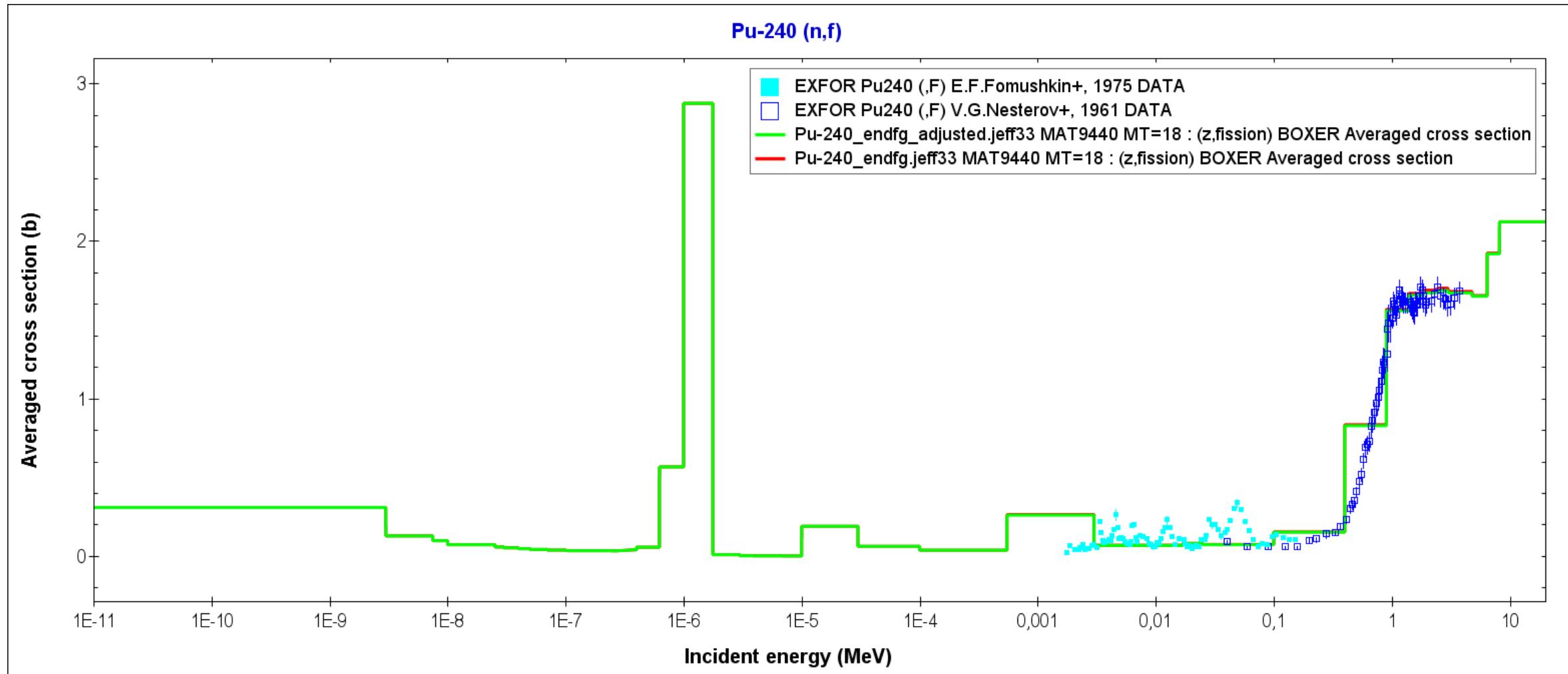
Pu-239 nubar prompt



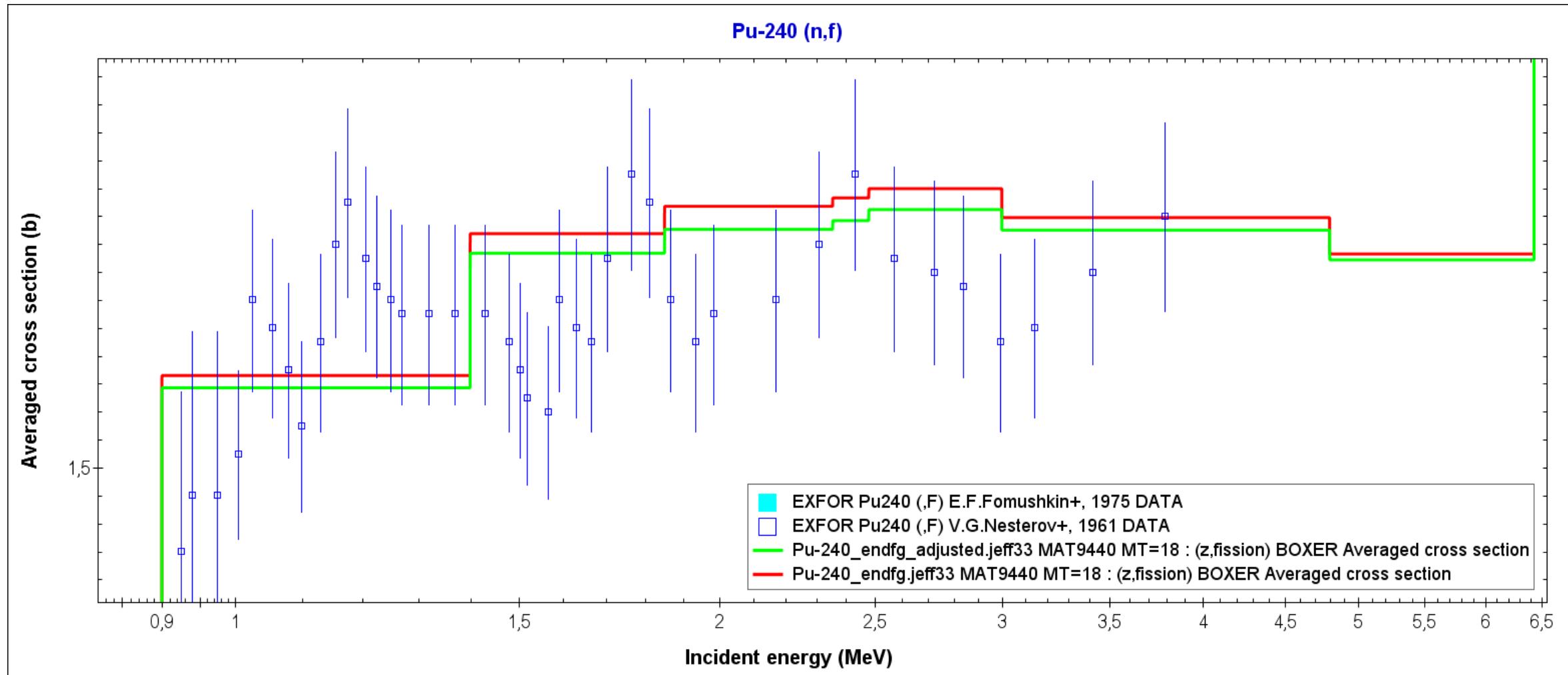
JEZEBEL



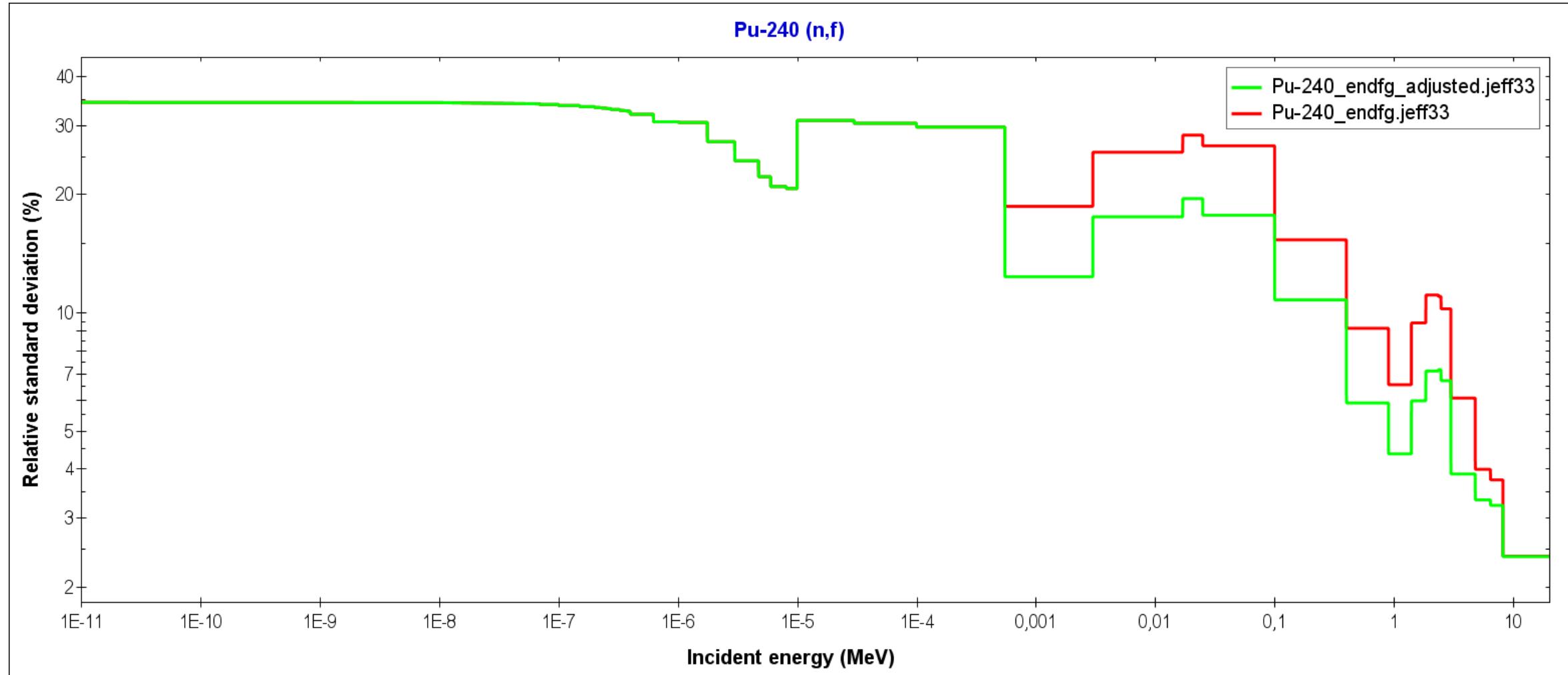
^{240}Pu JEZEBEL



^{240}Pu JEZEBEL

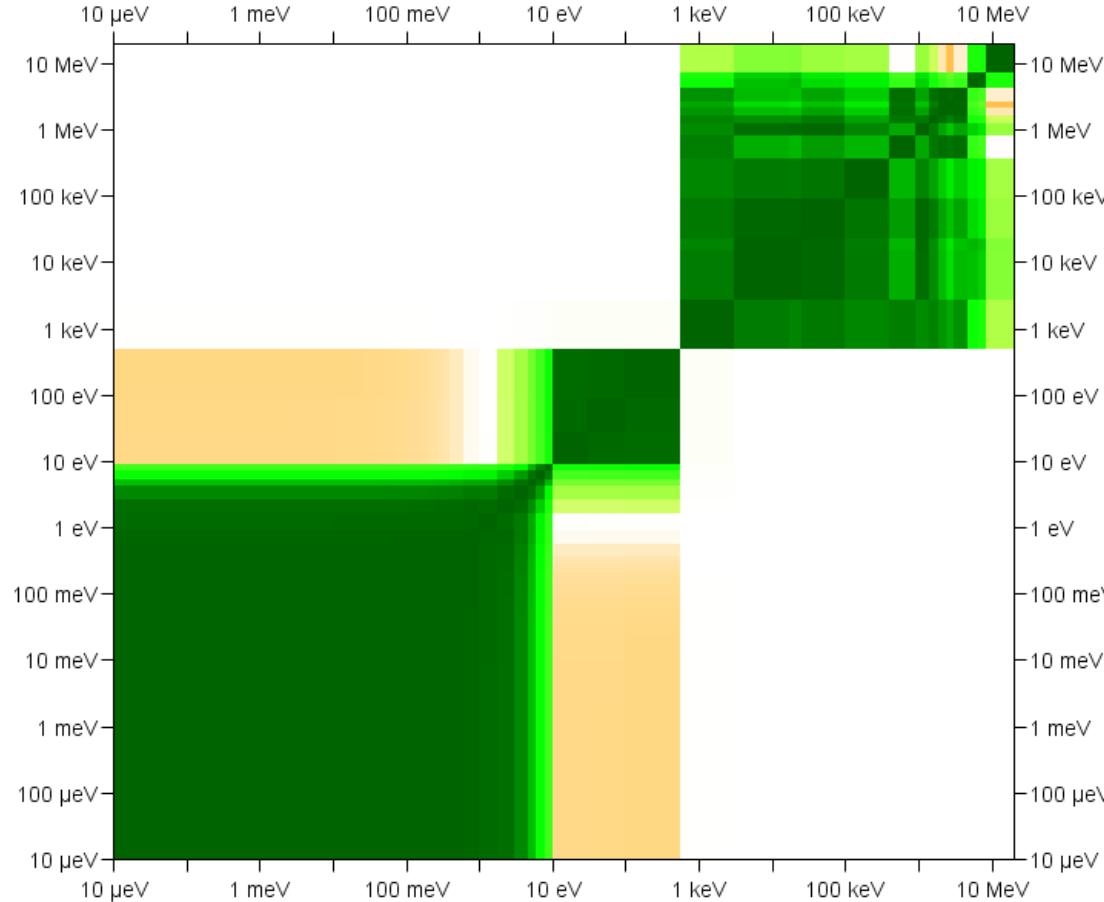


^{240}Pu JEZEBEL

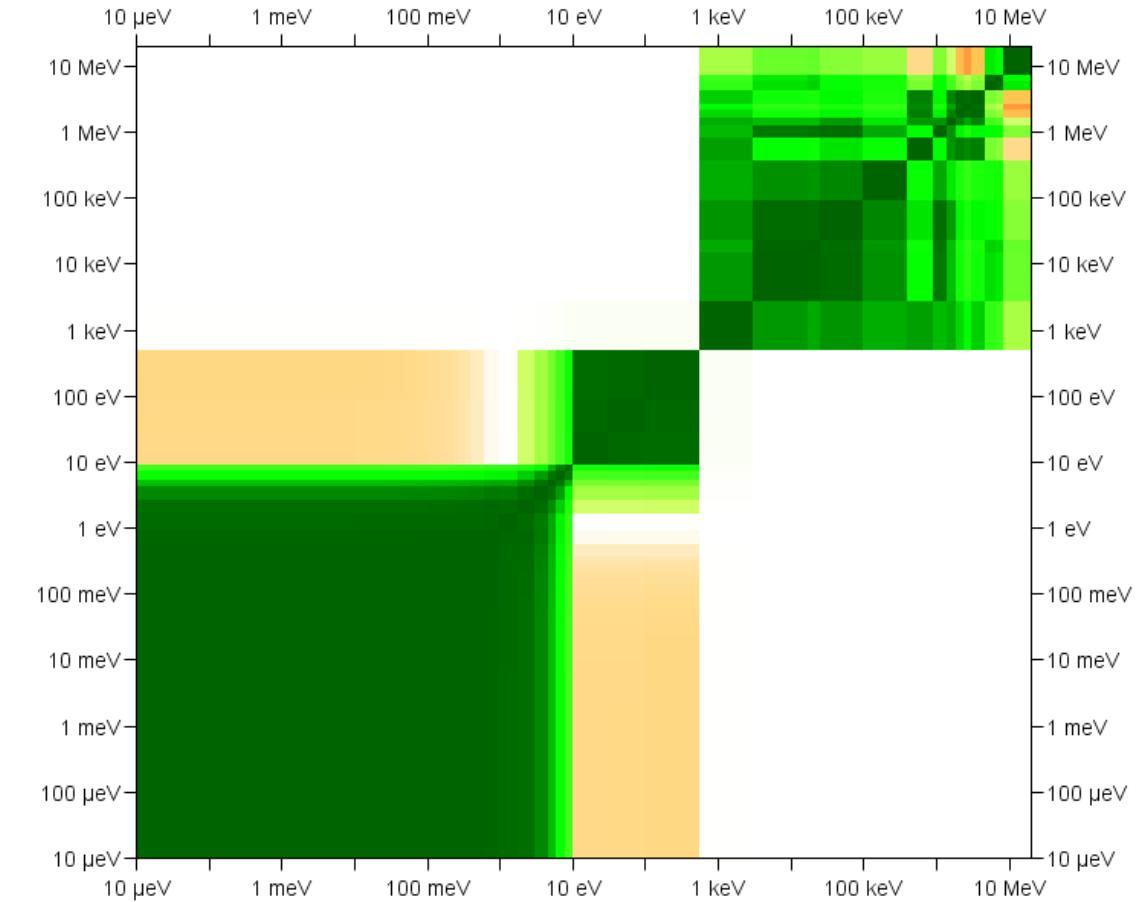


$^{240}\text{Pu JEZEBEL}$

Original Pu-240 (n,f)



Adjusted Pu-240 (n,f)



- Up to ~200 pcm of reduction of uncertainty with just one integral experiment
- Recommended the use of integral experiments representative of our system with simple geometry and high sensitivity to a single isotope
- Necessary correlation between integral experiments
- DA is a methodology capable of propagating back the information of integral experiments to improve the input parameters consistently with differential data