DLFR

Demonstration Lead-cooled Fast Reactor

S & U Analysis

Sensitivity & Uncertainty Analysis

Jin Li

Department of Engineering Physics, Tsinghua University

CONTENT

PART 01

Introduction

DLFR By Westinghouse, U.S.

Demonstration Lead-cooled Fast Reactor

Design Parameter

Power rate: 500MWt

Neutron flux: Peak ~ 2×10^{15} n/cm^2

Reactor Type

Lead-cooled

Pool-type

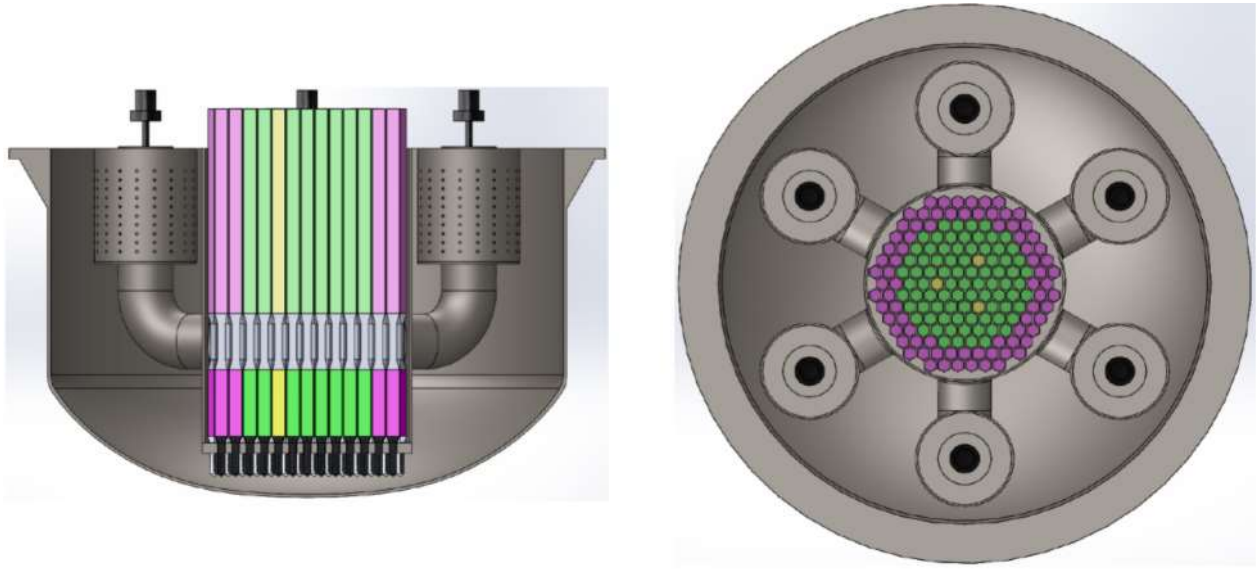
Fast reactor

Objective

Feasibility

Basic performance

Uprate

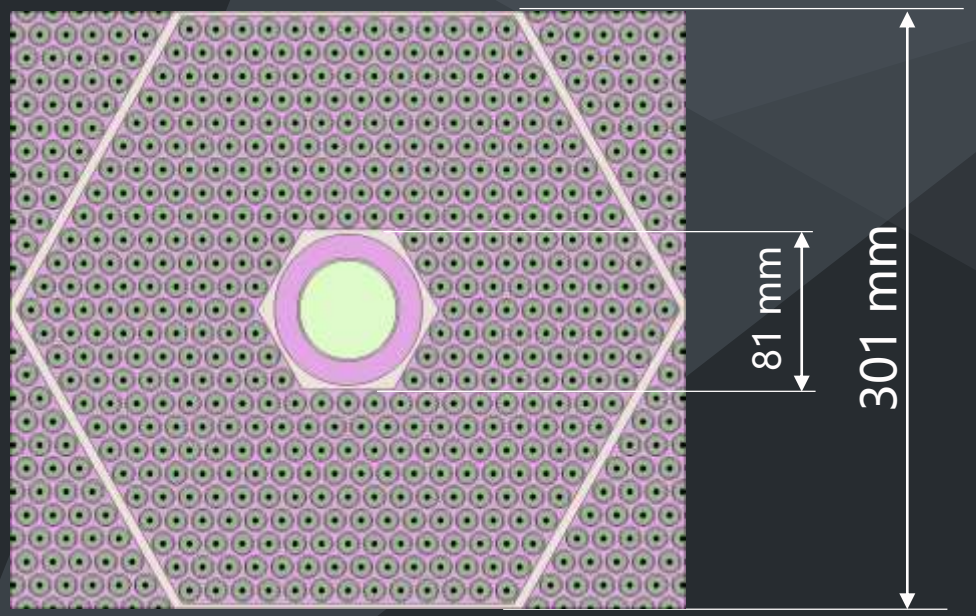


DLFR primary system layout, vertical and horizontal cross section
(pre-conceptual, not in scale, DHRS not shown)

PART 02

Modeling

Assembly



Coolant Pb
Cladding Steel
Hollow Void
Fuel

Boundary: Periodical

Calculation:

Periodical Boundary

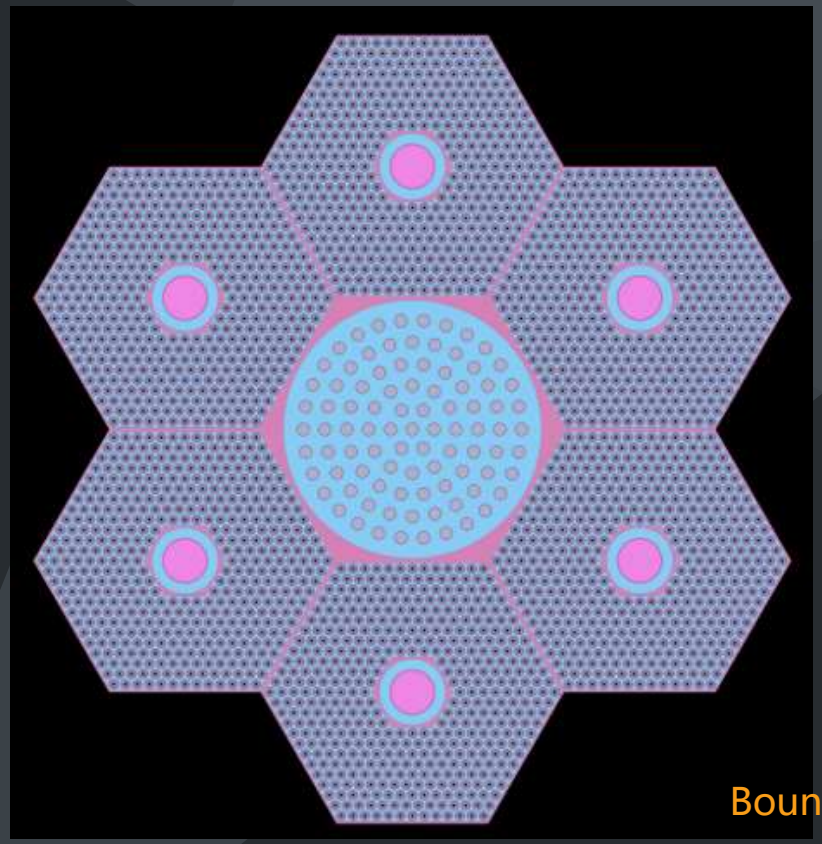
Inner Core Assembly

Fuel	K-inf	Error
BoL	1.26791	0.00246
BoC	1.19807	0.00278
EoC	1.16523	0.00278
EoL	1.10776	0.00316

Outer Core Assembly

Fuel	K-inf	Error
BoL	1.34074	0.00291
BoC	1.28491	0.00289
EoC	1.26066	0.00292
EoL	1.19467	0.00281

Safety Rod



Coolant -Pb
Cladding -Steel
Hollow -Void
Inner Core Fuel

Reflector -YSZ 8% mol
Safety $-B_4C$

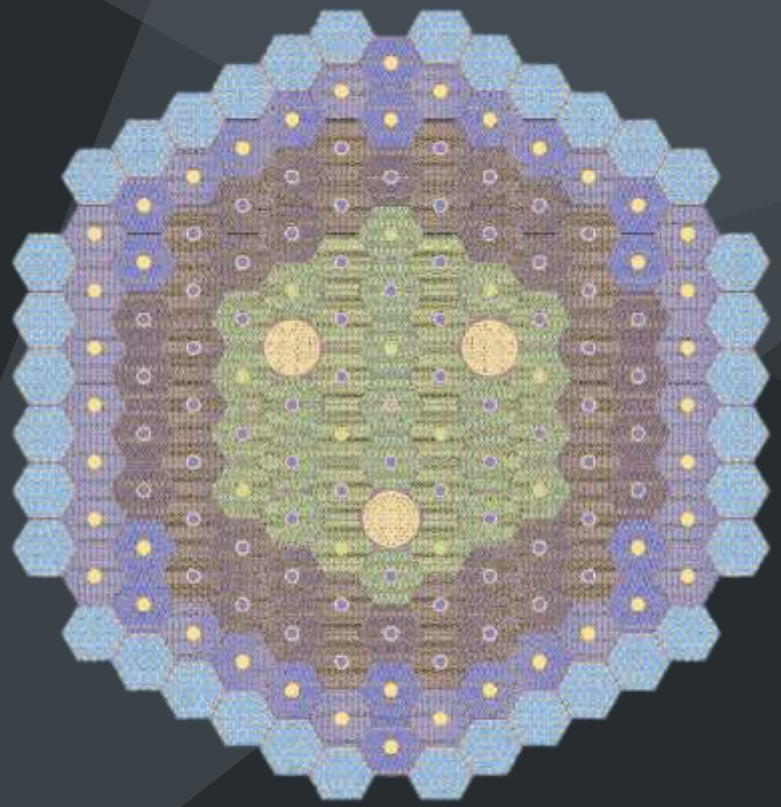
Calculation:

Black Boundary

Safety surrounded by Inner Core Assembly

Fuel	K-inf	Error
BoL	1.02864	0.00361
BoC	0.98266	0.00377
EoC	0.96995	0.00349
EoL	0.94755	0.00392

Core

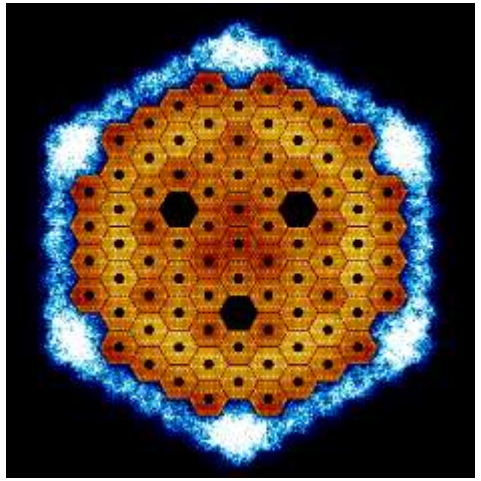


Coolant	-Pb	Reflector	-YSZ 8% mol
Cladding	-Steel	Shield	-Borated Steel
Inner Fuel		Safety	$-B_4C$
Outer Fuel		Plenum	

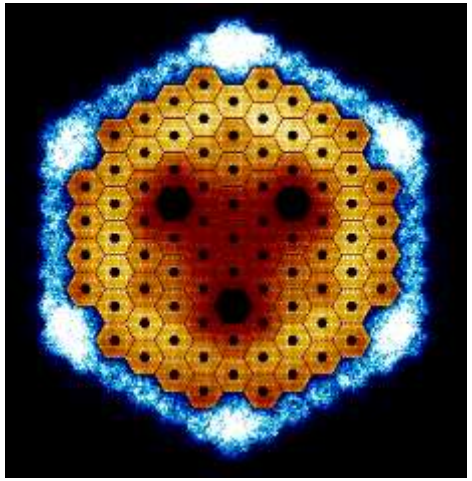
Calculation:

Time	$k_{inf} \pm$ error	
	Safety Rod out	Safety Rod in
BoL	1.14892 ± 0.00335	1.12366 ± 0.00312
BoC	1.08653 ± 0.00255	1.07694 ± 0.00234
EoC	1.06150 ± 0.00313	1.04444 ± 0.00281
EoL	1.01073 ± 0.00341	0.99147 ± 0.00316

Power Distribution:



Safety Rod out



Safety Rod in

PART 03

Calculation

Sensitivity

Definition

$$S_x^R = \frac{\partial R/R}{\partial x/x}$$

$$R = \frac{\langle \Sigma_1, \Psi \rangle}{\langle \Sigma_2, \Psi \rangle}$$

R — Response function
x — A certain perturbed parameter
S_x^R — Sensitivity coefficient of R with respect to x

$$S_x^R = \frac{\partial R/R}{\partial x/x} = \left\langle \frac{\frac{d\Sigma_1}{dx}\Psi x}{\Sigma_1 \Psi} - \frac{\frac{d\Sigma_2}{dx}\Psi x}{\Sigma_2 \Psi} + \frac{\partial R}{\partial \Psi}\frac{\partial \Psi}{\partial x}\frac{x}{R} \right\rangle$$

$\langle\,\rangle$ — Inner product
Ψ — Neutron flux
Σ_1, Σ_2 — Any kind of macroscopic cross section

Sensitivity

Calculation

Direct effect terms Indirect effect terms

$$S_x^R = \frac{\partial R/R}{\partial x/x} = \left\langle \frac{\frac{d\Sigma_1}{dx}\Psi x}{\Sigma_1 \Psi} - \frac{\frac{d\Sigma_2}{dx}\Psi x}{\Sigma_2 \Psi} + \frac{\partial R}{\partial \Psi}\frac{\partial \Psi}{\partial x}\frac{x}{R} \right\rangle$$

Direct Terms

Describe impact on generalized response
Relatively easy to compute

Indirect Term

Describe impact on flux
Complicated to compute

Method for Indirect Term

- GEAR (Generalized Adjoint Response) method based on GPT (Generalized perturbation theory) used by TSUNAMI-3D
- Collision-based History method based on accepted and rejected events used by SERPENT2

Uncertainty

Definition

$$\vec{S} = \left(S_{x_1}^k, S_{x_2}^k, \dots, S_{x_n}^k\right)$$

$n = Nuclide{\sim}Reaction\ number \times Energy\ Bin\ number$

$15543 = 471 \times 33$

$$\mathrm{cov}(x_i, x_j) = \int \left(x_i - E(x_i)\right)\left(x_j - E\left(x_j\right)\right) p(x_1, \dots, x_n) dx_1 \dots dx_n$$

Sandwich Rule

$$r_k^2 = \vec{S} V \vec{S}^T$$

— V is (relative) covariance matrix

$$V = \begin{bmatrix} r_{x_1}^2 & \mathrm{rcov}(x_1, x_2) & \cdots & \mathrm{rcov}(x_1, x_n) \\ \mathrm{rcov}(x_2, x_1) & r_{x_1}^2 & \cdots & \mathrm{rcov}(x_2, x_n) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{rcov}(x_n, x_1) & \mathrm{rcov}(x_n, x_2) & \cdots & \mathrm{rcov}(x_n, x_n) \end{bmatrix}$$

$$\mathrm{rcov}(x_i, x_j) = \frac{\mathrm{cov}(x_i, x_j)}{x_i x_j}$$

$$r_{x_i}^2 = \frac{\sigma_{x_i}^2}{x_i^2}$$

—$r_{x_i}^2$ is relative variance

COMMARA-2.0

Released by BNL & LANL in March 2011

Based on ENDF/B-VII.0

Including 110 Nuclides:

12 Light Nuclei (Coolant & Moderator)
78 Structural Materials & Fission products
20 Actinides

Reaction Channels

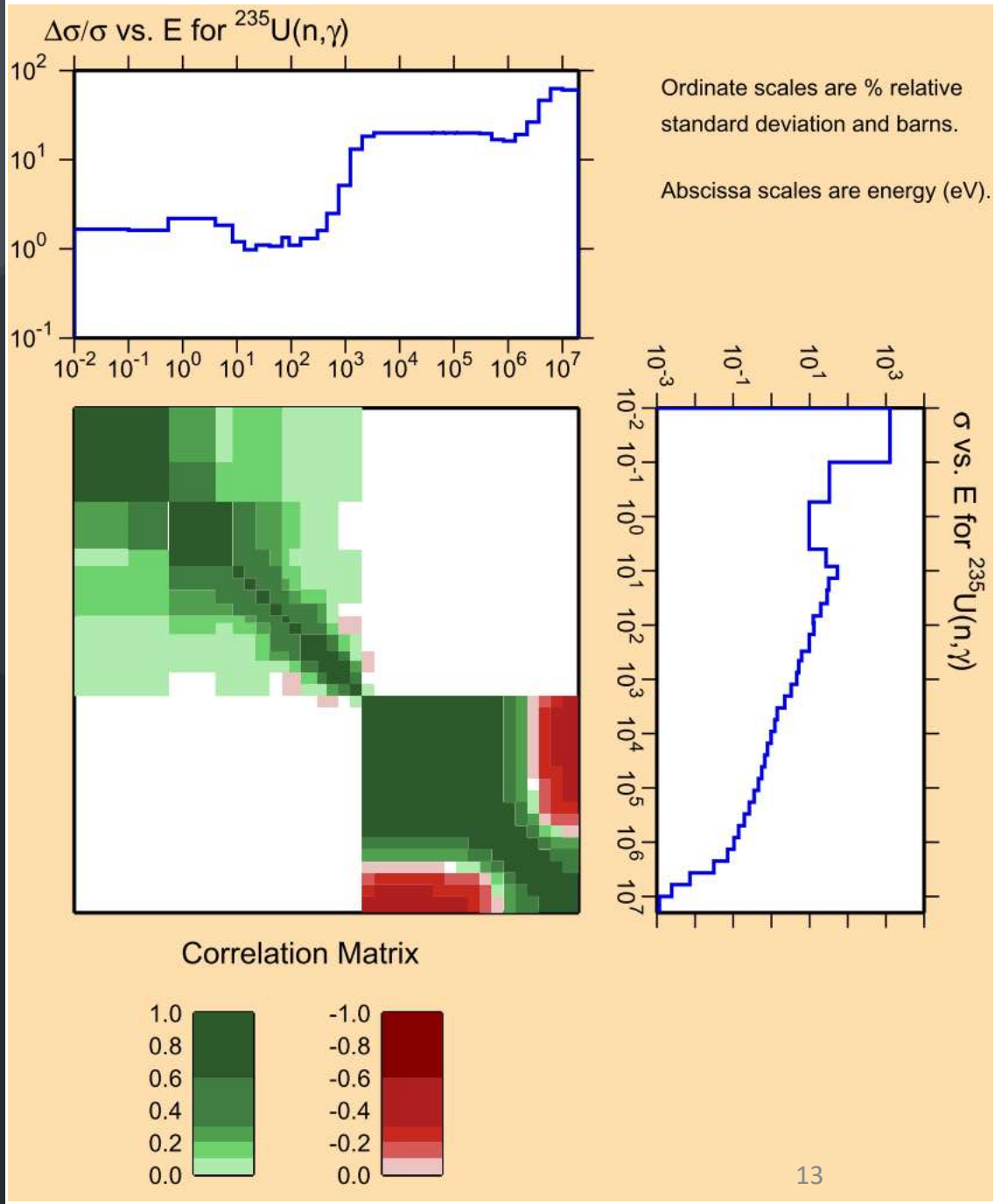
Elastic/Inelastic Scattering $(n,n)/(n,n')$
Capture (n,γ)
Neutron Multiplication (n,xn)
Fission (n,f)、 $\bar{\nu}$、 χ

Total Files (Nuclide-Reaction)

569

Energy

10^{-5} eV – 19.6 MeV
33 Groups



Covariance Matrix

Calculation

NEA provides COMMARA-2.0 correlation matrices and relative uncertainty:
https://www.oecd-nea.org/science/wpec/sg33/benchmark/results/data.html

$$C = \begin{bmatrix} 1 & cor(x_1, x_2) & \cdots & cor(x_1, x_n) \\ cor(x_2, x_1) & 1 & \cdots & cor(x_2, x_n) \\ \vdots & \vdots & \ddots & \vdots \\ cor(x_n, x_1) & cor(x_n, x_2) & \cdots & 1 \end{bmatrix}$$

$$\boxed{r_{x_i} = \frac{\sigma_{x_i}}{x_i}}$$

— r_{x_i} is relative uncertainty

Obtain relative covariance matrix from correlation matrices and relative uncertainty:

$$\mathrm{rcov}(x_i, x_j) = r_{x_i} r_{x_j} cor(x_i, x_j)$$

$$V = \begin{bmatrix} r_{x_1}^2 & \mathrm{rcov}(x_1, x_2) & \cdots & \mathrm{rcov}(x_1, x_n) \\ \mathrm{rcov}(x_2, x_1) & r_{x_1}^2 & \cdots & \mathrm{rcov}(x_2, x_n) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{rcov}(x_n, x_1) & \mathrm{rcov}(x_n, x_2) & \cdots & \mathrm{rcov}(x_n, x_n) \end{bmatrix}$$

Relative Uncertainty

Definition

$$U_{total} = r_k^2 = \vec{S} V \vec{S}^T = \sum_i S_i V_{ii} S_i + \sum_i \sum_{j \neq i} S_i V_{ij} S_j$$

Sensitivity Index: $$SI_i = \frac{U_i}{U_{total}}$$

The conservative estimate of uncertainty:

$$\widetilde{\boldsymbol{U_i}} = S_i V_{ii} S_i + 2 \times \sum_{j \neq i} S_i V_{ij} S_j$$

Conservative Sensitivity Index: $$\widetilde{SI_i} = \frac{\widetilde{\boldsymbol{U_i}}}{U_{total}}$$

Calculation

Serpent

Output Files

***_res.m** – General Results

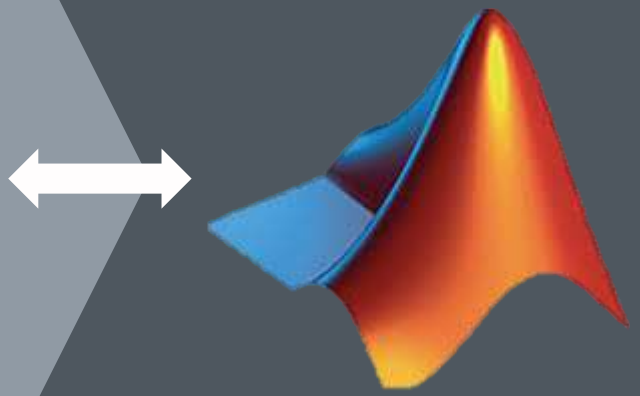
***_sens.m** – Sensitivity Data

C++

- Output File Preprocess
- Extract Information
- Generate MATLAB Script

MATLAB

Mixed Programming!



- Arrange Covariance Matrix
- Calculate Uncertainty
- Plot Distribution Graph

Results

Sensitivity & Uncertainty **Distribution**

- Nuclide-Reaction List
- Uncertainty Value
- Stairs Graph

C++

- Read Serpent Output File
- Generate Nuclide-Reaction Index
- Match Sensitivity with Covariance

Generate MATLAB Scripts to :

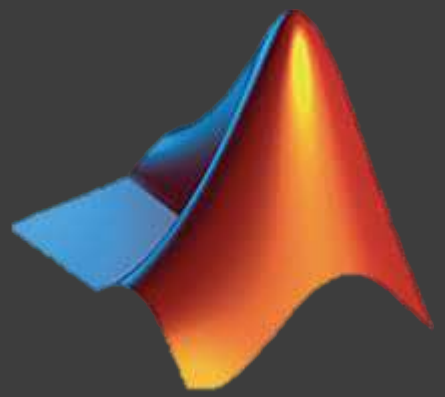
Arrange Covariance Matrix
Calculate Uncertainty
Sort Data
Plot Stairs Graph
……

Interface

MATLAB Engine
Dynamic-link Library

Index Files
Temporary Files
MATLAB Scripts

MATLAB



- Read Covariance Matrix
- Calculate Uncertainty
- Sort Data by Importance
- Plot Stairs Graph

Generate Temporary Files to :

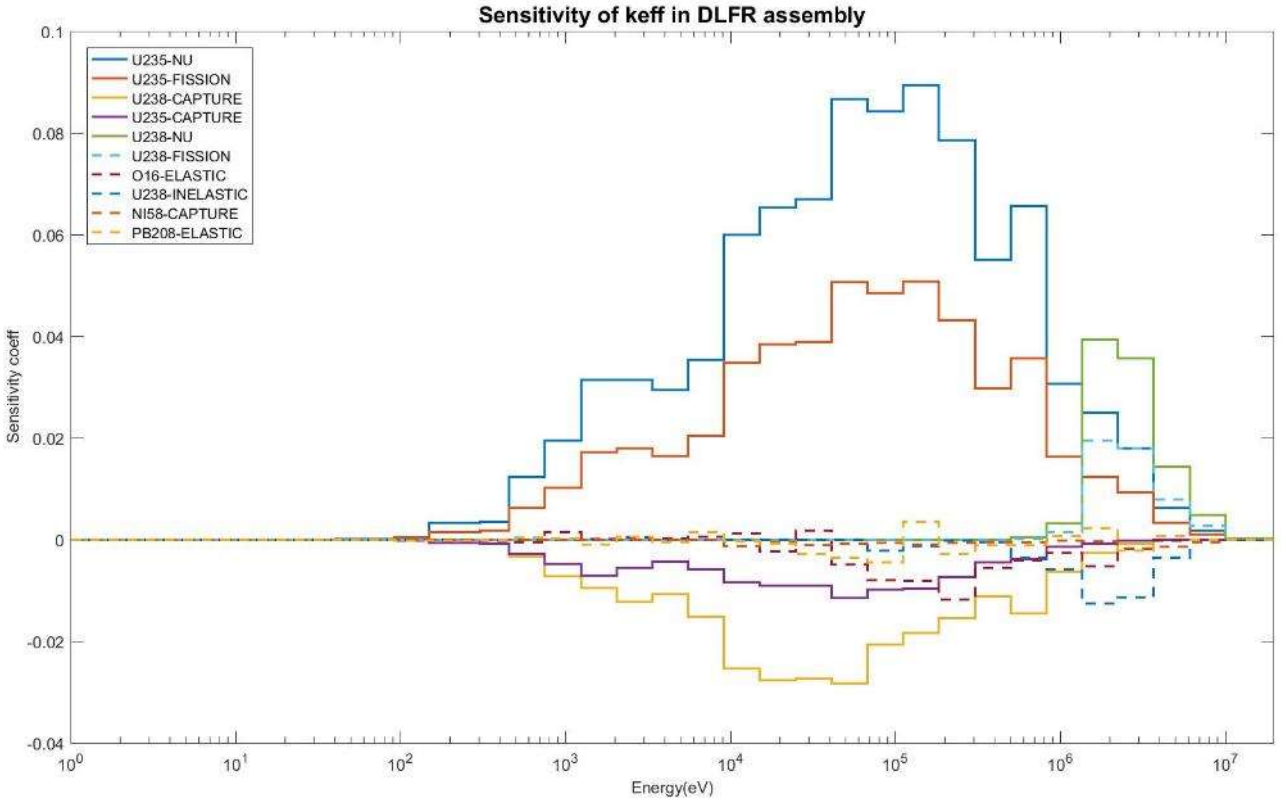
Match Data by Name-Value
Extract Calculation Results
Transfer Data
……

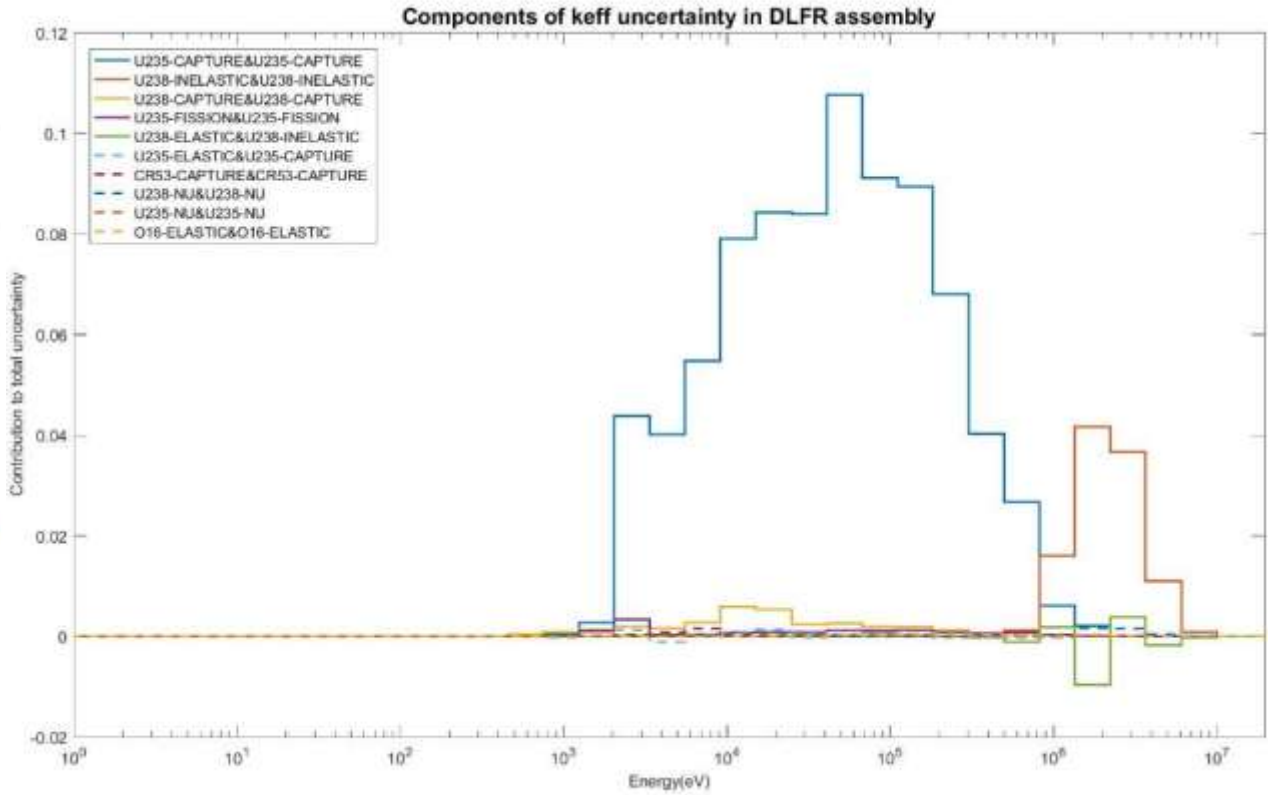
PART 3.1

Fuel Assembly

Distribution of S/U Corresponding to the Most Important 20 Parameters

Inner Core Fuel Assembly at Beginning of Life





BoL inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.019226

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	82.1235
$^{238}U - \sigma_{n,n'}$	10.8820
$^{238}U - \sigma_{n,\gamma}$	3.2416
$^{235}U - \sigma_{f}$	1.4514
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	-0.7076

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.56768	-0.107003
$^{238}U - \sigma_{n,n'}$	0.17516	-0.041029
$^{238}U - \sigma_{n,\gamma}$	0.05615	-0.257976
$^{235}U - \sigma_{f}$	0.02490	0.506052
$^{53}Cr - \sigma_{n,\gamma}$	0.00684	0.007763

BoL outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.019821

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	86.7332
$^{238}U - \sigma_{n,n'}$	7.0166
$^{238}U - \sigma_{n,\gamma}$	2.4011
$^{235}U - \sigma_{f}$	1.2345
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	0.4458

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.64995	-0.110411
$^{238}U - \sigma_{n,n'}$	0.122642	-0.041853
$^{238}U - \sigma_{n,\gamma}$	0.041575	-0.232542
$^{235}U - \sigma_{f}$	0.021593	0.488544
$^{53}Cr - \sigma_{n,\gamma}$	0.005432	0.007141

BoC inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.015357

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	65.8074
$^{238}U - \sigma_{n,n'}$	19.0909
$^{238}U - \sigma_{n,\gamma}$	5.1079
$^{235}U - \sigma_{f}$	1.7412
$^{56}Fe - \sigma_{n,n}$	1.7377

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.25340	-0.078050
$^{238}U - \sigma_{n,n'}$	0.33066	-0.051604
$^{238}U - \sigma_{n,\gamma}$	0.08877	-0.256832
$^{235}U - \sigma_{f}$	0.02919	0.431738
$^{56}Fe - \sigma_{n,n}$	0.02974	-0.023070

BoC outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.016577

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	86.7332
$^{238}U - \sigma_{n,n'}$	7.0166
$^{238}U - \sigma_{n,\gamma}$	2.4011
$^{235}U - \sigma_{f}$	1.2345
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	0.4458

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.513810	-0.090276
$^{238}U - \sigma_{n,n'}$	0.204594	-0.044881
$^{238}U - \sigma_{n,\gamma}$	0.062313	-0.235775
$^{235}U - \sigma_{f}$	0.027417	0.454963
$^{16}O - \sigma_{n,n}$	0.011894	-0.067184

EoC inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.014014

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	54.7410
$^{238}U - \sigma_{n,n'}$	27.9248
$^{238}U - \sigma_{n,\gamma}$	5.8622
$^{235}U - \sigma_{f}$	1.8119
$^{16}O - \sigma_{n,n}$	1.5251

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.04262	-0.065688
$^{238}U - \sigma_{n,n'}$	0.48038	-0.050797
$^{238}U - \sigma_{n,\gamma}$	0.10185	-0.250996
$^{235}U - \sigma_{f}$	0.02997	0.397506
$^{16}O - \sigma_{n,n}$	0.02818	-0.087629

EoC outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.015726

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	76.2761
$^{238}U - \sigma_{n,n'}$	12.9362
$^{238}U - \sigma_{n,\gamma}$	4.0763
$^{235}U - \sigma_{f}$	1.6353
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	0.9269

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.451030	-0.084109
$^{238}U - \sigma_{n,n'}$	0.226971	-0.044512
$^{238}U - \sigma_{n,\gamma}$	0.070649	-0.236758
$^{235}U - \sigma_{f}$	0.027646	0.433899
$^{53}Cr - \sigma_{n,\gamma}$	0.010715	-0.007833

EoL inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.012044

Parameter Pair	Contribution to Total Uncertainty (%)
$^{238}U - \sigma_{n,n'}$	38.9070
$^{235}U - \sigma_{n,\gamma}$	33.2131
$^{238}U - \sigma_{n,\gamma}$	7.3113
$^{238}U - (\sigma_{n,n}\,,\ \sigma_{n,n'})$	3.9664
$^{16}O - \sigma_{n,n}$	2.7469

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}U - \sigma_{n,n'}$	0.68714	-0.059305
$^{235}U - \sigma_{n,\gamma}$	0.63359	-0.044578
$^{238}U - \sigma_{n,\gamma}$	0.12726	-0.238941
$^{16}O - \sigma_{n,n}$	0.05135	0.100010
$^{238}U - \sigma_{n,n}$	0.04130	-0.005715

EoL outer Assembly Uncertainty Analysis:

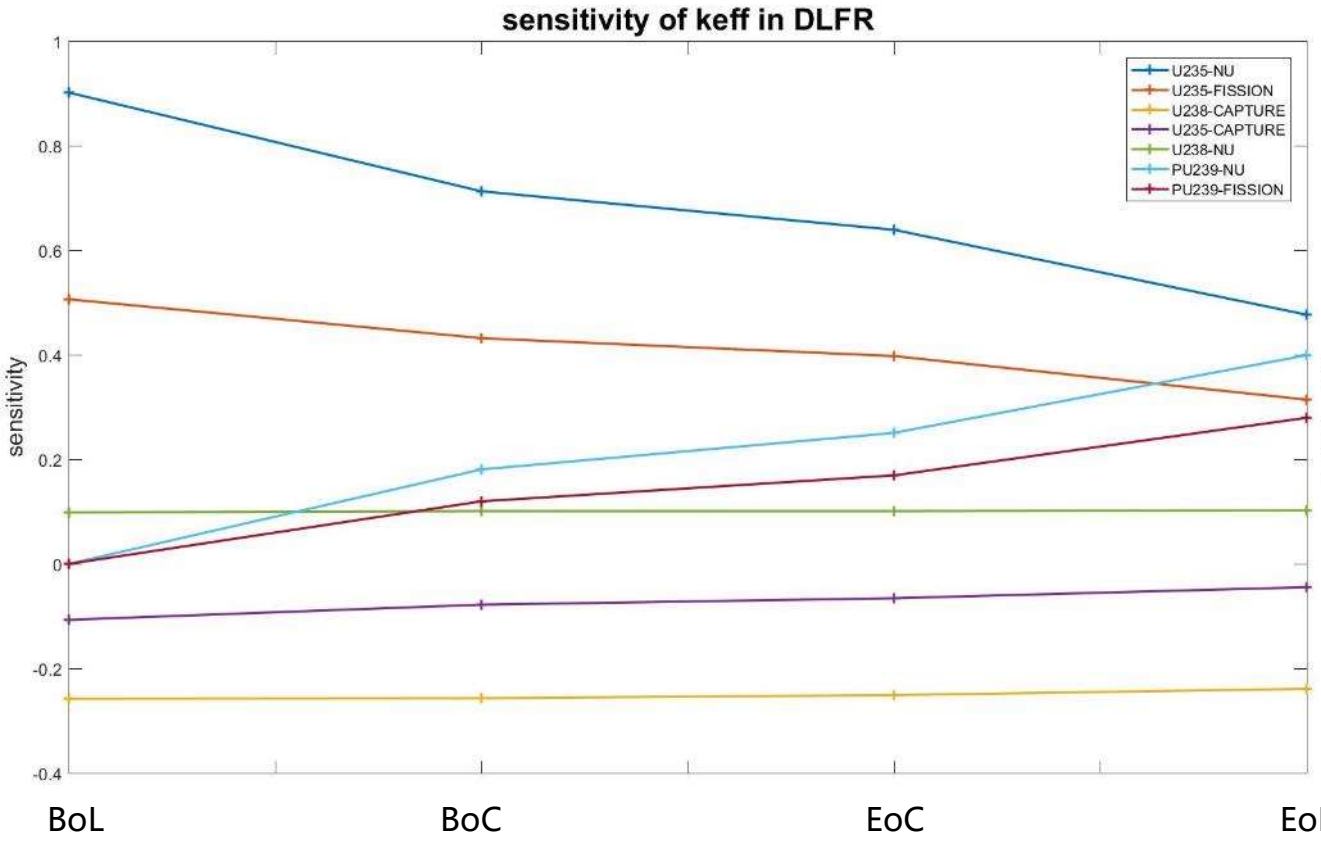
K_{eff} Standard Deviation: 0.013416

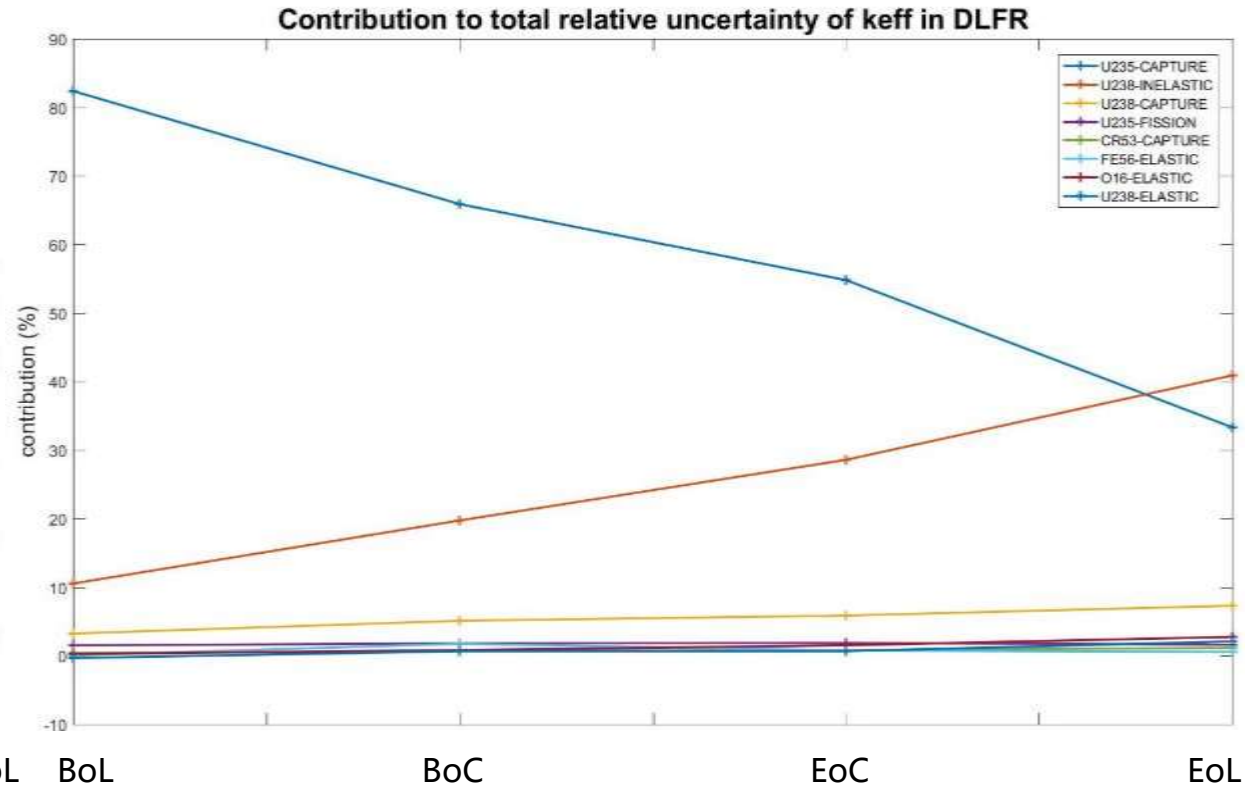
Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	62.8492
$^{238}U - \sigma_{n,n'}$	21.0056
$^{238}U - \sigma_{n,\gamma}$	5.5305
$^{235}U - \sigma_{f}$	1.8597
$^{16}O - \sigma_{n,n}$	1.0447

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.201250	-0.066350
$^{238}U - \sigma_{n,n'}$	0.360621	-0.047198
$^{238}U - \sigma_{n,\gamma}$	0.095879	-0.234376
$^{235}U - \sigma_{f}$	0.031221	0.392085
$^{16}O - \sigma_{n,n}$	0.018994	-0.070047

Sensitivity and Uncertainty Contributed to Total in Different Periods

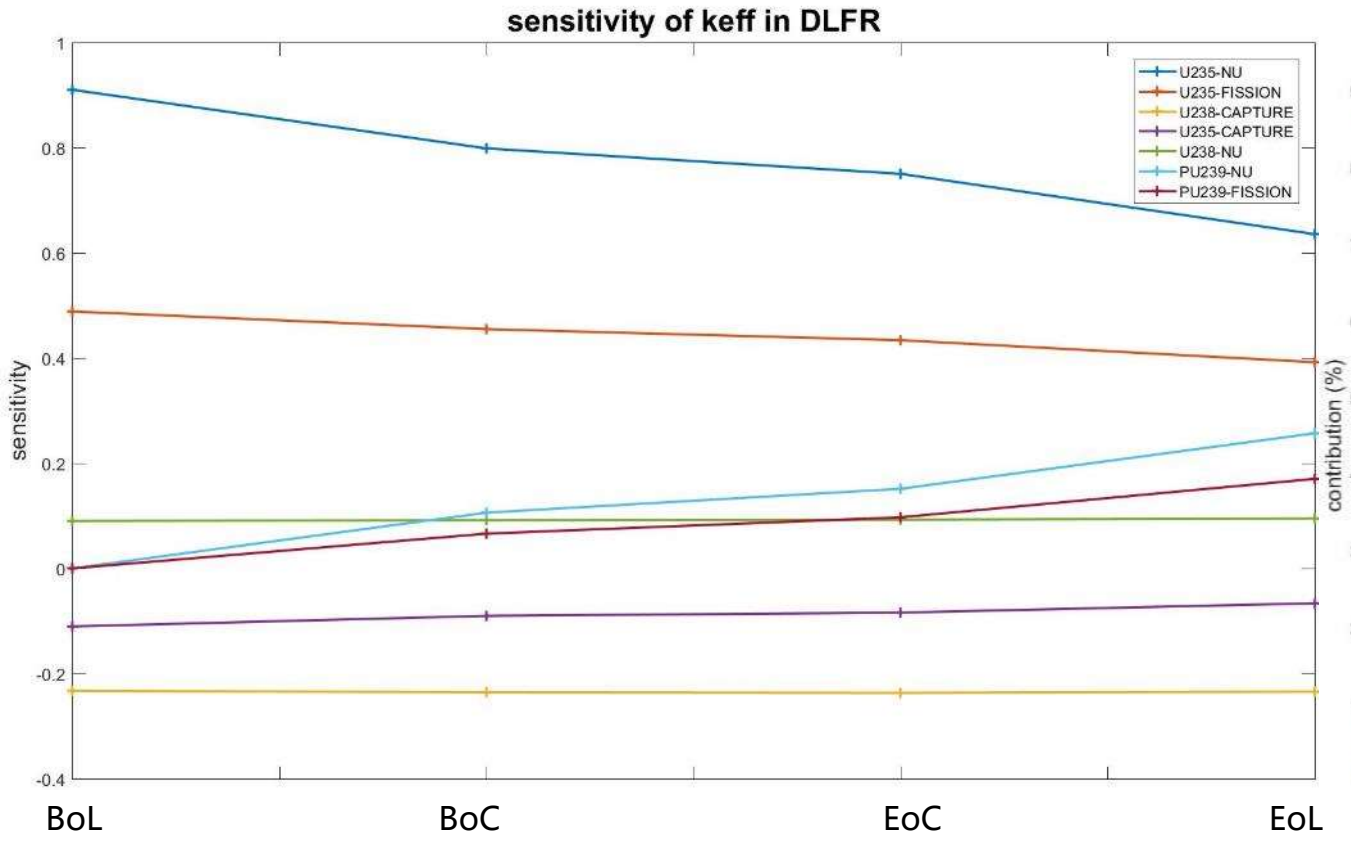
Inner Core Fuel Assembly

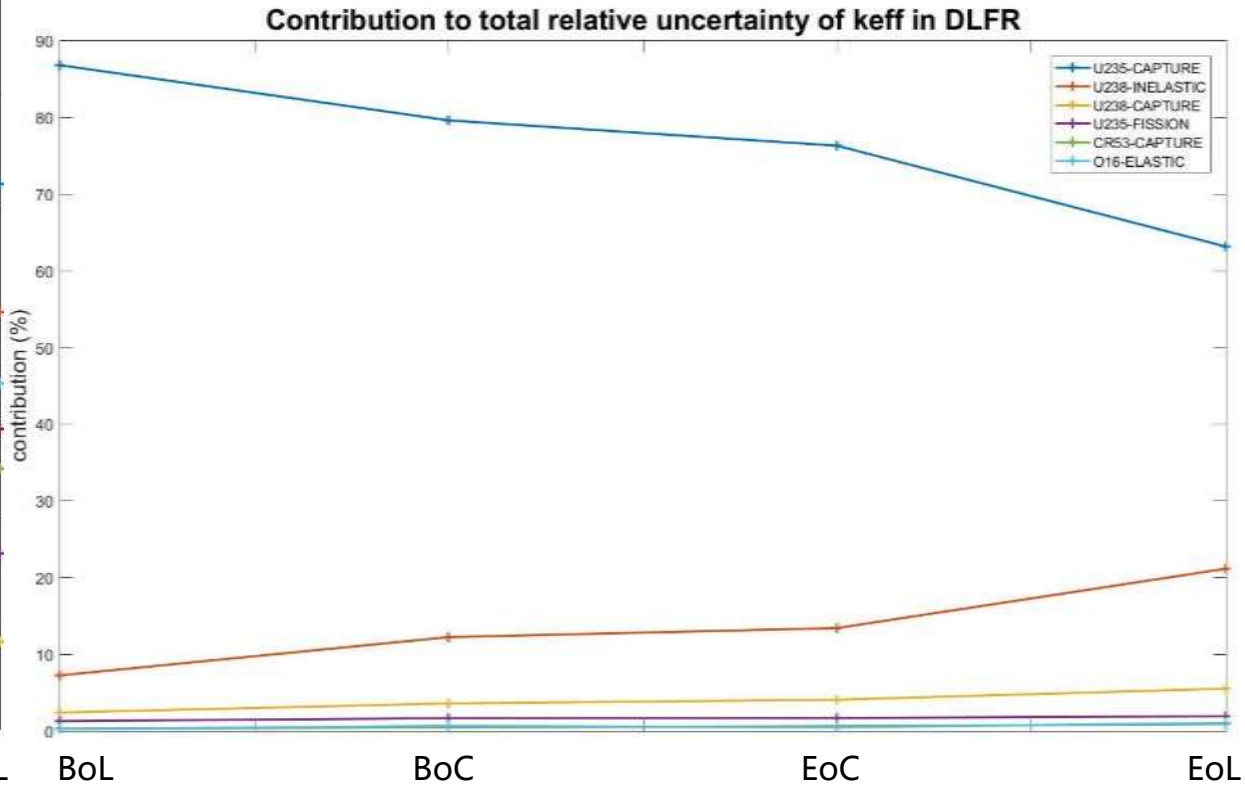




Sensitivity and Uncertainty Contributed to Total in Different Periods

Outer Core Fuel Assembly



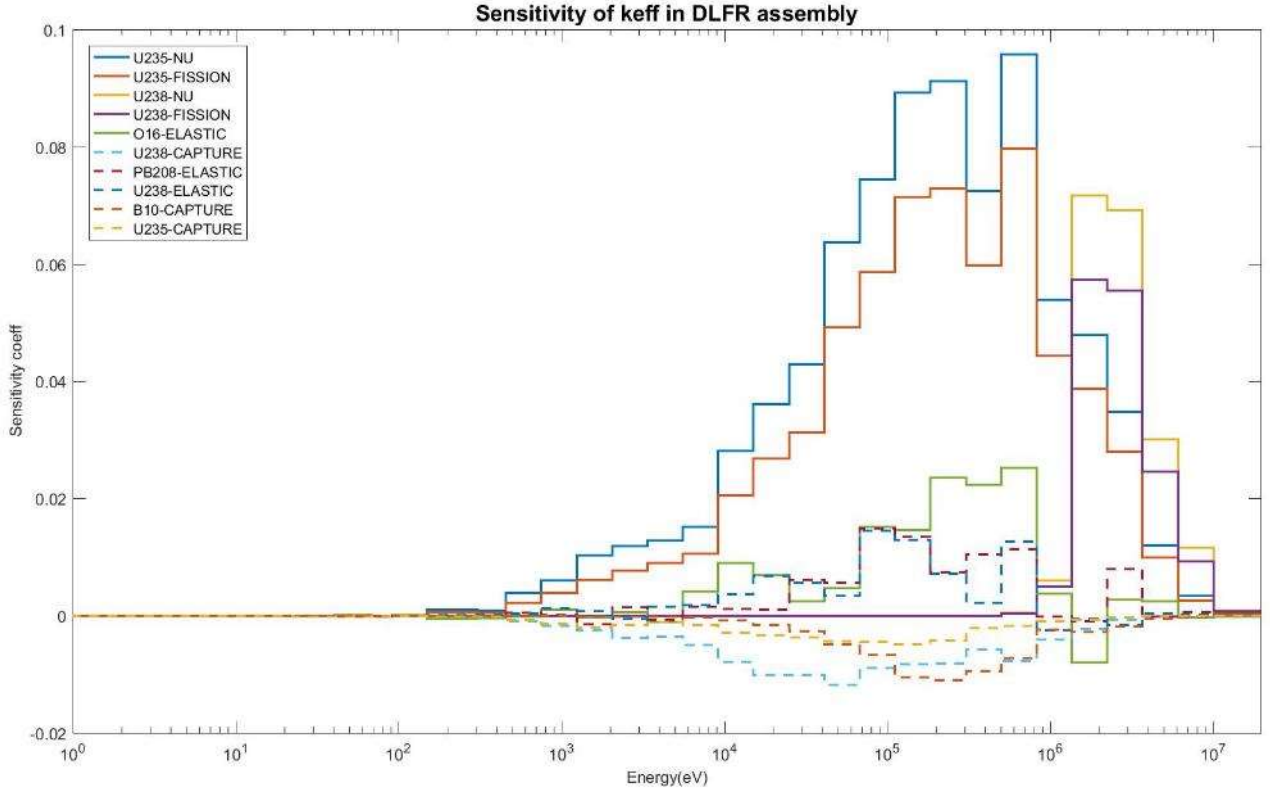


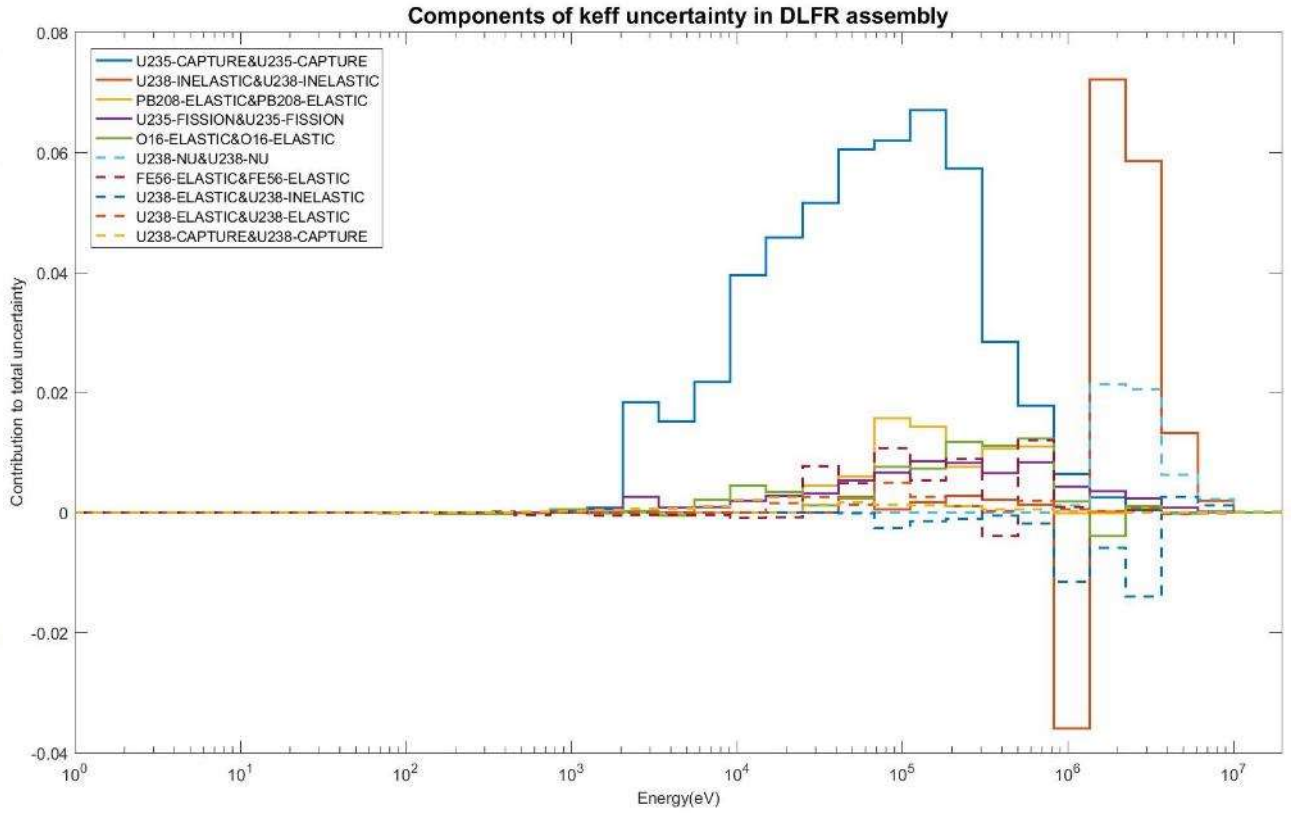
PART 3.2

Safety Rod

Distribution of S/U Corresponding to the Most Important 20 Parameters

Safety Rod surrounded by Inner Core Fuel Assembly at Beginning of Life





Safety Rod surrounded by BoL inner Assembly:

K_{eff} Standard Deviation: 0.009983

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	49.6019
$^{238}U - \sigma_{n,n'}$	12.1277
$^{208}Pb - \sigma_{n,n}$	7.0904
$^{235}U - \sigma_{f}$	6.8442
$^{16}O - \sigma_{n,n}$	6.2960

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	0.94729	-0.041557
$^{208}Pb - \sigma_{n,n}$	0.12561	0.081090
$^{235}U - \sigma_{f}$	0.12502	0.635583
$^{16}O - \sigma_{n,n}$	0.11627	0.129220
$^{238}U - \sigma_{n,n'}$	0.09061	-0.102597

Safety Rod surrounded by BoC inner Assembly:

K_{eff} Standard Deviation: 0.010595

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	20.9232
$^{56}Fe - \sigma_{n,n}$	19.4188
$^{238}U - \sigma_{n,n'}$	14.8347
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	9.8891
$^{16}O - \sigma_{n,n}$	6.8959

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	0.405438	-0.028904
$^{56}Fe - \sigma_{n,n}$	0.340385	0.057541
$^{238}U - \sigma_{n,n'}$	0.298071	-0.006460
$^{238}U - \sigma_{n,n}$	0.155563	0.074835
$^{16}O - \sigma_{n,n}$	0.129392	0.142088

Safety Rod surrounded by EoC inner Assembly:

K_{eff} Standard Deviation: 0.009616

Parameter Pair	Contribution to Total Uncertainty (%)
$^{238}U - \sigma_{n,n'}$	27.4812
$^{235}U - \sigma_{n,\gamma}$	16.2871
$^{56}Fe - \sigma_{n,n}$	15.8962
$^{238}U - (\sigma_{n,n}\,,\ \sigma_{n,n'})$	7.1493
$^{238}U - \bar{\nu}$	5.9046

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}U - \sigma_{n,n'}$	0.44838	-0.006568
$^{235}U - \sigma_{n,\gamma}$	0.31823	-0.023141
$^{56}Fe - \sigma_{n,n}$	0.28609	0.049147
$^{238}U - \sigma_{n,n}$	0.11081	0.075307
$^{238}U - \bar{\nu}$	0.09529	0.194659

Safety Rod surrounded by EoL inner Assembly:

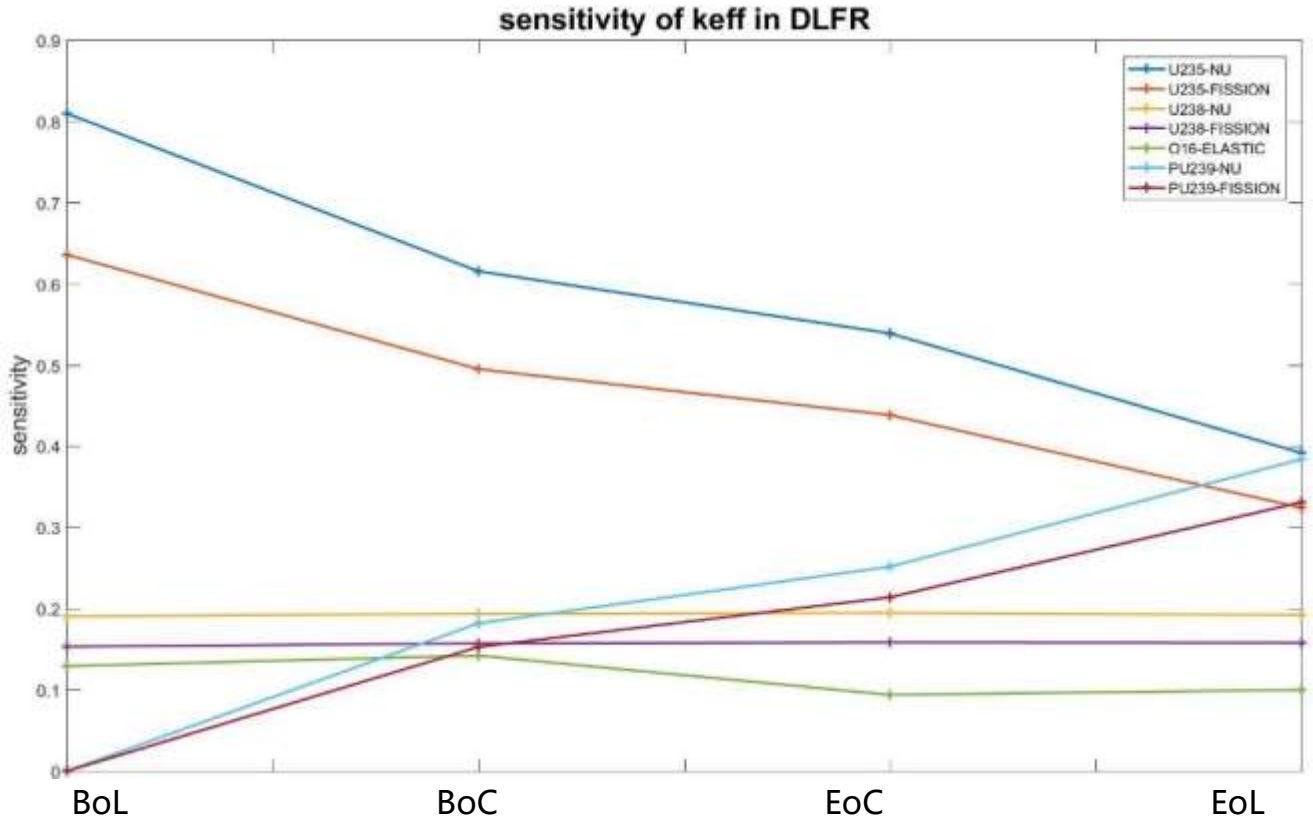
K_{eff} Standard Deviation: 0.008373

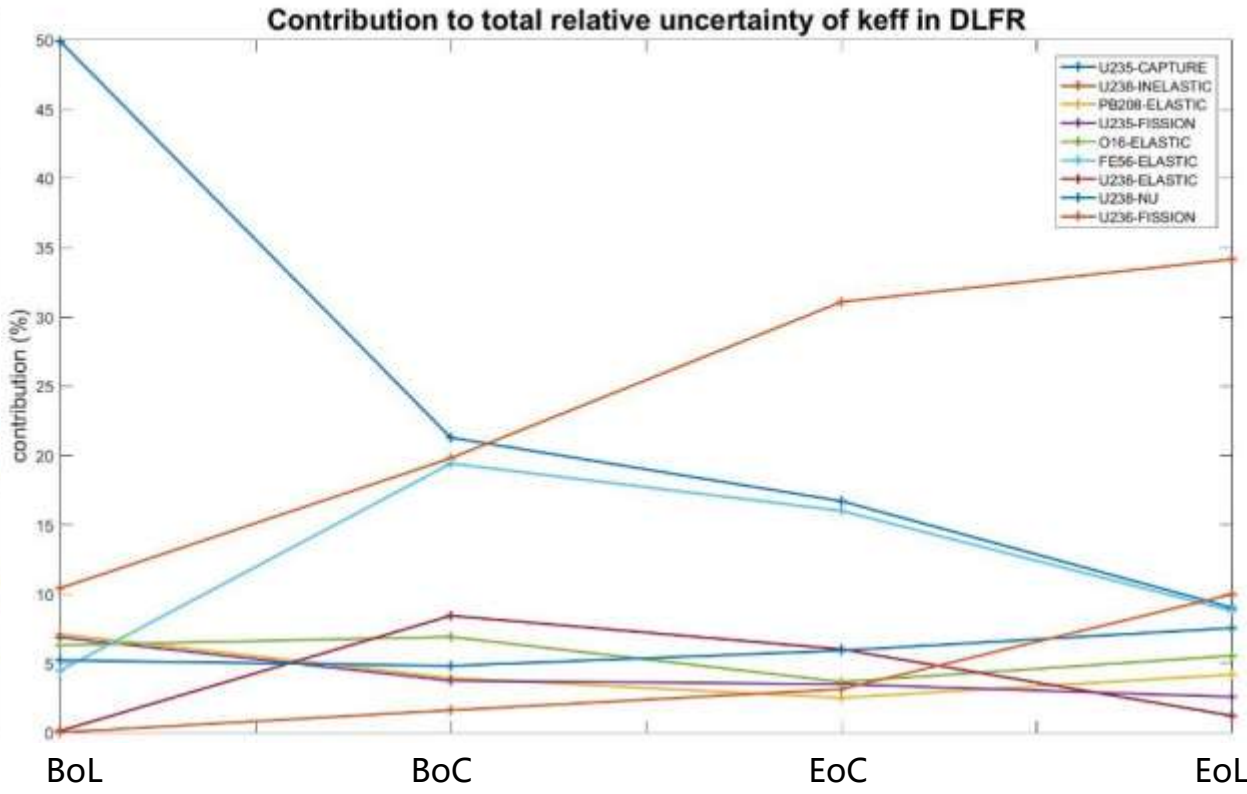
Parameter Pair	Contribution to Total Uncertainty (%)
$^{238}U - \sigma_{n,n'}$	34.8277
$^{236}U - \sigma_{f}$	9.9612
$^{235}U - \sigma_{n,\gamma}$	8.8226
$^{56}Fe - \sigma_{n,n}$	8.7255
$^{238}U - \bar{\nu}$	7.5280

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}U - \sigma_{n,n'}$	0.465302	-0.017072
$^{235}U - \sigma_{n,\gamma}$	0.171462	-0.015318
$^{236}U - \sigma_{f}$	0.170007	0.010268
$^{56}Fe - \sigma_{n,n}$	0.139694	0.028763
$^{238}U - \bar{\nu}$	0.121730	0.191956

Sensitivity and Uncertainty Contributed to Total in Different Periods

Safety Rod



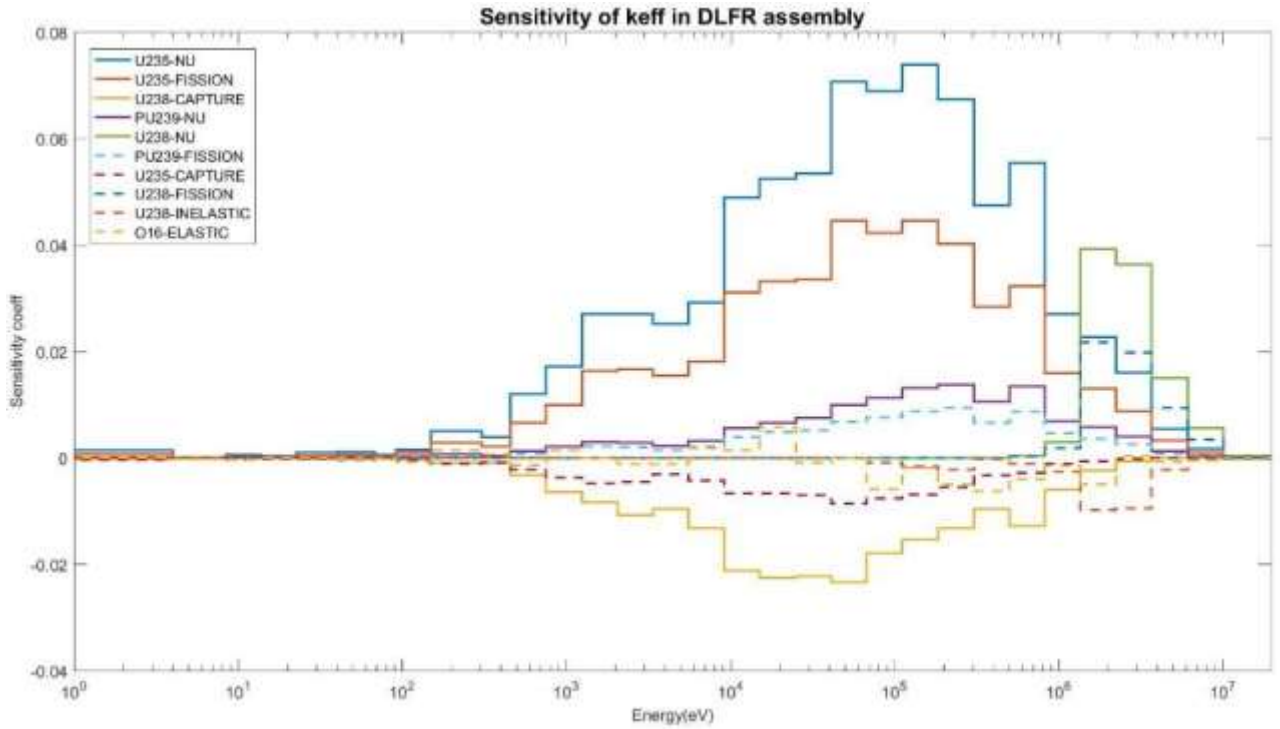


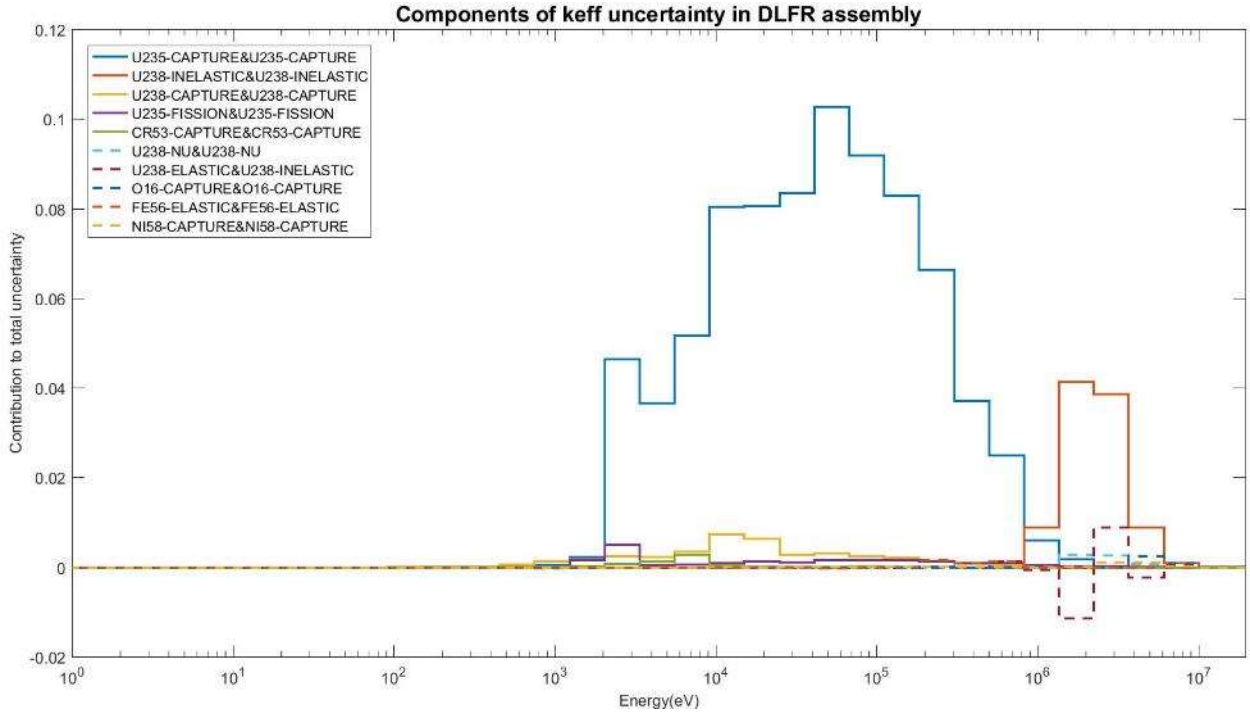
PART 3.3

2D Whole Core

Distribution of S/U Corresponding to the Most Important 10 Parameters

2D Whole Core with Safety Rod out at Beginning of Life





2D Whole Core with Safety Rod out at BoL:

K_{eff} Standard Deviation: 0.017122

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	84.7604
$^{238}U - \sigma_{n,n'}$	9.2950
$^{238}U - \sigma_{n,\gamma}$	2.7068
$^{235}U - \sigma_{f}$	1.8171
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	-1.3867

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.61504	-0.098547
$^{238}U - \sigma_{n,n'}$	0.13958	-0.034373
$^{238}U - \sigma_{n,\gamma}$	0.04700	-0.213675
$^{235}U - \sigma_{f}$	0.03180	0.526743
$^{238}U - \sigma_{n,n}$	-0.01317	0.007237

2D Whole Core with Safety Rod in at BoL:

K_{eff} Standard Deviation: 0.016627

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	84.8102
$^{238}U - \sigma_{n,n'}$	8.3663
$^{238}U - \sigma_{n,\gamma}$	2.6780
$^{235}U - \sigma_{f}$	1.9128
$^{235}U - (\sigma_{n,n}, \sigma_{n,\gamma})$	-0.0078

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.607250	-0.096055
$^{238}U - \sigma_{n,n'}$	0.139454	-0.029788
$^{238}U - \sigma_{n,\gamma}$	0.046401	-0.207413
$^{235}U - \sigma_{f}$	0.033683	0.529179
$^{238}U - \bar{\nu}$	0.009034	-0.103665

2D Whole Core with Safety Rod out at BoC:

K_{eff} Standard Deviation: 0.014614

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	70.9466
$^{238}U - \sigma_{n,n'}$	16.4545
$^{238}U - \sigma_{n,\gamma}$	3.7255
$^{235}U - \sigma_{f}$	2.0054
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	1.6438

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.35330	-0.077559
$^{238}U - \sigma_{n,n'}$	0.29119	-0.042023
$^{238}U - \sigma_{n,\gamma}$	0.06472	-0.212163
$^{235}U - \sigma_{f}$	0.03487	0.468207
$^{238}U - \sigma_{n,n}$	0.01699	0.010483

2D Whole Core with Safety Rod in at BoC:

K_{eff} Standard Deviation: 0.014419

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	70.3116
$^{238}U - \sigma_{n,n'}$	14.6748
$^{238}U - \sigma_{n,\gamma}$	3.6564
$^{238}U - (\sigma_{n,n}, \sigma_{n,n'})$	3.2333
$^{235}U - \sigma_{f}$	2.0707

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.350580	-0.076630
$^{238}U - \sigma_{n,n'}$	0.266992	-0.035847
$^{238}U - \sigma_{n,\gamma}$	0.063624	-0.207103
$^{235}U - \sigma_{f}$	0.036008	0.473907
$^{238}U - \sigma_{n,n}$	0.035553	0.023593

2D Whole Core with Safety Rod out at EoC:

K_{eff} Standard Deviation: 0.013229

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	65.1362
$^{238}U - \sigma_{n,n'}$	22.5490
$^{238}U - \sigma_{n,\gamma}$	4.4631
$^{235}U - \sigma_f$	2.2424
$^{238}U - \bar{\nu}$	0.9324

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.23615	-0.068290
$^{238}U - \sigma_{n,n'}$	0.36535	-0.038401
$^{238}U - \sigma_{n,\gamma}$	0.07786	-0.210651
$^{235}U - \sigma_f$	0.03846	0.442943
$^{238}U - \bar{\nu}$	0.01503	0.106290

2D Whole Core with Safety Rod in at EoC:

K_{eff} Standard Deviation: 0.013081

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	72.2246
$^{238}U - \sigma_{n,n'}$	16.0571
$^{238}U - \sigma_{n,\gamma}$	4.3330
$^{235}U - \sigma_f$	2.3320
$^{238}U - \bar{\nu}$	0.9553

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.372160	-0.071178
$^{238}U - \sigma_{n,n'}$	0.258783	-0.032237
$^{238}U - \sigma_{n,\gamma}$	0.075305	-0.204820
$^{235}U - \sigma_f$	0.040107	0.447814
$^{238}U - \bar{\nu}$	0.015403	0.106501

2D Whole Core with Safety Rod out at EoL:

K_{eff} Standard Deviation: 0.010885

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	53.8269
$^{238}U - \sigma_{n,n'}$	29.1961
$^{238}U - \sigma_{n,\gamma}$	6.3703
$^{238}U - (\sigma_{n,n}\,,\ \sigma_{n,n'})$	-4.3104
$^{235}U - \sigma_{f}$	2.4146

Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.01789	-0.051801
$^{238}U - \sigma_{n,n'}$	0.43188	-0.046472
$^{238}U - \sigma_{n,\gamma}$	0.11114	-0.205452
$^{235}U - \sigma_{f}$	0.04106	0.375887
$^{238}U - \sigma_{n,n}$	-0.03818	0.019358

2D Whole Core with Safety Rod in at EoL:

K_{eff} Standard Deviation: 0.011287

Parameter Pair	Contribution to Total Uncertainty (%)
$^{235}U - \sigma_{n,\gamma}$	53.0769
$^{238}U - \sigma_{n,n'}$	27.3726
$^{238}U - \sigma_{n,\gamma}$	5.8802
$^{235}U - \sigma_{f}$	2.3522
$^{238}U - \bar{\nu}$	1.3014

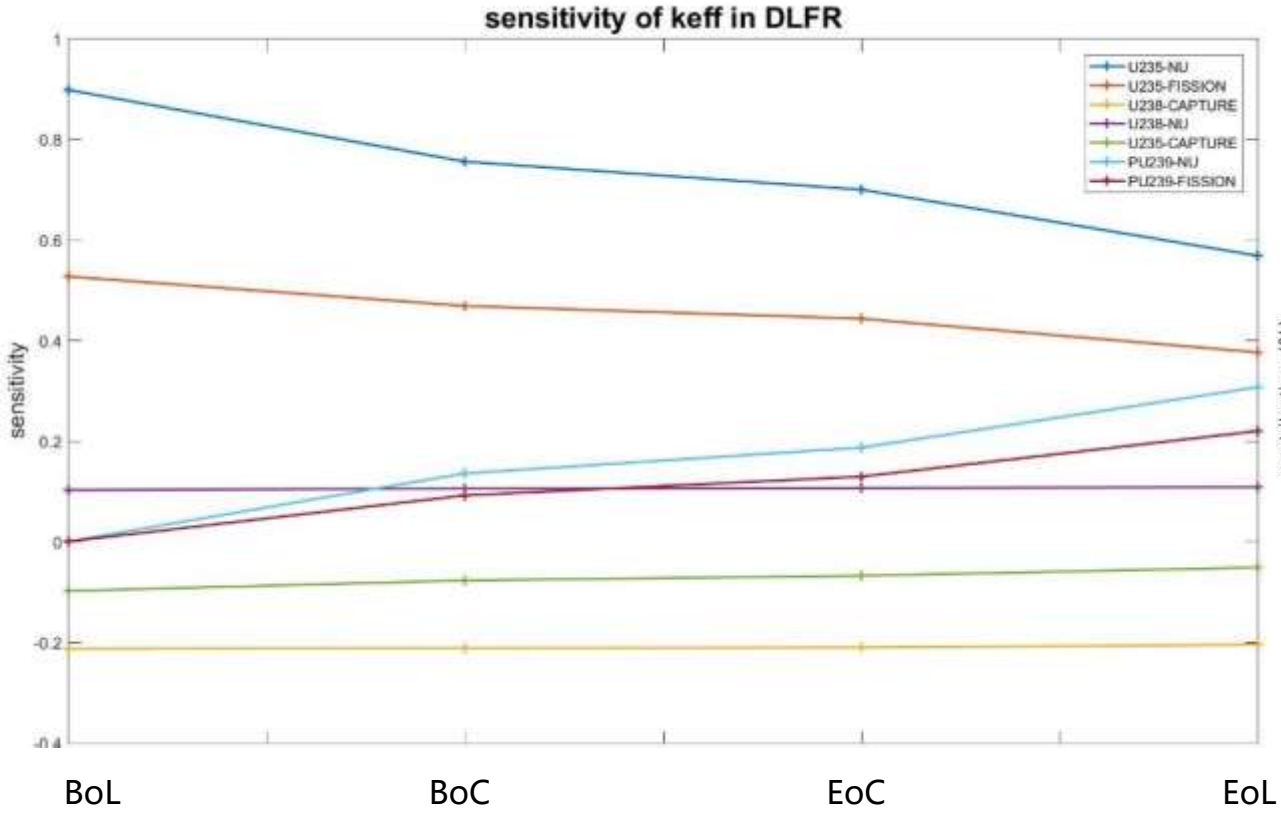
Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}U - \sigma_{n,\gamma}$	1.016330	-0.053765
$^{238}U - \sigma_{n,n'}$	0.454822	-0.037794
$^{238}U - \sigma_{n,\gamma}$	0.102275	-0.209787
$^{235}U - \sigma_{f}$	0.039774	0.384521
$^{238}U - \bar{\nu}$	0.020972	0.107249

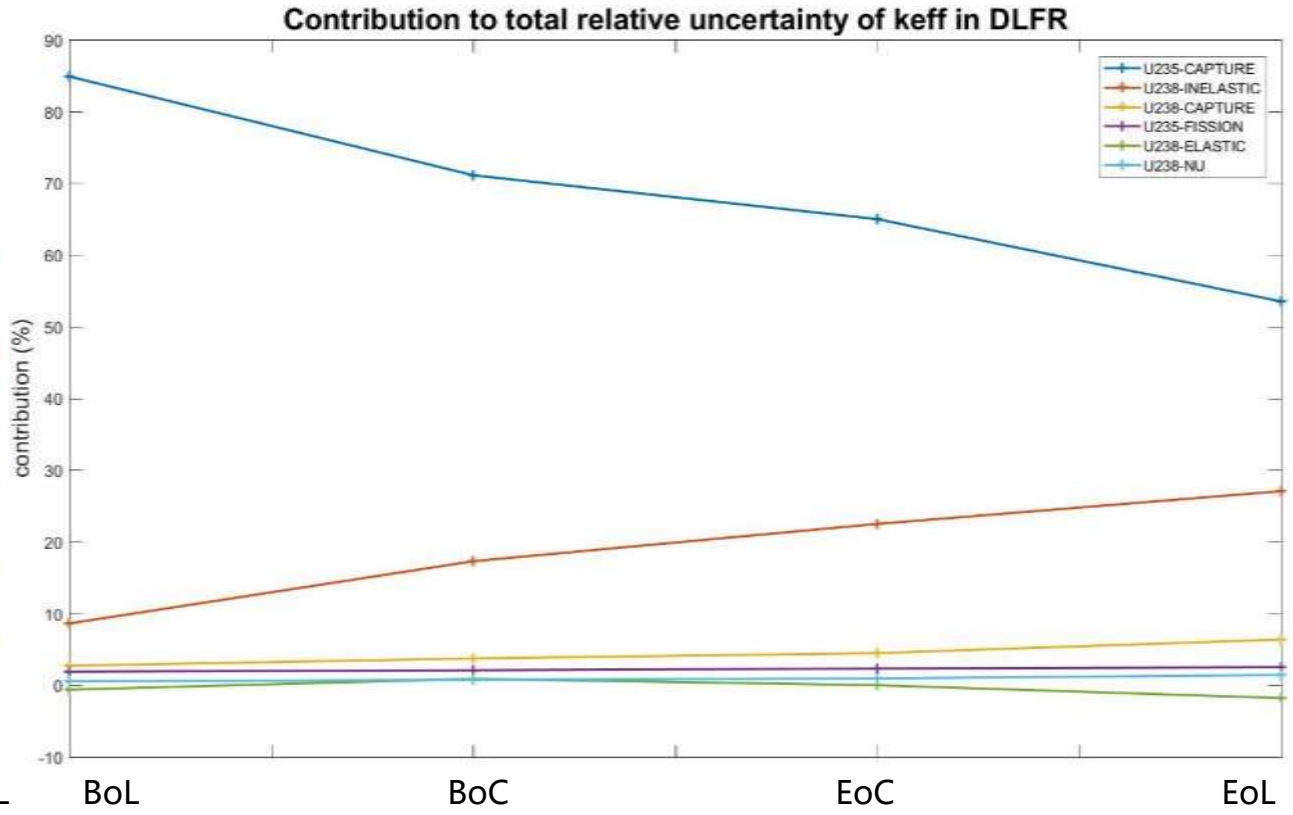
PART 04

Conclusion

Sensitivity and Uncertainty Contributed to Total in Different Periods

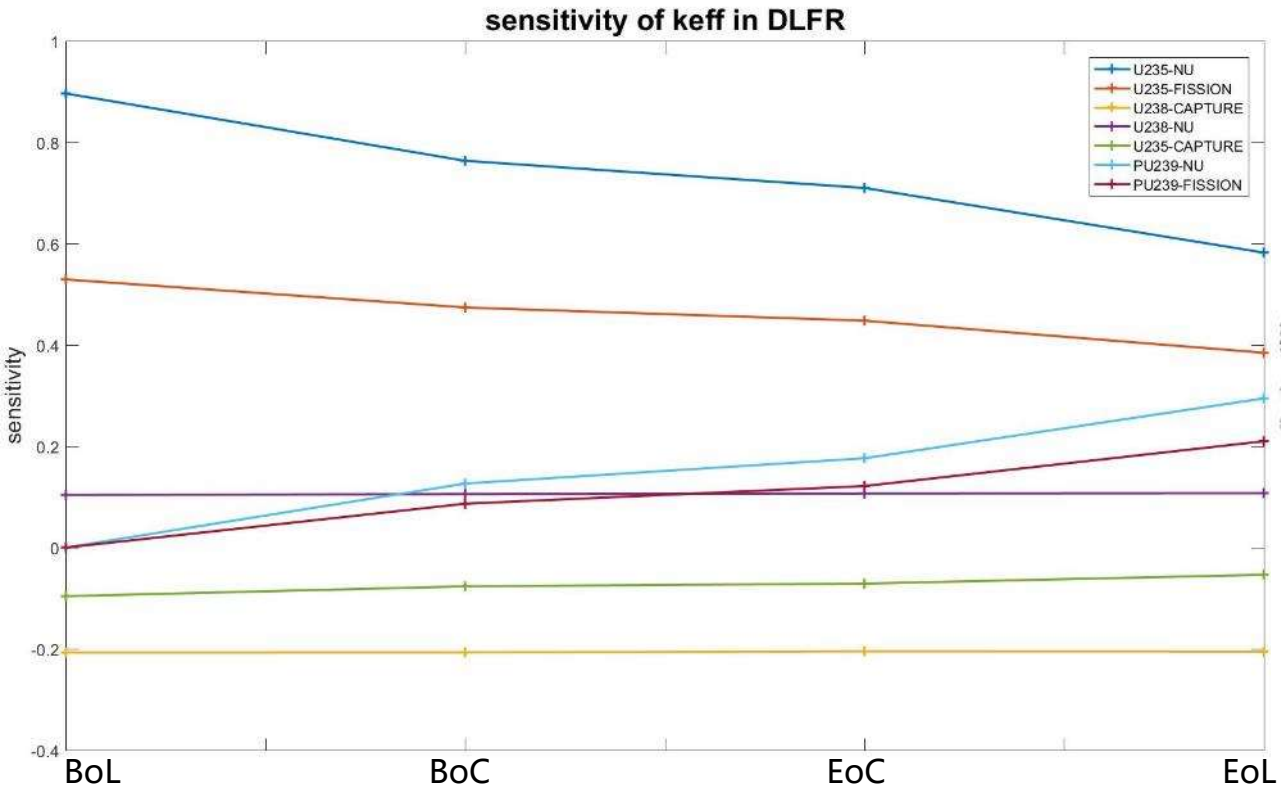
2D Whole Core with Safety Rod out

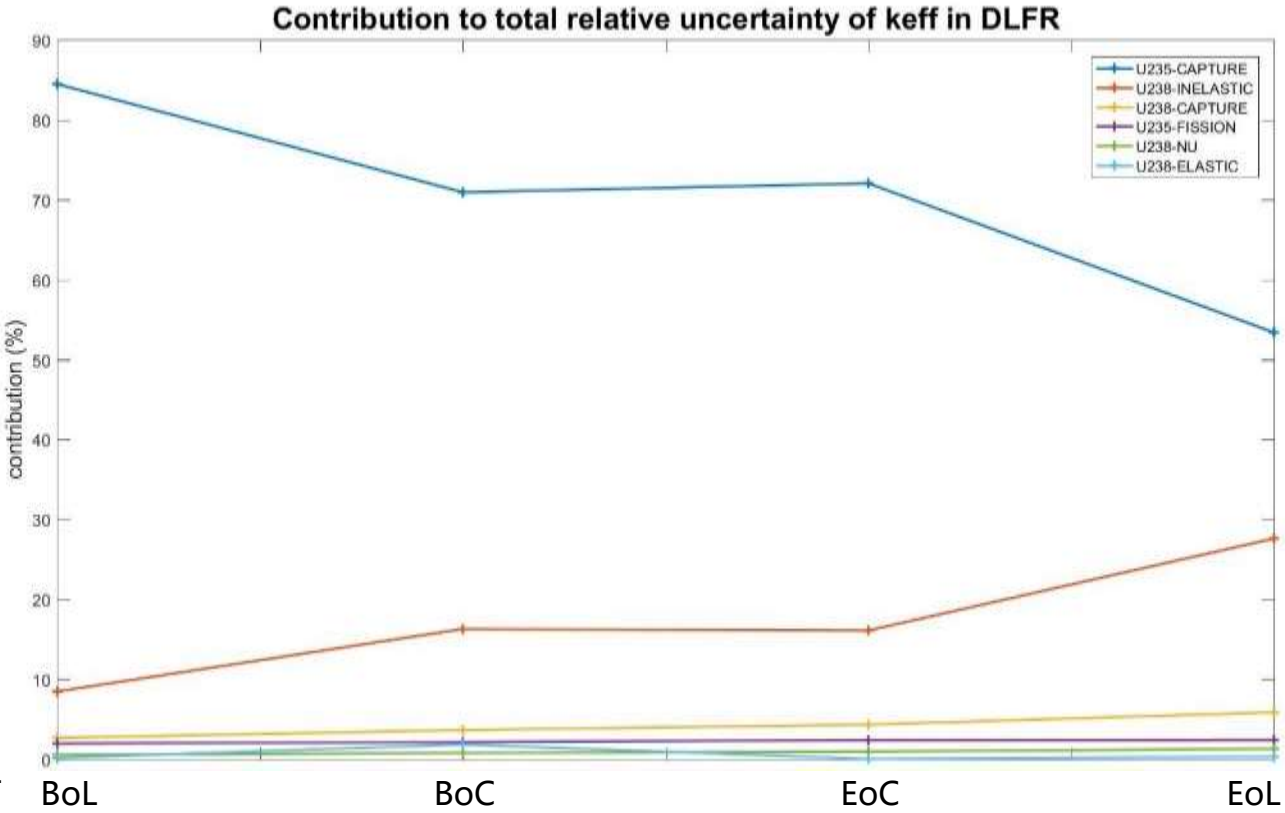




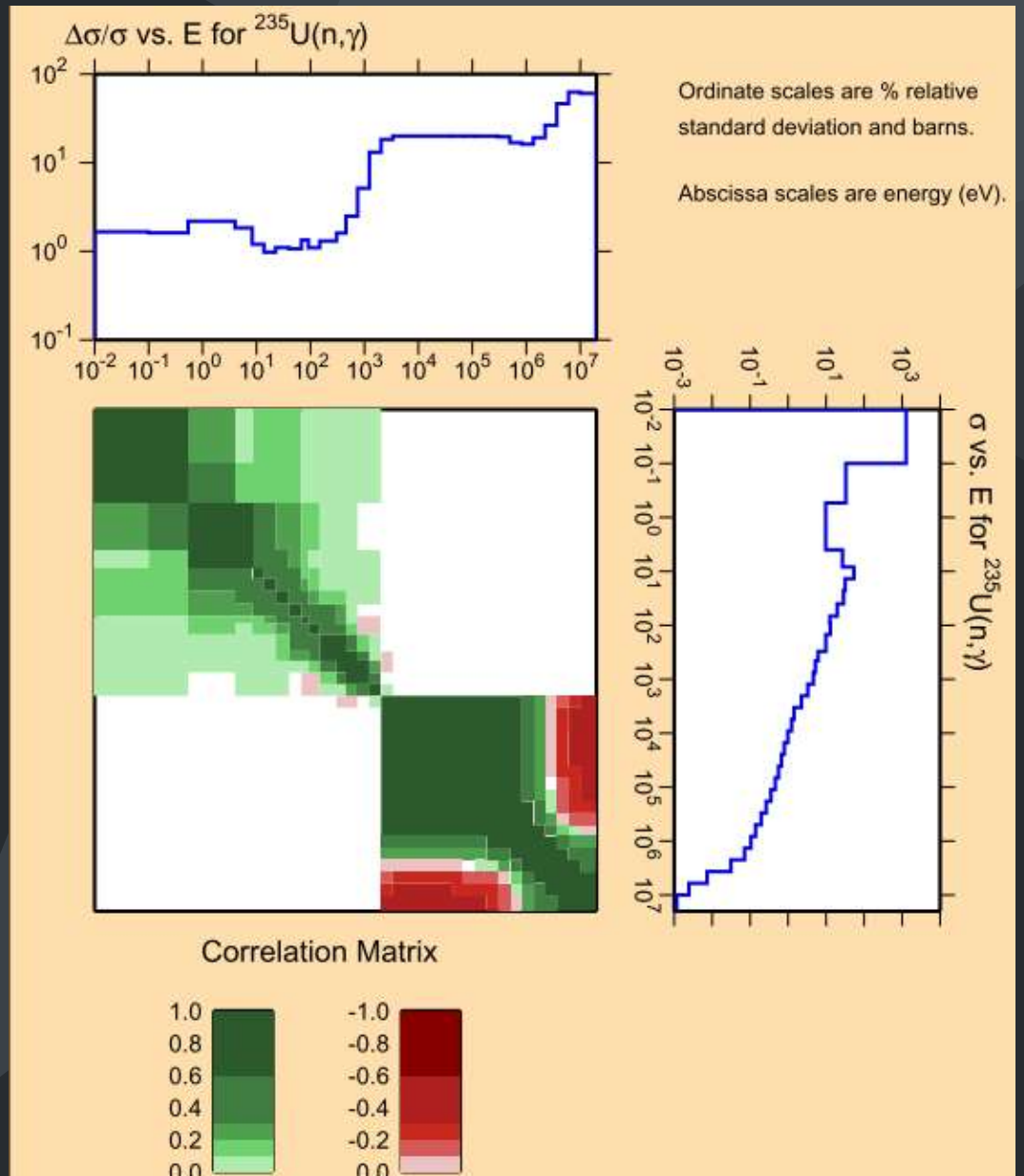
Sensitivity and Uncertainty Contributed to Total in Different Periods

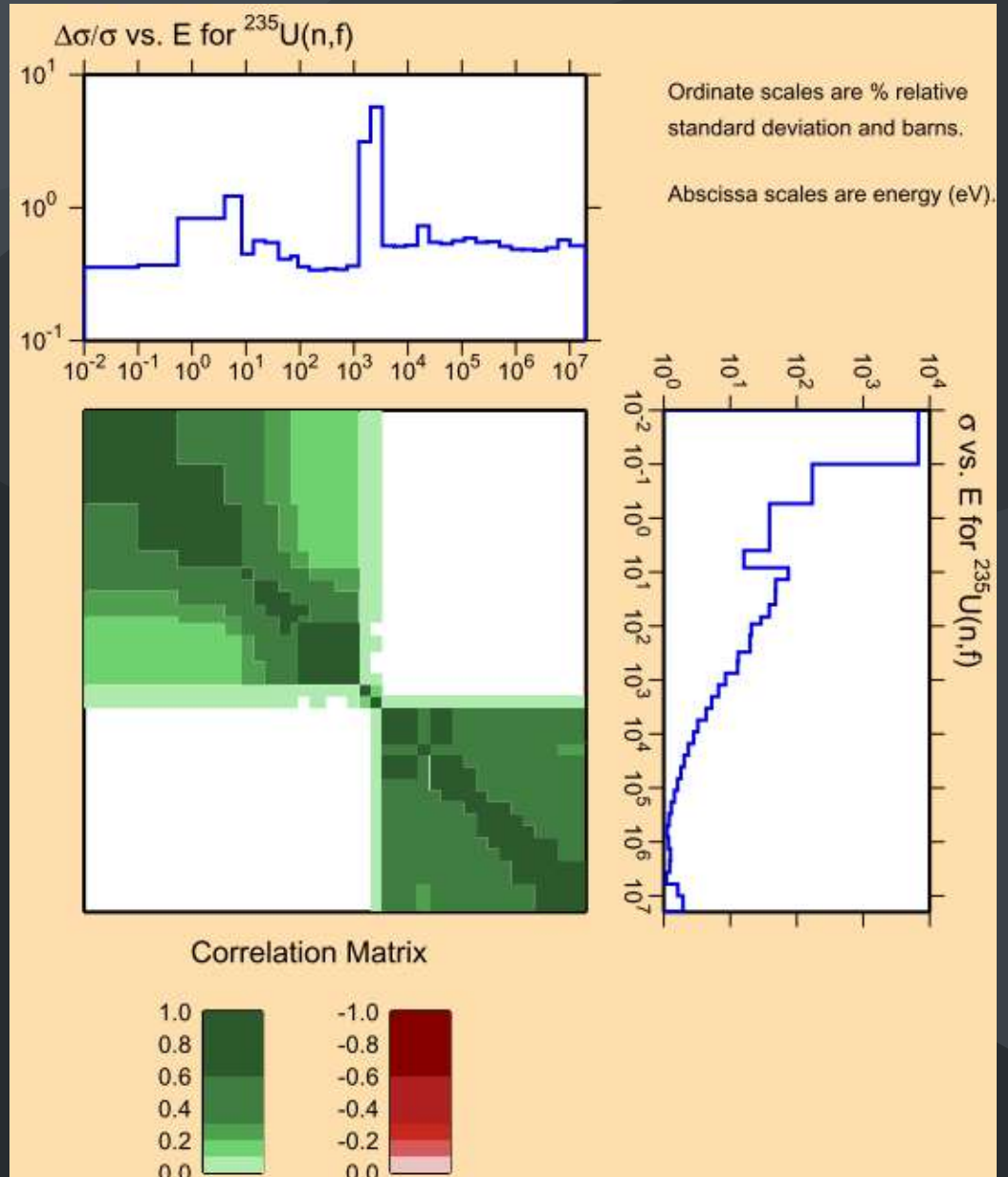
2D Whole Core with Safety Rod in





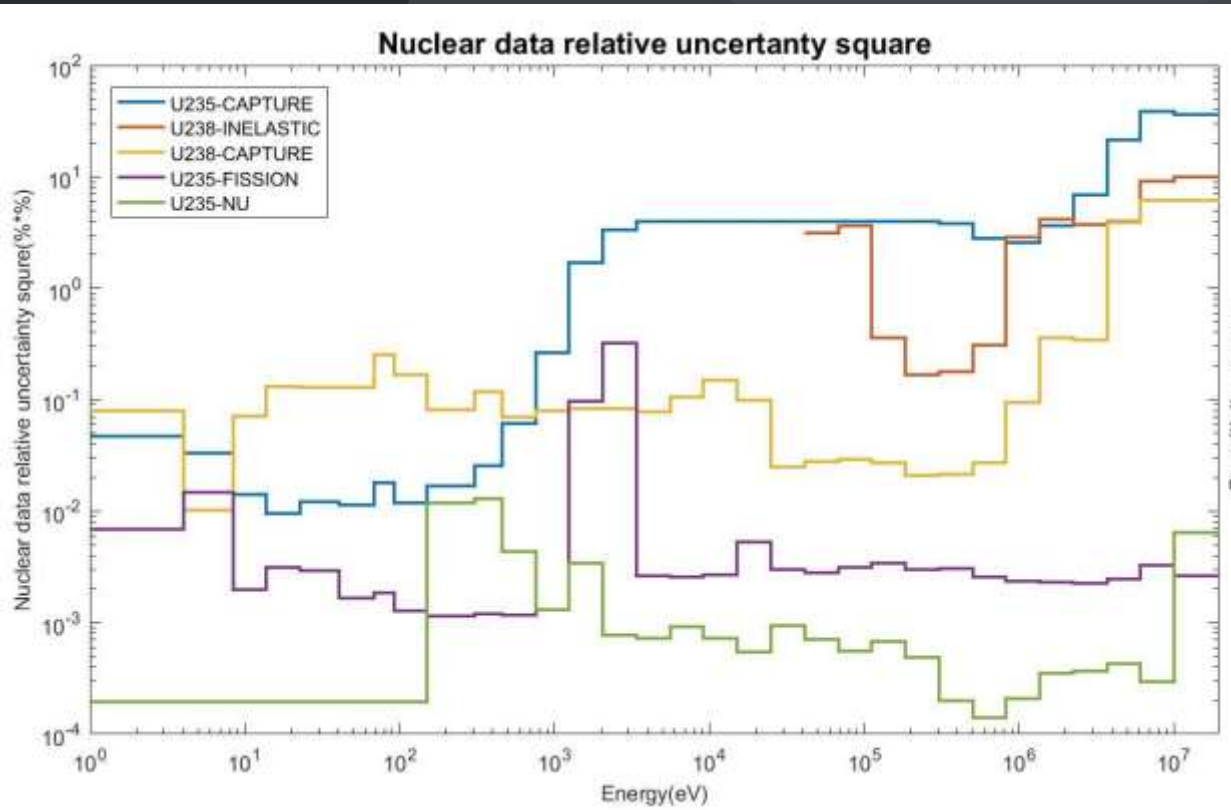
Correlation Matrices

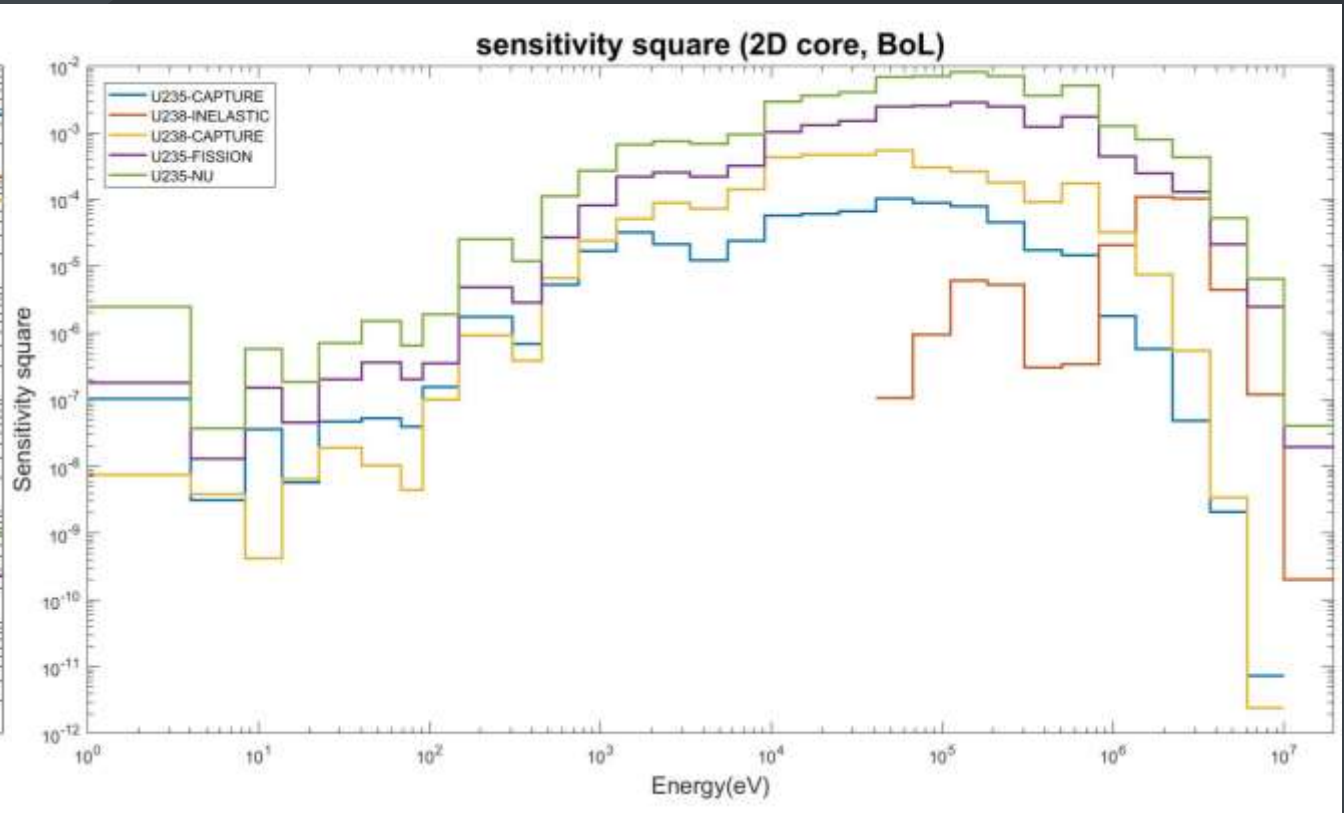




Nuclear Data Relative Uncertainty

(Elements on diagonal of each relative covariance matrix)



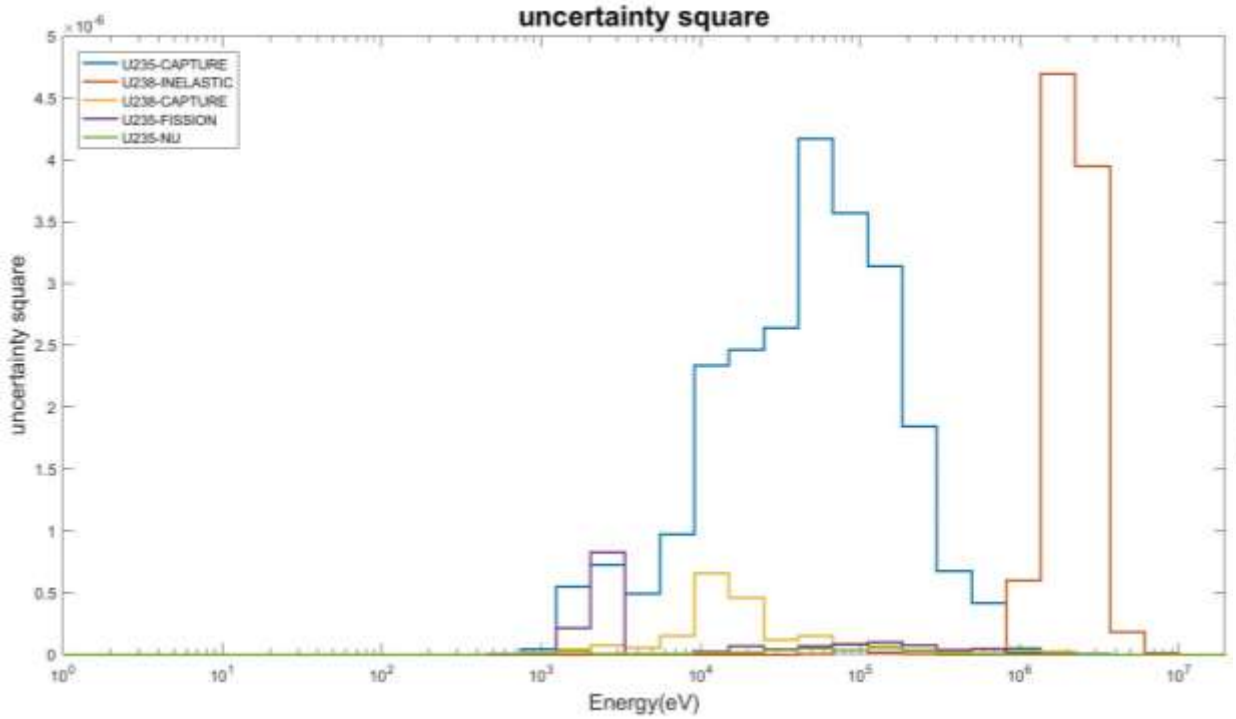


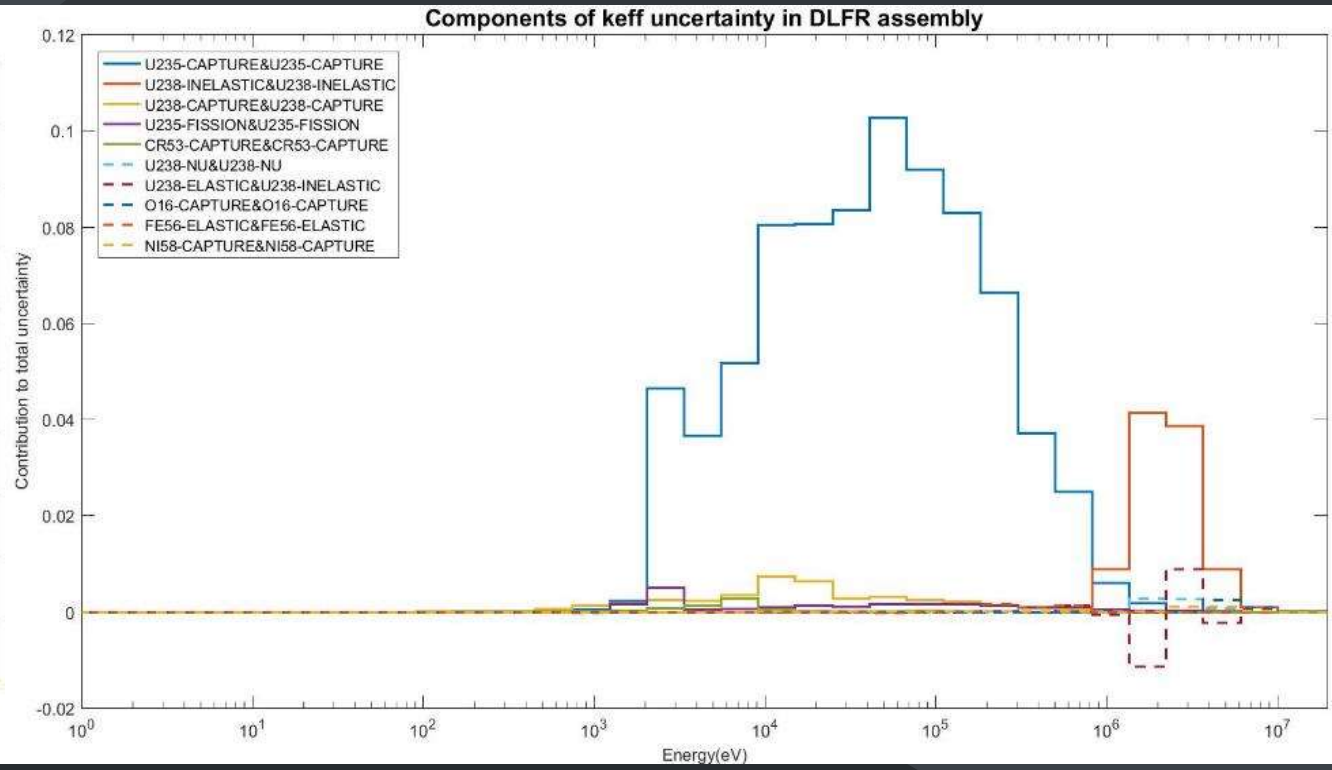
Uncertainty

$S_i \times r_{x_i}^2 \times S_i$, which is uncertainty square when considering that nuclear data in different energy groups are uncorrelated.

i.e. arithmetic product of the curves in the two figures in last page

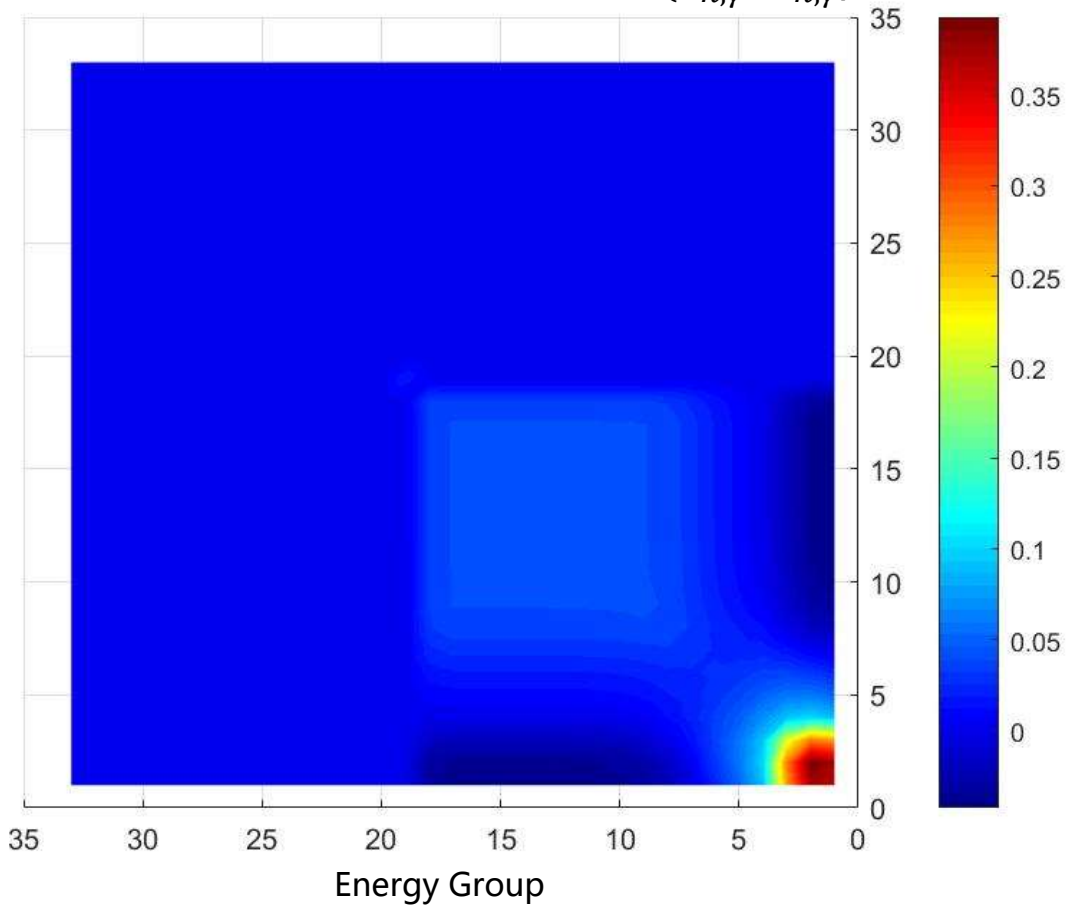
$S_i \times r_{x_i}^2 \times S_i + S_i \cdot r_{x_i}\, r_{x_j} \cdot S_j$, real uncertainty



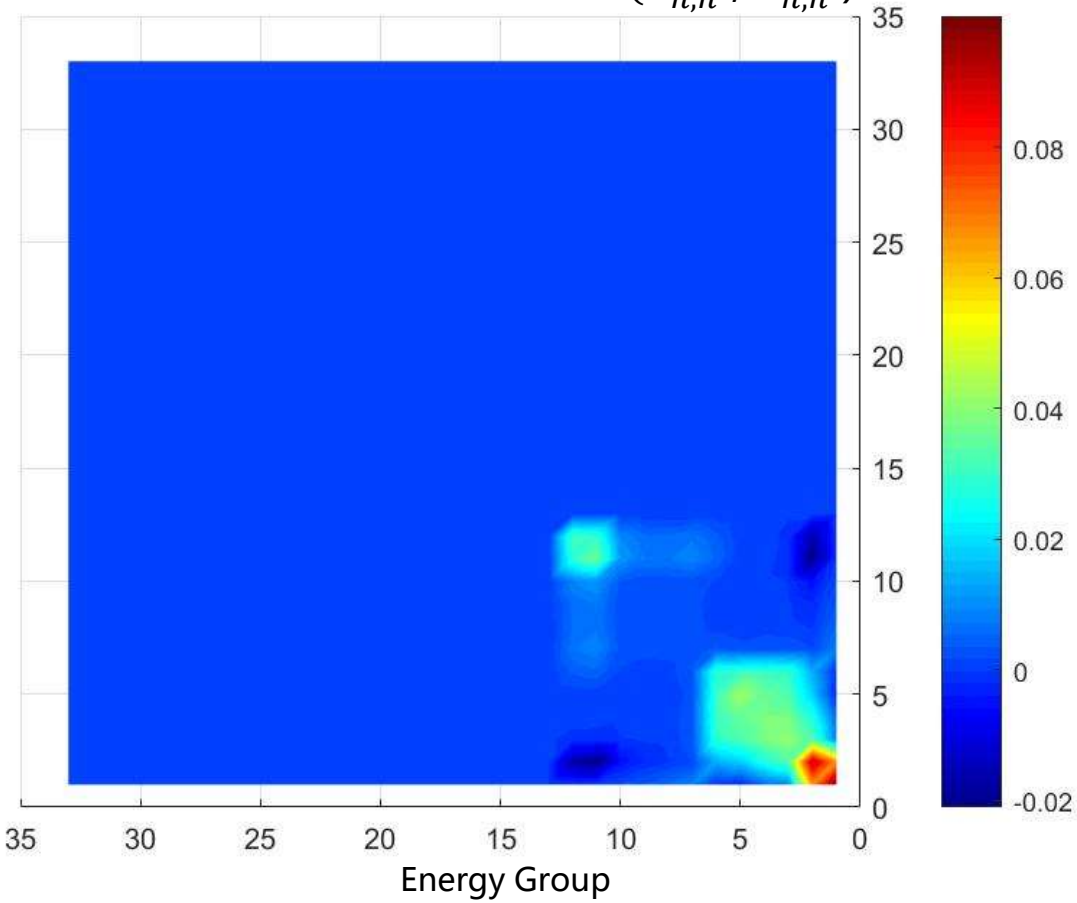


Covariance Matrix

Covariance Matrix of $^{235}U - (\sigma_{n,\gamma}, \sigma_{n,\gamma})$



Covariance Matrix of $^{238}U - (\sigma_{n,n'}, \sigma_{n,n'})$

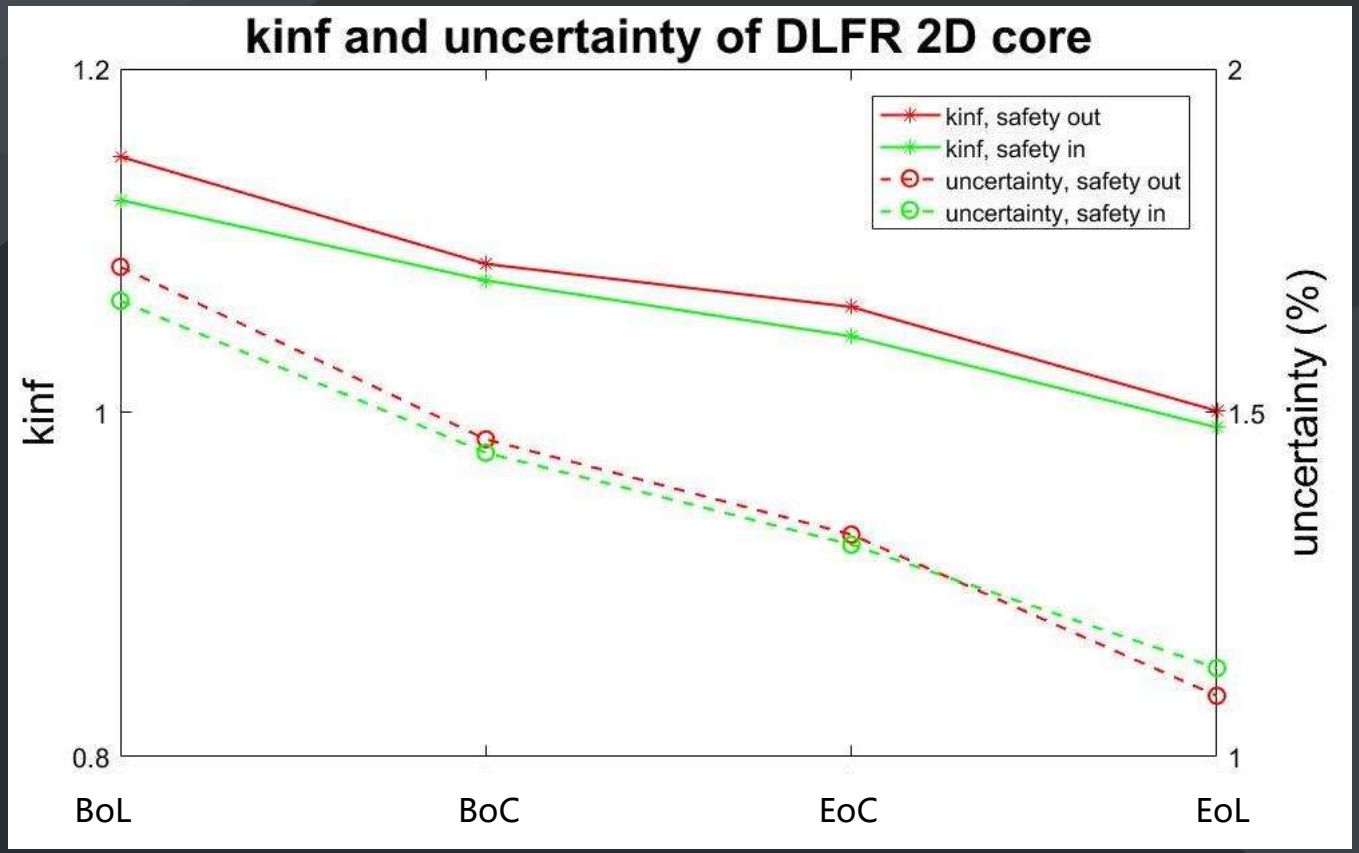


Conclusion

Sensitivity	Uncertainty Contribution
$^{235}U - \bar{\nu}$	$^{235}U - \sigma_{n,\gamma}$
$^{235}U - \sigma_f$	$^{238}U - \sigma_{n,n'}$
$^{238}U - \sigma_{n,\gamma}$	$^{238}U - \sigma_{n,\gamma}$
$^{235}U - \sigma_{n,\gamma}$	$^{235}U - \sigma_f$
$^{238}U - \bar{\nu}$	$^{238}U - \sigma_{n,n}$
$^{239}Pu - \bar{\nu}$	$^{238}U - \bar{\nu}$
$^{239}Pu - \sigma_f$	$^{53}Cr - \sigma_{n,\gamma}$

Period	Relative Uncertainty
BoL	1.71%
BoC	1.46%
EoC	1.32%
EoL	1.09%

k-inf & Uncertainty of 2D Whole Core

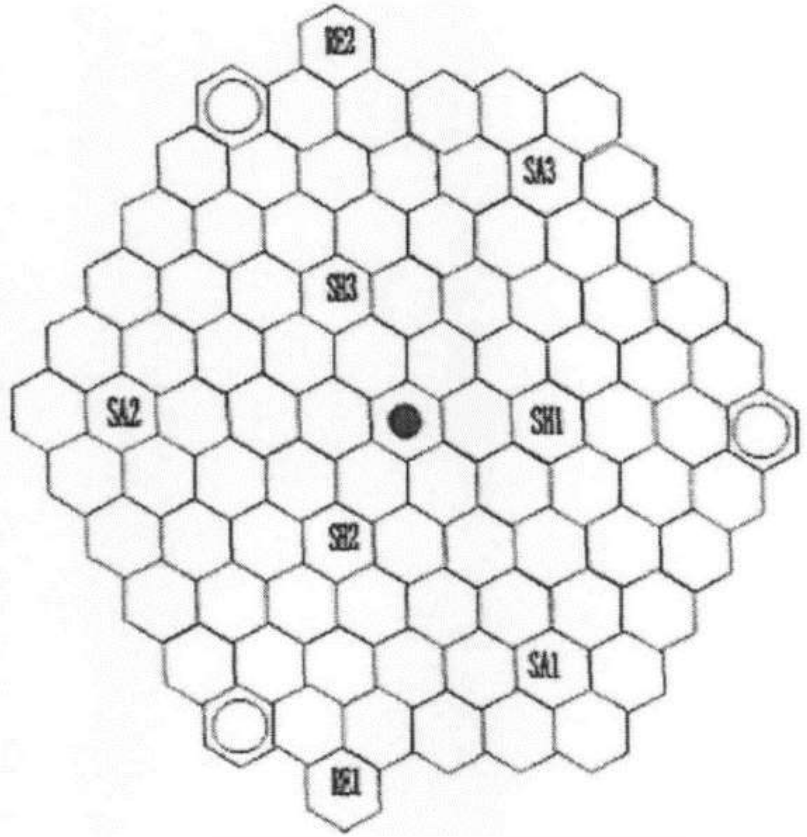


Comparison[1]

Reactor: CEFR (China Experimental Fast Reactor)
Fuel: UO_2 , $^{235}U\%$ = 64.4%
Radius: 30.2 cm
Covariance: Based on Transportation Calculation via ANISN
Code: SUCA1D
(Sensitivity and Uncertainty Code of Analysis, one dimension)

Total Uncertainty	2.65%
Reference Total Uncertainty[2]	1.90%

Number	Parameter Pair	Uncertainty	Contribution to Total (%)
1	$^{235}U - \sigma_f$	1.27%	22.97
2	$^{235}U - \sigma_{n,\gamma}$	2.20%	68.92
3	$^{238}U - \sigma_f$	0.15%	0.32
4	$^{238}U - \sigma_{n,\gamma}$	0.73%	7.59
5	$^{56}Fe - \sigma_{n,\gamma}$	0.12%	0.21



SA Safety Rod
SH Compensation Control Rod
RE Regulation Control Rod
Fuel Assembly
Neutron Source Assembly
Stainless Steel Assembly

CEFR Core in Equilibrium State

[1]刚直. 核截面引起积分参数k_eff不确定度的一维分析程序开发[D].中国原子能科学研究院,2006.
[2]俄罗斯技术报告. CEFR堆芯物理特性计算误差分析
([2] is just mentioned but not cited by [1], reference is not given in [1].)

Reference

[1]Westinghouse Electric Company LLC, Demonstration Lead-cooled Fast Reactor Details: Westinghouse Lead-cooled Fast Reactor. March 2016.

[2] Yishu Qiu, Manuele Aufiero, Kan Wang, Massimiliano Fratoni, Development of sensitivity analysis capabilities of generalized responses to nuclear data in Monte Carlo code RMC, *In Annals of Nuclear Energy*, Volume 97, 2016, Pages 142-152.

[3] N. Touran and J. Yang, "Sensitivities and Uncertainties Due to Nuclear Data in a Traveling Wave Reactor," *Proceedings of the PHYSOR 2016 Meeting in Sun Valley*, ID, May 2016.

[4] 丘意书. 基于RMC的核数据敏感性与燃耗不确定度分析方法研究[D]. 清华大学，2017

[5] Cacuci D G. *Handbook of Nuclear Engineering, Vol. I: Nuclear Engineering Fundamentals*. Springer, 2010.

[6] M. Herman, P. Obložinský, P. Talou, M.B. Chadwick, et al. COMMARA-2.0 Neutron Cross Section Covariance Library. U.S. Department of Energy Office of Science, Office of Nuclear Physics. March 2011.

[7] D. Rochman, M. Herman, P. Obložinský, and S. F. Mughabghab, “Preliminary Cross Section Covariances for WPEC Subgroup 26,” Report BNL-77407-2007-IR, Brookhaven National Laboratory (2007). See also addition to this report, “Preliminary nubar Covariances for 77407-2007-IR-Suppl.1.

[8] Aufiero, M. et al. "A collision history-based approach to sensitivity/perturbation calculations in the continuous energy Monte Carlo code SERPENT", *Ann. Nucl. Energy*, 152 (2015) 245-258.

[9] Zhu, T., Vasiliev, A., Ferroukhi, H., Pautz, A., & Tarantola, S. (2015). NUSS-RF: stochastic sampling-based tool for nuclear data sensitivity and uncertainty quantification. *Journal of Nuclear Science and Technology*, 52(7-8), 1000-1007.

[10] 刚直. 核截面引起积分参数k_eff不确定度的一维分析程序开发[D]. 中国原子能科学研究院, 2006.

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Yishu QIU (Tsinghua, Department of Engineering Physics)

Lidong WANG (Tsinghua, Institute of Nuclear and New Energy Technology)

Ishita TRIVEDI (NCSU, Department of Nuclear Engineering)

Kaiyue ZENG (NCSU, Department of Nuclear Engineering)

Jun SHI (UCB, Engineering Research Centers)

END | THANK YOU!

PRESENTED BY LI JIN