

DLFR

Demonstration Lead-cooled Fast Reactor

S & U Analysis

Sensitivity & Uncertainty Analysis

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CONTENT



PART 01

Introduction



PART 02

Modeling



PART 03

Calculation



PART 04

Conclusion

PART

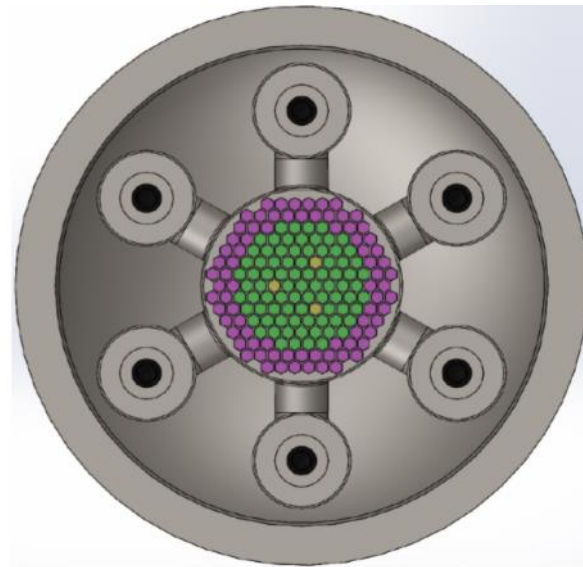
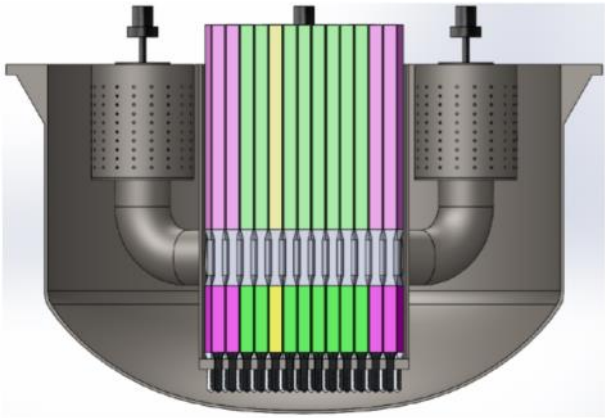
01

Introduction

DLFR

By Westinghouse, U.S.

Demonstration Lead-cooled Fast Reactor



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

Design Parameter

Power rate: 500MWt

Neutron flux: Peak $\sim 2 \times 10^{15}$ n/cm²

Reactor Type

Lead-cooled
Pool-type
Fast reactor

Objective

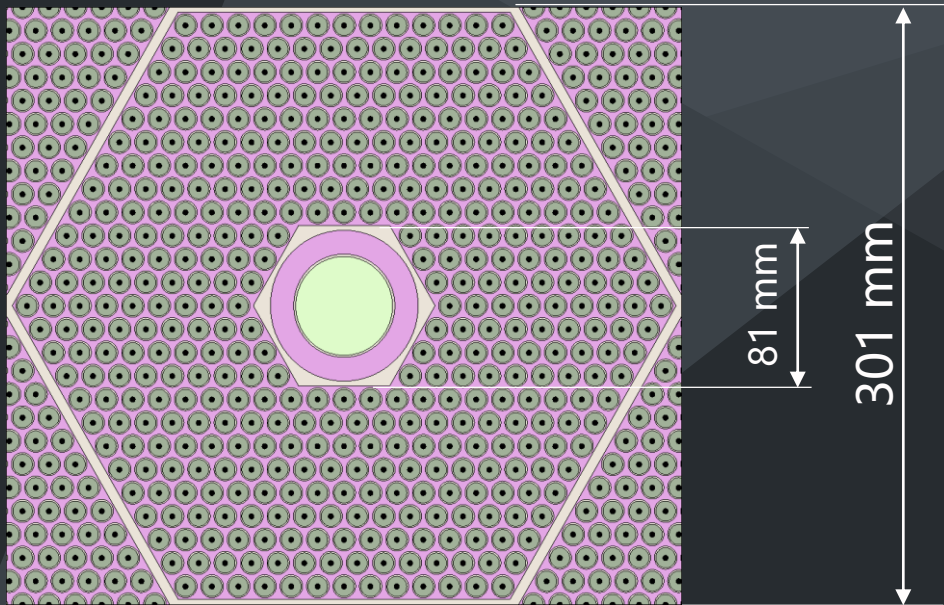
Feasibility
Basic performance
Upgrade





PART

02

Modeling

Assembly



-  Coolant Pb
-  Cladding Steel
-  Hollow Void
-  Fuel

Boundary: Periodical

Calculation:

Periodical Boundary

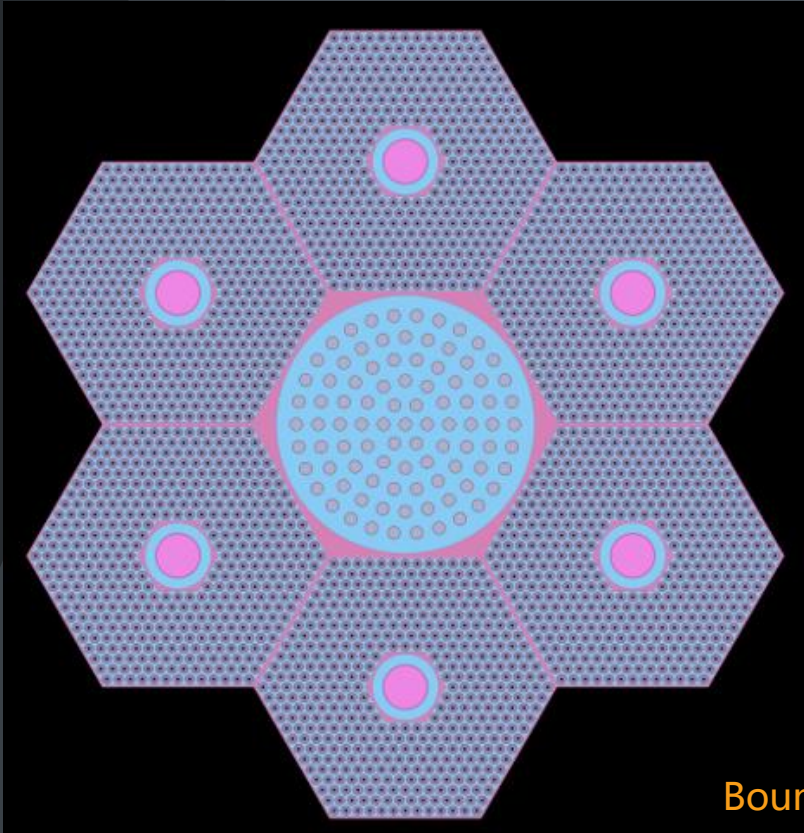
Inner Core Assembly

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



Boundary: Black

- Coolant -Pb
- Cladding -Steel
- Hollow -Void
- Inner Core Fuel
- Reflector -YSZ 8% mol
- Safety - B_4C

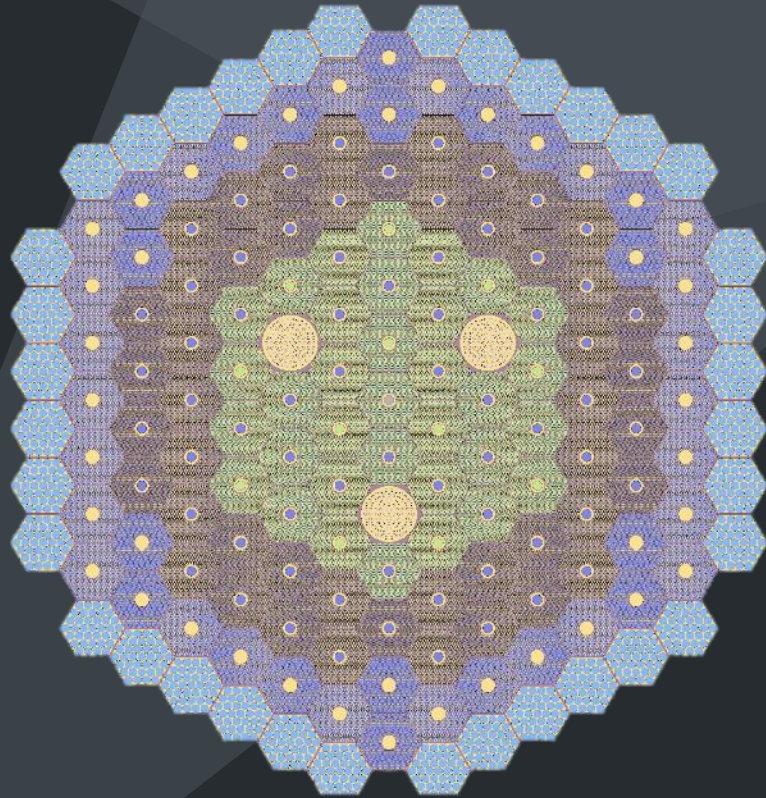
Calculation:








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

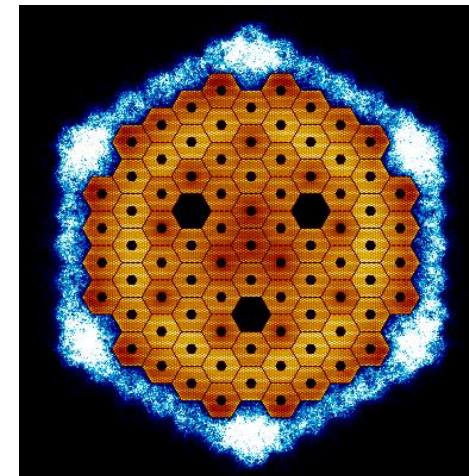


	Coolant	-Pb		Reflector	-YSZ 8% mol
	Cladding	-Steel		Shield	-Borated Steel
	Inner Fuel			Safety	-B ₄ C
	Outer Fuel			Plenum	

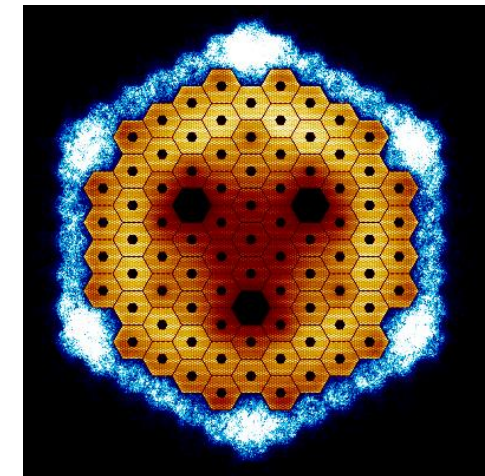
Calculation:

Time	$k_{inf} \pm \text{error}$	
	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

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

Indirect effect terms

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

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

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

$$15543 = 471 \times 33$$

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

Sandwich Rule

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

— V is (relative) covariance matrix

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

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

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

— $r_{x_i}^2$ 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

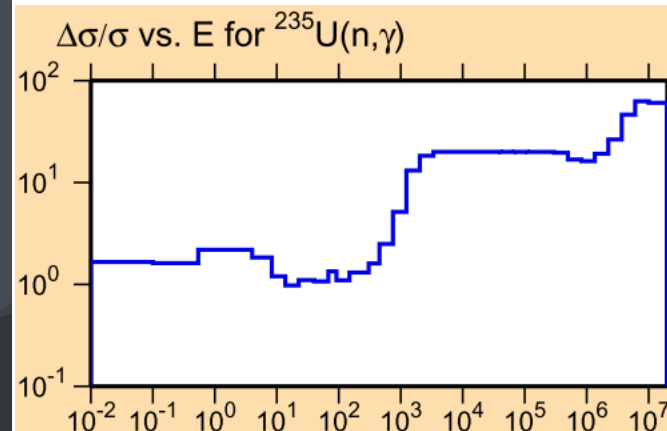
Elastic/Inelastic Scattering $(n, n)/(n, n')$
Capture (n, γ)
Neutron Multiplication (n, xn)
Fission (n, f) , $\bar{\nu}$, χ

Total Files (Nuclide-Reaction)

569

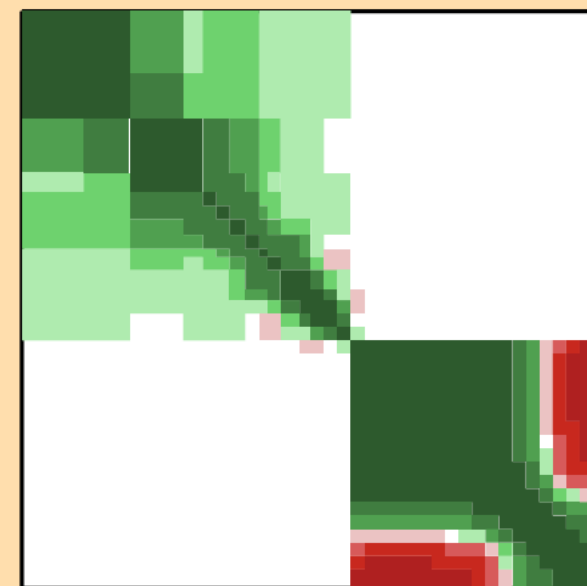
Energy

10^{-5} eV – 19.6 MeV
33 Groups

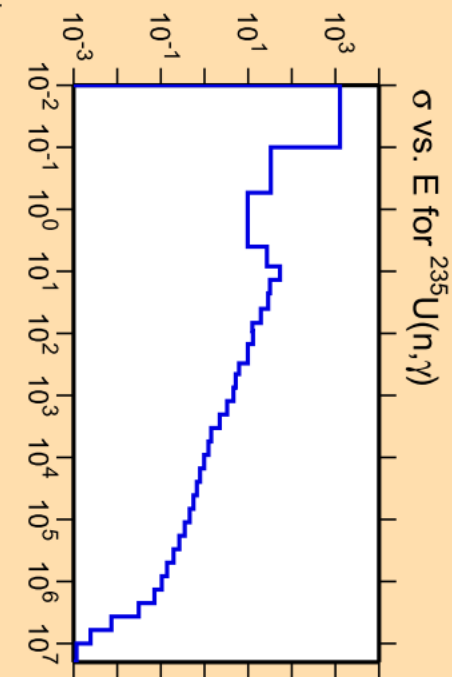
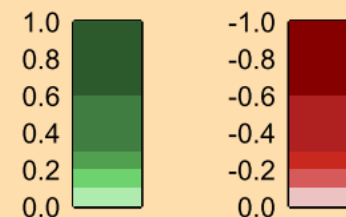


Ordinate scales are % relative standard deviation and barns.

Abscissa scales are energy (eV).



Correlation Matrix





Calculation

Covariance Matrix

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

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

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

— r_{x_i} is relative uncertainty

Obtain relative covariance matrix from correlation matrices and relative uncertainty:

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

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

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:

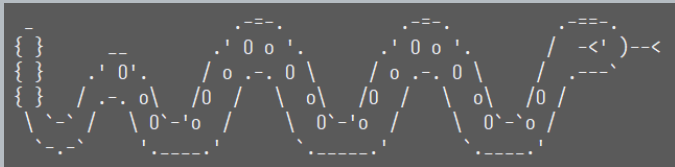
$$\widetilde{U}_i = S_i V_{ii} S_i + 2 \times \sum_{j \neq i} S_i V_{ij} S_j$$

Conservative Sensitivity Index:

$$\widetilde{SI}_i = \frac{\widetilde{U}_i}{U_{total}}$$

Calculation

Serpent Output Files



- * **_res.m** – General Results
- * **_sens.m** – Sensitivity Data

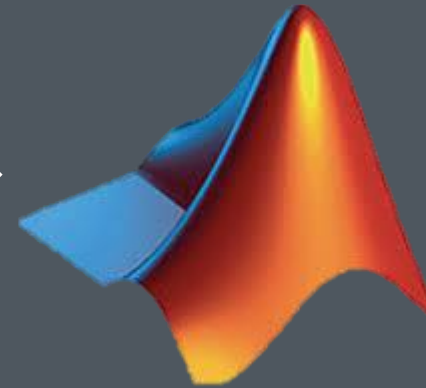
C++



- 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 :

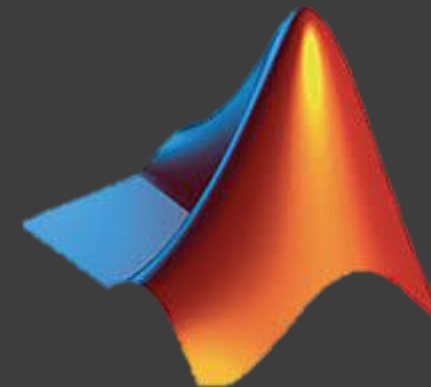
Arrange Covariance Matrix
Calculate Uncertainty
Sort Data
Plot Stairs Graph
.....

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
.....

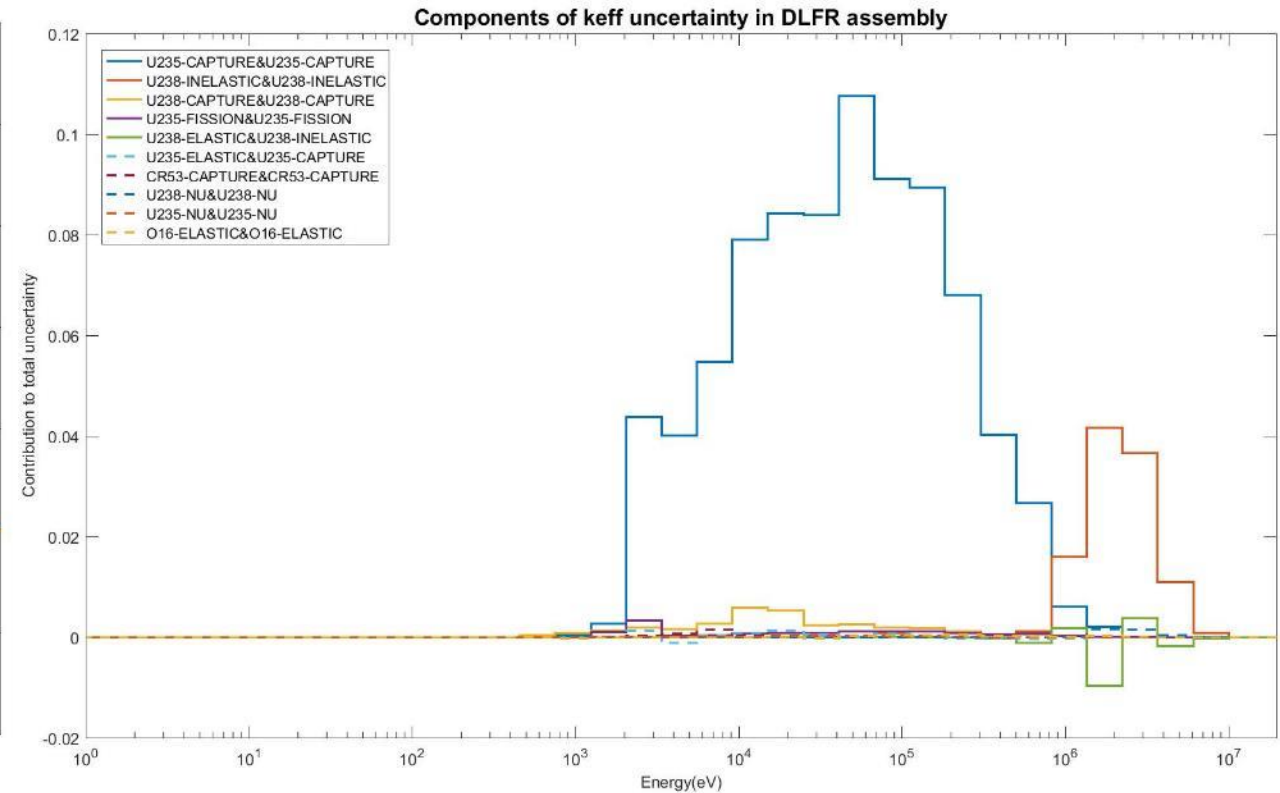
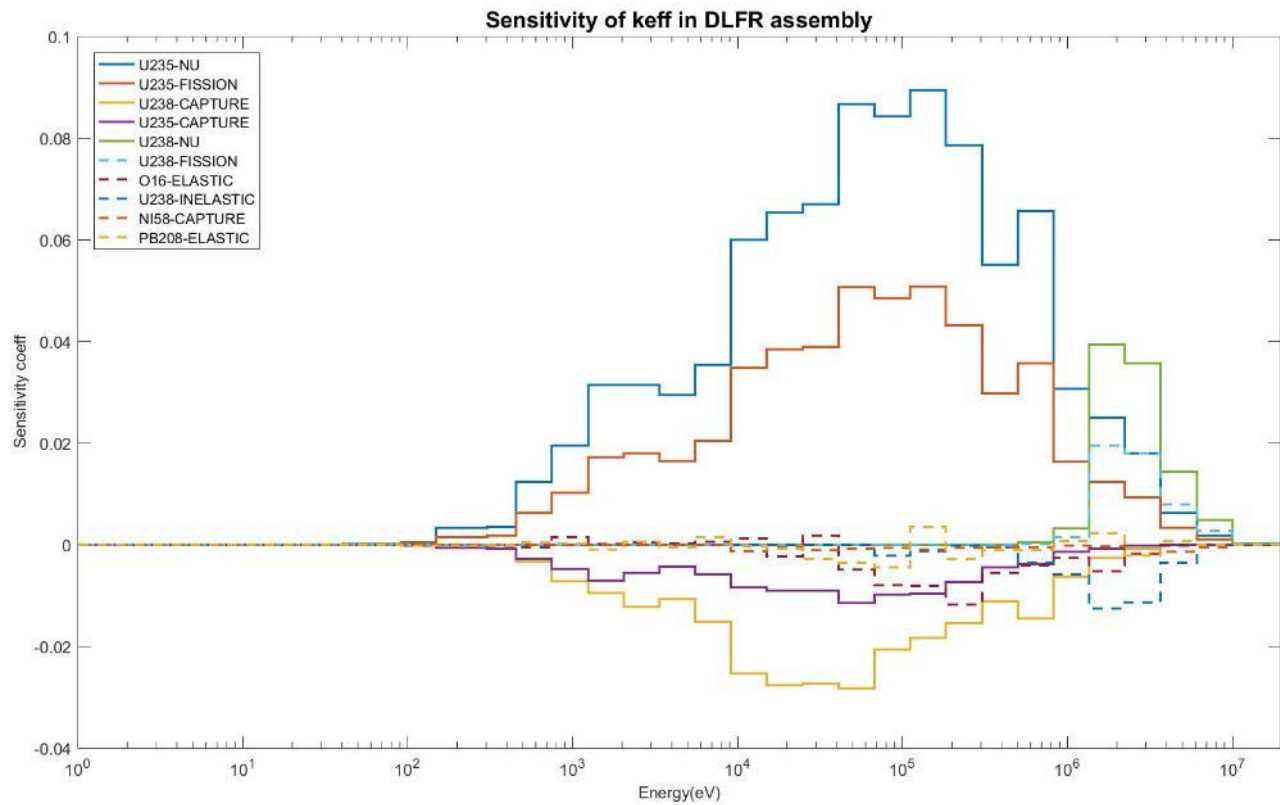
PART

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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	82.1235	$^{235}\text{U} - \sigma_{n,\gamma}$	1.56768	-0.107003
$^{238}\text{U} - \sigma_{n,n'}$	10.8820	$^{238}\text{U} - \sigma_{n,n'}$	0.17516	-0.041029
$^{238}\text{U} - \sigma_{n,\gamma}$	3.2416	$^{238}\text{U} - \sigma_{n,\gamma}$	0.05615	-0.257976
$^{235}\text{U} - \sigma_f$	1.4514	$^{235}\text{U} - \sigma_f$	0.02490	0.506052
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	-0.7076	$^{53}\text{Cr} - \sigma_{n,\gamma}$	0.00684	0.007763

BoL outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.019821

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	86.7332	$^{235}\text{U} - \sigma_{n,\gamma}$	1.64995	-0.110411
$^{238}\text{U} - \sigma_{n,n'}$	7.0166	$^{238}\text{U} - \sigma_{n,n'}$	0.122642	-0.041853
$^{238}\text{U} - \sigma_{n,\gamma}$	2.4011	$^{238}\text{U} - \sigma_{n,\gamma}$	0.041575	-0.232542
$^{235}\text{U} - \sigma_f$	1.2345	$^{235}\text{U} - \sigma_f$	0.021593	0.488544
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	0.4458	$^{53}\text{Cr} - \sigma_{n,\gamma}$	0.005432	0.007141

BoC inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.015357

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	65.8074	$^{235}\text{U} - \sigma_{n,\gamma}$	1.25340	-0.078050
$^{238}\text{U} - \sigma_{n,n'}$	19.0909	$^{238}\text{U} - \sigma_{n,n'}$	0.33066	-0.051604
$^{238}\text{U} - \sigma_{n,\gamma}$	5.1079	$^{238}\text{U} - \sigma_{n,\gamma}$	0.08877	-0.256832
$^{235}\text{U} - \sigma_f$	1.7412	$^{235}\text{U} - \sigma_f$	0.02919	0.431738
$^{56}\text{Fe} - \sigma_{n,n}$	1.7377	$^{56}\text{Fe} - \sigma_{n,n}$	0.02974	-0.023070

BoC outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.016577

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	86.7332	$^{235}\text{U} - \sigma_{n,\gamma}$	1.513810	-0.090276
$^{238}\text{U} - \sigma_{n,n'}$	7.0166	$^{238}\text{U} - \sigma_{n,n'}$	0.204594	-0.044881
$^{238}\text{U} - \sigma_{n,\gamma}$	2.4011	$^{238}\text{U} - \sigma_{n,\gamma}$	0.062313	-0.235775
$^{235}\text{U} - \sigma_f$	1.2345	$^{235}\text{U} - \sigma_f$	0.027417	0.454963
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	0.4458	$^{16}\text{O} - \sigma_{n,n}$	0.011894	-0.067184

EoC inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.014014

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	54.7410	$^{235}\text{U} - \sigma_{n,\gamma}$	1.04262	-0.065688
$^{238}\text{U} - \sigma_{n,n'}$	27.9248	$^{238}\text{U} - \sigma_{n,n'}$	0.48038	-0.050797
$^{238}\text{U} - \sigma_{n,\gamma}$	5.8622	$^{238}\text{U} - \sigma_{n,\gamma}$	0.10185	-0.250996
$^{235}\text{U} - \sigma_f$	1.8119	$^{235}\text{U} - \sigma_f$	0.02997	0.397506
$^{16}\text{O} - \sigma_{n,n}$	1.5251	$^{16}\text{O} - \sigma_{n,n}$	0.02818	-0.087629

EoC outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.015726

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	76.2761	$^{235}\text{U} - \sigma_{n,\gamma}$	1.451030	-0.084109
$^{238}\text{U} - \sigma_{n,n'}$	12.9362	$^{238}\text{U} - \sigma_{n,n'}$	0.226971	-0.044512
$^{238}\text{U} - \sigma_{n,\gamma}$	4.0763	$^{238}\text{U} - \sigma_{n,\gamma}$	0.070649	-0.236758
$^{235}\text{U} - \sigma_f$	1.6353	$^{235}\text{U} - \sigma_f$	0.027646	0.433899
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	0.9269	$^{53}\text{Cr} - \sigma_{n,\gamma}$	0.010715	-0.007833

EoL inner Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.012044

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}\text{U} - \sigma_{n,n'}$	38.9070	$^{238}\text{U} - \sigma_{n,n'}$	0.68714	-0.059305
$^{235}\text{U} - \sigma_{n,\gamma}$	33.2131	$^{235}\text{U} - \sigma_{n,\gamma}$	0.63359	-0.044578
$^{238}\text{U} - \sigma_{n,\gamma}$	7.3113	$^{238}\text{U} - \sigma_{n,\gamma}$	0.12726	-0.238941
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	3.9664	$^{16}\text{O} - \sigma_{n,n}$	0.05135	0.100010
$^{16}\text{O} - \sigma_{n,n}$	2.7469	$^{238}\text{U} - \sigma_{n,n}$	0.04130	-0.005715

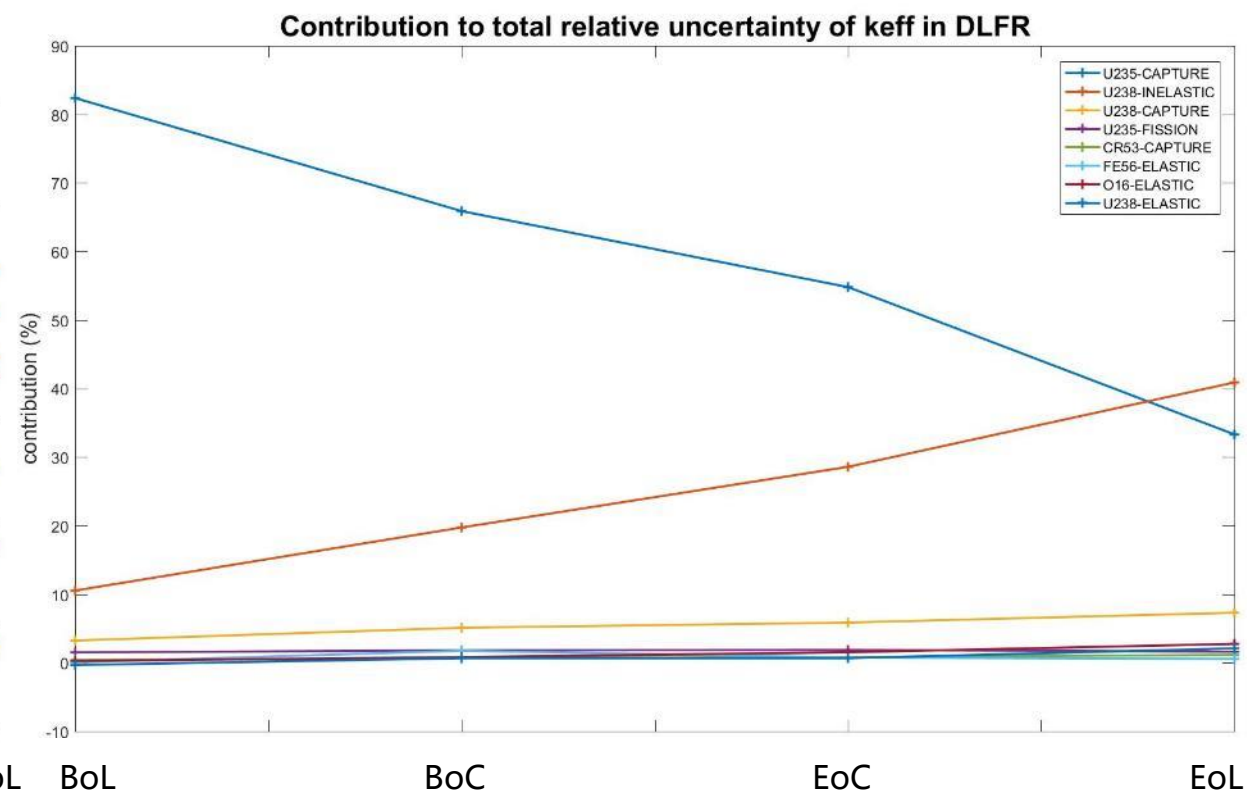
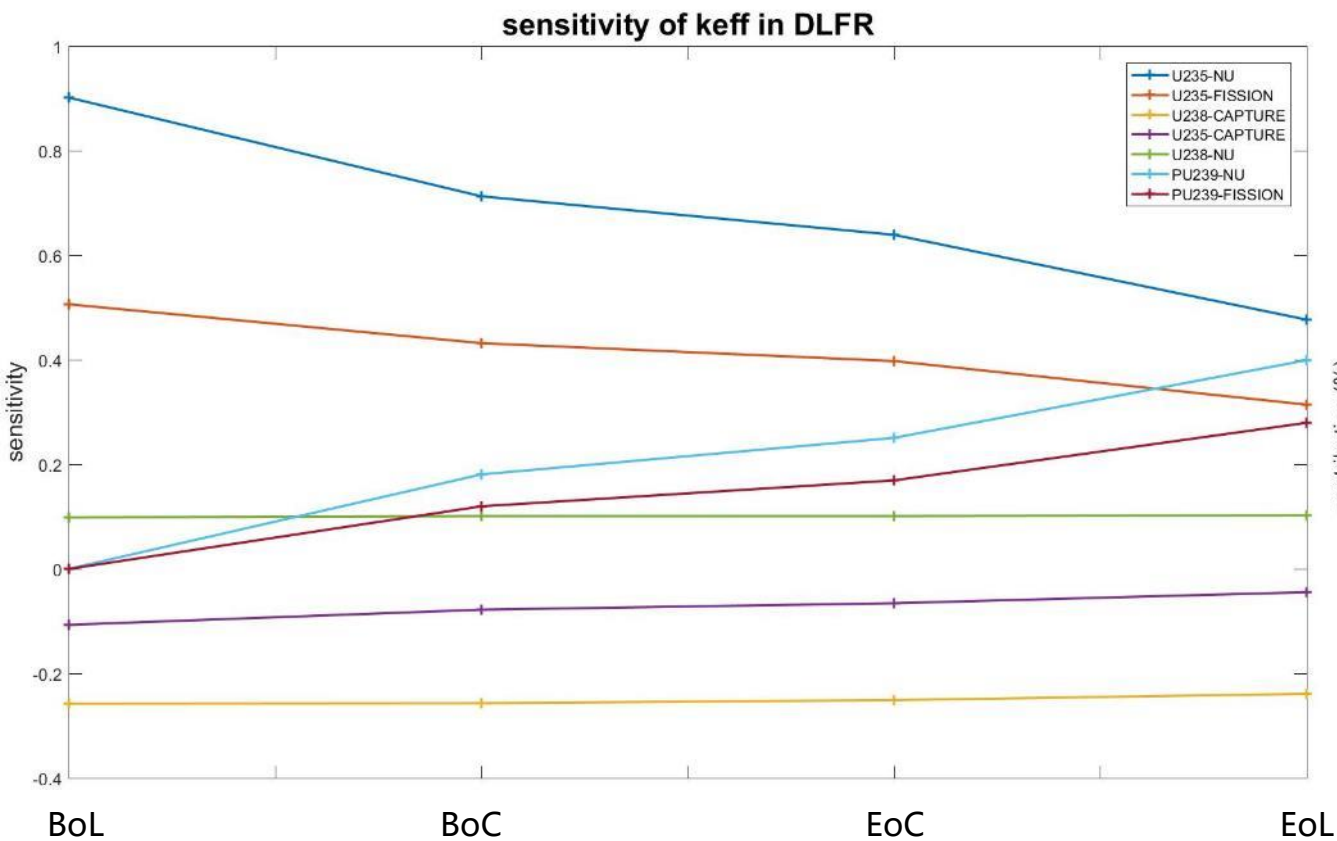
EoL outer Assembly Uncertainty Analysis:

K_{eff} Standard Deviation: 0.013416

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	62.8492	$^{235}\text{U} - \sigma_{n,\gamma}$	1.201250	-0.066350
$^{238}\text{U} - \sigma_{n,n'}$	21.0056	$^{238}\text{U} - \sigma_{n,n'}$	0.360621	-0.047198
$^{238}\text{U} - \sigma_{n,\gamma}$	5.5305	$^{238}\text{U} - \sigma_{n,\gamma}$	0.095879	-0.234376
$^{235}\text{U} - \sigma_f$	1.8597	$^{235}\text{U} - \sigma_f$	0.031221	0.392085
$^{16}\text{O} - \sigma_{n,n}$	1.0447	$^{16}\text{O} - \sigma_{n,n}$	0.018994	-0.070047

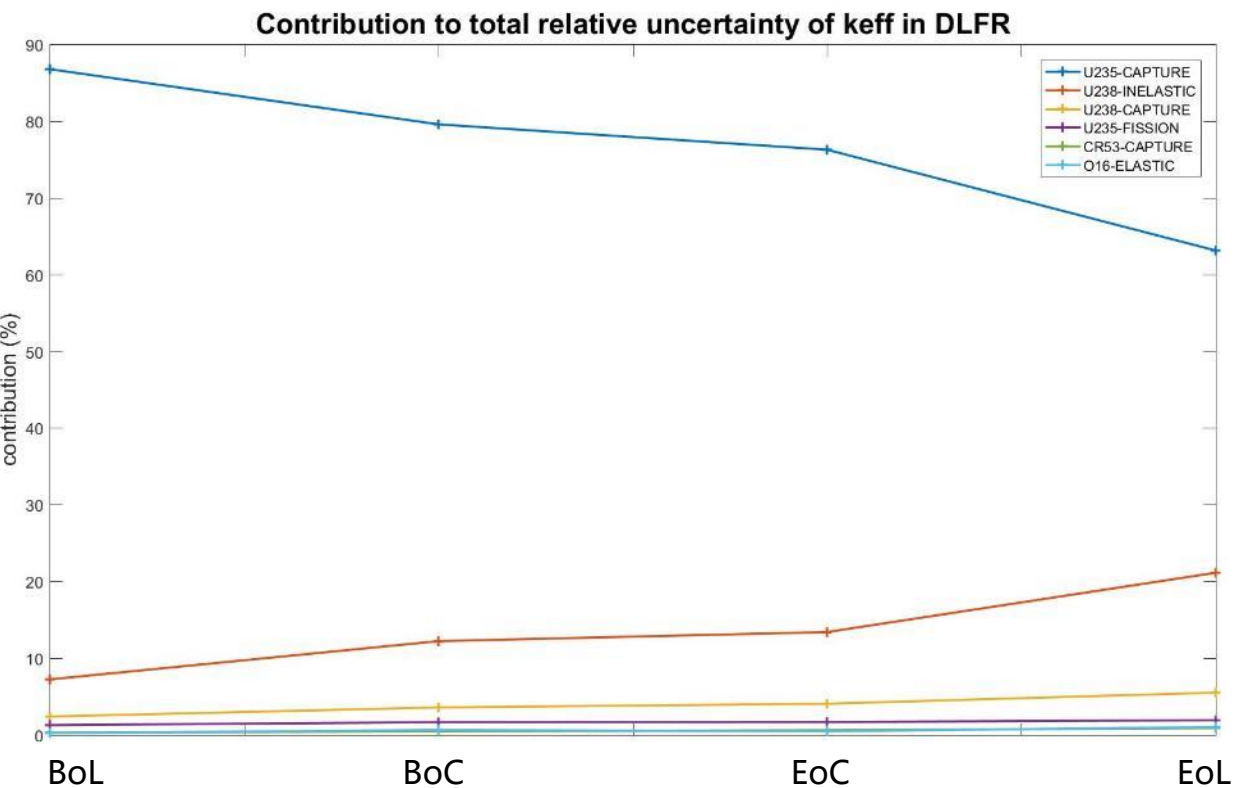
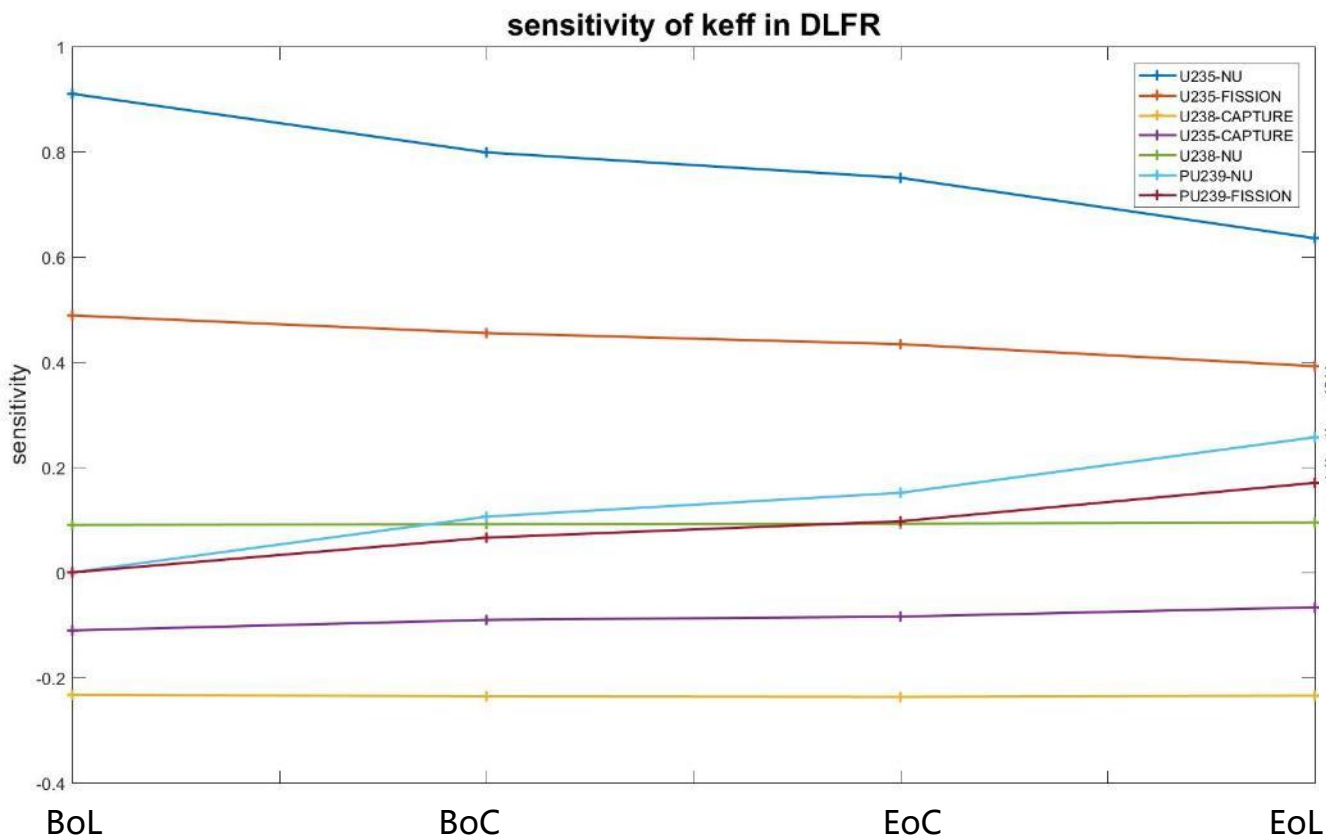
Sensitivity and Uncertainty Contributed to Total in Different Periods

Inner Core Fuel Assembly



Sensitivity and Uncertainty Contributed to Total in Different Periods

Outer Core Fuel Assembly



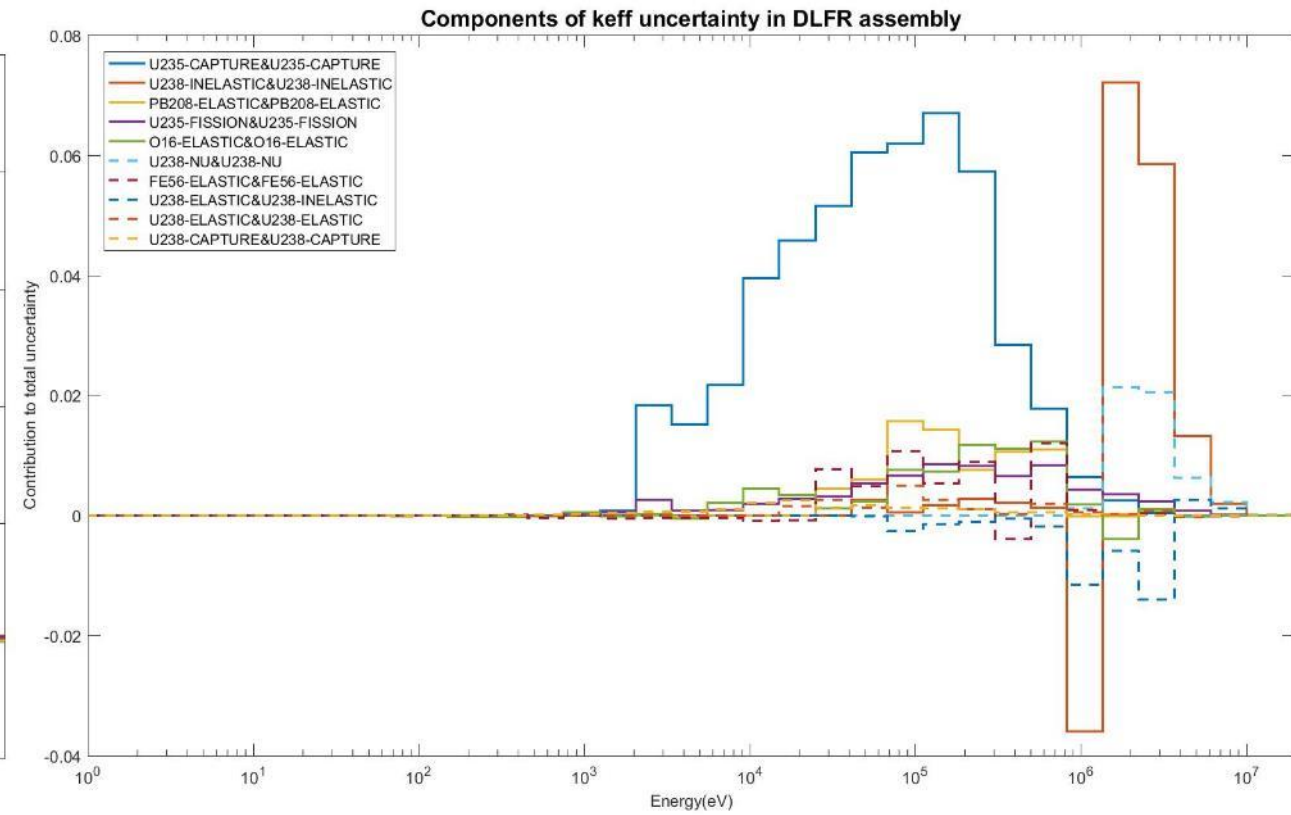
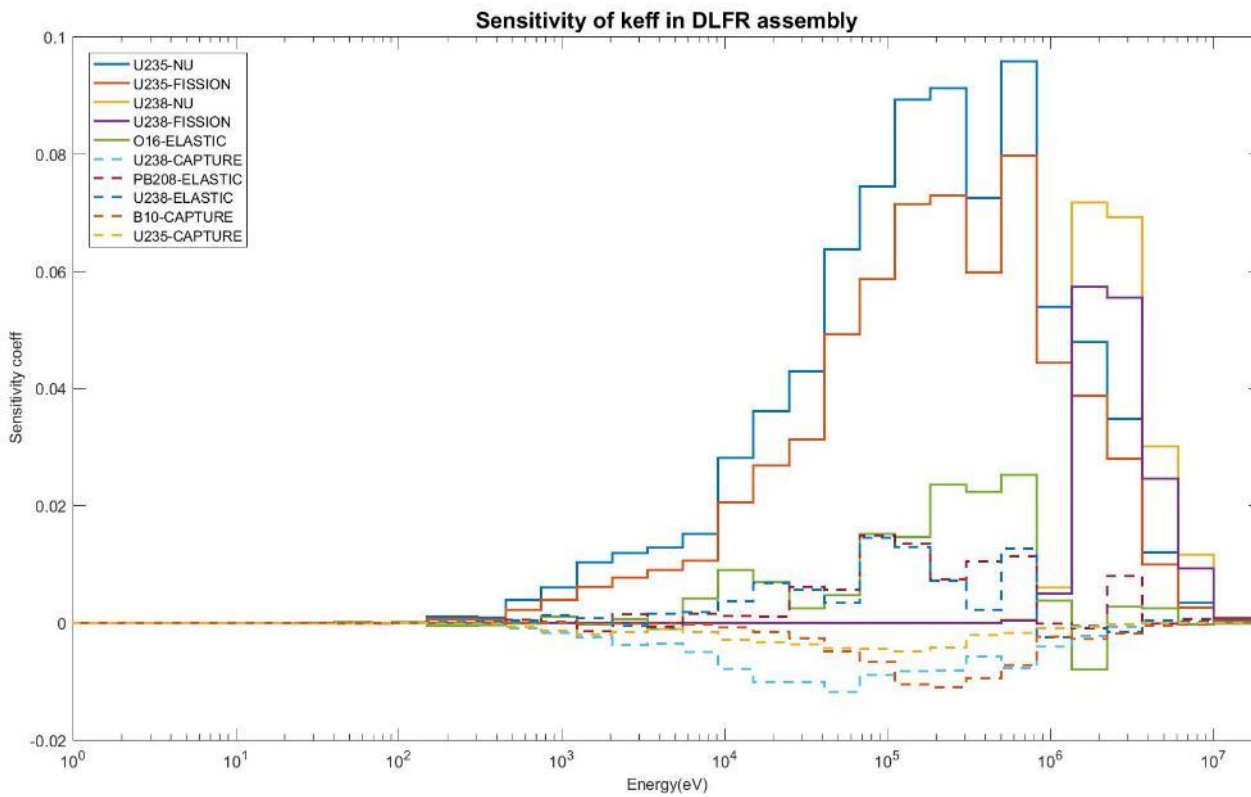
PART

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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	49.6019	$^{235}\text{U} - \sigma_{n,\gamma}$	0.94729	-0.041557
$^{238}\text{U} - \sigma_{n,n'}$	12.1277	$^{208}\text{Pb} - \sigma_{n,n}$	0.12561	0.081090
$^{208}\text{Pb} - \sigma_{n,n}$	7.0904	$^{235}\text{U} - \sigma_f$	0.12502	0.635583
$^{235}\text{U} - \sigma_f$	6.8442	$^{16}\text{O} - \sigma_{n,n}$	0.11627	0.129220
$^{16}\text{O} - \sigma_{n,n}$	6.2960	$^{238}\text{U} - \sigma_{n,n'}$	0.09061	-0.102597

Safety Rod surrounded by BoC inner Assembly:

K_{eff} Standard Deviation: 0.010595

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	20.9232	$^{235}\text{U} - \sigma_{n,\gamma}$	0.405438	-0.028904
$^{56}\text{Fe} - \sigma_{n,n}$	19.4188	$^{56}\text{Fe} - \sigma_{n,n}$	0.340385	0.057541
$^{238}\text{U} - \sigma_{n,n'}$	14.8347	$^{238}\text{U} - \sigma_{n,n'}$	0.298071	-0.006460
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	9.8891	$^{238}\text{U} - \sigma_{n,n}$	0.155563	0.074835
$^{16}\text{O} - \sigma_{n,n}$	6.8959	$^{16}\text{O} - \sigma_{n,n}$	0.129392	0.142088

Safety Rod surrounded by EoC inner Assembly:

K_{eff} Standard Deviation: 0.009616

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}\text{U} - \sigma_{n,n'}$	27.4812	$^{238}\text{U} - \sigma_{n,n'}$	0.44838	-0.006568
$^{235}\text{U} - \sigma_{n,\gamma}$	16.2871	$^{235}\text{U} - \sigma_{n,\gamma}$	0.31823	-0.023141
$^{56}\text{Fe} - \sigma_{n,n}$	15.8962	$^{56}\text{Fe} - \sigma_{n,n}$	0.28609	0.049147
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	7.1493	$^{238}\text{U} - \sigma_{n,n}$	0.11081	0.075307
$^{238}\text{U} - \bar{\nu}$	5.9046	$^{238}\text{U} - \bar{\nu}$	0.09529	0.194659

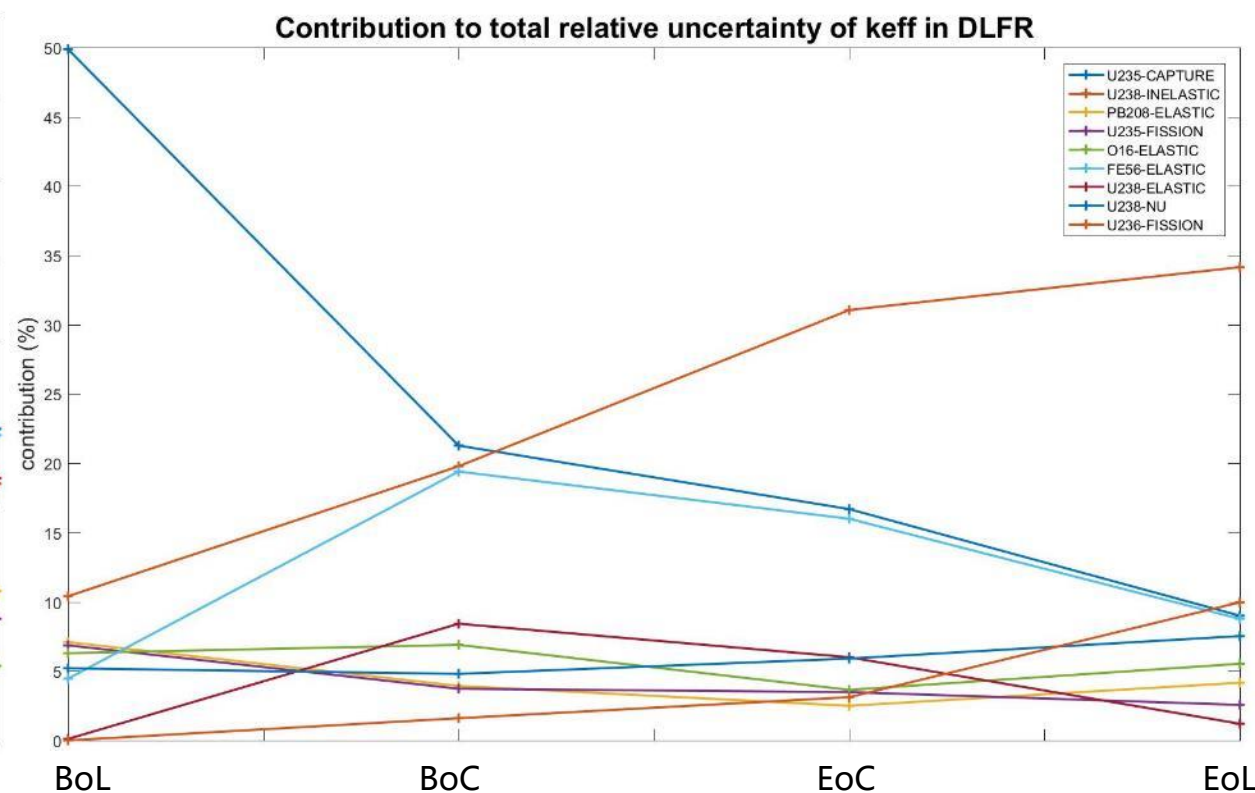
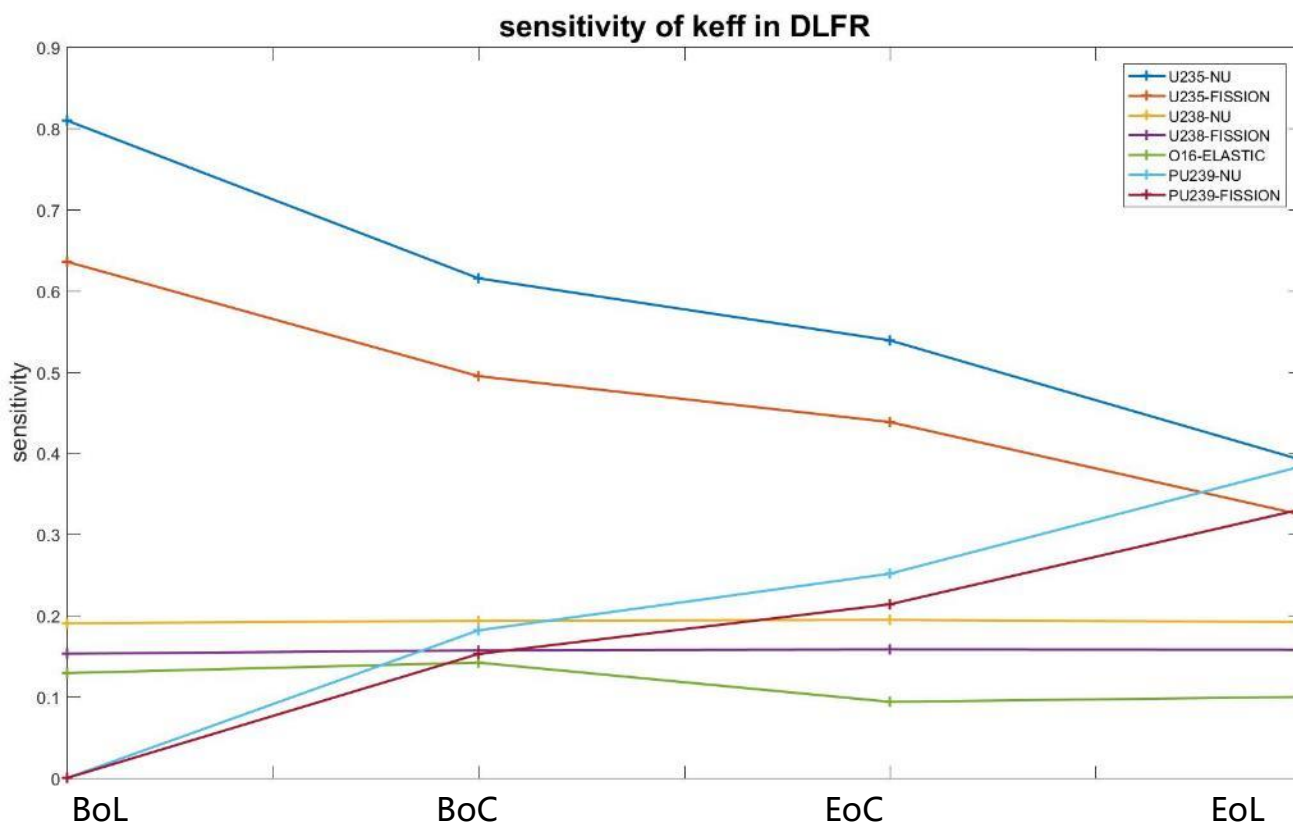
Safety Rod surrounded by EoL inner Assembly:

K_{eff} Standard Deviation: 0.008373

Parameter Pair	Contribution to Total Uncertainty (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{238}\text{U} - \sigma_{n,n'}$	34.8277	$^{238}\text{U} - \sigma_{n,n'}$	0.465302	-0.017072
$^{236}\text{U} - \sigma_f$	9.9612	$^{235}\text{U} - \sigma_{n,\gamma}$	0.171462	-0.015318
$^{235}\text{U} - \sigma_{n,\gamma}$	8.8226	$^{236}\text{U} - \sigma_f$	0.170007	0.010268
$^{56}\text{Fe} - \sigma_{n,n}$	8.7255	$^{56}\text{Fe} - \sigma_{n,n}$	0.139694	0.028763
$^{238}\text{U} - \bar{\nu}$	7.5280	$^{238}\text{U} - \bar{\nu}$	0.121730	0.191956

Sensitivity and Uncertainty Contributed to Total in Different Periods

Safety Rod



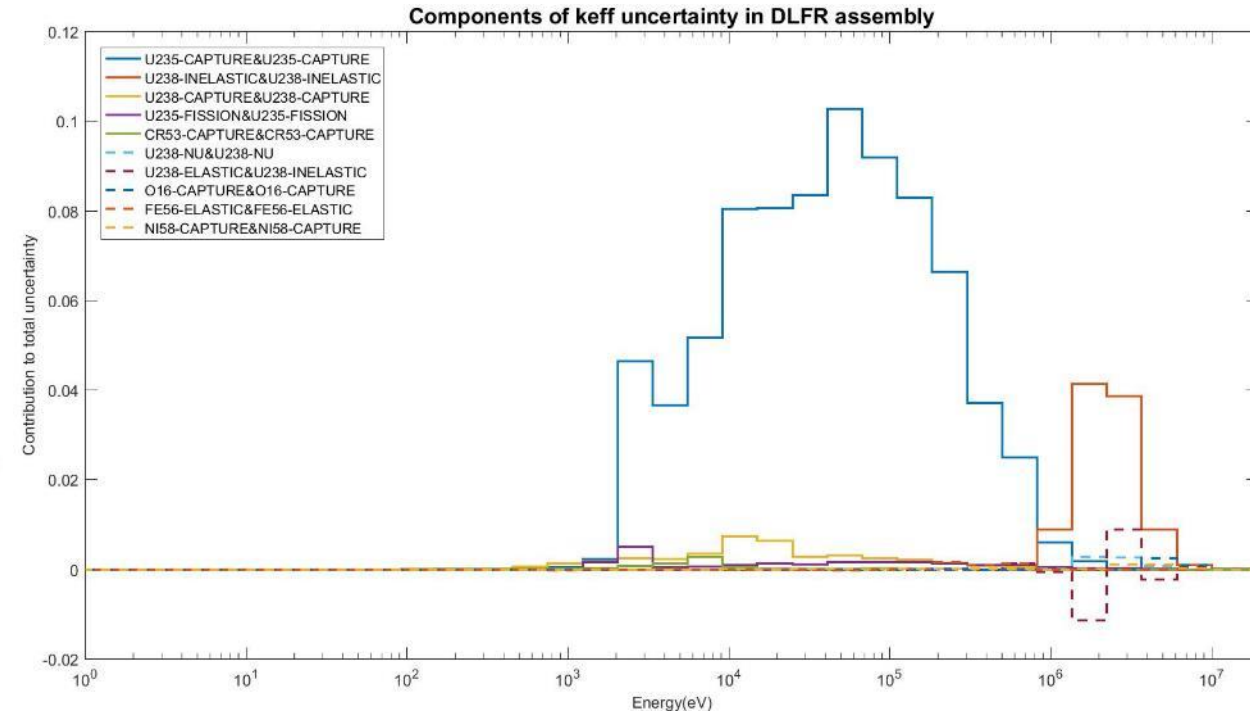
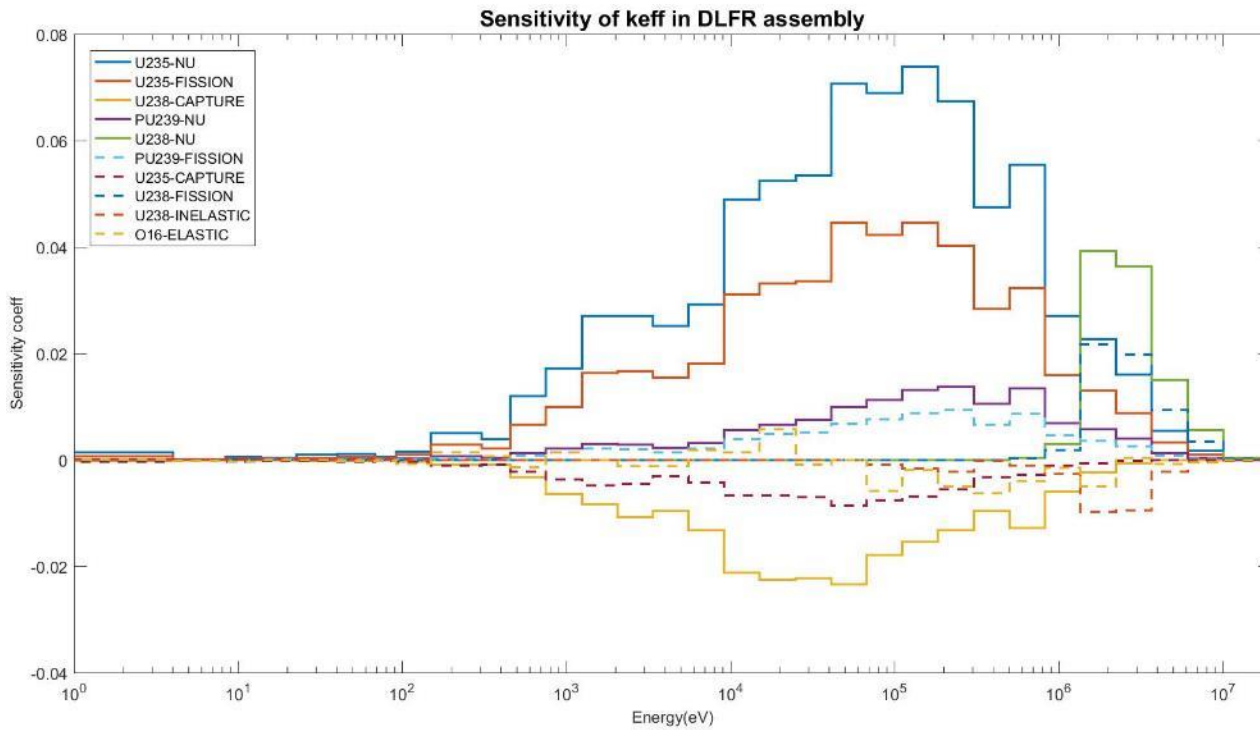
PART

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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	84.7604	$^{235}\text{U} - \sigma_{n,\gamma}$	1.61504	-0.098547
$^{238}\text{U} - \sigma_{n,n'}$	9.2950	$^{238}\text{U} - \sigma_{n,n'}$	0.13958	-0.034373
$^{238}\text{U} - \sigma_{n,\gamma}$	2.7068	$^{238}\text{U} - \sigma_{n,\gamma}$	0.04700	-0.213675
$^{235}\text{U} - \sigma_f$	1.8171	$^{235}\text{U} - \sigma_f$	0.03180	0.526743
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	-1.3867	$^{238}\text{U} - \sigma_{n,n}$	-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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	84.8102	$^{235}\text{U} - \sigma_{n,\gamma}$	1.607250	-0.096055
$^{238}\text{U} - \sigma_{n,n'}$	8.3663	$^{238}\text{U} - \sigma_{n,n'}$	0.139454	-0.029788
$^{238}\text{U} - \sigma_{n,\gamma}$	2.6780	$^{238}\text{U} - \sigma_{n,\gamma}$	0.046401	-0.207413
$^{235}\text{U} - \sigma_f$	1.9128	$^{235}\text{U} - \sigma_f$	0.033683	0.529179
$^{235}\text{U} - (\sigma_{n,n}, \sigma_{n,\gamma})$	-0.0078	$^{238}\text{U} - \bar{\nu}$	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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	70.9466	$^{235}\text{U} - \sigma_{n,\gamma}$	1.35330	-0.077559
$^{238}\text{U} - \sigma_{n,n'}$	16.4545	$^{238}\text{U} - \sigma_{n,n'}$	0.29119	-0.042023
$^{238}\text{U} - \sigma_{n,\gamma}$	3.7255	$^{238}\text{U} - \sigma_{n,\gamma}$	0.06472	-0.212163
$^{235}\text{U} - \sigma_f$	2.0054	$^{235}\text{U} - \sigma_f$	0.03487	0.468207
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	1.6438	$^{238}\text{U} - \sigma_{n,n}$	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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	70.3116	$^{235}\text{U} - \sigma_{n,\gamma}$	1.350580	-0.076630
$^{238}\text{U} - \sigma_{n,n'}$	14.6748	$^{238}\text{U} - \sigma_{n,n'}$	0.266992	-0.035847
$^{238}\text{U} - \sigma_{n,\gamma}$	3.6564	$^{238}\text{U} - \sigma_{n,\gamma}$	0.063624	-0.207103
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	3.2333	$^{235}\text{U} - \sigma_f$	0.036008	0.473907
$^{235}\text{U} - \sigma_f$	2.0707	$^{238}\text{U} - \sigma_{n,n}$	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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	65.1362	$^{235}\text{U} - \sigma_{n,\gamma}$	1.23615	-0.068290
$^{238}\text{U} - \sigma_{n,n'}$	22.5490	$^{238}\text{U} - \sigma_{n,n'}$	0.36535	-0.038401
$^{238}\text{U} - \sigma_{n,\gamma}$	4.4631	$^{238}\text{U} - \sigma_{n,\gamma}$	0.07786	-0.210651
$^{235}\text{U} - \sigma_f$	2.2424	$^{235}\text{U} - \sigma_f$	0.03846	0.442943
$^{238}\text{U} - \bar{\nu}$	0.9324	$^{238}\text{U} - \bar{\nu}$	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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	72.2246	$^{235}\text{U} - \sigma_{n,\gamma}$	1.372160	-0.071178
$^{238}\text{U} - \sigma_{n,n'}$	16.0571	$^{238}\text{U} - \sigma_{n,n'}$	0.258783	-0.032237
$^{238}\text{U} - \sigma_{n,\gamma}$	4.3330	$^{238}\text{U} - \sigma_{n,\gamma}$	0.075305	-0.204820
$^{235}\text{U} - \sigma_f$	2.3320	$^{235}\text{U} - \sigma_f$	0.040107	0.447814
$^{238}\text{U} - \bar{\nu}$	0.9553	$^{238}\text{U} - \bar{\nu}$	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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	53.8269	$^{235}\text{U} - \sigma_{n,\gamma}$	1.01789	-0.051801
$^{238}\text{U} - \sigma_{n,n'}$	29.1961	$^{238}\text{U} - \sigma_{n,n'}$	0.43188	-0.046472
$^{238}\text{U} - \sigma_{n,\gamma}$	6.3703	$^{238}\text{U} - \sigma_{n,\gamma}$	0.11114	-0.205452
$^{238}\text{U} - (\sigma_{n,n}, \sigma_{n,n'})$	-4.3104	$^{235}\text{U} - \sigma_f$	0.04106	0.375887
$^{235}\text{U} - \sigma_f$	2.4146	$^{238}\text{U} - \sigma_{n,n}$	-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 (%)	Parameter	Conservatively Estimated Relative Uncertainty	Sensitivity
$^{235}\text{U} - \sigma_{n,\gamma}$	53.0769	$^{235}\text{U} - \sigma_{n,\gamma}$	1.016330	-0.053765
$^{238}\text{U} - \sigma_{n,n'}$	27.3726	$^{238}\text{U} - \sigma_{n,n'}$	0.454822	-0.037794
$^{238}\text{U} - \sigma_{n,\gamma}$	5.8802	$^{238}\text{U} - \sigma_{n,\gamma}$	0.102275	-0.209787
$^{235}\text{U} - \sigma_f$	2.3522	$^{235}\text{U} - \sigma_f$	0.039774	0.384521
$^{238}\text{U} - \bar{\nu}$	1.3014	$^{238}\text{U} - \bar{\nu}$	0.020972	0.107249

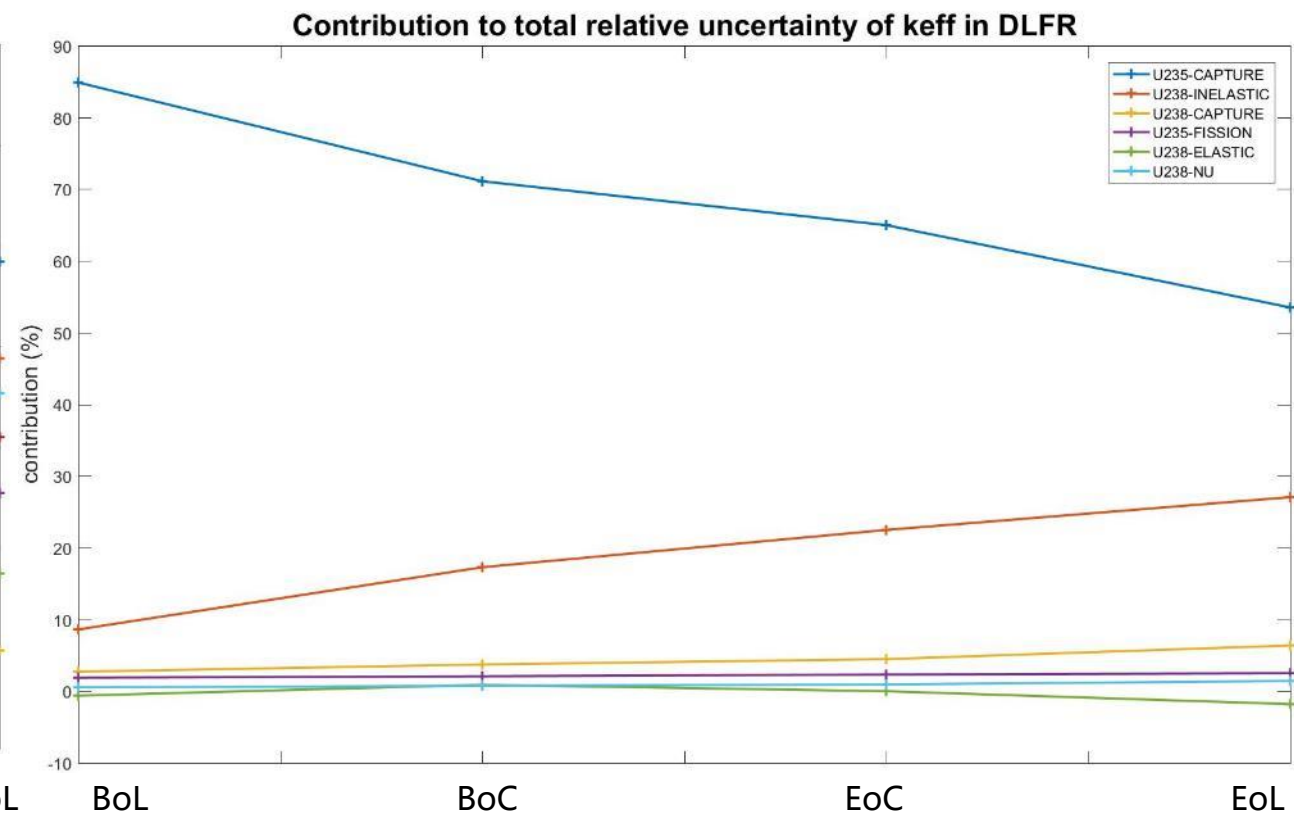
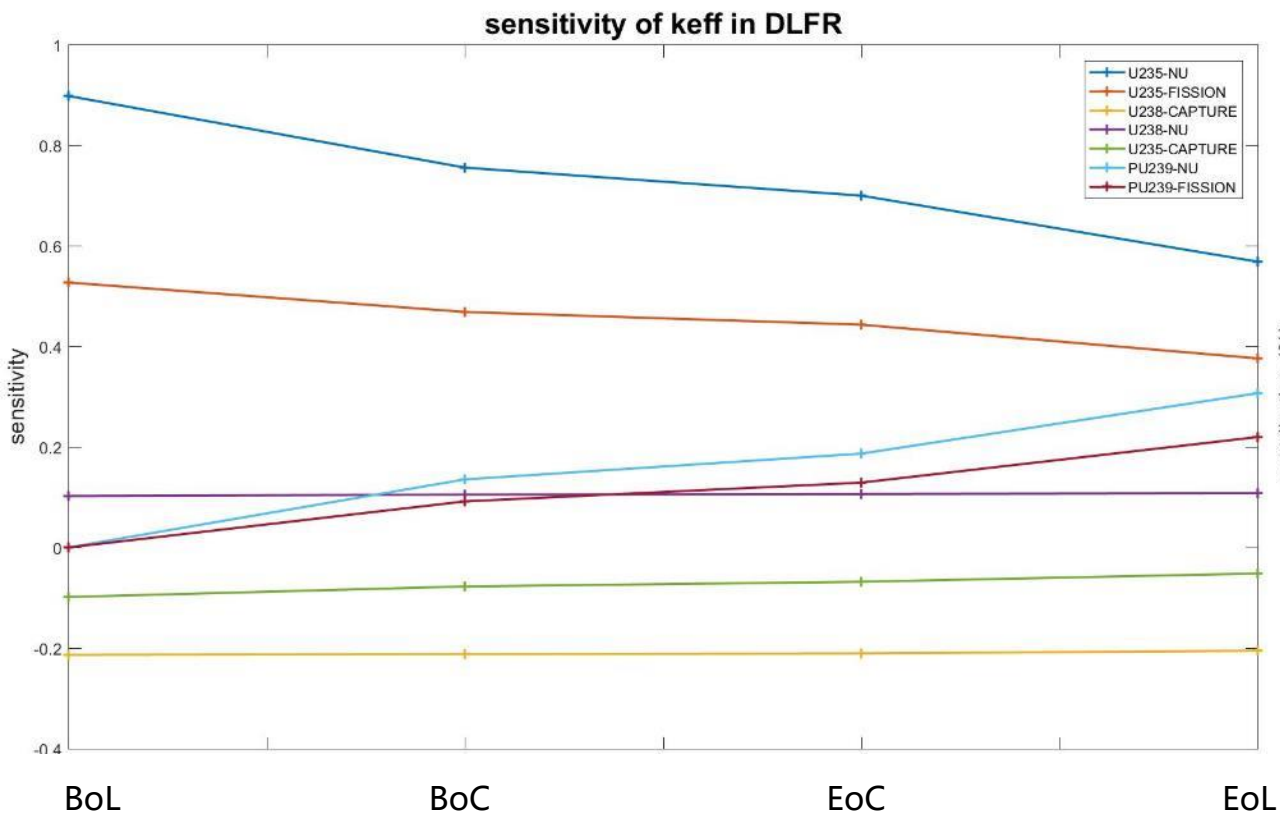
PART

04

Conclusion

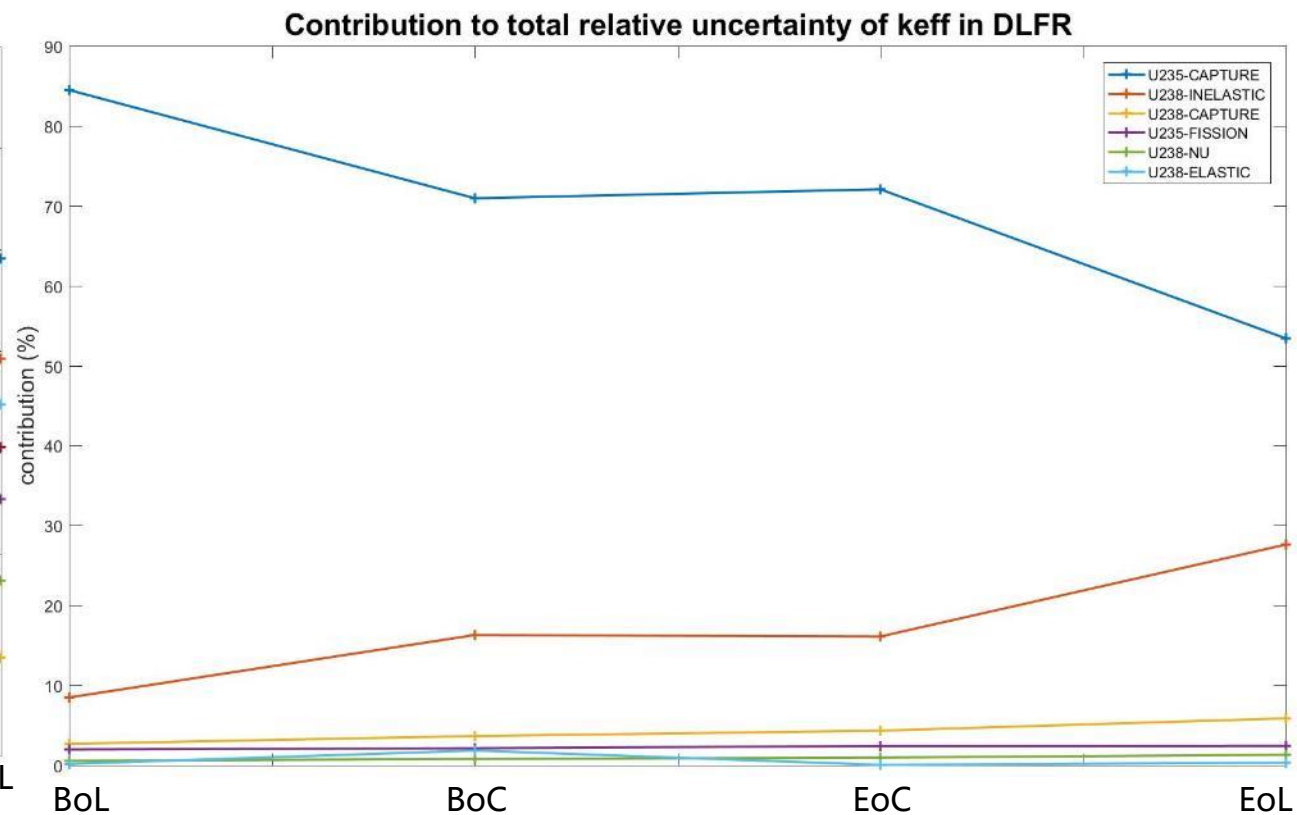
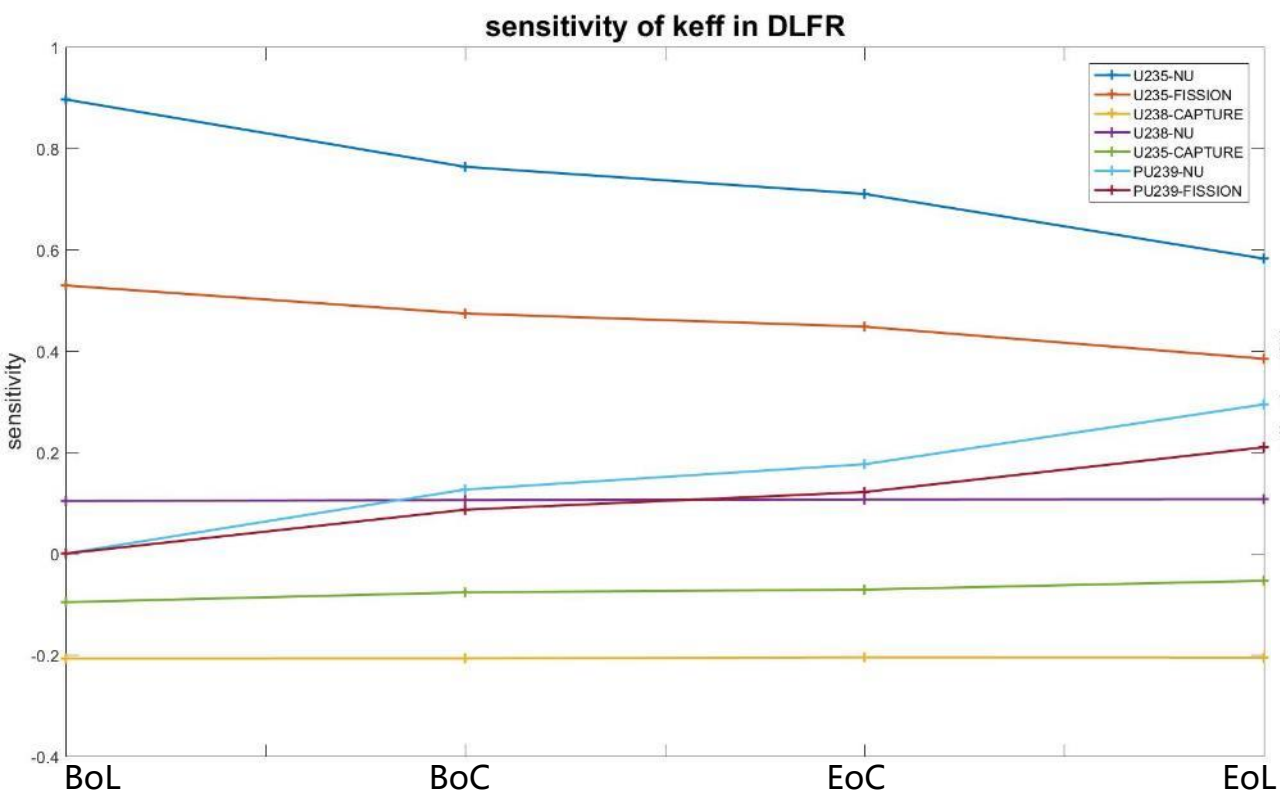
Sensitivity and Uncertainty Contributed to Total in Different Periods

2D Whole Core with Safety Rod out

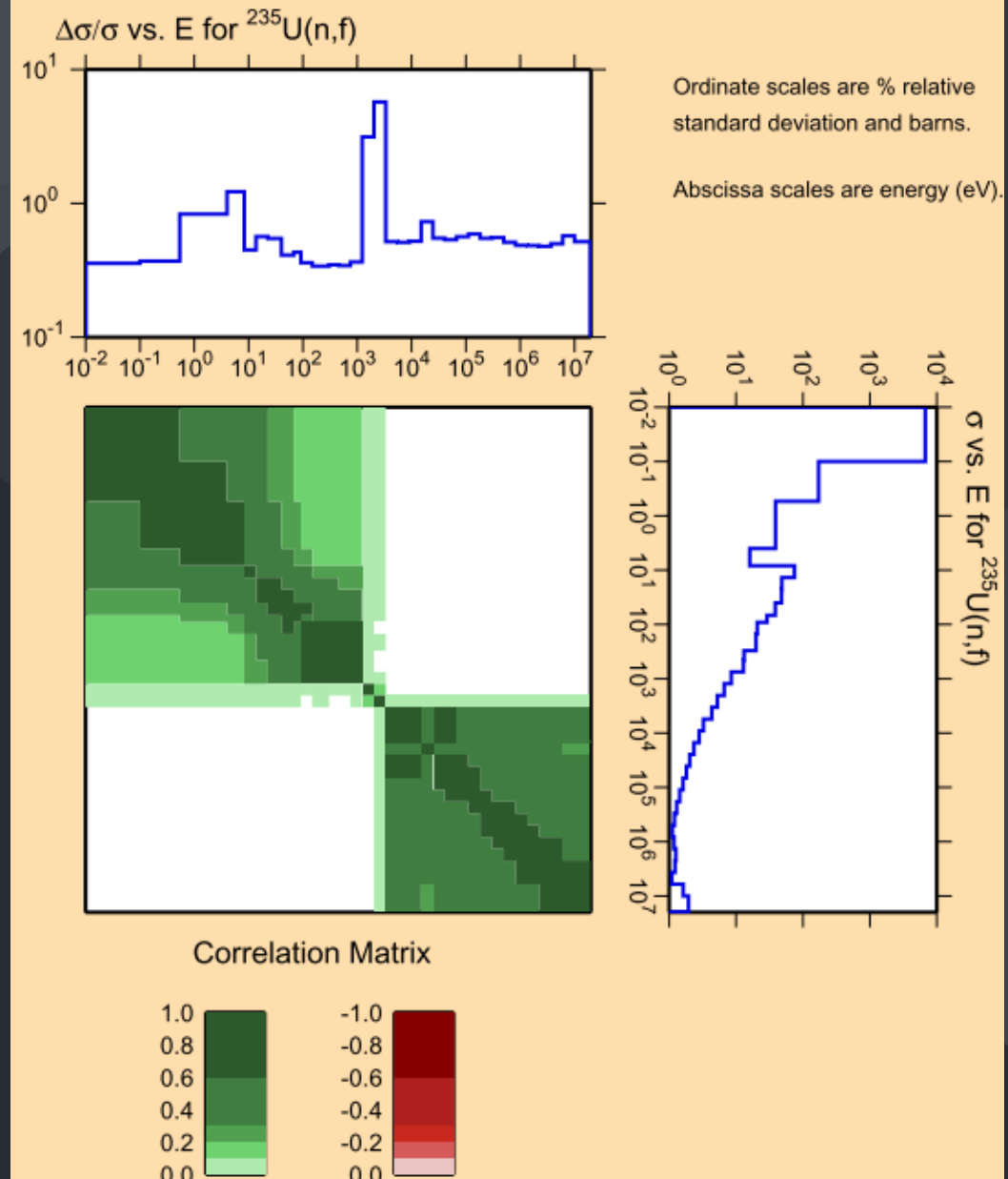
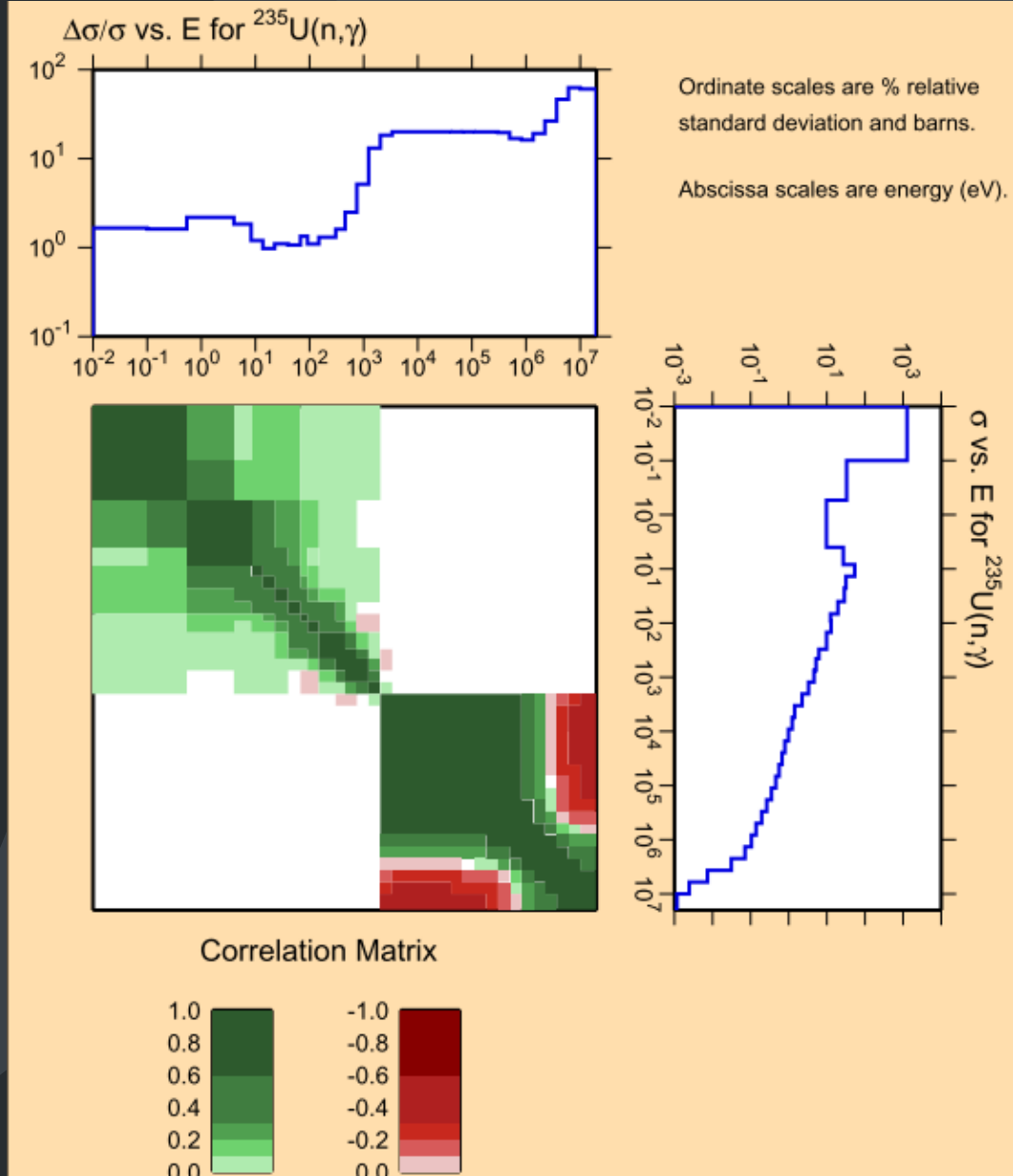


Sensitivity and Uncertainty Contributed to Total in Different Periods

2D Whole Core with Safety Rod in

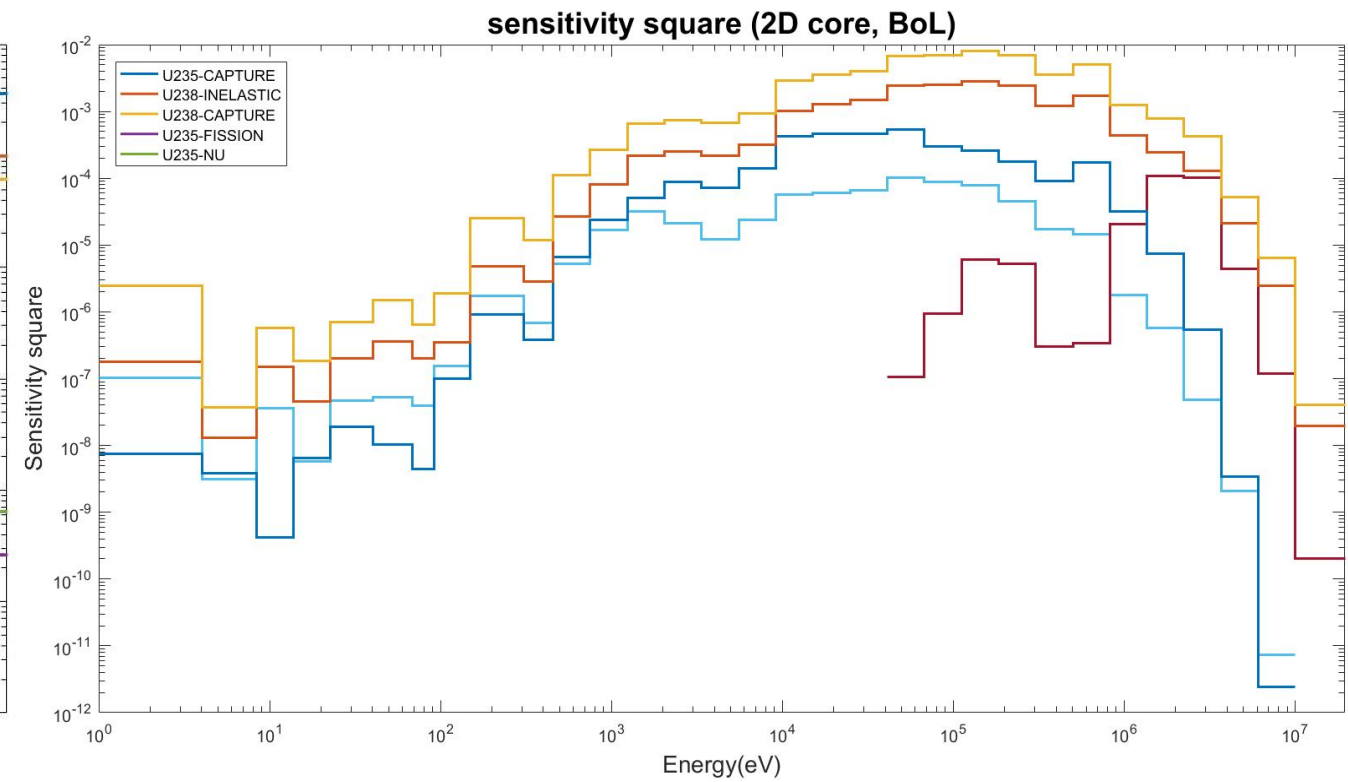
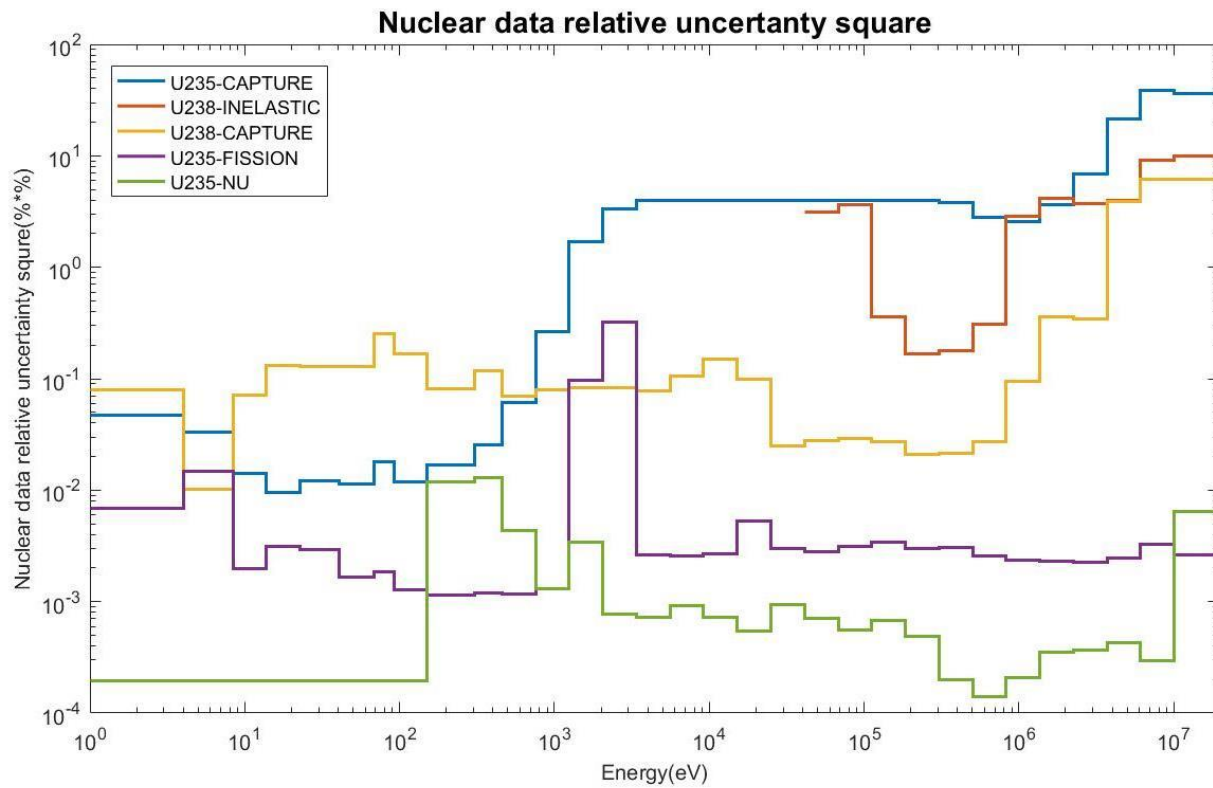


Correlation Matrices

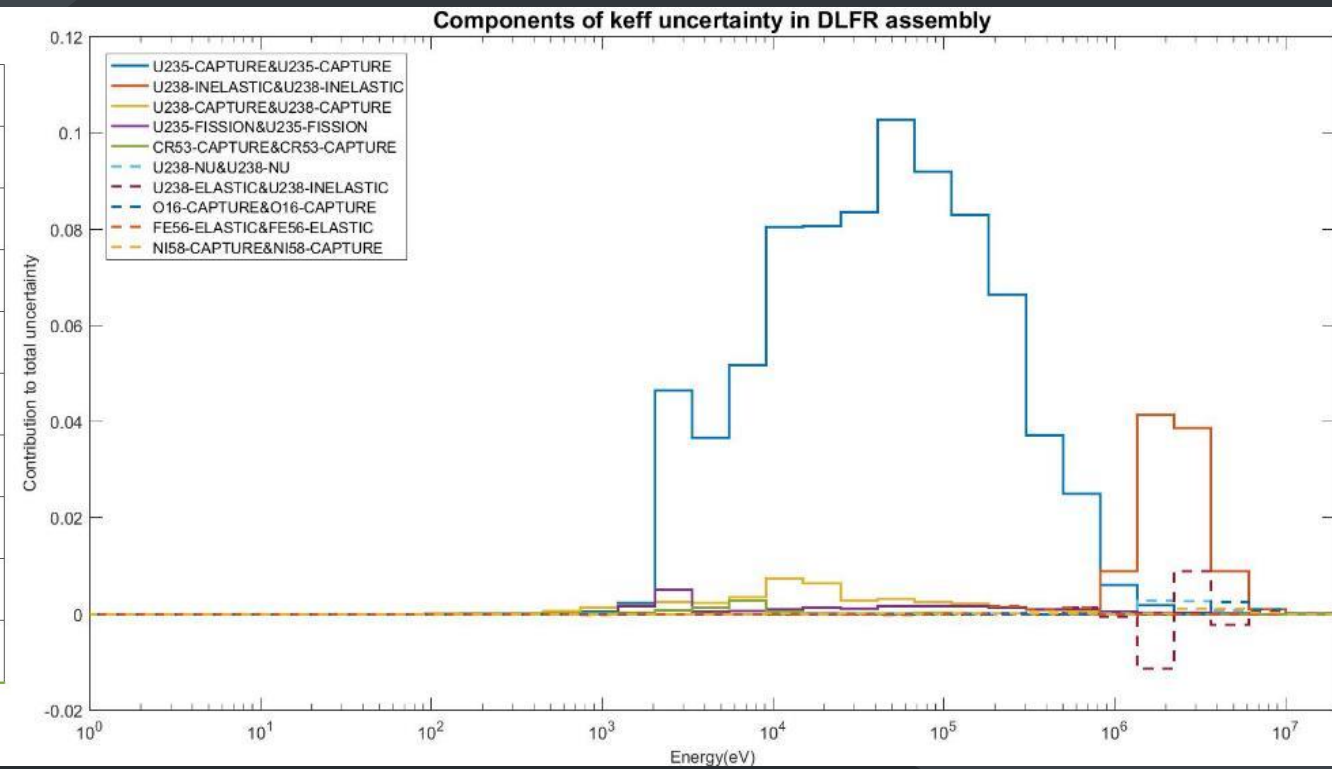
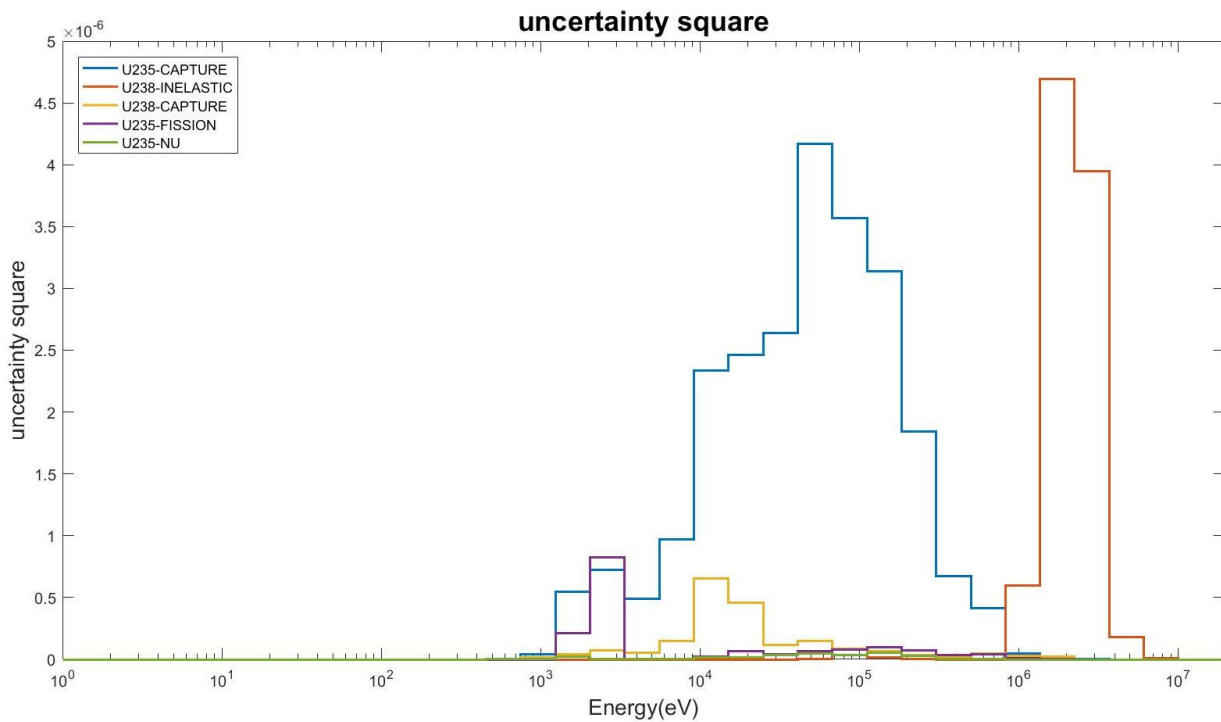


Nuclear Data Relative Uncertainty

(Elements on diagonal of each relative covariance matrix)



Uncertainty

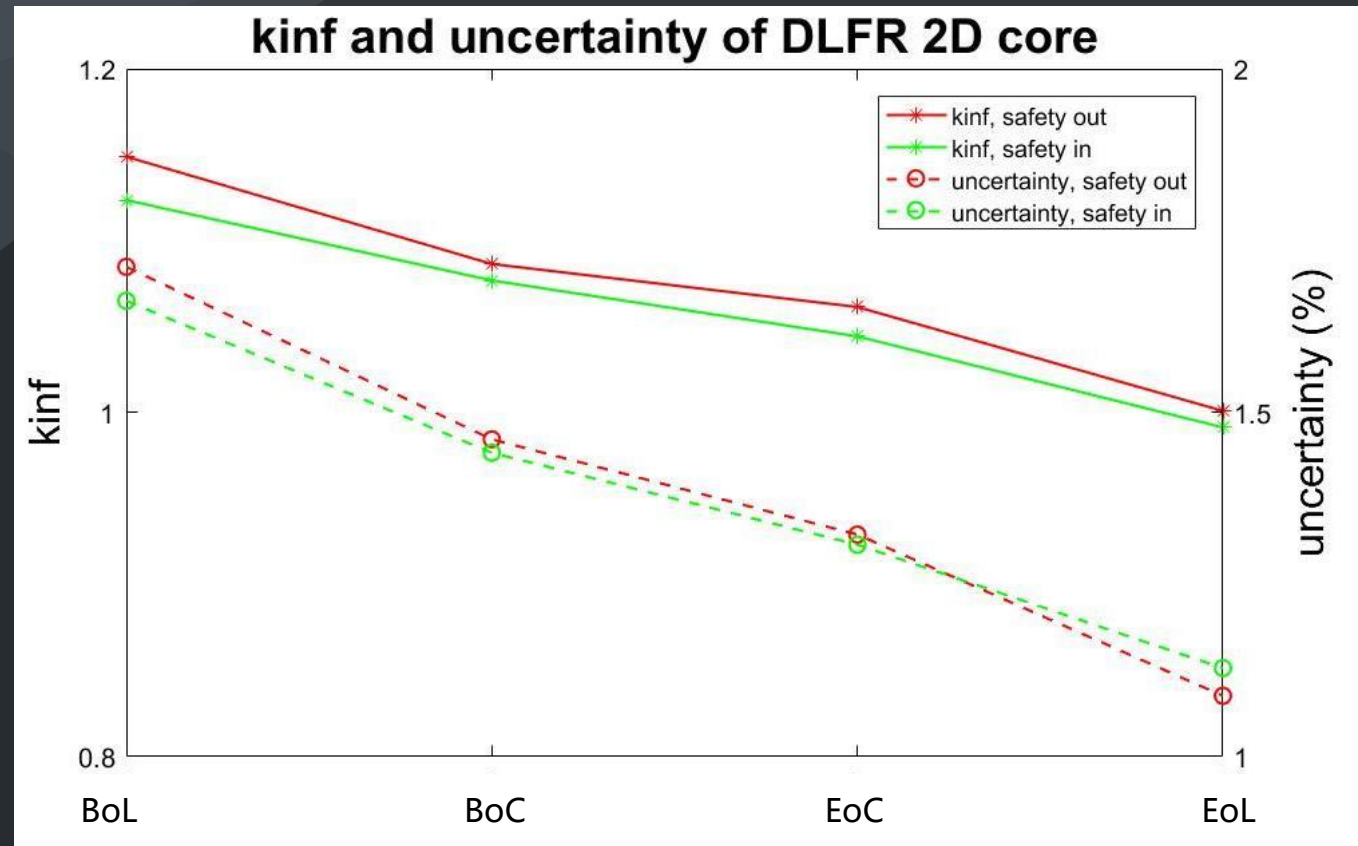


Conclusion

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

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

k-inf & Uncertainty of 2D Whole Core

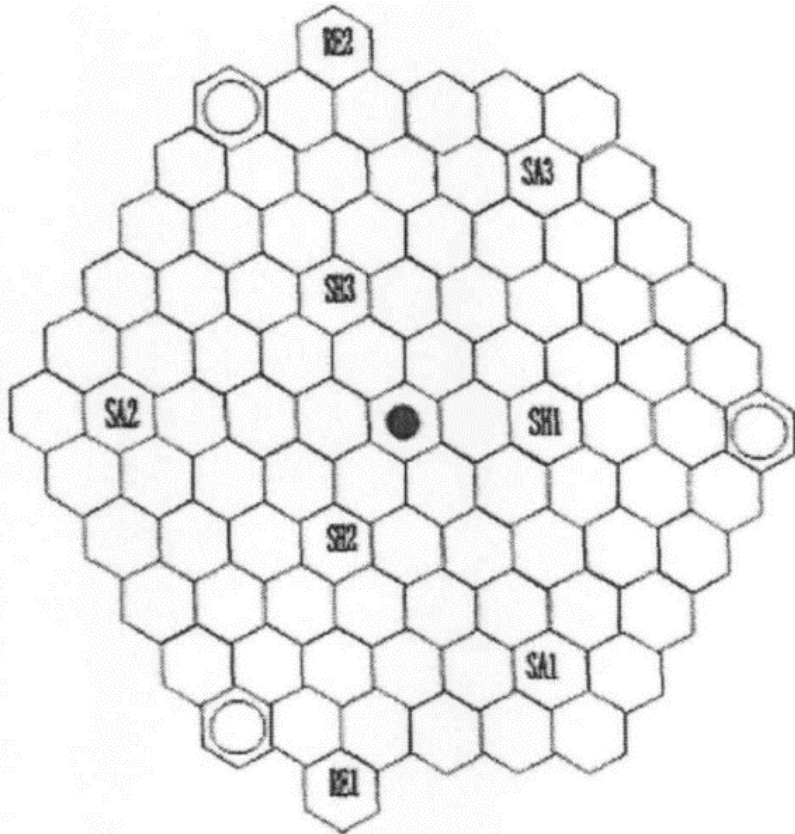


Comparison^[1]

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

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[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

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END | THANK YOU!

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