KIT and INL Results of the NEA/EGIEMAM-II Benchmark problems for TRU's central fission rate ratios of FCA-IX assemblies

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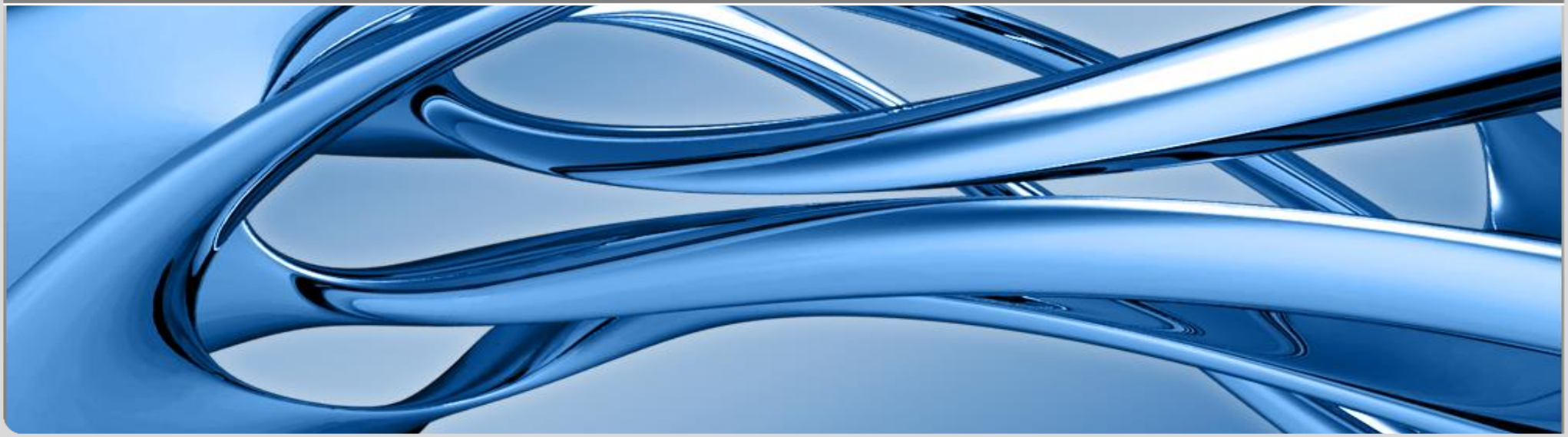


Calculation Details

- The **ERANOS 2.2 code** has been employed for analyzing the IX-1, IX-6, and IX-7 configurations of the FCA facility in Japan.
- Self-shielded neutron XSs **33 energy-groups (collapsed from 1968 groups)** have been processed by means of the ECCO code.
- Reference Libraries: **ENDF/B VII.0 (INL)** and **JEFF3.1 (KIT)**.
- 3D (XYZ) models have been assessed for evaluating the spectral indexes, the VARIANT transport solver being employed (P1-SP3 and P1-P3).
- 2D (RZ) models have been assessed for performing sensitivity and uncertainty analyses, the BISTRO transport solver being employed (P1-S4).
- **Sensitivity and uncertainty analyses have been performed, the GPT being employed**.
- **COMMARA2.0 Covariance Matrix data employed**.

Region compositions

Nuclide	IX-1	IX-6		IX-7	Blanket	Empty matrix
	CH2	VH6	VH6V	LEU	DUB	(MTX)
H	7.696E-05	1.760E-04	1.760E-04	3.767E-04	—	—
C	6.578E-02	1.896E-04	1.896E-04	3.182E-04	—	—
O	3.462E-05	7.645E-05	7.645E-05	1.642E-04	—	—
F	1.944E-05	5.831E-05	5.831E-05	—	—	—
Si	3.372E-06	9.648E-06	9.648E-06	—	—	—
Cr	1.810E-03	4.721E-03	4.760E-03	1.810E-03	1.810E-03	1.229E-03
Mn	1.203E-04	2.848E-04	3.437E-04	1.203E-04	1.203E-04	8.167E-05
Fe	6.475E-03	1.678E-02	1.649E-02	6.472E-03	6.472E-03	4.393E-03
Ni	7.893E-04	1.996E-03	2.121E-03	7.893E-04	7.893E-04	5.357E-04
^{235}U	2.260E-03	6.779E-03	6.779E-03	7.840E-03	8.442E-05	—
^{238}U	1.673E-04	5.020E-04	5.020E-04	3.112E-02	4.017E-02	—

- Graphite employed in the IX-1 configuration.

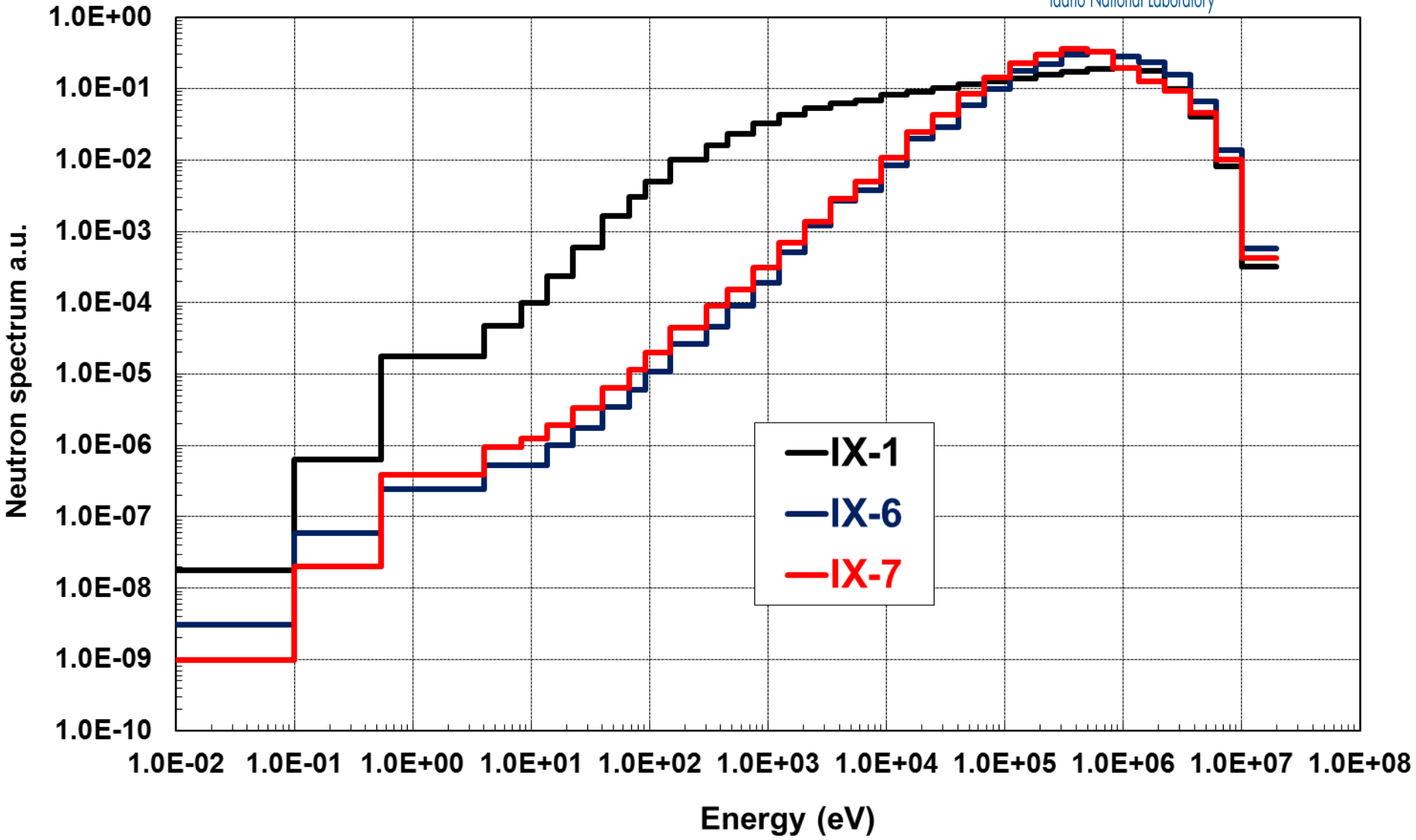
Criticality Level

- Reference Library: **JEFF3.1 (KIT)**.

	3D (P3)	3D (SP3)	2D (RZ, S4-P1)
IX-1	1.00031	1.00209	1.00317
IX-6	1.00293	1.01006	1.00613
IX-7	1.00284	1.00241	1.00878

- 3D (P3) results assumed as reference.
- 2D (RZ) model has been assessed in view of the sensitivity and uncertainty analysis.

Neutron Spectra in the Reactor Center



Reaction Rates Results: INL (ENDF/B VII.0)

	3D VARIANT P3			3D VARIANT SP3			2D ERANOS BISTRO		
Spectral Index	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7
Np237/Pu239	0.2247	0.4582	0.3429	0.2249	0.4593	0.3430	0.2260	0.4624	0.3443
Pu238/Pu239	0.6112	0.8822	0.7927	0.6114	0.8831	0.7928	0.6123	0.8857	0.7941
Pu242/Pu239	0.1845	0.3731	0.2685	0.1847	0.3740	0.2686	0.1856	0.3766	0.2695
Am241/Pu239	0.2067	0.4062	0.2759	0.2069	0.4074	0.2761	0.2079	0.4105	0.2771
Am243/Pu239	0.1549	0.3038	0.2050	0.1551	0.3047	0.2051	0.1558	0.3070	0.2058
Cm244/Pu239	0.2792	0.5412	0.4092	0.2795	0.5425	0.4094	0.2806	0.5460	0.4108

➢ **2D vs. 3D results show a very good agreement → Deviation less than 1%.**

	2D ERANOS BISTRO			Experiment			C/E		
Spectral Index	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7
Np237/Pu239	0.2260	0.4624	0.3443	0.2276	0.4693	0.3457	0.993	0.985	0.996
Pu238/Pu239	0.6123	0.8857	0.7941	0.6261	0.9212	0.8221	0.980	0.961	0.966
Pu242/Pu239	0.1856	0.3766	0.2695	0.1762	0.3597	0.2564	1.053	1.046	1.051
Am241/Pu239	0.2079	0.4105	0.2771	0.2181	0.4373	0.2954	0.958	0.939	0.938
Am243/Pu239	0.1558	0.3070	0.2058	0.1683	0.3349	0.2187	0.926	0.917	0.941
Cm244/Pu239	0.2806	0.5460	0.4108	0.2875	0.5277	0.4007	0.976	1.035	1.025

Reaction Rates Results: KIT (JEFF3.1)

	3D VARIANT P3			3D VARIANT SP3			2D ERANOS BISTRO		
Spectral Index	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7
Np237/Pu239	0.2272	0.4588	0.3424	0.2274	0.4599	0.3425	**0.2285**	**0.4629**	**0.3438**
Pu238/Pu239	0.7091	0.9002	0.8138	0.7092	0.9010	0.8138	**0.7098**	**0.9034**	**0.8150**
Pu242/Pu239	0.1935	0.3884	0.2781	0.1937	0.3893	0.2782	**0.1946**	**0.3920**	**0.2792**
Am241/Pu239	0.2110	0.4101	0.2734	0.2113	0.4112	0.2735	**0.2123**	**0.4142**	**0.2744**
Am243/Pu239	0.1568	0.3064	0.2026	0.1570	0.3073	0.2026	**0.1577**	**0.3096**	**0.2033**
Cm244/Pu239	0.2822	0.5507	0.4135	0.2825	0.5519	0.4136	**0.2837**	**0.5554**	**0.4150**

➢ **2D vs. 3D results show a very good agreement → Deviation less than 1%.**

	2D ERANOS BISTRO			Experiment			C/E		
Spectral Index	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7	IX-1	IX-6	IX-7
Np237/Pu239	**0.2285**	**0.4629**	**0.3438**	0.2276	0.4693	0.3457	1.004	0.986	0.994
Pu238/Pu239	**0.7098**	**0.9034**	**0.8150**	0.6261	0.9212	0.8221	1.134	0.981	0.991
Pu242/Pu239	**0.1946**	**0.3920**	**0.2792**	0.1762	0.3597	0.2564	1.104	1.090	1.089
Am241/Pu239	**0.2123**	**0.4142**	**0.2744**	0.2181	0.4373	0.2954	0.973	0.947	0.929
Am243/Pu239	**0.1577**	**0.3096**	**0.2033**	0.1683	0.3349	0.2187	0.937	0.925	0.930
Cm244/Pu239	**0.2837**	**0.5554**	**0.4150**	0.2875	0.5277	0.4007	0.987	1.052	1.036

Sensitivity and Uncertainty Calculations

- Uncertainties associated to the XS ↔ d_{ij} represent the expected values related to the parameters σ_j, and σ_i.

$$D_\sigma = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1J} \\ d_{12} & d_{22} & \cdots & d_{2J} \\ \cdots & \cdots & \cdots & \cdots \\ d_{1J} & d_{2J} & \cdots & d_{JJ} \end{pmatrix}$$

- If **R** is an integral parameter, $\mathbf{S_R}$ the corresponding sensitivity coefficient arrays, and **D**, the uncertainty $\Delta\mathbf{R}$ on **R** is given by the standard sandwich formula.

$$\Delta \mathbf{R}^2 = \mathbf{S}_\mathbf{R}^+ \mathbf{D} \mathbf{S}_\mathbf{R}$$

- Individual contribution the uncertainty associated to a single cross section σ_{lmn}

$$\Delta \mathbf{R}_{lmn} = \sqrt{\mathbf{S}_{lmn}^2 \mathbf{d}_{lmn}^2 + \sum_{k}^{Ncorr} \mathbf{Corr}_k \mathbf{S}_{lmn} \mathbf{d}_{lmn} \mathbf{S}_k \mathbf{d}_k}$$

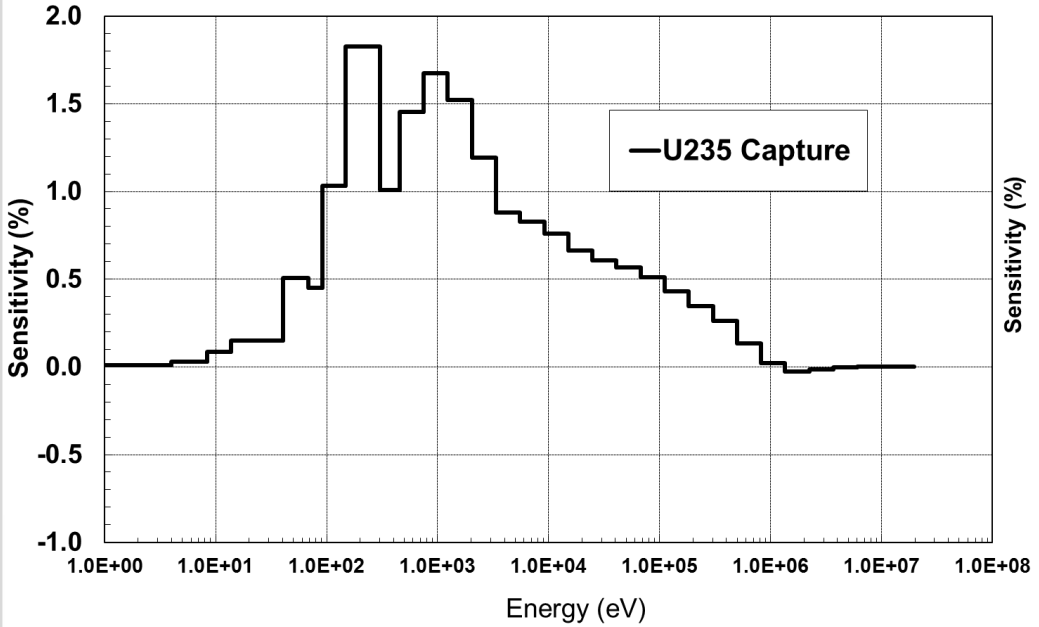
Sensitivity: Results Configuration IX-1

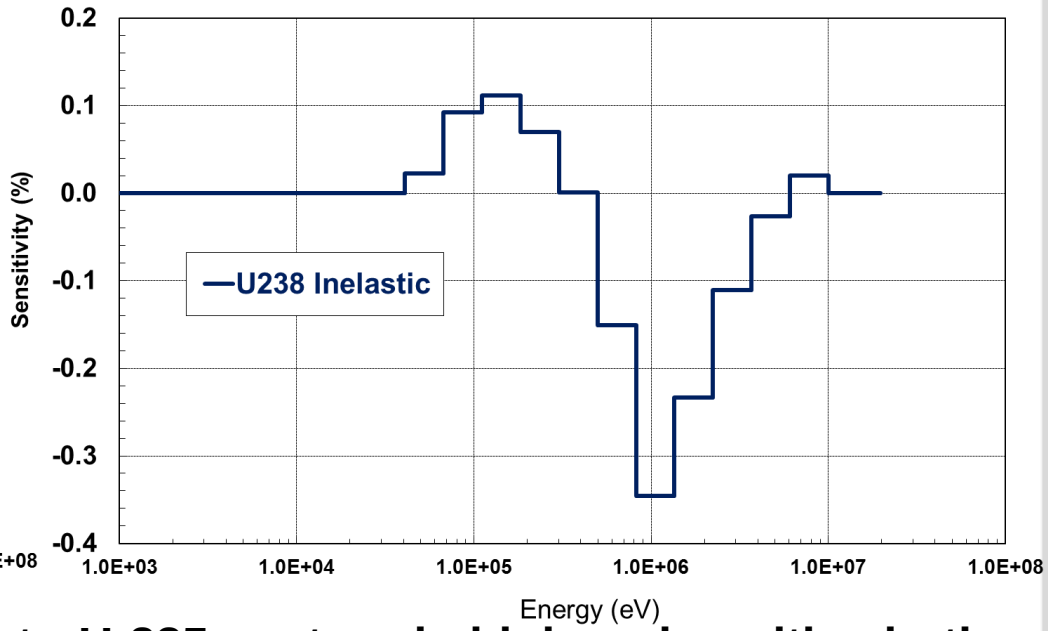
- **XS-wise sensitivities in % of the spectral index for 100% variation of the macroscopic XSs.**

Spectral Index	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	χ	$\sigma_{n,xn}$	σ_{P1el}
Np237/Pu239	22.7%	-78.6%	-11.8%	1.1%	45.1%	1.1%	-0.1%	0.5%
Pu238/Pu239	13.2%	-43.3%	-4.0%	0.4%	25.5%	0.4%	0.0%	0.2%
Pu242/Pu239	22.9%	-79.2%	-12.3%	1.2%	45.6%	1.2%	-0.1%	0.5%
Am241/Pu239	22.4%	-77.4%	-13.3%	1.2%	44.6%	1.2%	-0.1%	0.5%
Am243/Pu239	22.6%	-78.0%	-13.8%	1.2%	45.1%	1.2%	-0.1%	0.5%
Cm244/Pu239	21.1%	-72.6%	-10.6%	1.1%	41.9%	1.1%	-0.1%	0.5%

- **Good agreement between INL (ENDF/B VII.0) and KIT results (JEFF3.1).**
- **Capture contribution mainly from ^{235}U and ^{238}U.**
- **Elastic contribution mainly from C and ^{238}U.**
- **Inelastic contribution from Fe and ^{235}U.**

IX-1: Sensitivity of Np-237/Pu-239 spectrum index to ^{235}U σ_{cap} and ^{238}U σ_{inel}





- **IX-1 spectrum fairly soft and sensitivity to U-235 capture is high and positive in the epithermal energy region: any increase of U-235 low energy capture will reduce the low energy nueutron contribution to the denominator.**

- **Inelastic cross sections sensitivity is high (and negative) at energies above the Np-237 fission threshold: the elastic/inelastic x-section increase in this energy region will reduce the high energy neutron contribution to the numerator.**

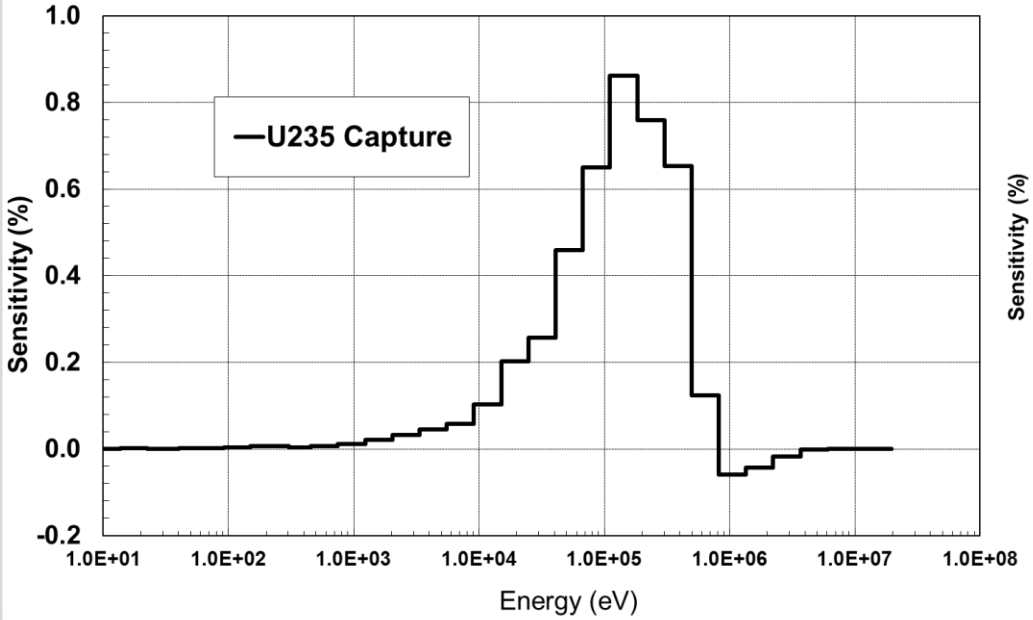
Sensitivity: Results Configuration IX-6

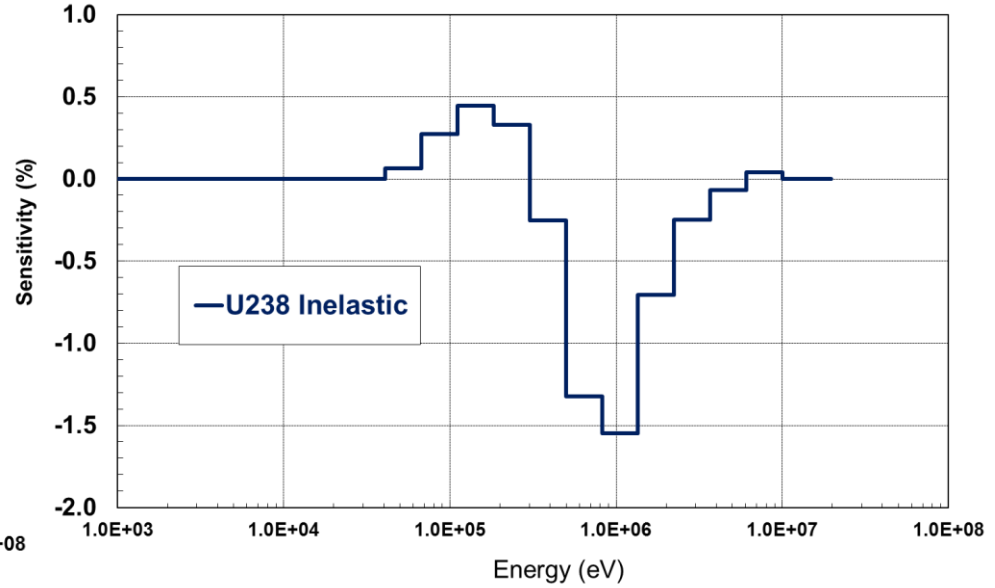
- **XS-wise sensitivities in % of the spectral indexes for 100% variation of the macroscopic XSs.**

Spectral Index	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	χ	$\sigma_{n,xn}$	σ_{P1el}
Np237/Pu239	9.3%	-5.8%	-18.4%	1.6%	18.8%	1.6%	-0.1%	-1.5%
Pu238/Pu239	4.3%	-2.3%	-7.8%	0.7%	8.5%	0.7%	0.0%	-0.8%
Pu242/Pu239	9.6%	-5.7%	-19.5%	1.7%	19.6%	1.7%	-0.1%	-1.4%
Am241/Pu239	10.4%	-7.2%	-22.8%	1.8%	21.4%	1.8%	-0.2%	-1.5%
Am243/Pu239	10.7%	-6.1%	-24.1%	1.4%	22.1%	1.4%	-0.2%	-1.5%
Cm244/Pu239	9.0%	-5.7%	-17.7%	1.6%	18.2%	1.6%	-0.1%	-1.6%

- **Good agreement between INL (ENDF/B VII.0) and KIT results (JEFF3.1).**
- **Capture contribution mainly from ^{235}U and ^{238}U.**
- **Elastic contribution from ^{238}U.**
- **Inelastic contribution from Fe and ^{235}U.**

IX-6: Sensitivity of Np-237/Pu-239 spectrum index to ^{235}U σ_{cap} and ^{238}U σ_{inel}





- **IX-6 spectrum is hard. Inelastic cross sections sensitivity is high (and negative) at energies above the Np-237 fission threshold: the elastic/inelastic x-section increase in this energy region will reduce the high energy neutron contribution to the numerator.**

- **Sensitivity to U-235 capture is still relatively high and positive in the high energy region: any increase of U-235 high energy capture will slightly reduce the high energy neutron contribution to the denominator.**

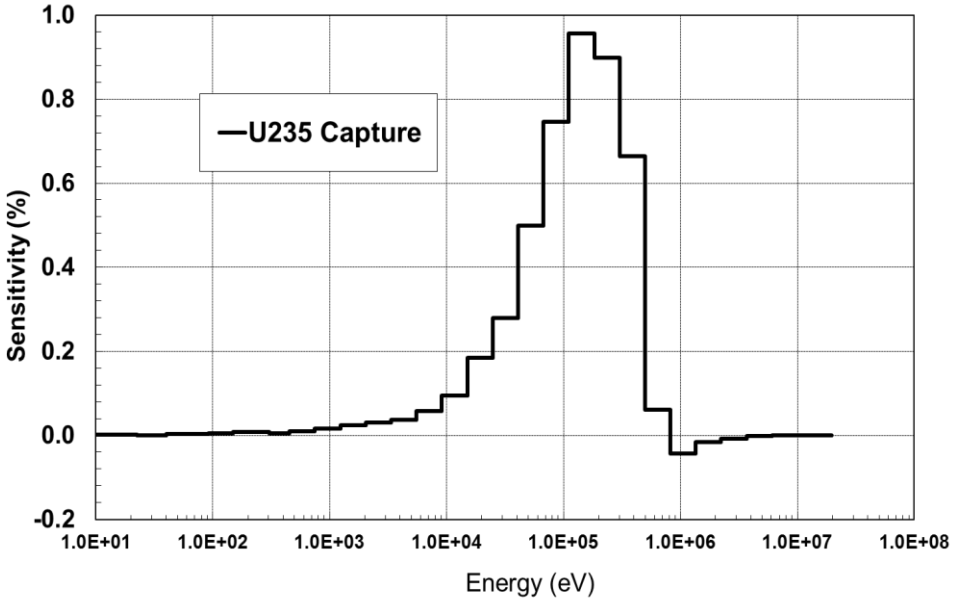
Sensitivity: Results Configuration IX-7

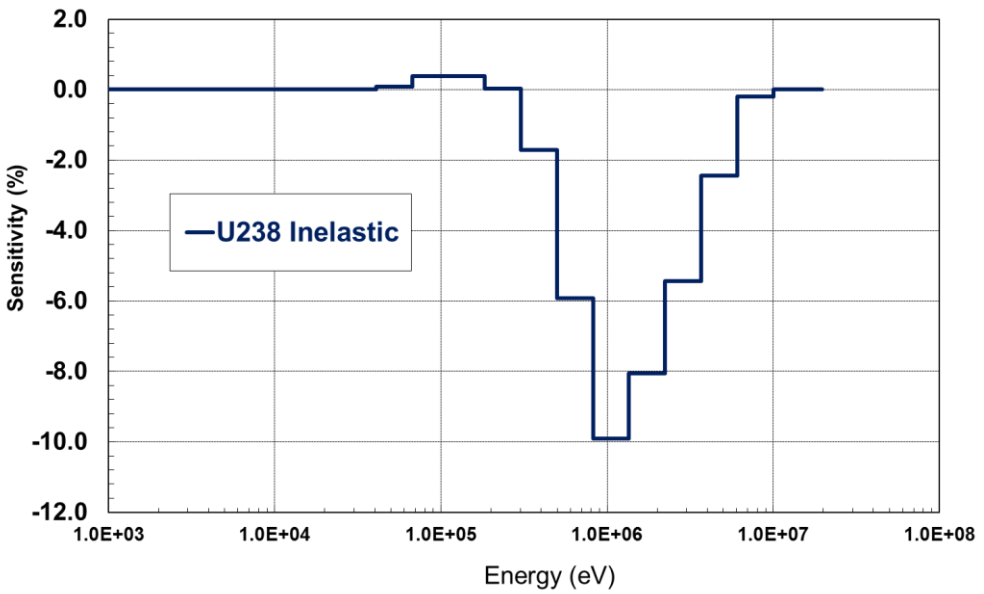
- **XS-wise sensitivities in % of the spectral index for 100% variation of the macroscopic XSs.**

Spectral Index	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	χ	$\sigma_{n,xn}$	σ_{P1el}
Np237/Pu239	15.3%	-11.5%	-41.2%	0.9%	18.2%	0.9%	-0.4%	1.2%
Pu238/Pu239	6.3%	-4.6%	-15.7%	0.4%	7.5%	0.4%	-0.1%	0.3%
Pu242/Pu239	16.0%	-12.1%	-44.1%	1.0%	18.9%	1.0%	-0.5%	1.6%
Am241/Pu239	17.4%	-13.3%	-50.3%	1.0%	20.0%	1.0%	-0.6%	2.2%
Am243/Pu239	18.1%	-13.7%	-52.7%	1.0%	20.6%	1.0%	-0.8%	2.4%
Cm244/Pu239	14.6%	-11.2%	-39.8%	0.9%	17.5%	0.9%	-0.4%	1.4%

- **Good agreement between INL (ENDF/B VII.0) and KIT results (JEFF3.1).**
- **Capture contribution mainly from ^{235}U and ^{238}U.**
- **Elastic contribution from ^{238}U.**
- **Inelastic contribution from Fe and ^{235}U.**

IX-7: Sensitivity of Np-237/Pu-239 spectrum index to ^{235}U σ_{cap} and ^{238}U σ_{inel}



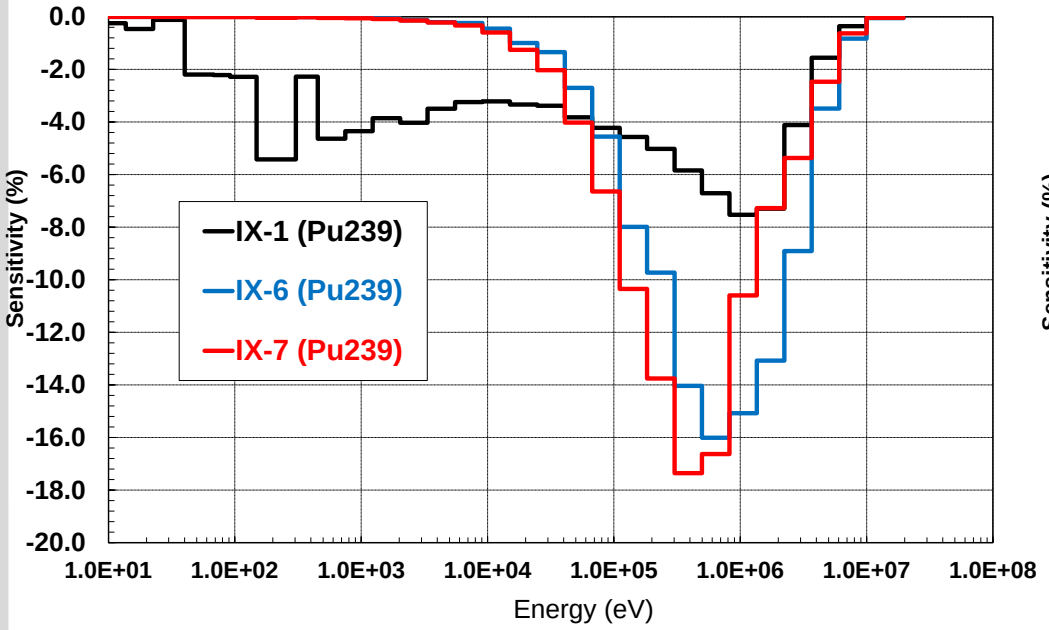


- **IX-7 spectrum is the hardest. Inelastic cross sections sensitivity is high (and negative) at energies above the Np-237 fission threshold: the elastic/inelastic x-section increase in this energy region will reduce the high energy neutron contribution to the numerator.**

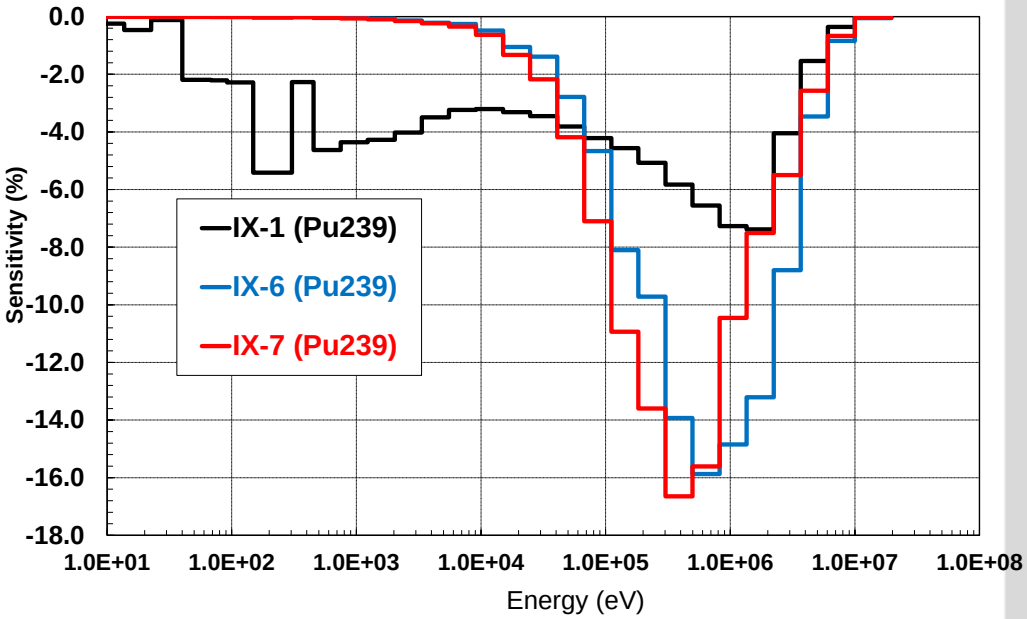
- **Sensitivity to U-235 capture is still relatively high and positive in the high energy region: any increase of U-235 high energy capture will slightly reduce the high energy neutron contribution to the denominator.**

Sensitivity of ^{239}Pu σ_{fiss} (direct effect on spectrum index denominator)

ENDF/B VII.0



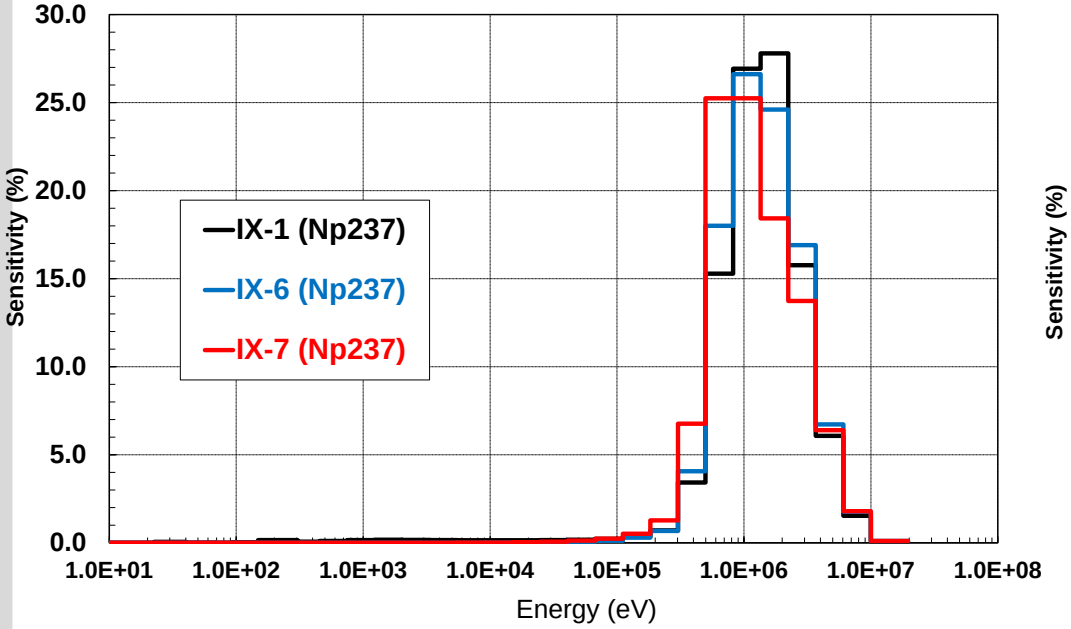
JEFF3.1



- **Denominator → Negative contribution.**

Sensitivity of ^{237}Np σ_{fiss} (direct effect on spectrum index numerator)

ENDF/B VII.0



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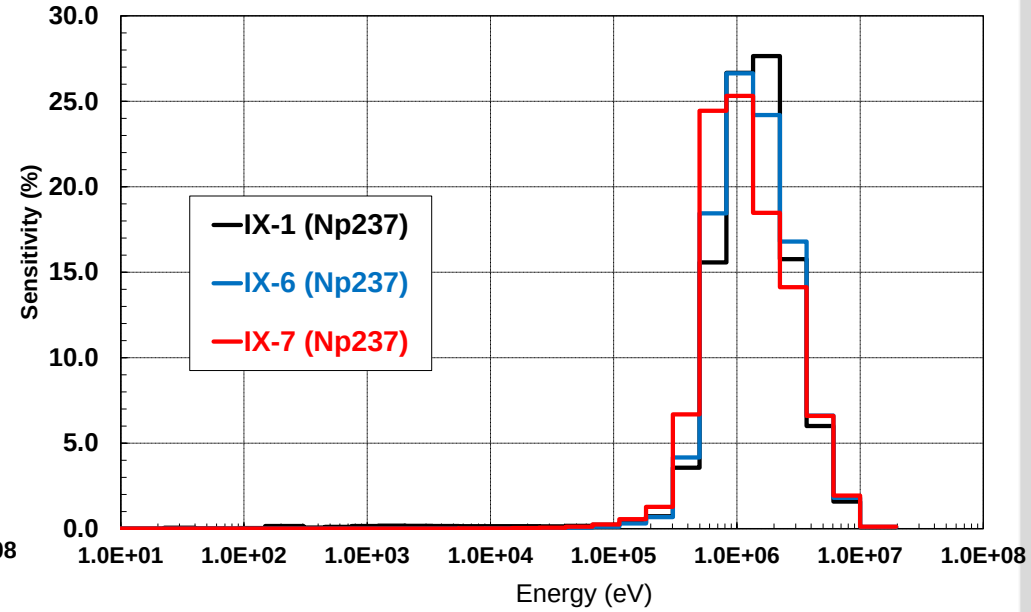

Sensitivity of ^{238}Pu σ_{fiss}(direct effect on spectrum index numerator)

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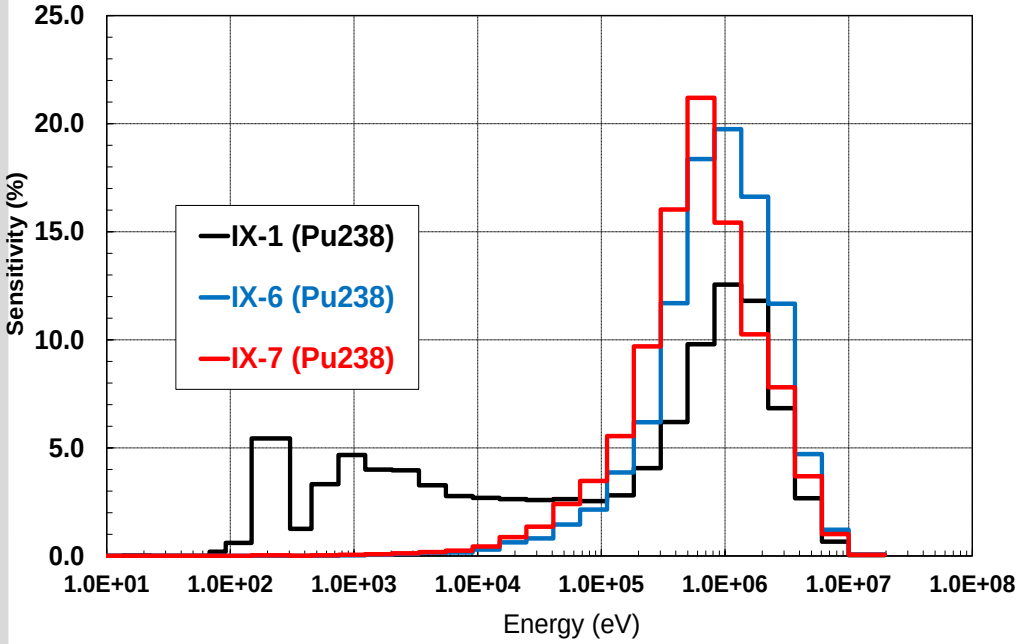
ENDF/B VII.0



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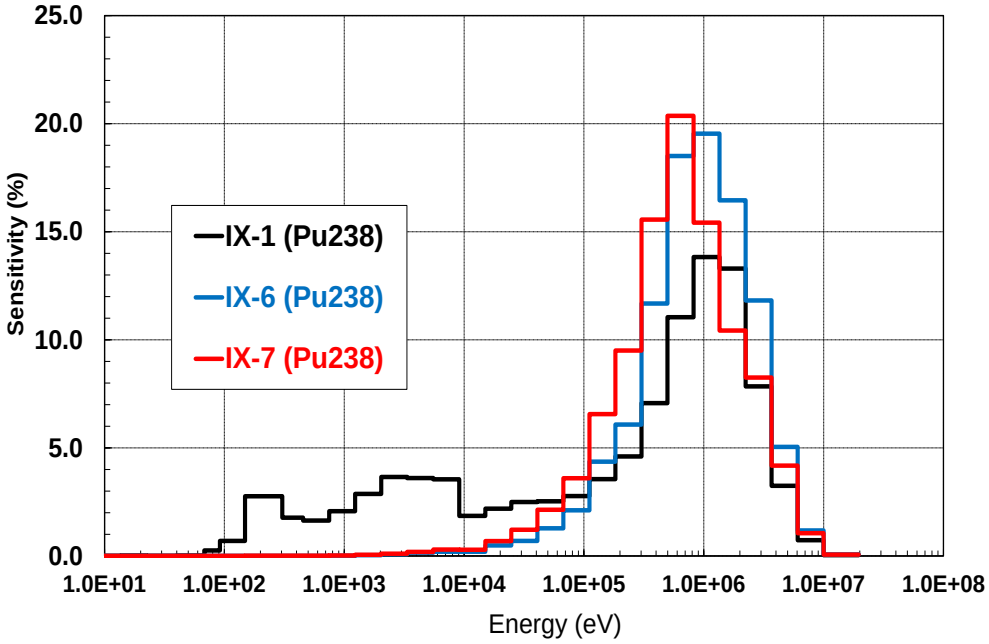
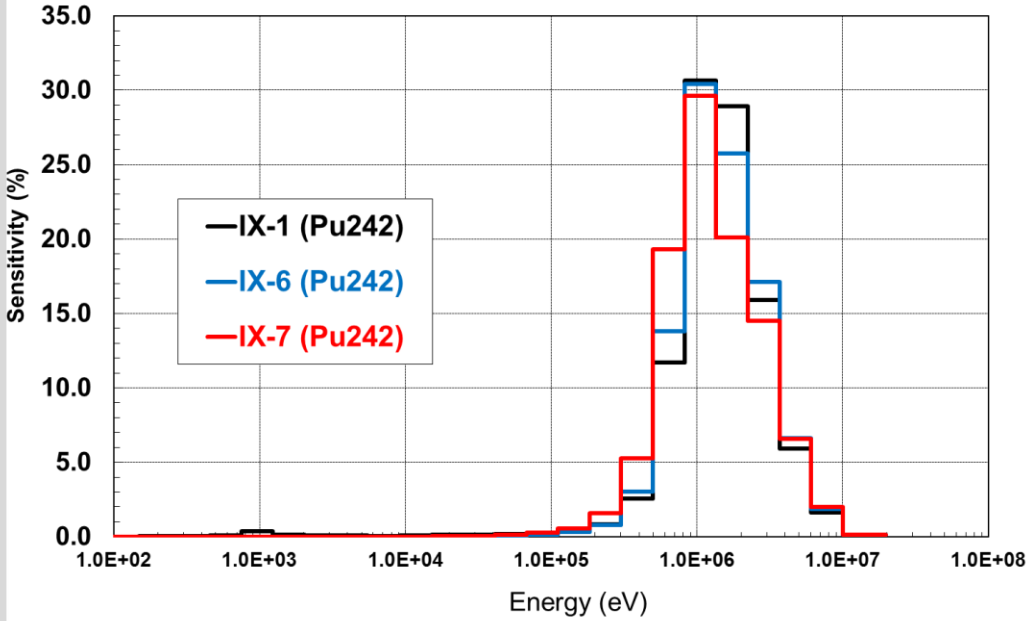
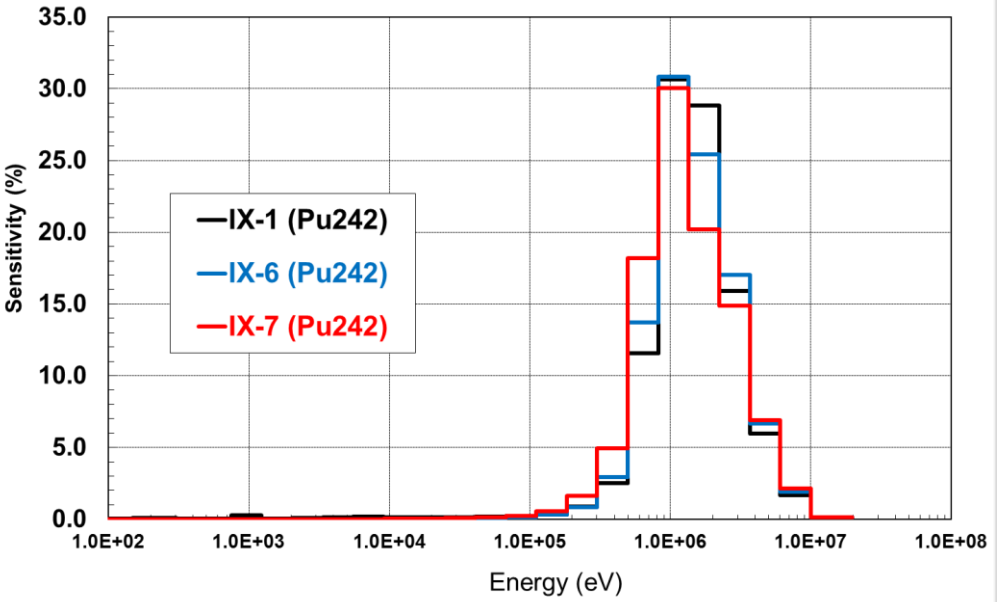


Sensitivity of ^{242}Pu σ_{fiss}(direct effect on spectrum index numerator)

ENDF/B VII.0

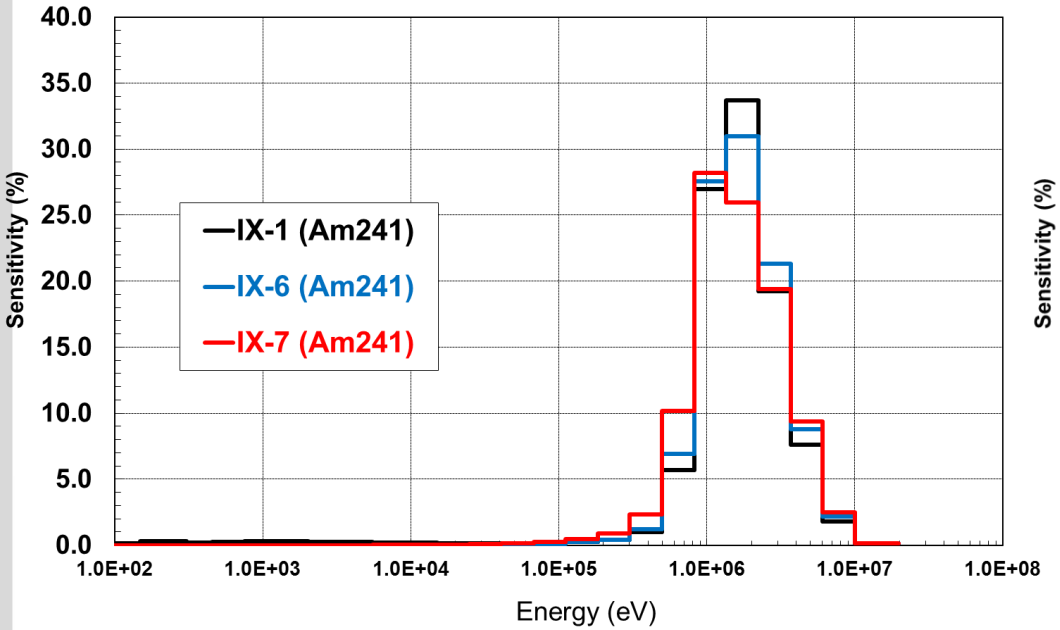


JEFF3.1



Sensitivity of ^{241}Am σ_{fiss}(direct effect on spectrum index numerator)

ENDF/B VII.0



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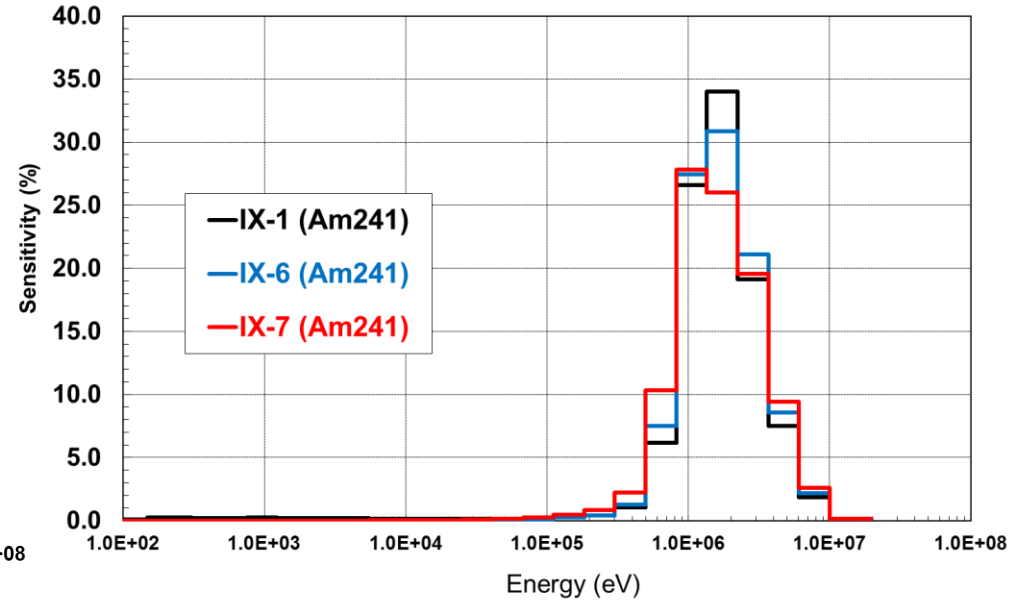
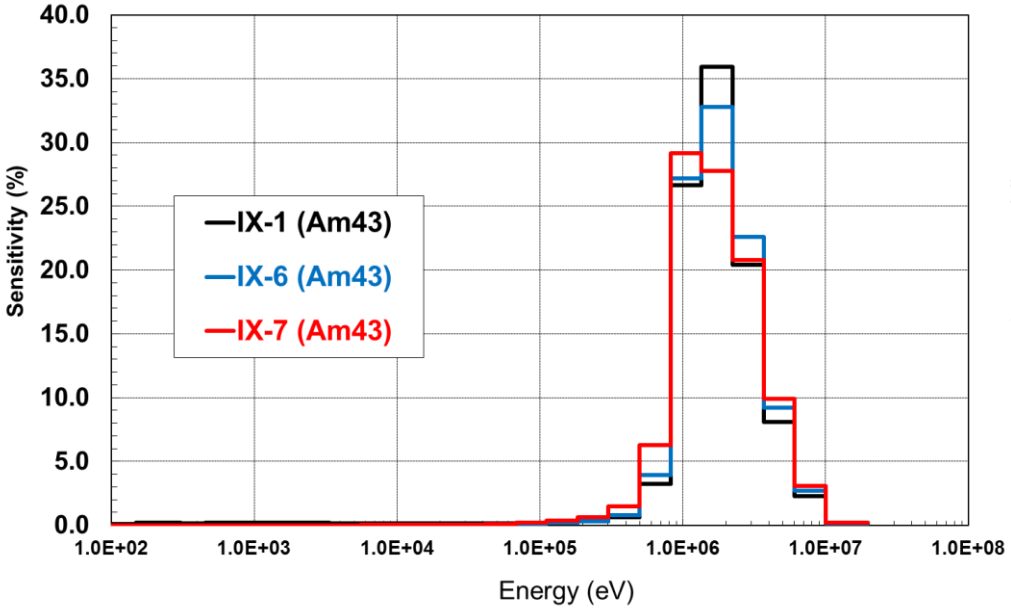


Sensitivity of ^{243}Am σ_{fiss}(direct effect on spectrum index numerator)

ENDF/B VII.0



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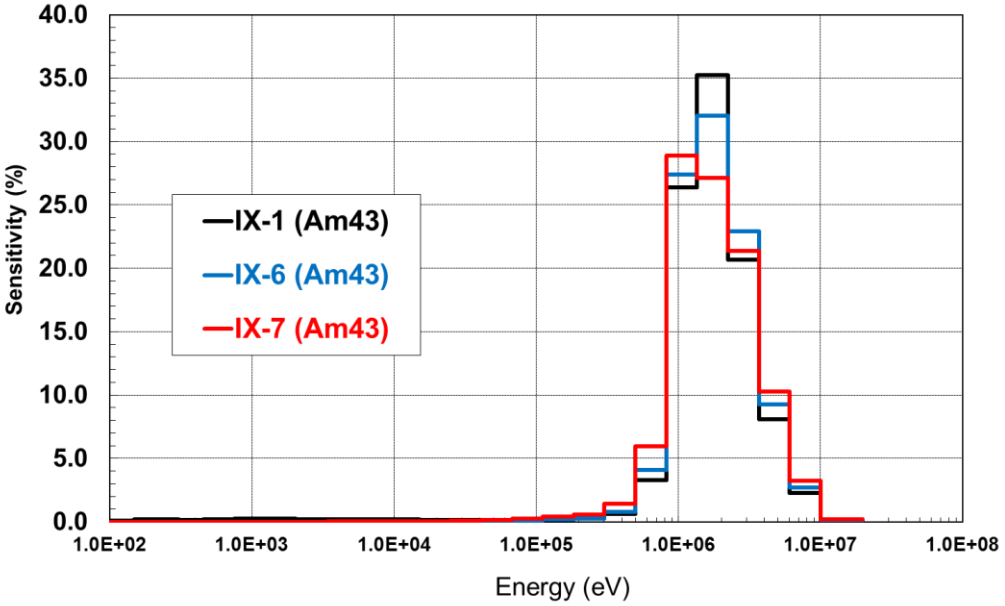
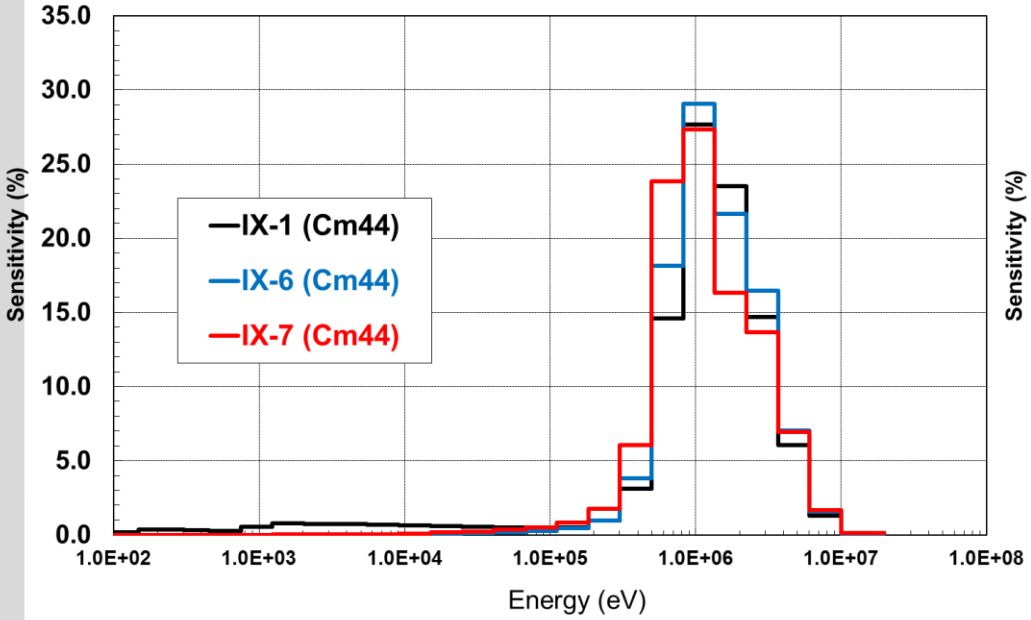
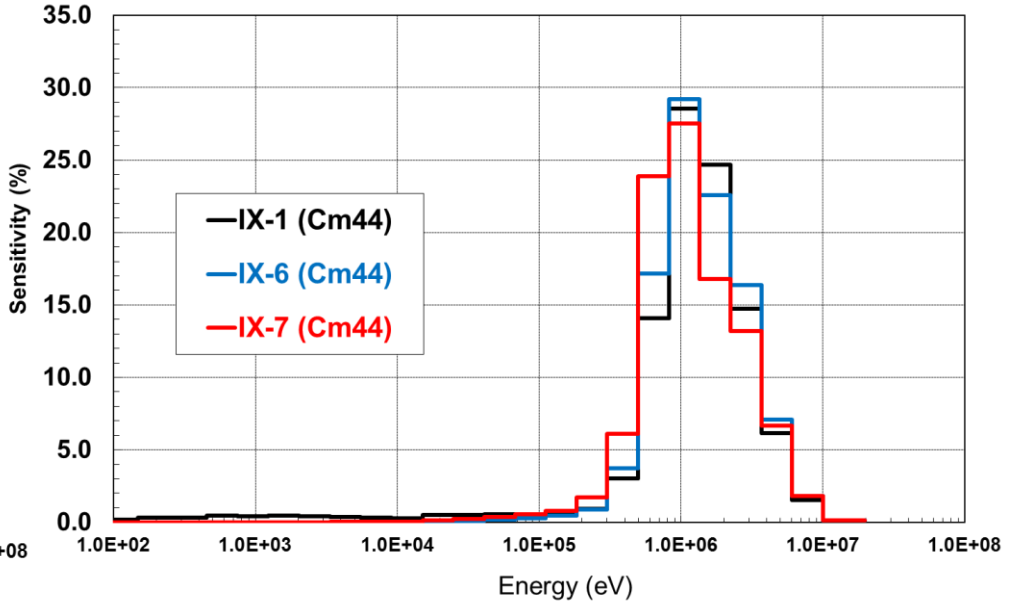


Sensitivity of ^{244}Cm σ_{fiss}(direct effect on spectrum index numerator)

ENDF/B VII.0



JEFF3.1



Uncertainty Analysis: Configuration IX-1

*Uncertainties due to ^{239}Pu fission are the same for each spectral index.

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
	^{239}Pu (*)	0.00%	0.00%	0.00%	0.00%	0.43%	± 0.43%
Np237/Pu239	^{235}U	1.42%	0.12%	0.39%	0.01%	0.22%	**± 1.49%**
	^{237}Np	0.00%	0.00%	0.00%	0.00%	**2.92%**	**± 2.92%**
	Total	1.42%	0.14%	0.55%	0.03%	**2.96%**	**± 3.33%**
Pu238/Pu239	^{238}Pu	0.00%	0.00%	0.00%	0.00%	**5.18%**	**± 5.18%**
	Total	0.37%	0.06%	0.13%	0.01%	**5.19%**	**± 5.21%**
Pu242/Pu239	^{235}U	1.43%	0.12%	0.40%	0.01%	0.22%	**± 1.50%**
	^{242}Pu	0.00%	0.00%	0.00%	0.00%	**4.01%**	**± 4.01%**
	Total	1.43%	0.17%	0.55%	0.03%	**4.04%**	**± 4.32%**
Am241/Pu239	^{235}U	1.38%	0.11%	0.39%	0.01%	0.21%	**± 1.46%**
	^{241}Am	0.00%	0.00%	0.00%	0.00%	**1.27%**	**± 1.27%**
	Total	1.38%	0.15%	0.56%	0.03%	**1.36%**	**± 2.03%**

Uncertainty Analysis: Configuration IX-1

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
Am243/Pu239	^{235}U	1.41%	0.12%	0.40%	0.01%	0.22%	± 1.49%
	^{243}Am	0.00%	0.00%	0.00%	0.00%	**8.60%**	**± 8.60%**
	Total	1.41%	0.15%	0.58%	0.03%	**8.61%**	**± 8.75%**
Cm244/Pu239	^{235}U	1.32%	0.11%	0.36%	0.01%	0.21%	1.39%
	^{244}Cm	0.00%	0.00%	0.00%	0.00%	**14.70%**	**± 14.70%**
	Total	1.32%	0.16%	0.49%	0.03%	**14.71%**	**± 14.78%**

Uncertainty Analysis: Configuration IX-6

*Uncertainties of ^{239}Pu fission are the same for each spectral index

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
	^{239}Pu (*)	0.00%	0.00%	0.00%	0.00%	0.44%	± 0.44%
Np237/Pu239	^{235}U	0.81%	0.11%	0.75%	0.00%	0.09%	± 1.11%
	^{237}Np	0.00%	0.00%	0.00%	0.00%	**2.98%**	**± 2.98%**
	Total	0.81%	0.20%	0.97%	0.04%	**3.01%**	**± 3.27%**
Pu238/Pu239	^{238}Pu	0.00%	0.00%	0.00%	0.00%	**2.00%**	**± 2.00%**
	Total	0.35%	0.09%	0.40%	0.01%	**2.05%**	**± 2.11%**
Pu242/Pu239	^{235}U	0.82%	0.12%	0.77%	0.00%	0.09%	1.13%
	^{242}Pu	0.00%	0.00%	0.00%	0.00%	**3.99%**	**± 3.99%**
	Total	0.83%	0.22%	1.03%	0.04%	**4.01%**	**± 4.23%**
Am241/Pu239	^{235}U	0.87%	0.13%	0.80%	0.00%	0.10%	1.19%
	^{241}Am	0.00%	0.00%	0.00%	0.00%	**1.27%**	**± 1.27%**
	Total	0.87%	0.19%	1.16%	0.05%	**1.35%**	**± 1.99%**

Uncertainty Analysis: Configuration IX-6

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
Am243/Pu239	^{235}U	0.88%	0.13%	0.82%	0.01%	0.11%	± 1.22%
	^{243}Am	0.00%	0.00%	0.00%	0.00%	**8.74%**	**± 8.74%**
	Total	0.89%	0.17%	1.23%	0.05%	**8.75%**	**± 8.88%**
Cm244/Pu239	^{235}U	0.78%	0.11%	0.72%	0.00%	0.09%	1.08%
	^{244}Cm	0.00%	0.00%	0.00%	0.00%	**15.22%**	**± 15.22%**
	Total	0.79%	0.21%	0.94%	0.04%	**15.23%**	**± 15.28%**

Uncertainty Analysis: Configuration IX-7

*Uncertainties of ^{239}Pu fission are the same for each spectral index.

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
	^{239}Pu (*)	0.00%	0.00%	0.00%	0.00%	0.44%	± 0.44%
Np237/Pu239	^{235}U	0.87%	-0.02%	0.52%	0.00%	0.09%	± 1.02%
	^{238}U	0.14%	0.42%	4.83%	0.01%	0.01%	**± 4.85%**
	^{237}Np	0.00%	0.00%	0.00%	0.00%	**3.17%**	**± 3.17%**
	Total	0.88%	0.43%	4.86%	0.01%	**3.20%**	**± 5.90%**
Pu238/Pu239	^{235}U	0.33%	-0.02%	0.22%	0.00%	0.03%	0.40%
	^{238}U	0.05%	0.12%	1.48%	0.00%	0.00%	**± 1.48%**
	^{238}Pu	0.00%	0.00%	0.00%	0.00%	**2.14%**	**± 2.14%**
	Total	0.33%	0.13%	1.49%	0.00%	**2.18%**	**± 2.67%**
Pu242/Pu239	^{235}U	0.89%	-0.01%	0.50%	0.00%	0.09%	1.03%
	^{238}U	0.15%	0.45%	5.55%	0.01%	0.01%	**5.57%**
	^{242}Pu	0.00%	0.00%	0.00%	0.00%	**4.16%**	**± 4.16%**
	Total	0.90%	0.46%	5.57%	0.01%	**4.18%**	**± 7.04%**

Uncertainty Analysis: Configuration IX-7

Spectral Index	Isotope	σ_{cap}	σ_{el}	σ_{inel}	ν	σ_{fiss}	**Total**
Am241/Pu239	^{235}U	0.94%	0.03%	0.47%	0.00%	0.10%	± 1.06%
	^{238}U	0.16%	0.35%	7.17%	0.01%	0.01%	**± 7.18%**
	^{241}Am	0.00%	0.00%	0.00%	0.00%	**1.26%**	**± 1.26%**
	Total	0.95%	0.36%	7.18%	0.01%	**1.34%**	**± 7.38%**
Am243/Pu239	^{235}U	0.96%	0.04%	0.47%	0.00%	0.10%	± 1.07%
	^{238}U	0.17%	0.30%	7.76%	0.01%	0.01%	**± 7.77%**
	^{243}Am	0.00%	0.00%	0.00%	0.00%	**8.50%**	**± 8.50%**
	Total	0.98%	0.31%	7.78%	0.01%	**8.51%**	**± 11.58%**
Cm244/Pu239	^{235}U	0.84%	-0.02%	0.49%	0.00%	0.08%	± 0.97%
	^{238}U	0.14%	0.42%	4.77%	0.01%	0.01%	**± 4.79%**
	^{244}Cm	0.00%	0.00%	0.00%	0.00%	**14.35%**	**± 14.35%**
	Total	0.85%	0.43%	4.80%	0.01%	**14.36%**	**± 15.17%**

Conclusions (1/2)

- KIT and INL did use the ERANOS 2.2 code to analyze the Benchmark problems for TRU's central fission rate ratios of FCA-IX assemblies.
- Two different reference data libraries have been used: ENDF/BV VII.0 (INL) and JEFF3.1 (KIT).
- The fission reaction rates ratios have been evaluated and results have been compared with the experimental values.
- Sensitivity and uncertainty analysis has been performed to support the analysis of the C/E deviations.
- C/E values are in some cases larger than what can be expected on the basis of calculated a-priori uncertainties (MA fission uncertainties possibly underestimated).
- IX-6 and IX-7 configurations are very similar in terms of neutron spectrum.

Conclusions (2/2)

- Despite the U-235/U-238 ratio would be very different in the IX-6 and IX-7 configurations, the spectral indexes for MAs are close.

- Some impact of U-235 capture and U-238 elastic and inelastic cross section uncertainties

Acknowledgements

KIT authors do wish to thank INL colleagues for the fundamental support in performing the present study.