Advanced Reactor Design and Analysis

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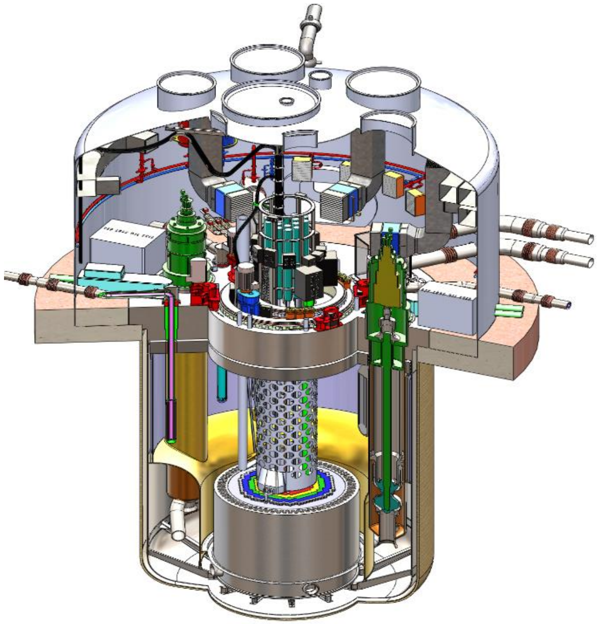
Workshop for Applied Nuclear Data Activities (WANDA)
2019-01-23

Background

- TerraPower was started by Bill Gates, Nathan Myhrvold, others after invention session in 2006. Privately funded.
- Goal: investigate advanced fission reactors for world-scale energy production
- Key requirements included high fuel utilization, low barriers to exportation, enhanced safety, and improved cost
- Traveling Wave Reactor was chosen
  - "Breed-and-burn" concept enables fast reactor without reprocessing
  - Has been discussed in literature since at least 1958
- Formed JV with CNNC in China, but now that's on hold
- Molten Chloride Fast Reactor efforts started in 2012, now significant US-based effort
- Several other reactor concepts under investigation



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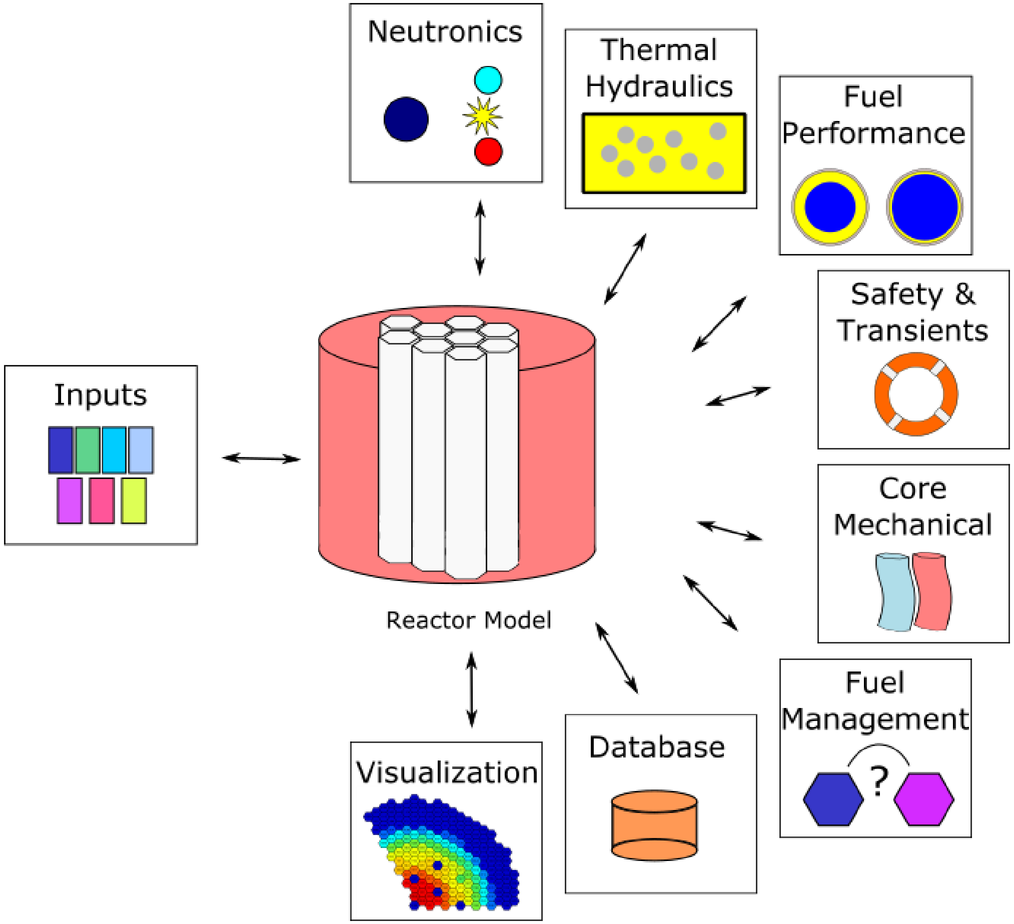
Modeling Software Environment

We built a reactor modeling system called the Advanced Reactor Modeling Interface (ARMI)



We built a sensitivity coefficient module

- Useful for UQ and design intuition
- Method:
  - Flux and adjoint computed in 3D on triangles by DIF3D
  - Production/destruction matrix derivatives are taken on the *hexagon* level
  - Verified results against numerical experiments with perturbed XS libraries
  - Responses so far: k_{eff}, reactivity coefficients, CR worth

$$S_g = \frac{\partial R}{R} \Big/ \frac{\partial \sigma_g}{\sigma_g} = \frac{\partial R}{\partial \sigma_g}\frac{\sigma_g}{R}$$

Cross Section Perturbed	R'_{CTC} direct	R'_{CTC} from module	C/E
^{235}U $\sigma_{f,5}$	0.0680154	0.0680151	1.0000038
^{235}U $\sigma_{f,15}$	0.0675466	0.0675471	0.9999936
^{238}U $\sigma_{\gamma,5}$	0.0677278	0.0677278	0.9999997
^{238}U $\sigma_{\gamma,15}$	0.0681021	0.0681013	1.0000117
Fe $\sigma_{elastic,5}$	0.0678285	0.0678285	0.9999998
^{238}U $\sigma_{inelastic,5}$	0.0678050	0.0678063	0.9999805
^{238}U $\sigma_{(n,2n),1}$	0.0678214	0.0678213	1.0000003

$$S_{k,g} = -\frac{\sigma_g \langle \phi^*, \left(\frac{\partial M}{\partial \sigma_g} - \frac{1}{k}\frac{\partial B}{\partial \sigma_g}\right)\phi\rangle}{\langle \phi^*, \frac{1}{k} B\phi\rangle}$$

$$\Sigma_{s,g} = N \sum_{g'=1}^{G} \sigma_{s,g} w_{g'\leftarrow g}$$

$$w_{g'\leftarrow g} = \frac{\sigma_{s,g'\leftarrow g}}{\sum_{g''=1}^{G} \sigma_{s,g''\leftarrow g}}$$

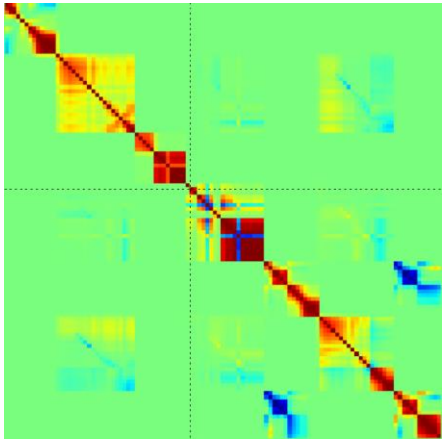
$$\frac{\partial \Sigma_{s,g'\leftarrow g}}{\partial \sigma_{s,g}} = N w_{g'\leftarrow g}$$

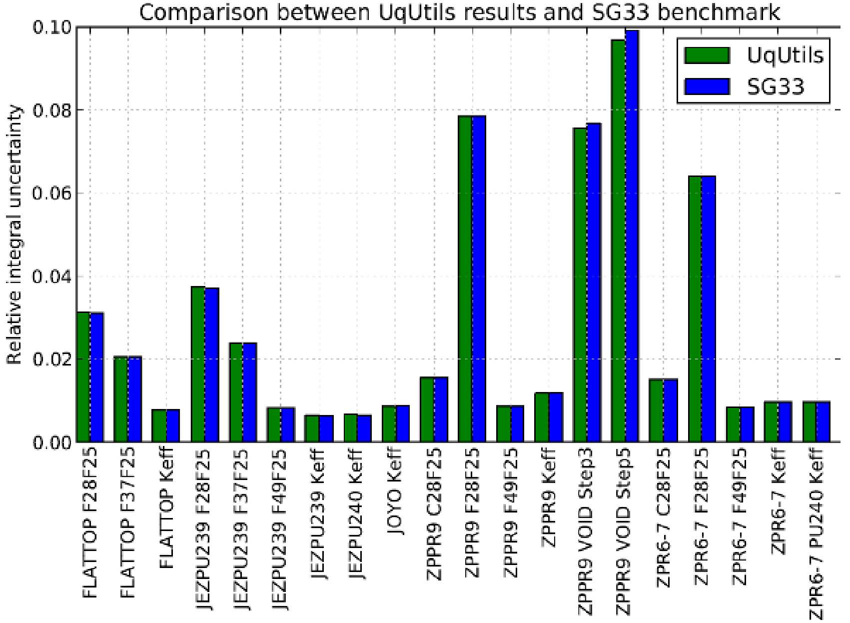
$$S_{\Delta\rho} = \frac{1}{\Delta\rho}\left(\frac{S_{k,2}}{k_2} - \frac{S_{k,1}}{k_1}\right),$$

Uncertainty Quantification Module

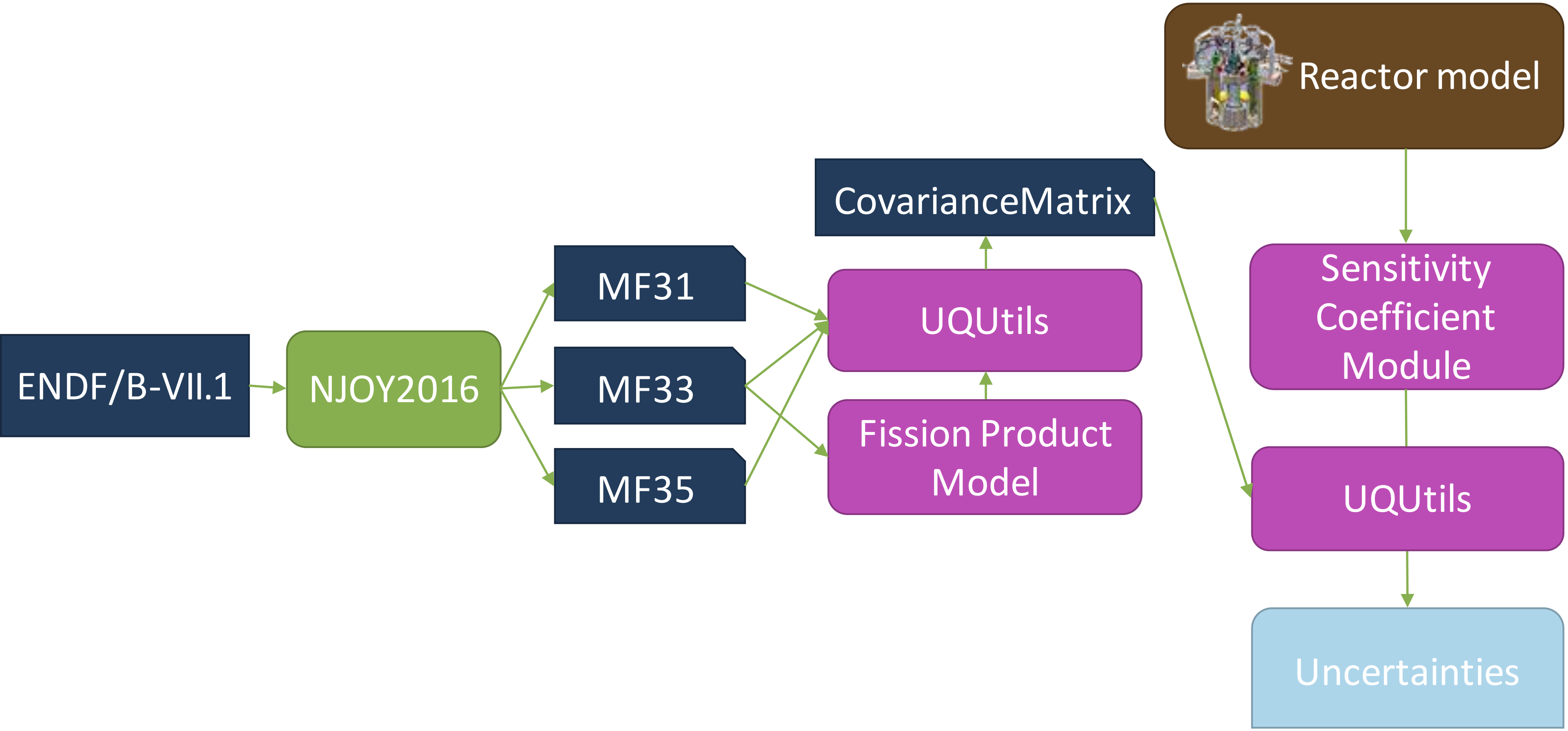
- We built a UQ module based on OECD/NEA SG33 benchmark
  - Read/writes sensitivity data in SG33 format
  - Reads/writes covariance matrix in SG33 format (COMMARA2)
  - Benchmarked basic calc's against SG33
- We wanted to spin our own multigroup covariance matrix because:
  - Wanted latest data (ENDF/B-VII.1)
  - The PFNS (MF5/MT18) of ^{235}U should be considered in the startup core of a TWR, which uses enriched uranium
  - Fission products build up substantially in TWRs and might contribute to uncertainty
  - Zirconium covariance should be considered due to U-Zr metallic fuel

Partial COMMARA 2.0 cov. matrix





Getting UQ Data from ENDF/B-VII.1



All these operations are automated in ARMI

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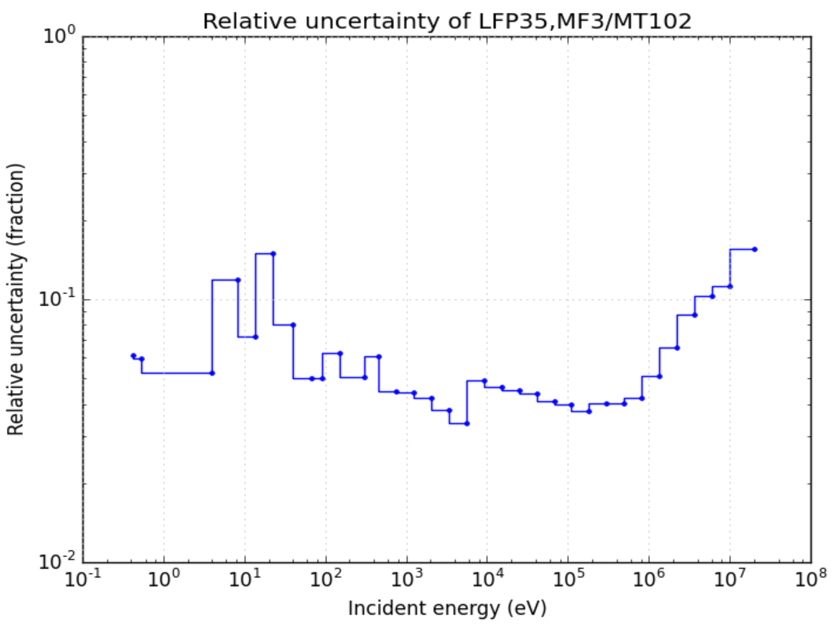
Lumped Fission Product Uncertainty

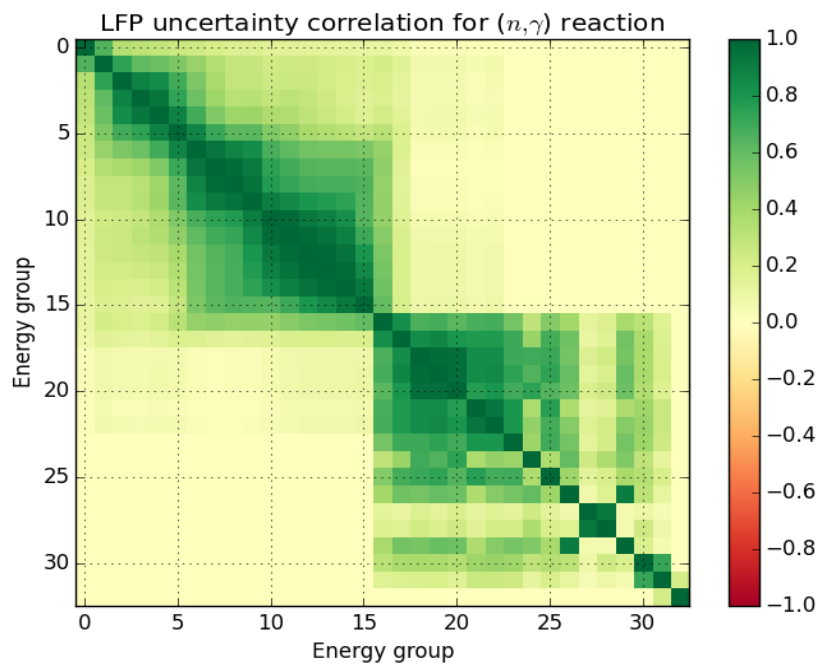
- LFPs build up in TWRs, so we must consider their uncertainty
- Used bilinearity property to derive expression for the covariance between LFP reactions 1 and 2.

$$\boldsymbol{\sigma_{LFP}} = 2\frac{\sum_{i=1}^{I}\boldsymbol{\gamma_i \sigma_i}}{\sum_{i=1}^{I}\boldsymbol{\gamma_i}}$$

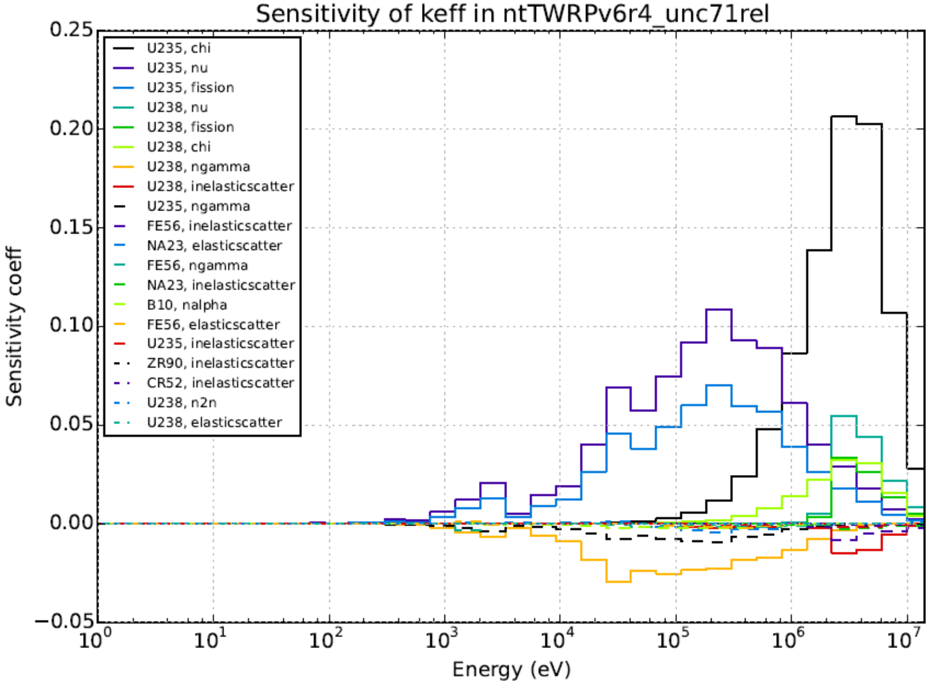
$$cov(\sigma_{LFP,1}, \sigma_{LFP,2}) = cov\left(\frac{2\sum_{i=1}^{I}\boldsymbol{\gamma_i \sigma_{i,1}}}{\sum_{i=1}^{I}\boldsymbol{\gamma_i}}, \frac{2\sum_{i=1}^{I}\boldsymbol{\gamma_i \sigma_{i,2}}}{\sum_{i=1}^{I}\boldsymbol{\gamma_i}}\right)$$

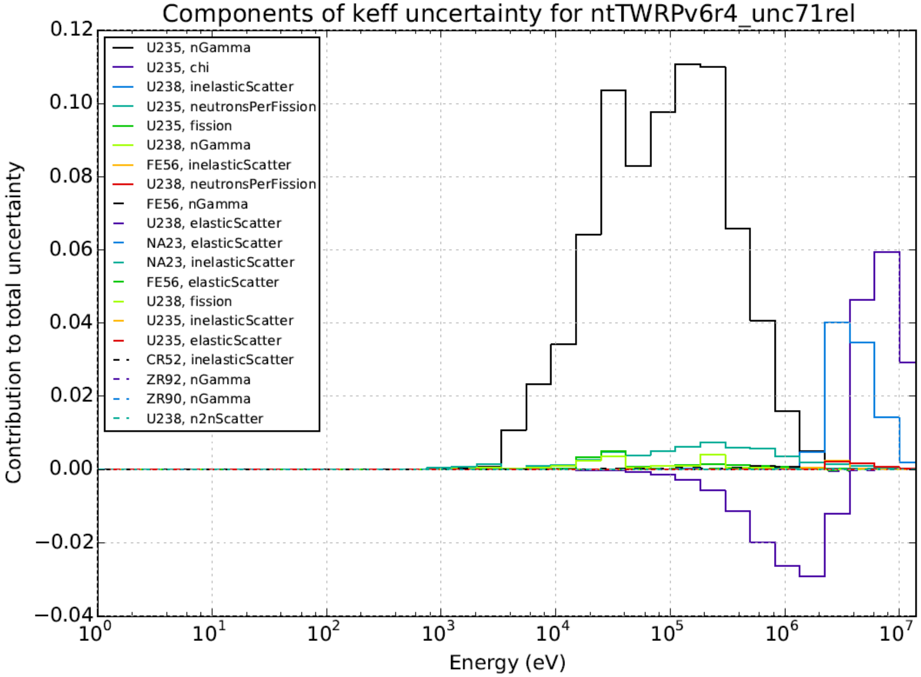
$$cov(\sigma_{LFP,1}, \sigma_{LFP,2}) = \frac{4}{(\sum_{i=1}^{I}\gamma_i\ )^2}\ \sum_{i=1}^{I}\sum_{j=1}^{I}\gamma_i\ \gamma_j cov(\sigma_{i,1}\ , \sigma_{j,2})$$



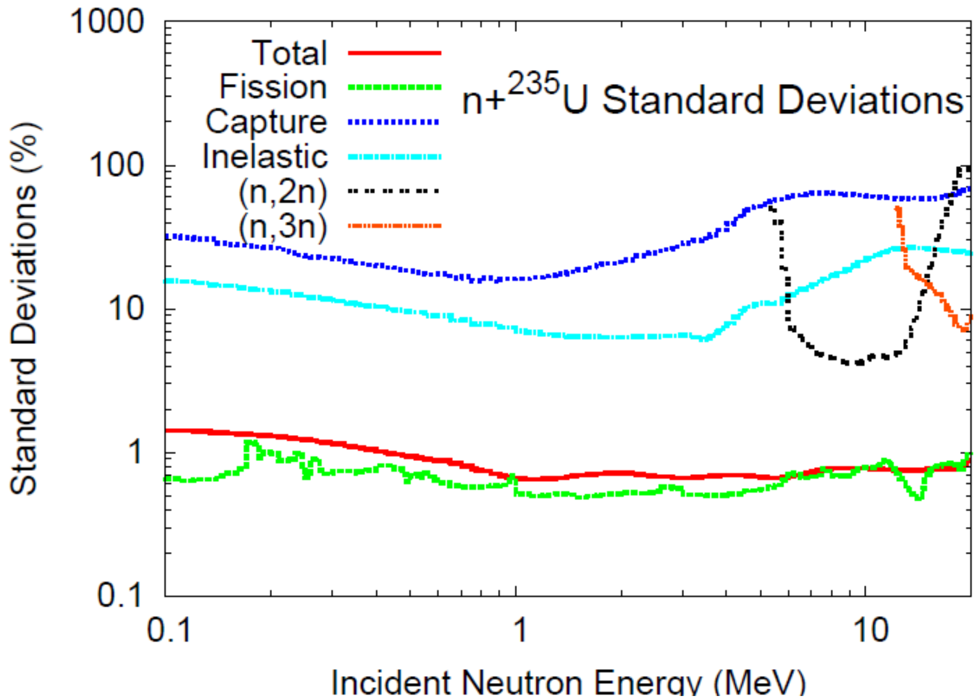


TWR-P BOL k_{eff} Results





^{235}U standard deviations in ENDF/B-VII.1



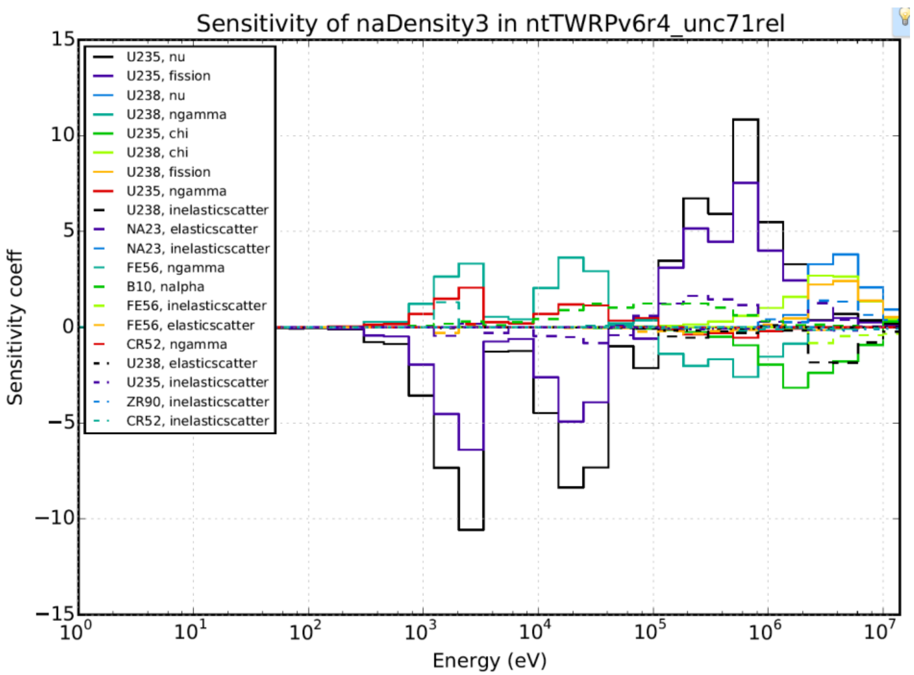
Standard deviations of ^{235}U in ENDF/VII.1

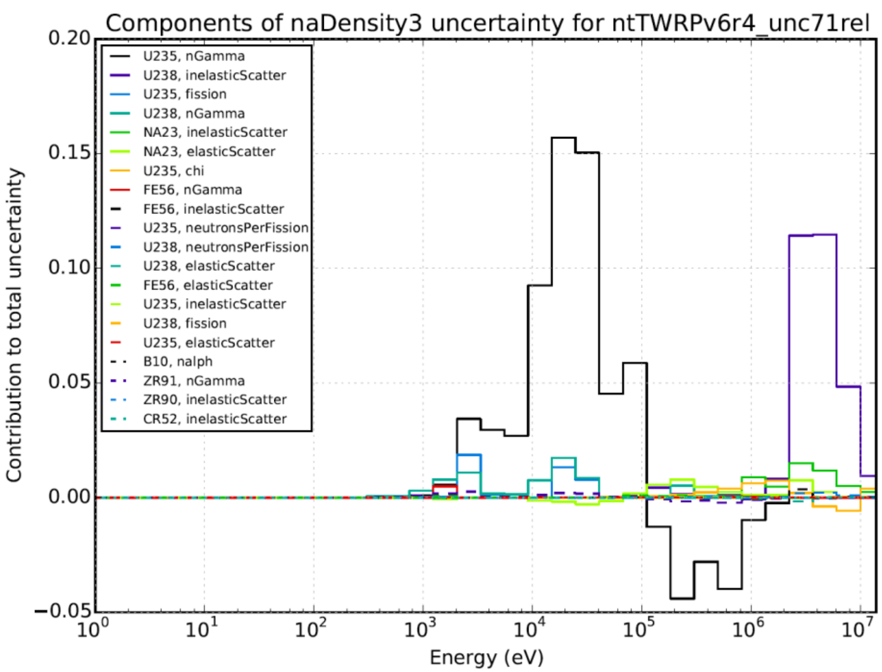
Talon, P., Young, P. "Quantification of Uncertainties for Evaluated Neutron-Induced Reactions on Actinides in the Fast Energy Range," Nuclear Data Sheets, 112, 12, 3054-3074 (2011).

TWR-P BOL CTC Results

Note that sensitivity shape is easy and instructive to interpret.

- If more fissions were occurring at 10 keV and then spectral hardening occurred, CTC would decrease (negative S)
- Capture reactions go in the opposite direction





TWR-P Uncertainty Results

Nominal values of key TWR-P integral parameters with uncertainties due to nuclear data

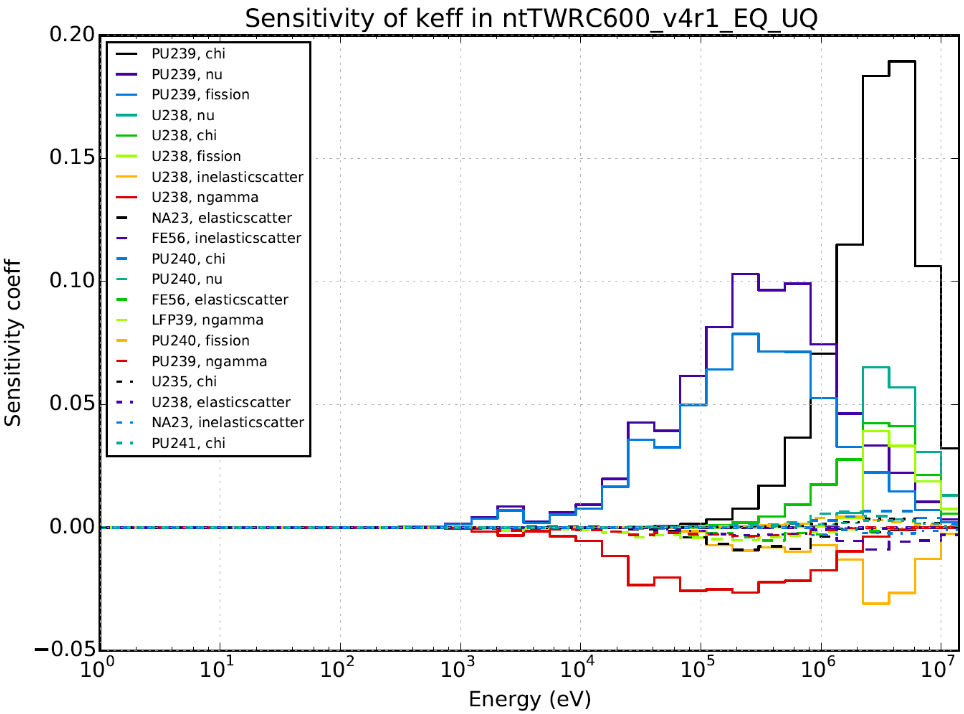
Integral Parameter	Nominal BOL	Nominal EOL	Uncertainty BOL	Uncertainty EOL
k_{eff}	0.997488	0.997980	2.24E-02	1.59E-02
Coolant temperature coefficient (₵/K)	3.62E-03	4.90E-02	4.99E-03	5.64E-03
Doppler coefficient (₵/K)	-8.27E-02	-9.43E-02	4.77E-03	4.82E-03
Void worth ($)	2.42E-01	3.33E+00	3.55E-01	3.82E-01
Control Rod worth ($)	-1.02E+00	-1.45E+00	2.99E-02	3.78E-02

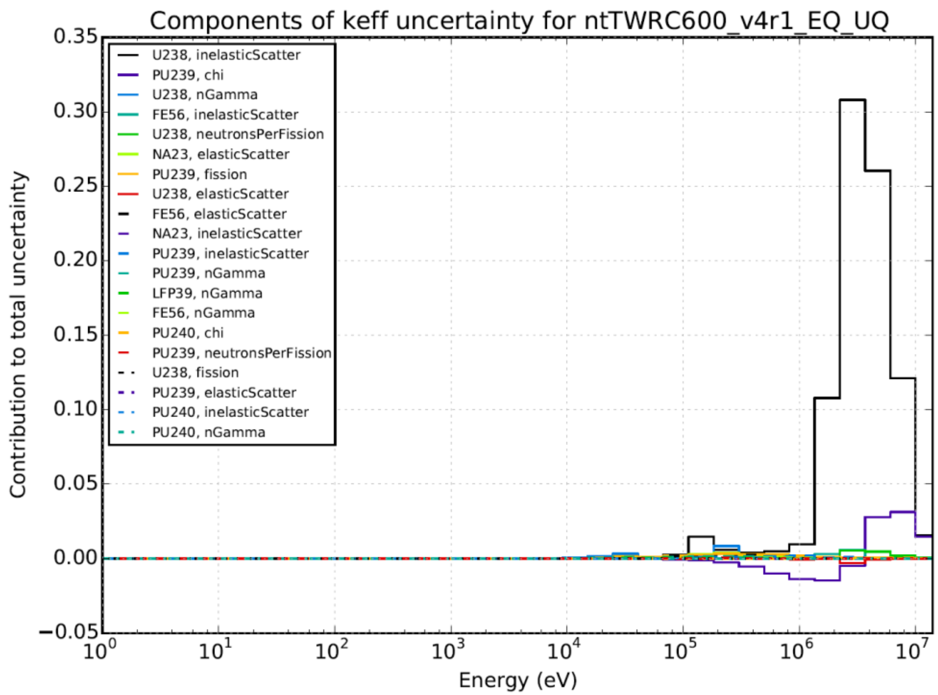
Relative uncertainties due to nuclear data in key TWR-P integral parameters

Integral Parameter	TWR-P BOL	TWR-P EOL
k_{eff}	2.25E-02	1.59E-02
Coolant temperature coefficient	1.38E+00*	1.15E-01
Doppler coefficient	5.77E-02	5.11E-02
Void worth	1.47E+00	1.15E-01
Control Rod worth	2.92E-02	2.61E-02

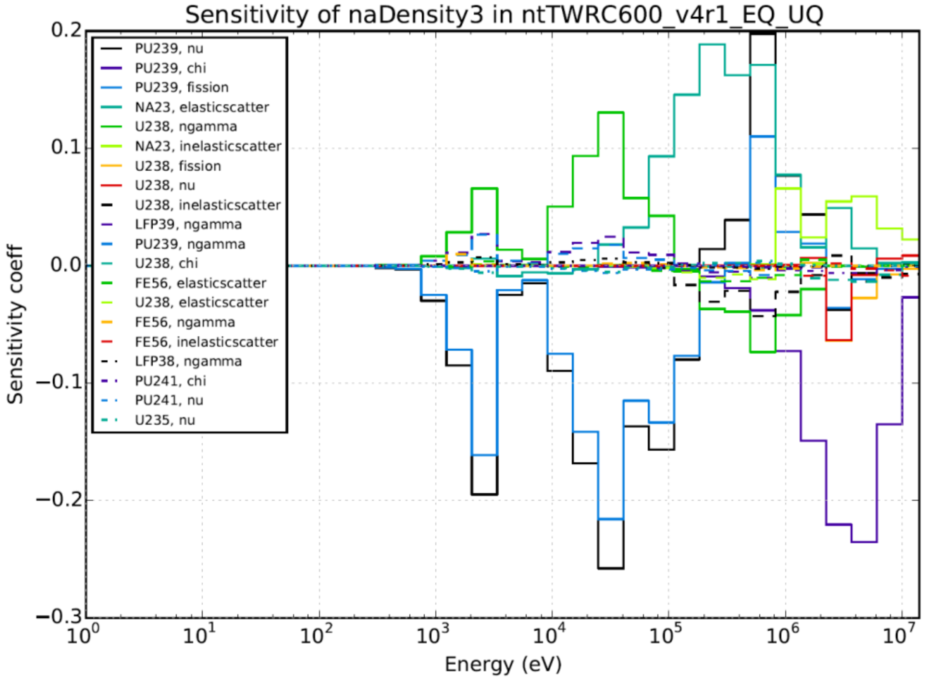
* Note high relative uncertainty due to very small absolute

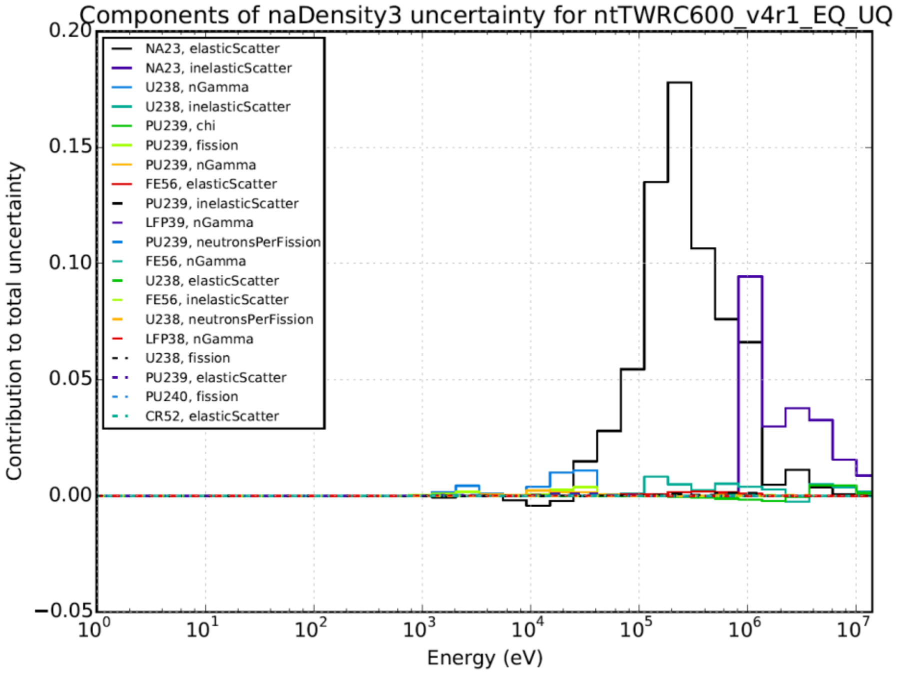
TWR-C Equilibrium k_{eff} Results



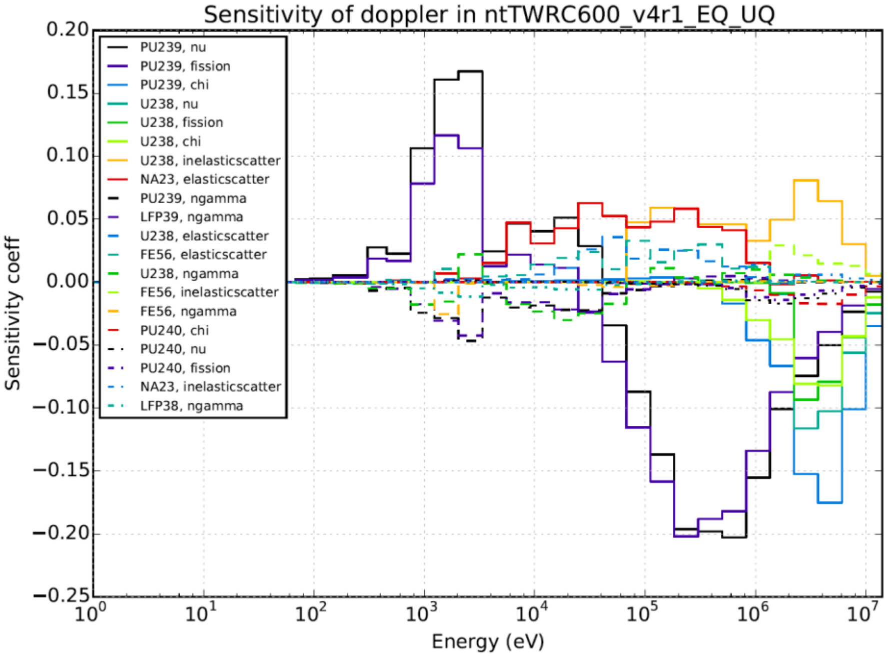


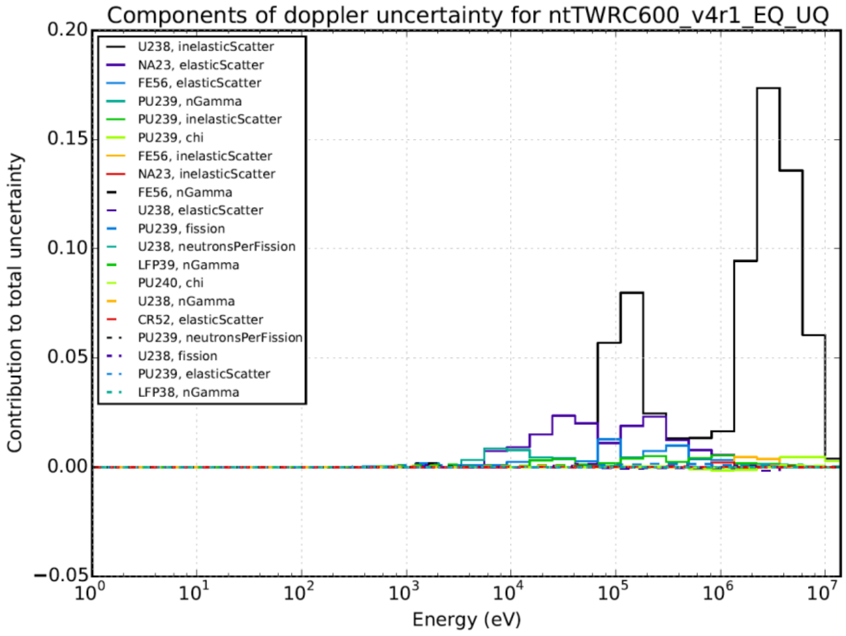
TWR-C Equilibrium CTC Results





TWR-C Equilibrium Doppler Results





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TWR-C Equilibrium Results

Integral Parameter	TWR-C Equilibrium Relative Uncertainty
k_{eff}	1770 pcm
Coolant temperature coefficient (CTC)	5.20E-02
Doppler coefficient	6.28E-02
Void worth	4.93E-02
Control rod worth	3.43E-02

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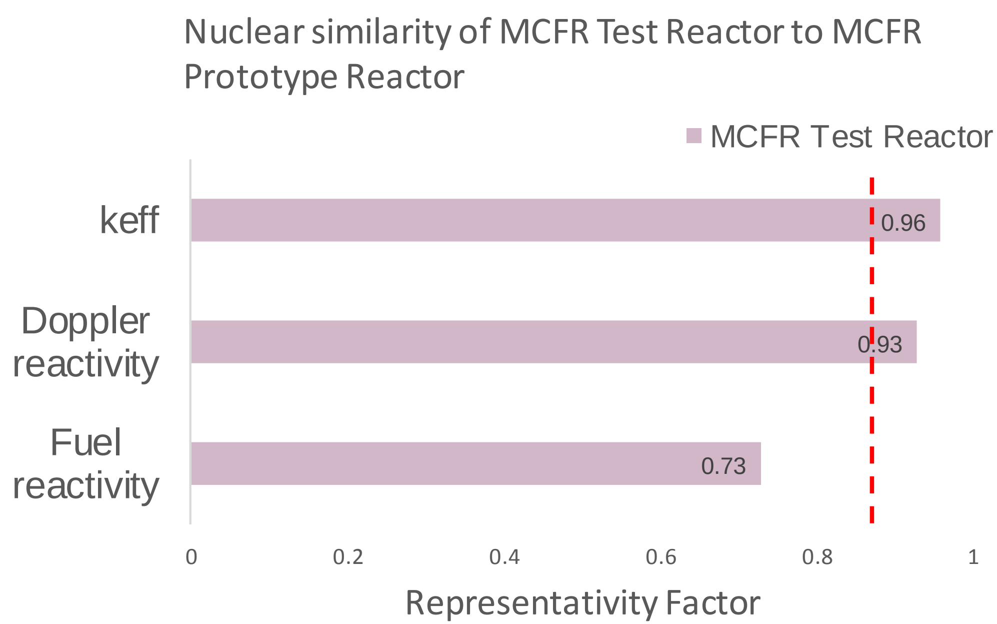
Started using sensitivity coefficient module for MCFR design



The assessment of how similar the MCFR Test Reactor is to the MCFR Prototype Reactor guides Test Reactor design choices

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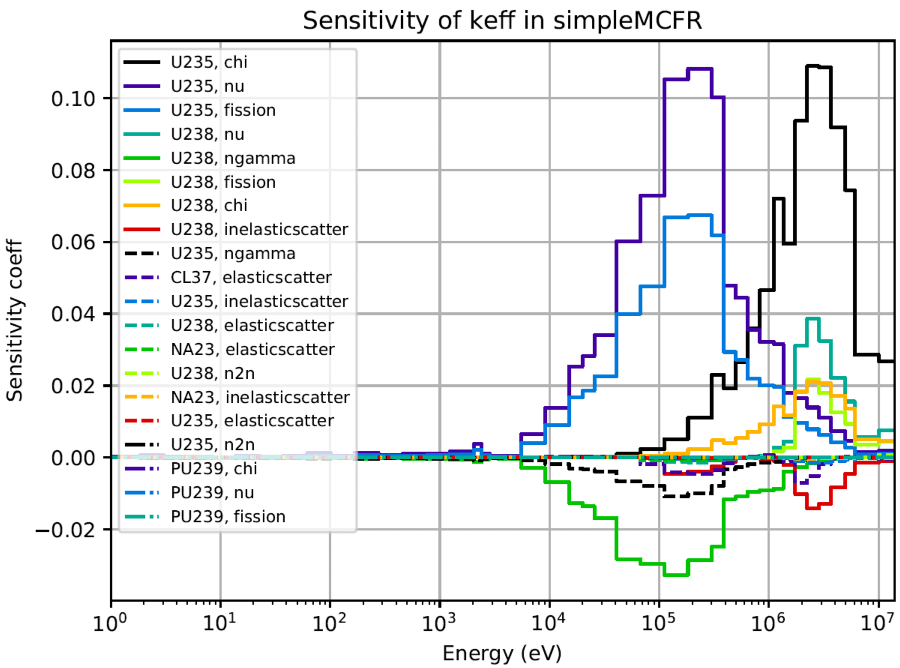
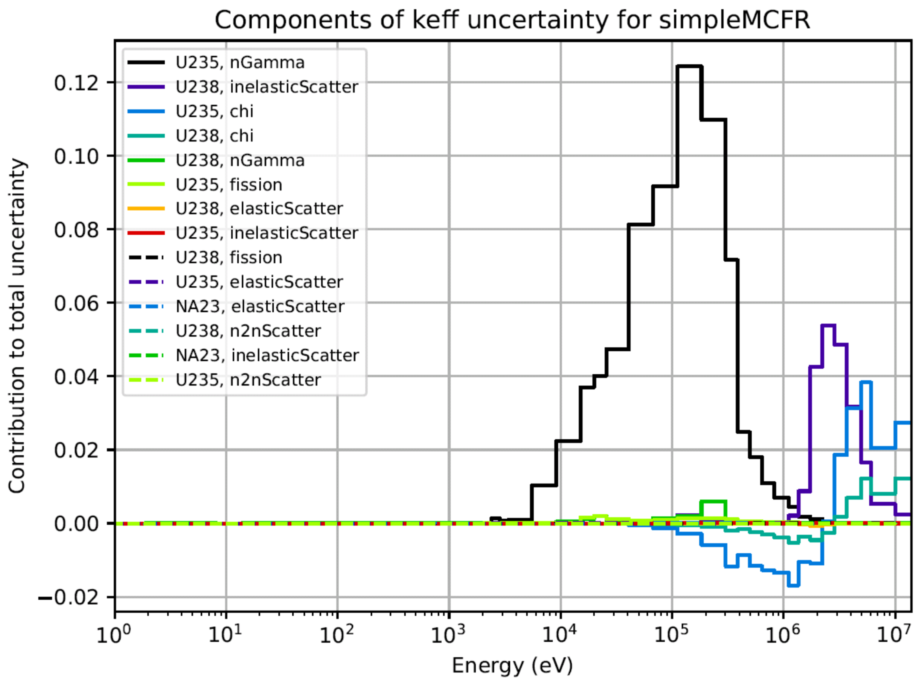
MCFR ENDF/B-VII.1 results





~2000 pcm without considering Chlorines

Since then

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New Precision Measurements of the $^{235}\mathrm{U}(n,\gamma)$ Cross Section

M. Jandel, T. A. Bredeweg, E. M. Bond, M. B. Chadwick, A. Couture, J. M. O'Donnell, M. Fowler, R. C. Haight, T. Kawano, R. Reifarth, R. S. Rundberg, J. L. Ullmann, D. J. Vieira, J. M. Wouters, J. B. Wilhelmy, C. Y. Wu, and J. A. Becker

Phys. Rev. Lett. **109**, 202506 – Published 16 November 2012

Conclusions

Key nuclides/reaction uncertainties:

- ^{235}U capture dominance likely resolved with Jandel results
- ^{238}U inelastic scatter
- ^{23}Na scattering cross sections (both elastic and inelastic) contribute significantly to void worth, Doppler, and CTC uncertainties.
- ^{235}U PFNS (χ) and ^{56}Fe elastic scatter
- Still unclear: Effects of Chlorine-35 and 37.

For Pu-fueled systems, the priority list is very similar, but ^{239}Pu χ replaces ^{235}U in the list.

Next Steps and Needs

Near-term

- Redo with ENDF/B-VIII.0 library for MC**2-3, or alternative lattice code
  - Need to identify issue with extraction of MF33
- Communicate updated results to experimenters and evaluators
- Continue Representativity studies as market shifts

Longer-term

- Perform data assimilation to reduce uncertainties

ACKNOWLEDGMENTS

The author acknowledges coaching from M. Salvatores and G. Palmiotti. Additionally, the continuing work of NEA/WPEC subgroups 26, 33, 39 and 40 has proved invaluable to this effort. Thanks also to Jeremy Conlin for his help extracting the ^{235}U MF35/MT18 file.

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