IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

IRSN Proposal on Conceptual Design for TEX Experiments

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TEX Feasibility Meeting
Sandia National Laboratories, Albuquerque, NM
July 12-13, 2011

Work Scope*

- Propose a conceptual design for integral experiments useful for testing neutron cross sections of fuel isotopes and structural materials in thermal and epithermal energy range (up to 1keV);
- Study conceptual feasibility of the design using water-moderated pin-fueled experimental installation with restriction on fuel elements inventory.
- Work scope does not include assessment of issues related to safety, test materials fabrication process and cost.

*Communication with J. Felty

Outline

- Need
- Existing experimental hardware
- Proposal on experiment designs
- Calculations
- Material replacement worth
- Sensitivity analysis
- Simulation of uncertainty analysis
  - *Methods*
  - *Results*
- Some proposals on design optimization
- General conclusions

Terminology

Energy ranges

Thermal: 0.025eV - 0.5eV

Epithermal : 0.5eV - 1keV

Intermediate: 1keV – 0.5MeV

Fast: 0.5MeV – 50MeV

EALF

The energy corresponding to the average neutron lethargy causing fission, *EALF (eV)*, defined by:

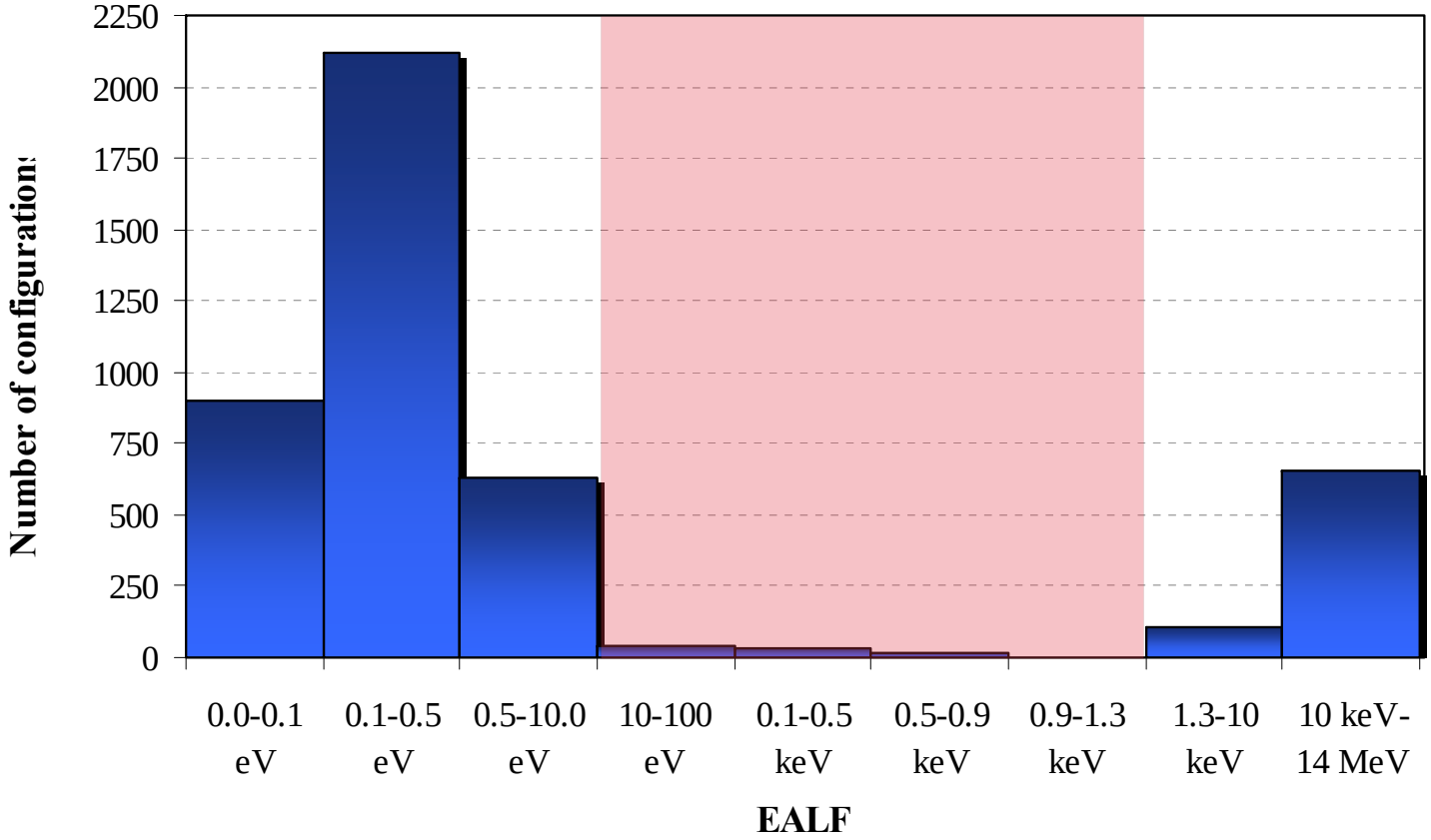
$$EALF = \frac{E_0}{e^{\bar{u}_g}}$$

where $\bar{u}_g$ is the midpoint of the gth lethargy group; E_0 indicates maximum neutron energy, in this case, 10 MeV.

K_{eff} sensitivity to neutron cross sections

Need: ICSBEP Handbook Data

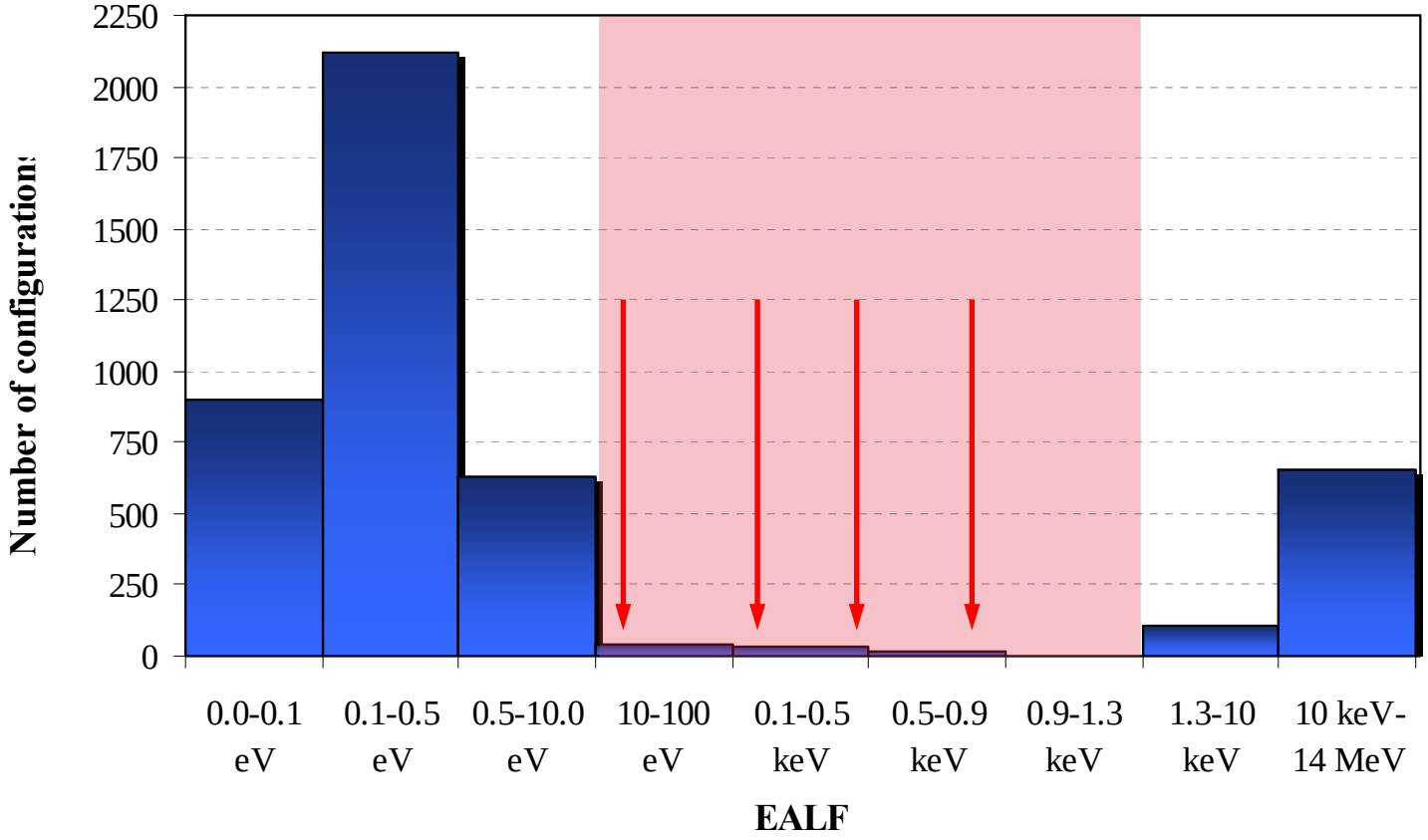
EALF* from 10eV to 1.3keV:
Very limited or NO experiments



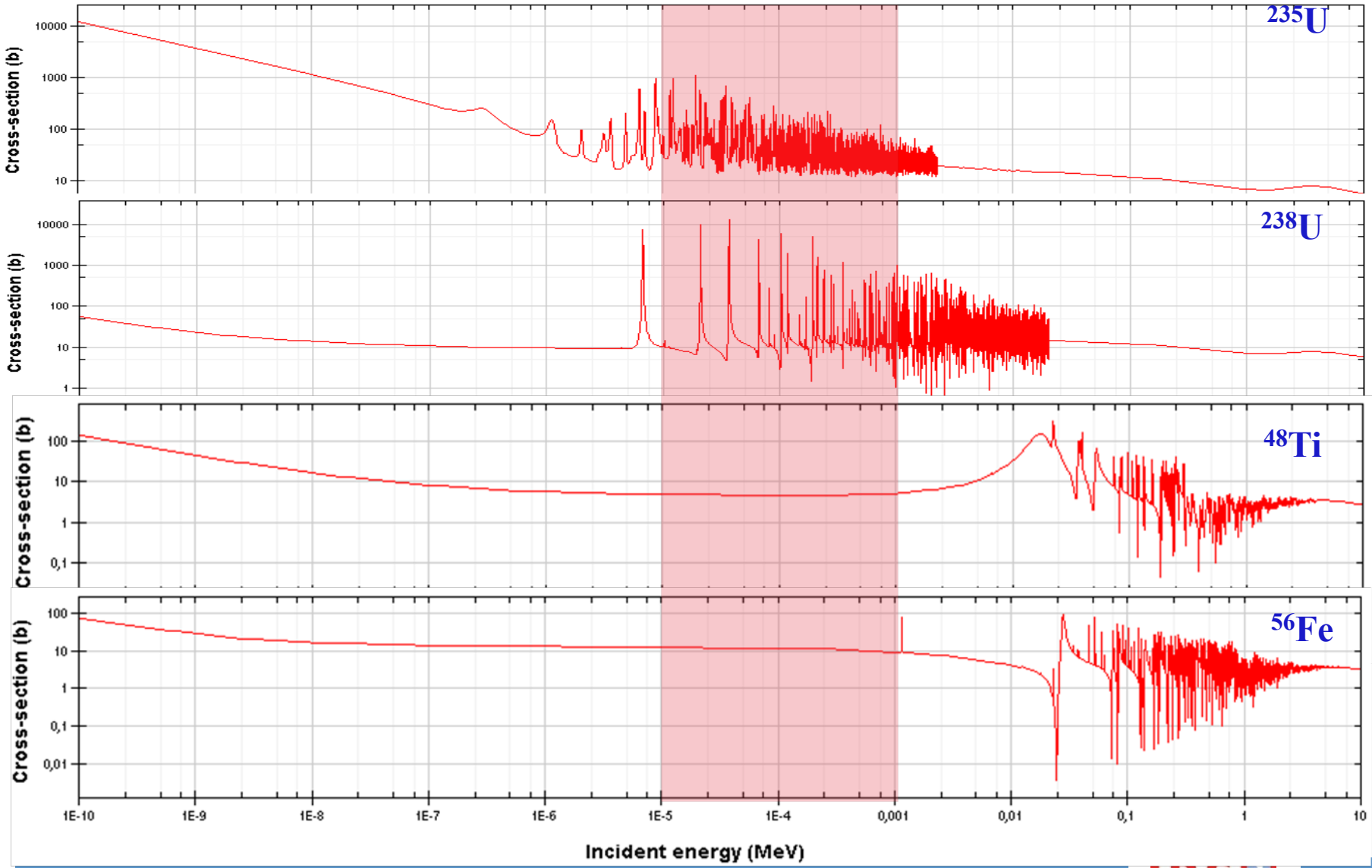
*EALF data presented in the ICSBEP Handbook DVD 2010 (DICE)

Need: Scenarios for Safety Assessment

Scenarios considering normal and abnormal conditions - steam in fuel storages and transport casks/others - provided by IRSN/SEC/BERAC



Need: Cross Sections



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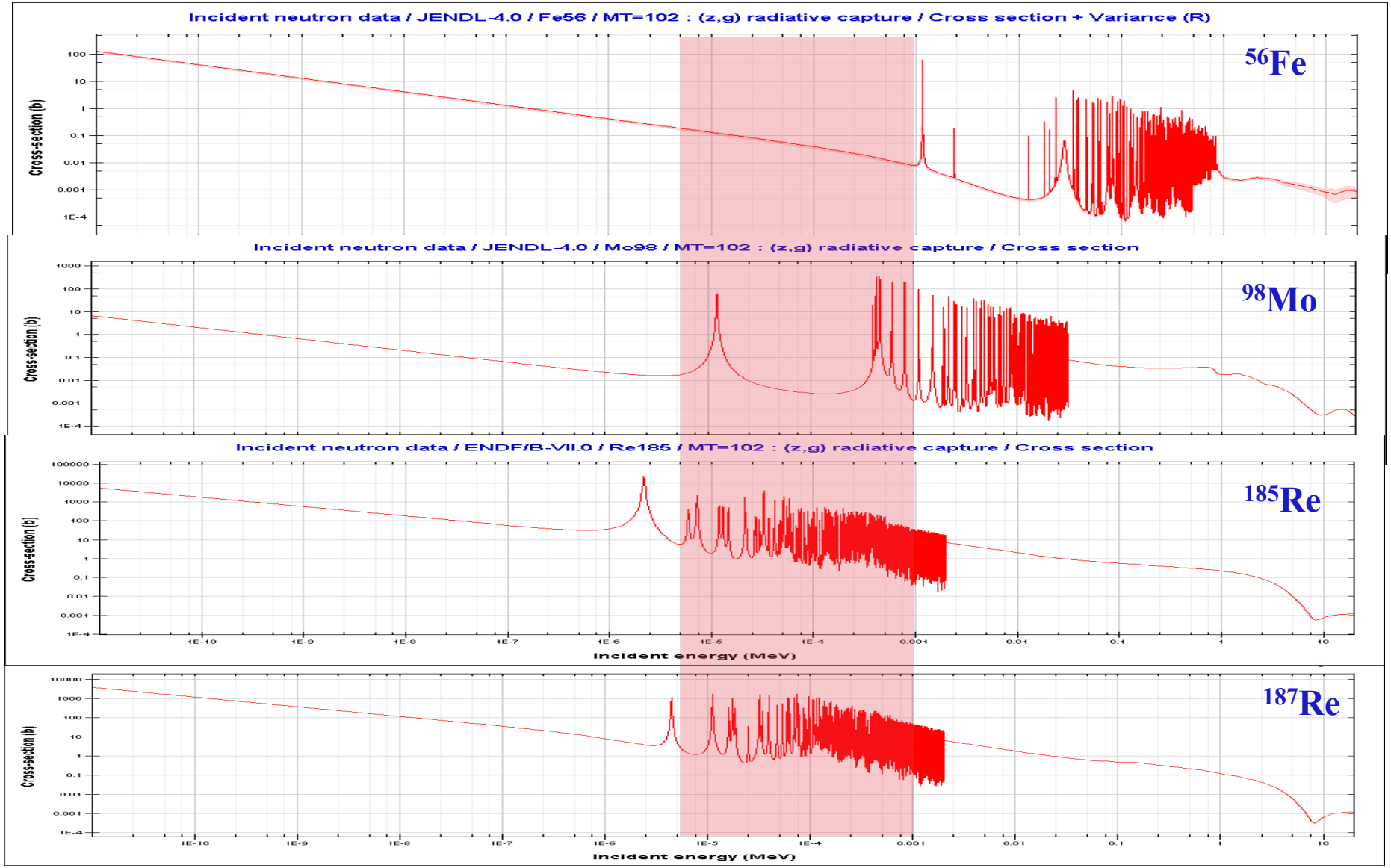
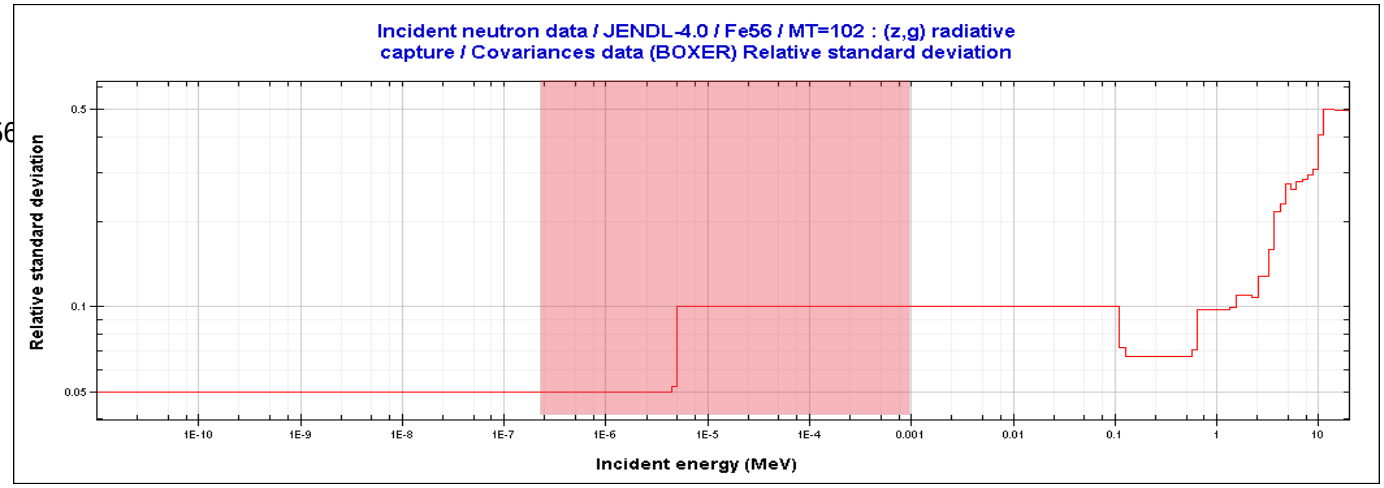
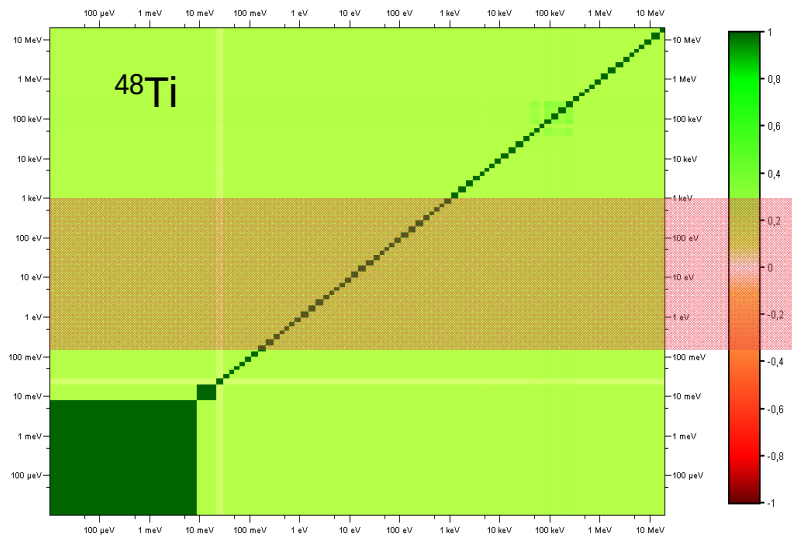
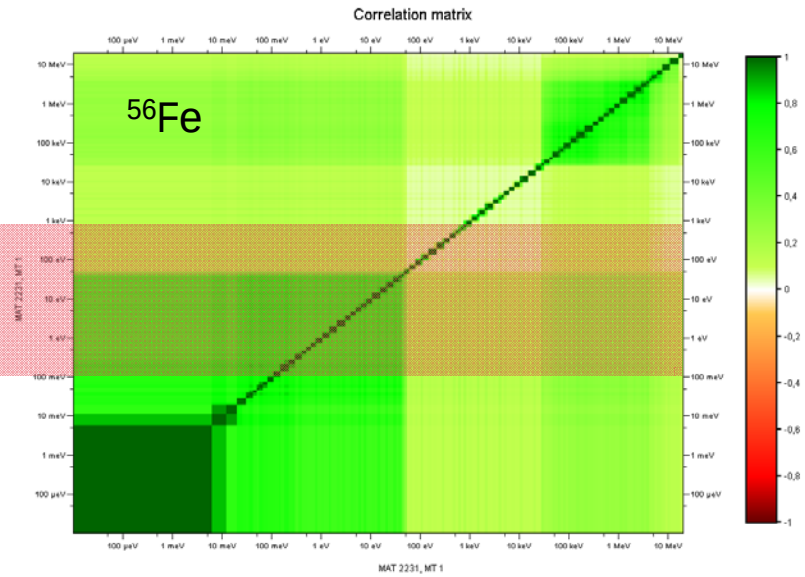


Need: Covariances

56







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Sandia Pulsed Reactor Facility (SPRF) Critical Experiments

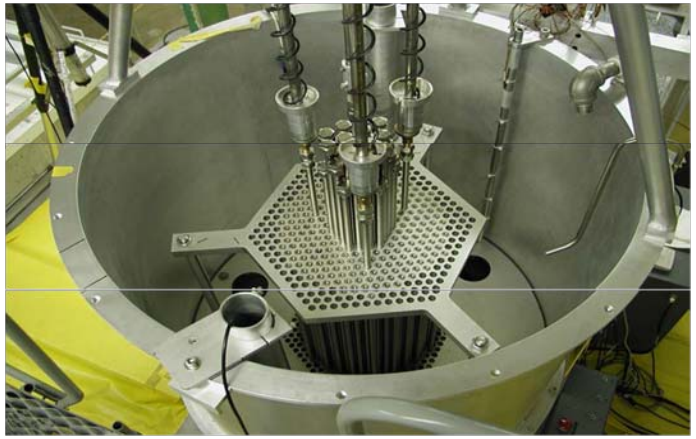
Facility description is available in the ICSBEP Handbook: LEU-COMP-THERM-079

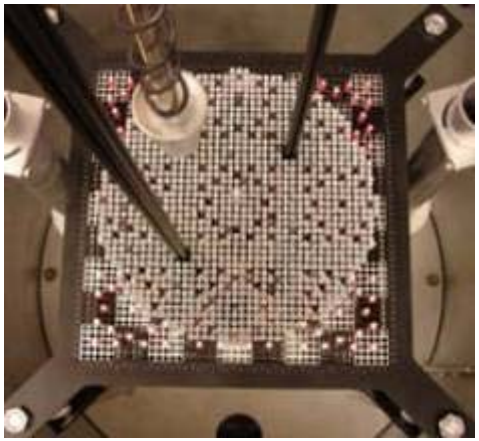
Water-Moderated U(4.31)O_2 Fuel Rod Lattices Containing Rhodium Foils

referred to as

Burnup Credit Critical Experiments (BUCCX).

Additional information on BUCCX is available in LEU-COMP-THERM-002.





Experimental method: approach-to-critical

Seven Percent Critical Experiments (7uPCX) description* in ANS publication, presentation, and SCALE/MCNP input decks.

*Provided by G. Harms

SPRF Experimental Facility Fuels*

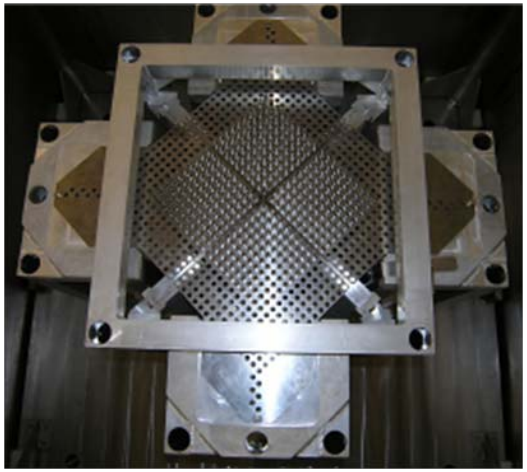
Fuel Type	BUCCX	7uPCX
Number Available	350	2199
Enrichment (%)	4.306	6.903
^{234}U Mass Fraction in U (%)	0.022	0.028
^{236}U Mass Fraction in U (%)	0.022	0.063
Fuel Column Mass (g)	637.73	108.72
Fuel Column Outer Diameter (cm)	1.2649	0.526
Fuel Column Length (cm)	48.6624	48.78
Fuel Column Density (g/cm^3)	10.429	10.265
Cladding	Zircaloy-4	3003 Aluminum
Cladding Outer Diameter (cm)	1.3818	0.635
Cladding Inner Diameter (cm)	1.2979	0.569
Benchmark Evaluation	LEU-COMP-THERM-079	LEU-COMP-THERM-080 (2012)

*Provided by G. Harms (SAND2011-2629 P)

Apparatus B, CEA Valduc

Facility description is available in the ICSBEP Handbook: 14 series of experiments (LCT-007, -027, -029, -034, -037, -038, 039, 040, -050, -052, -057, -071, -072, -073)

Water-Moderated U(4.74)O_2 Fuel Rod Lattices with various pitches and reflection configurations (189 experiments)



Experimental method: approach-to-critical

Recent contribution to the ICSBEP Handbook (2011) LEU-COMP-THERM-074 :

MIRTE Program: Four 4.738-wt.% Enriched Uranium-Dioxide Fuel-Rod Arrays in Water Separated by a Cross-Shaped Screen of Titanium (5 mm and 10 mm Thick)

Experiment Hardware

Sandia Pulsed Reactor Facility (SPRF) at Sandia National Lab, USA
(called SNL hereafter)

Apparatus B at CEA Valduc, France – considered to compare potential design with MIRTE and to show design performance for fuel of different enrichment and geometry
(called Valduc hereafter)

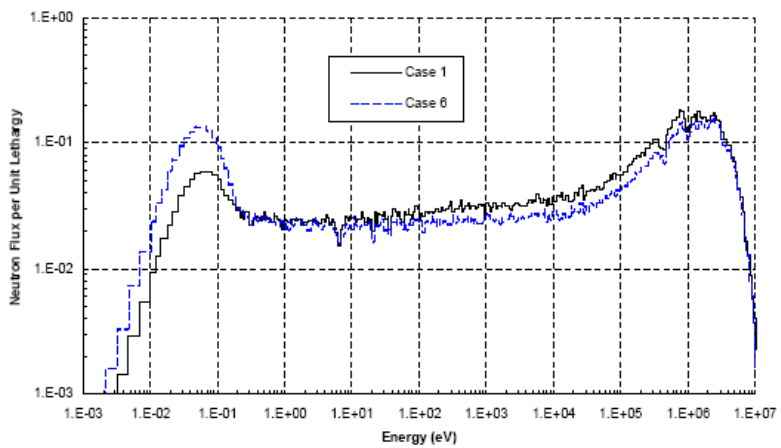
	Valduc	SNL	
Fuel elements:			
Enrichment, %	4.738	6.903	4.306
Fuel diameter, cm	0.789	0.526	1.2694
Length, cm	89.77	48.78	48.6624
Number	1200	2199	350
Tank dimension, cm	120 x 120 x 140	Diameter = 93.68 Height = 101.6	

Spectral Characteristics Examples

LCT-079 (BUCCX) SNL

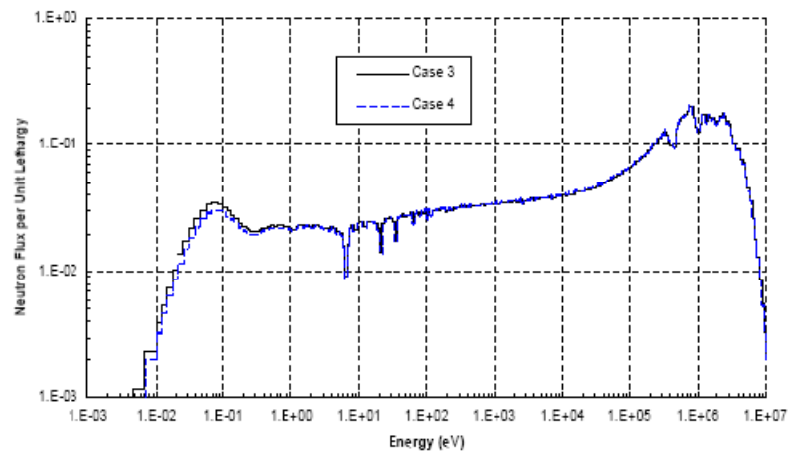
Case Number	EALF, eV
1	3.59×10^{-1}
2	3.60×10^{-1}
3	3.64×10^{-1}
4	3.68×10^{-1}
5	3.75×10^{-1}
6	1.23×10^{-1}
7	1.23×10^{-1}
8	1.24×10^{-1}
9	1.25×10^{-1}
10	1.26×10^{-1}

Neutron spectrum



LCT-071 (Tight-packed lattice) Valduc

Case Number	EALF, eV
1	9.48×10^{-1}
2	8.66×10^{-1}
3	8.22×10^{-1}
4	1.06×10^{0}



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Proposal on Experiment Concept

To increase sensitivity for structural materials

- place the materials as tubes (sleeves) around fuel elements (solution considered in the present study)

To "harden" neutron spectrum locally

- replace water moderator with a "transparent" material forming a test zone; and
- add a solid absorber in/around the test zone to "screen" thermal neutrons

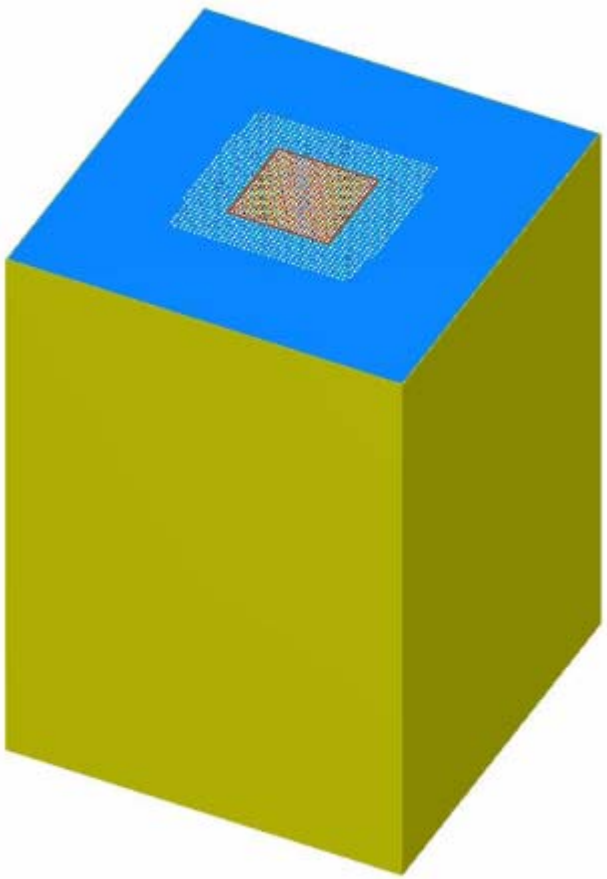
Material for water replacement – Aluminum (Al).

Absorber - Cadmium (Cd)/Hafnium (Hf) or others.

Perform set of replacement experiments for p r o g r e s s i v e neutron spectrum hardening

Models for Experiment Concept

Valduc Model



Test material sleeve (tube)

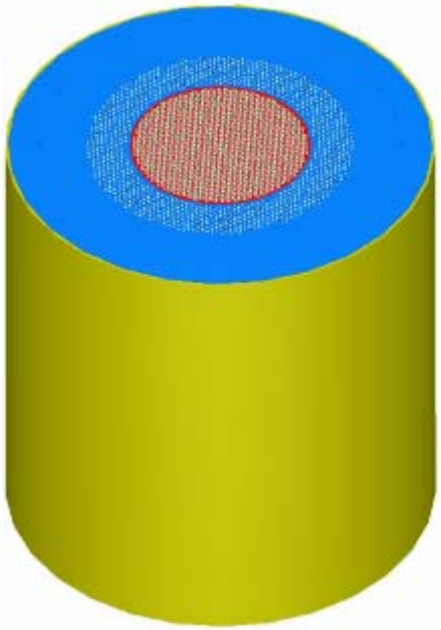
Test zone:
Al insert + UO_2 rods

Thin Cd screen

Driver zone:
Water + UO_2 rods

Water reflector

SNL Model



Al test zone allow modeling water density variation (steam) in the scenarios for criticality assessment.

Key Assumptions for SNL Design

- Postulated design is restricted to the following inventory of fuel elements:

  350 (~4%) and 2199 (~7%) rods for SNL;
  1200 (~4%) rods for Valduc.

- There is no restriction on the grid and support plates;
- Position of safety and control rods can change;
- Technological aspects; cost of tubing and Al insert fabrication was not investigated;
- Extension of the experimental tank is an option (Valduc model can serve as an example of design performance).

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Computational Method

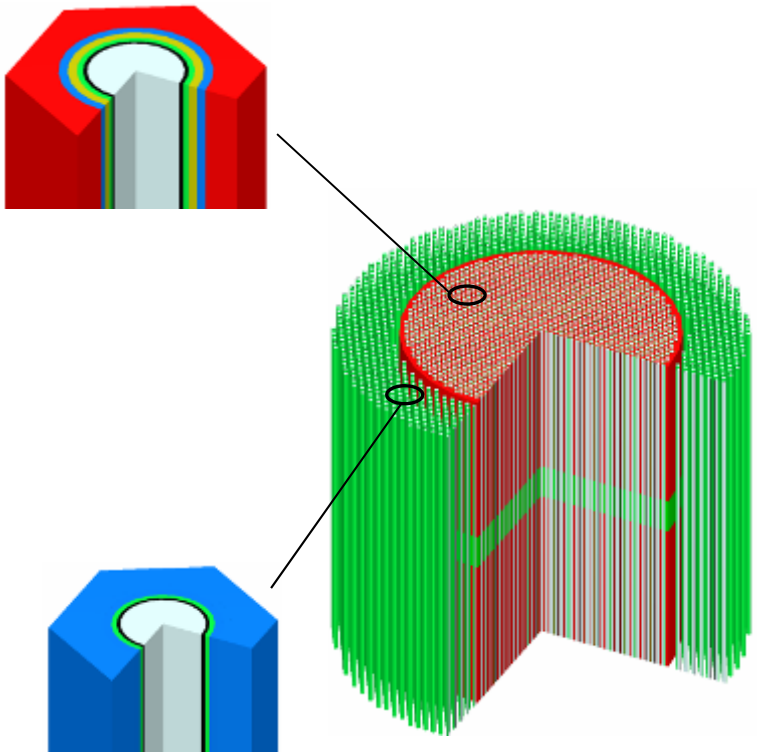
SCALE 6.0

- KENO-V.a
- ENDF/B-7 238 groups
- TSUNAMI-3D (Sensitivity computation)

IRSN CODE for data adjustment: same functions as TSURFER (Data Adjustment) and TSAR (Uncertainty analysis for reactivity)

SNL Modeling

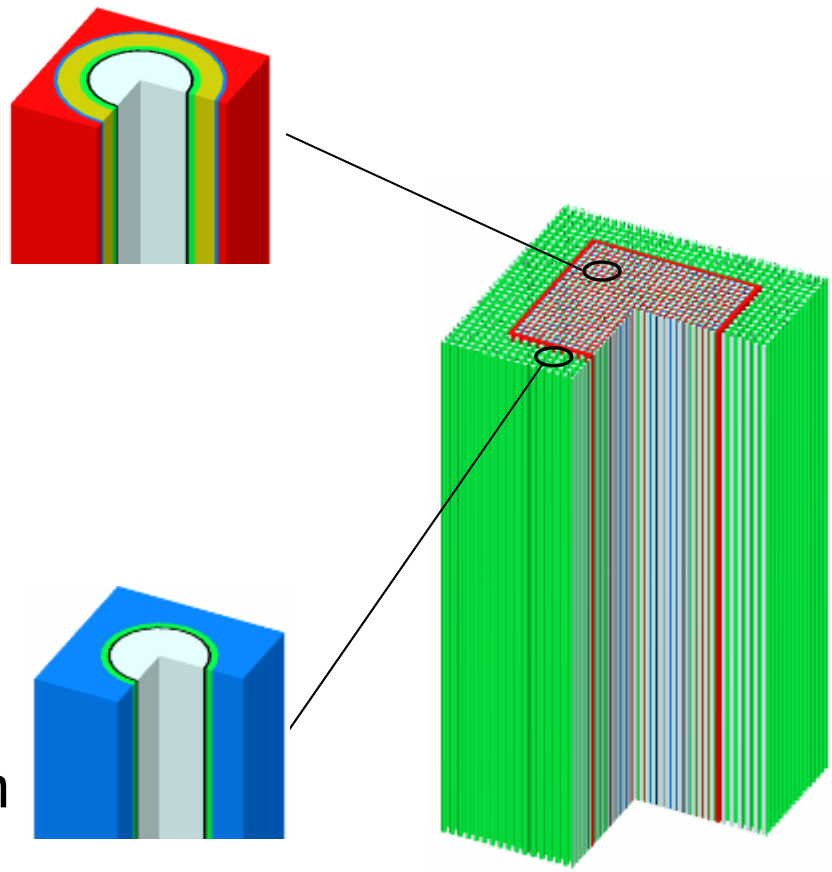
- Fuel element dimension, cm
  - Fuel radius=0.263
  - Fuel length = 48.78
- Triangular lattice pitch, cm
  - 1.2 (0.8)/1.2 cm (inner/outer)
- Tank dimension, cm
  - Radius = 46.83
  - Height = 101.6
- Al test zone dimension, cm
  - Radius = 19.7
  - Height = 48.78
- SS/Ti/Al Sleeve thickness, cm
  - 0.05, 0.15, 0.17



Cells Test and Driver zones

Valduc Modeling

- Fuel element dimension, cm
  Fuel radius = 0.394595
  Fuel length = 89.77
- Square lattice pitch, cm
  1.5 (1.2)/1.5 (inner/outer)
- Tank dimension, cm
  120 x 120 x 140
- Al test zone dimension, cm
  31.4 x 31.4 x 89.77
- SS/Fe/Ti/Al Sleeve thickness, cm
  0.05,0.15,0.17

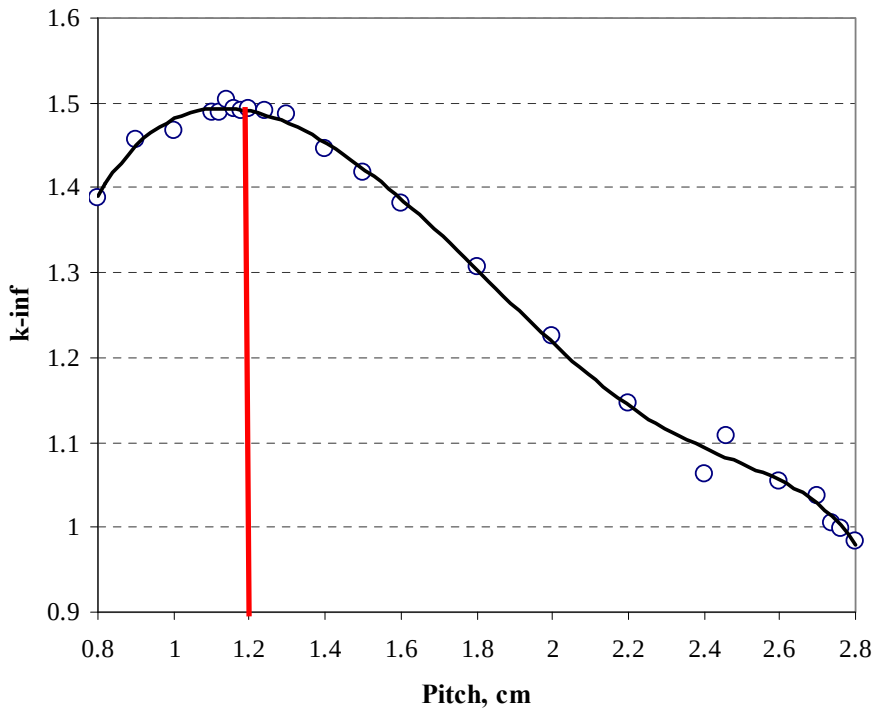


Cell

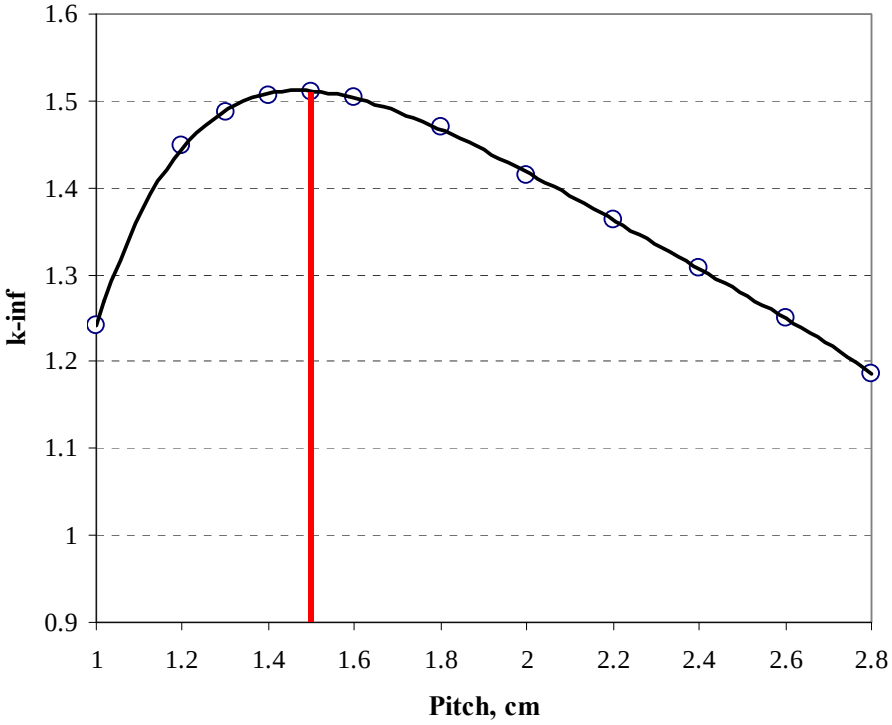
Test and Driver zones

Pitch Selection for Driver Zone

SNL Hexagonal Lattice



Valduc Square Lattice



Simplifications to the Models

- Source, control and safety elements replaced with fuel element (for SNL);
- No grids for fuel elements' support;
- No plugs, springs in the fuel elements.

Study is Performed for

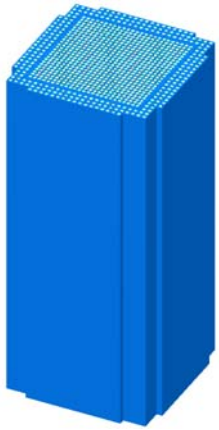
- Stainless steel (SS), Iron (Fe), and Titanium (Ti) test materials placed as sleeves around the fuel elements.

Replacement Experiments (1/2)

«Thermal» configurations

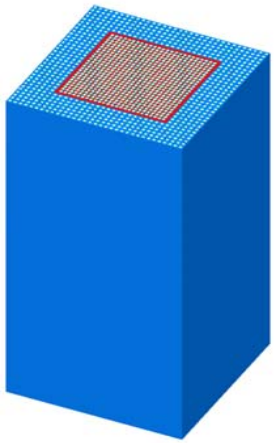
«Epithermal» configurations

Valduc



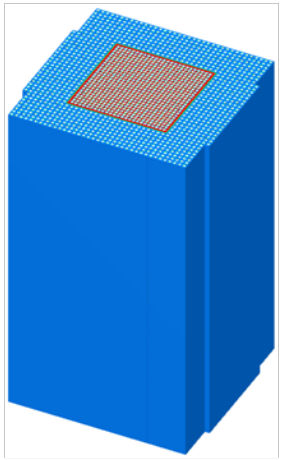
Sleeves/No sleeves around fuel rods in water

(called Water test zone hereafter)



Sleeves/No sleeves around fuel rods in Al test zone

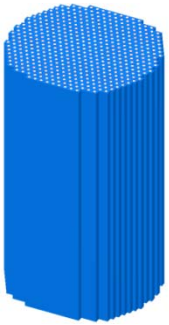
(called Al test zone hereafter)

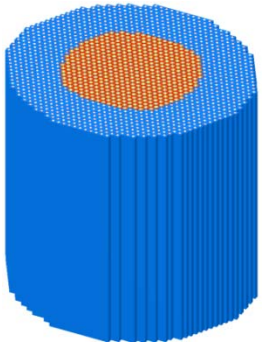


Sleeves/No sleeves around fuel rods in Al test zone surrounded by Cd layer

(called Al+Cd test zone hereafter)

SNL

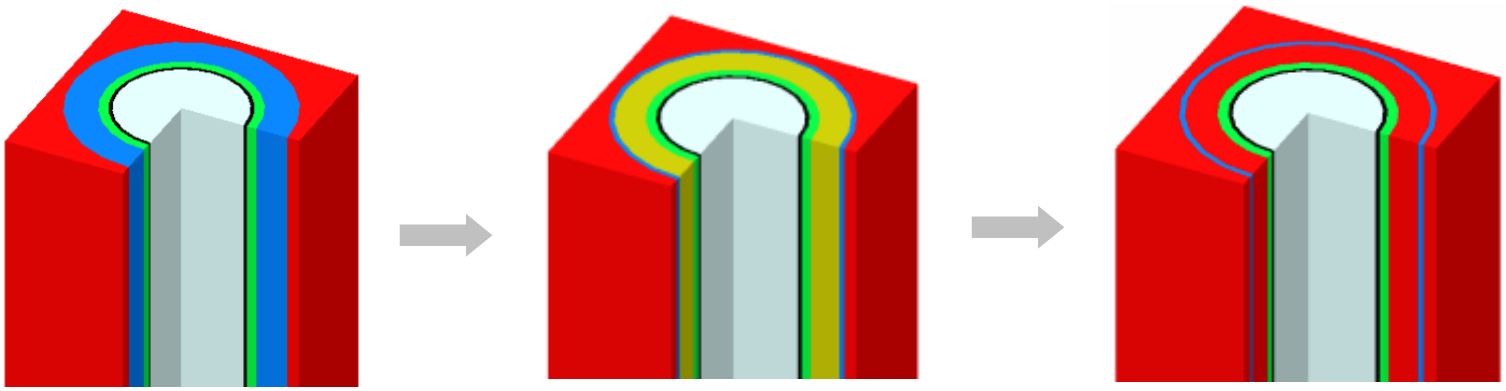




Water reflector is not shown

Replacement Experiments (2/2)

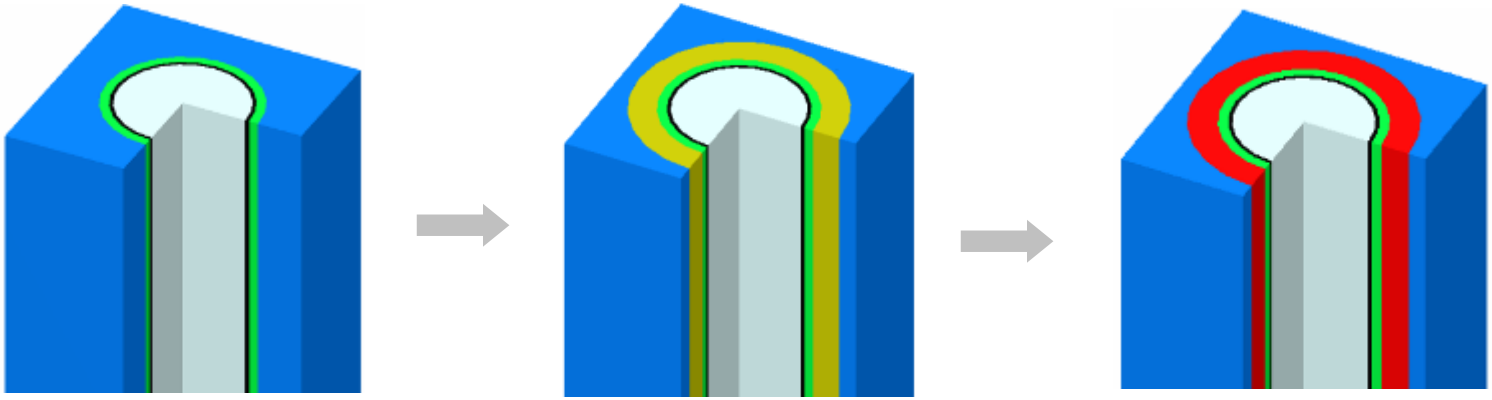
Al test zone CELL



Fuel **Void** **Cladding** **Water** **Al**

+ SS/Fe/Ti sleeve or **+ Al sleeve**

Water test zone CELL



Fuel Inventory Use

Number of fuel elements is provided for configurations with 1.7-mm sleeves

Number of fuel elements in ↓	Water Test Zone	Al Test Zone	Al+Cd Test Zone
SNL			
Test Zone	487	487	-
Total	1347	1493	-
Valduc			
Test Zone	441	441	441
Total	873	1081	1413

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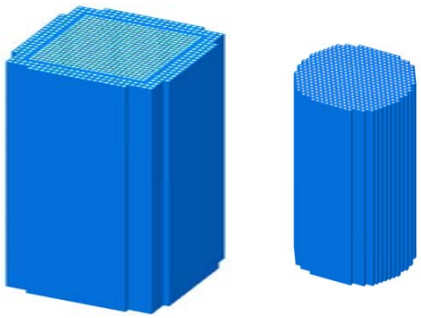
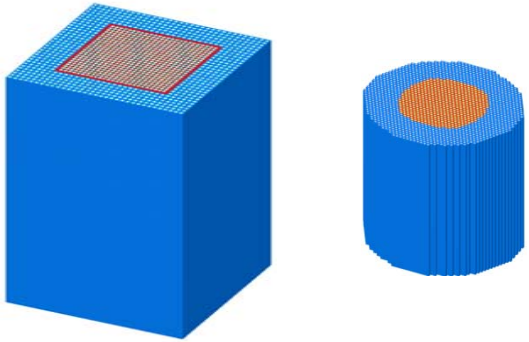
Comparison w/MIRTE: Configurations

Potential Design

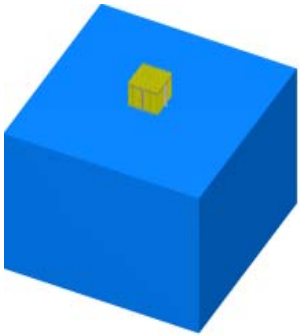
No/SS/Fe/Ti/Al sleeves in
water test zone



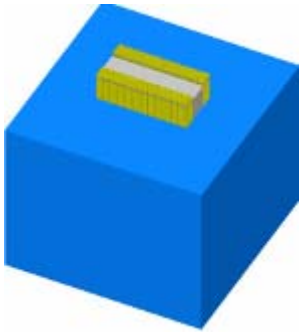
No/SS/Fe/Ti/Al sleeves in
Al test zone



MIRTE



Cruciform separator Fe 3 mm
Ti 5/10 mm



Separator Fe 20 cm

Fe Replacement Worth

Configuration →	Potential Design (Valduc)			MIRTE*	
	1.5-mm Fe Sleeves in Water	1.5-mm Fe Sleeves in Al	1.5-mm Fe Sleeves in Al + Cd	200-mm Fe Separator	3-mm Cruciform Fe Separator
k-eff					
Base (Fe)	1.0183	1.0074	1.0136	1.0083	1.0004
Water	1.2101	1.1112	1.0533	1.1109	1.0438
Void	1.1425	1.0379	1.0221	1.0837	1.0321
Replacement Worth, %Δk/k					
Fe-Water	**-18.8**	**-10.3**	**-3.9**	**-10.2**	**-4.3**
Fe-Void	**-12.2**	**-3.0**	**-0.8**	**-7.5**	**-3.2**
Water-Void	**5.6**	**6.6**	**3.0**	**2.5**	**1.1**

* Letter Report by B. Rearden and D. Hollenbach, ORNL, November 2007

SS/Fe Replacement Worth

Config. →	Potential Design/ Valduc 1.7-mm SS Sleeves in			Potential Design/SNL 1.7-mm SS Sleeves			MIRTE*	
	Water	Al	Al + Cd	Water	Al	Al + Cd	200-mm Separator	3-mm Cruciform Separator
k-eff								
Base (SS/Fe)	1.0019	1.0127	1.0123	0.9917	1.0006	-	1.0083	1.0004
Water	1.2211	1.1243	1.0556	1.2056	1.1253	-	1.1109	1.0438
Void	1.1419	1.0452	1.0201	1.1011	1.0244	-	1.0837	1.0321
Replacement Worth, %Δk/k								
SS/Fe-Water	**-21.9**	**-11.0**	**-4.3**	**-21.6**	**-12.5**	**-**	**-10.2**	**-4.3**
SS/Fe-Void	**-14.0**	**-3.2**	**-0.8**	**-11.0**	**-2.4**	**-**	**-7.5**	**-3.2**
Water-Void	**6.5**	**7.0**	**3.4**	**8.7**	**9.0**	**-**	**2.5**	**1.1**

* Letter Report by B. Rearden and D. Hollenbach, ORNL, November 2007

Ti Replacement Worth

Configuration →	Potential Design (Valduc)			MIRTE*	
	1.7-mm Ti Sleeves in Water	1.7-mm Ti Sleeves in Al	1.7-mm Ti Sleeves in Al + Cd	5-mm Ti Cruciform Separator	10-mm Ti Cruciform Separator
k-eff					
Base (Ti)	1.0056	1.0031	-	0.9953	0.9919
Water	1.2363	1.1260	-	1.0779	1.1044
Void	1.1659	1.0452	-	1.0603	1.0754
Replacement Worth, %Δk/k					
Ti-Water	-22.9	-12.3	-	-8.30	-11.34
Ti-Void	-13.0	-3.7	-	-6.53	-8.42
Water-Void	5.7	7.2	-	1.64	2.66

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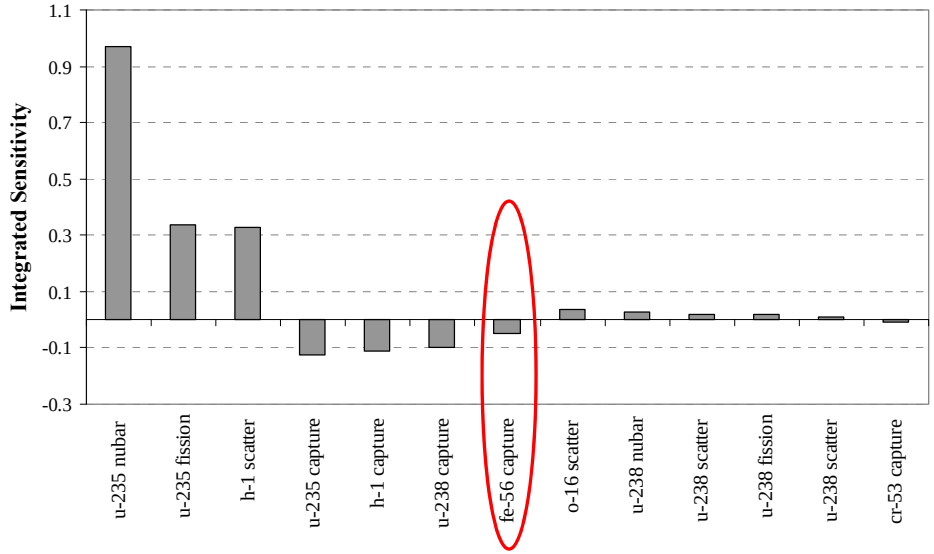
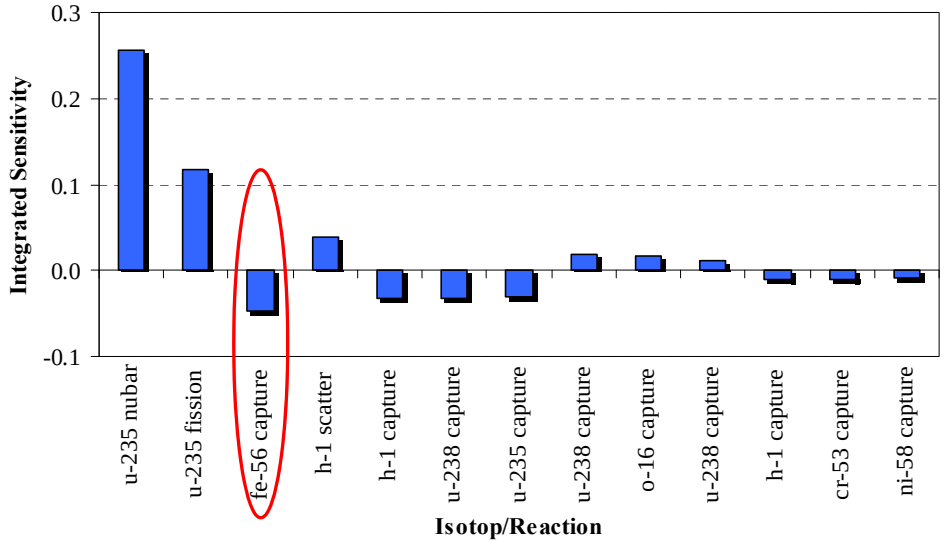
Sensitivities for "Thermal" Configurations

In Whole Configuration



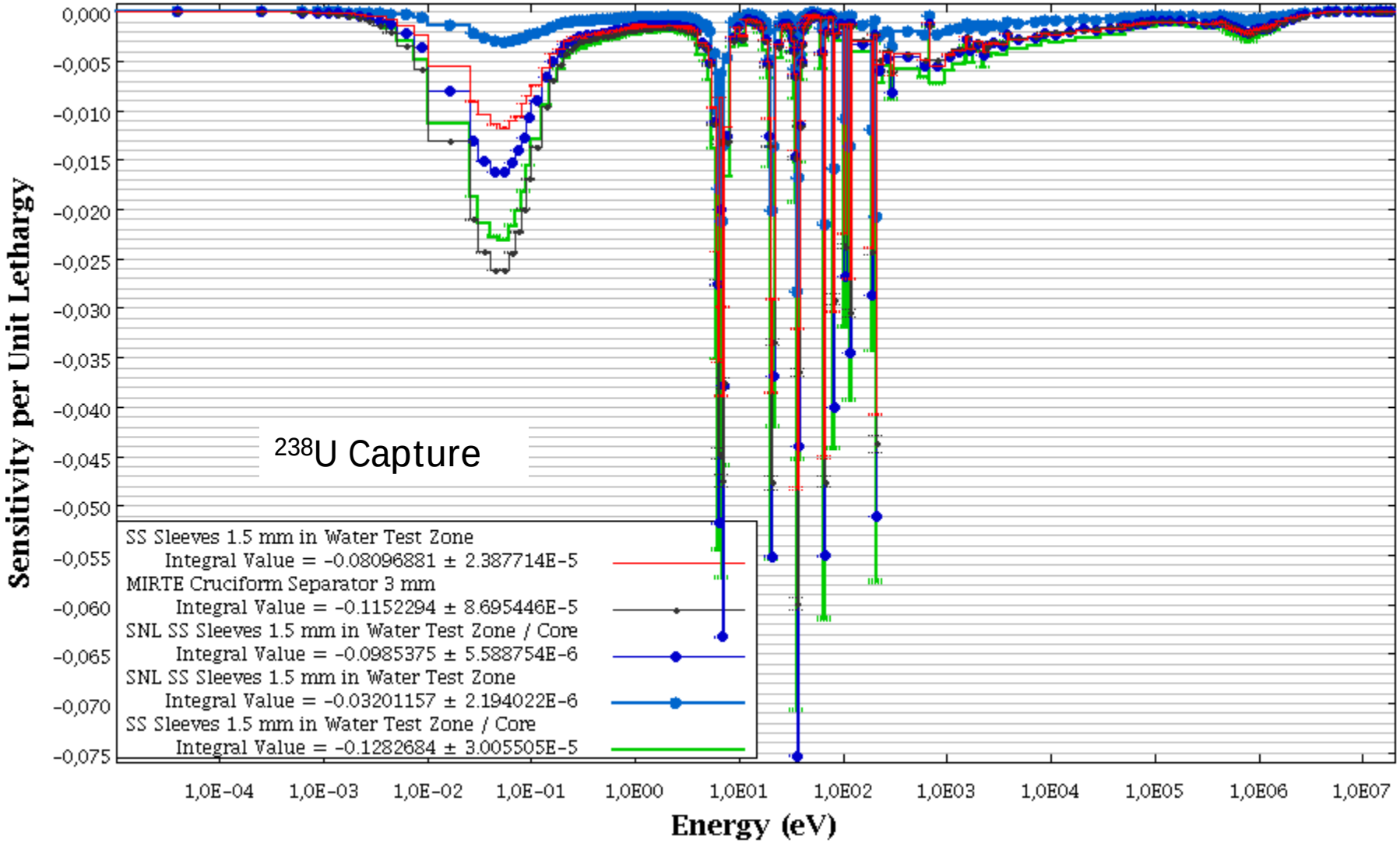
In Water Test Zone



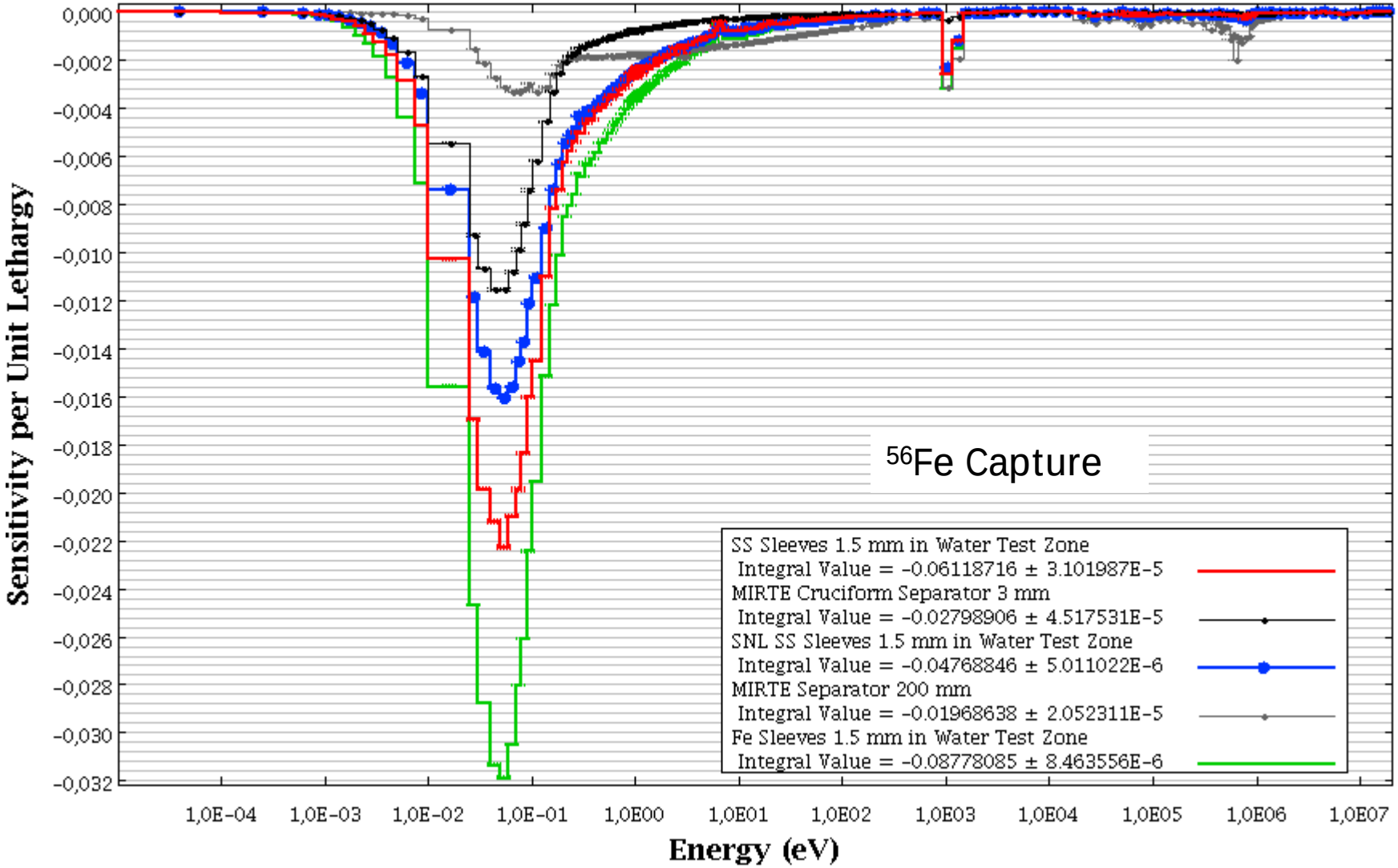
SNL

SS sleeves in water test zone

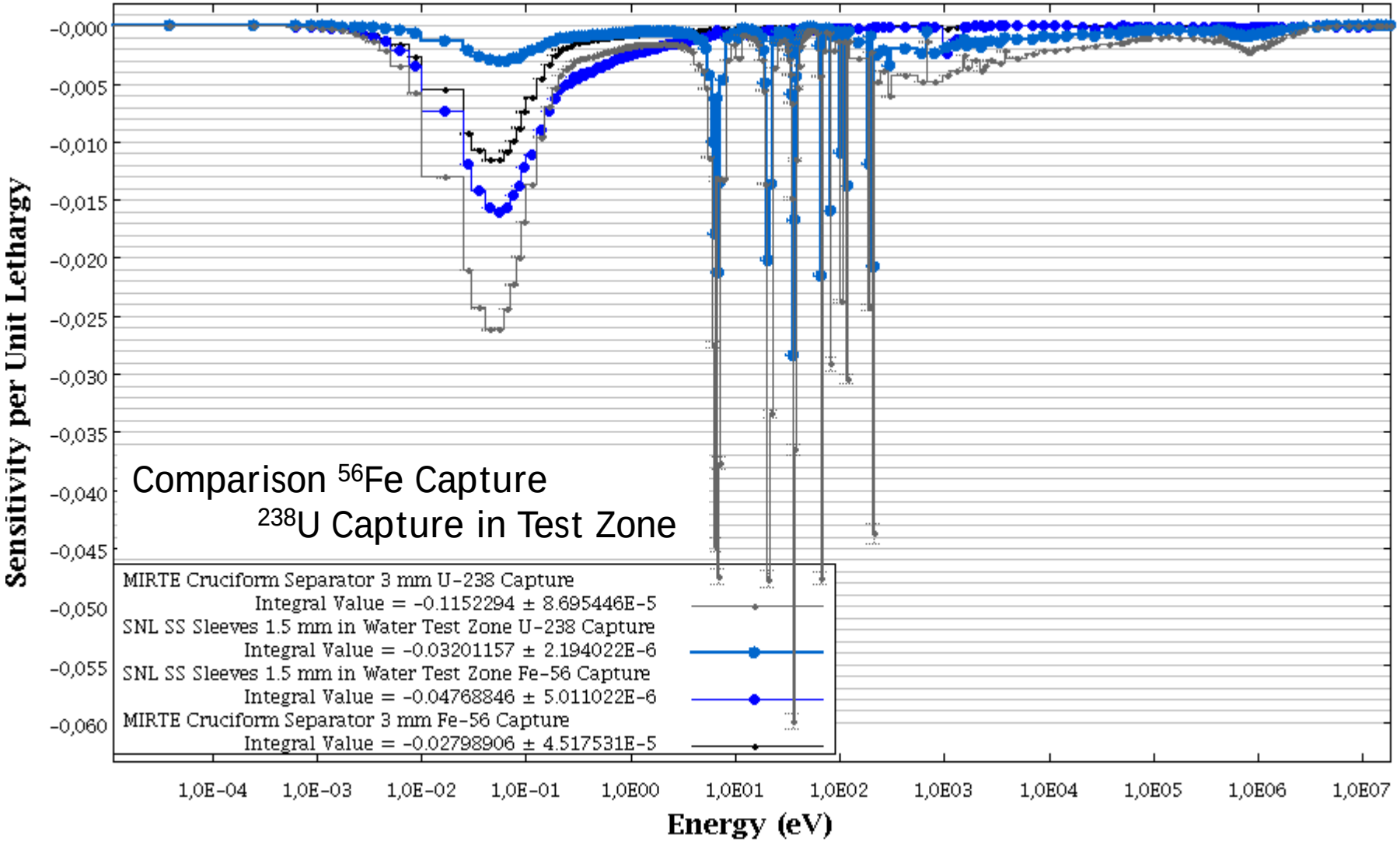
Sensitivities for "Thermal" Configurations



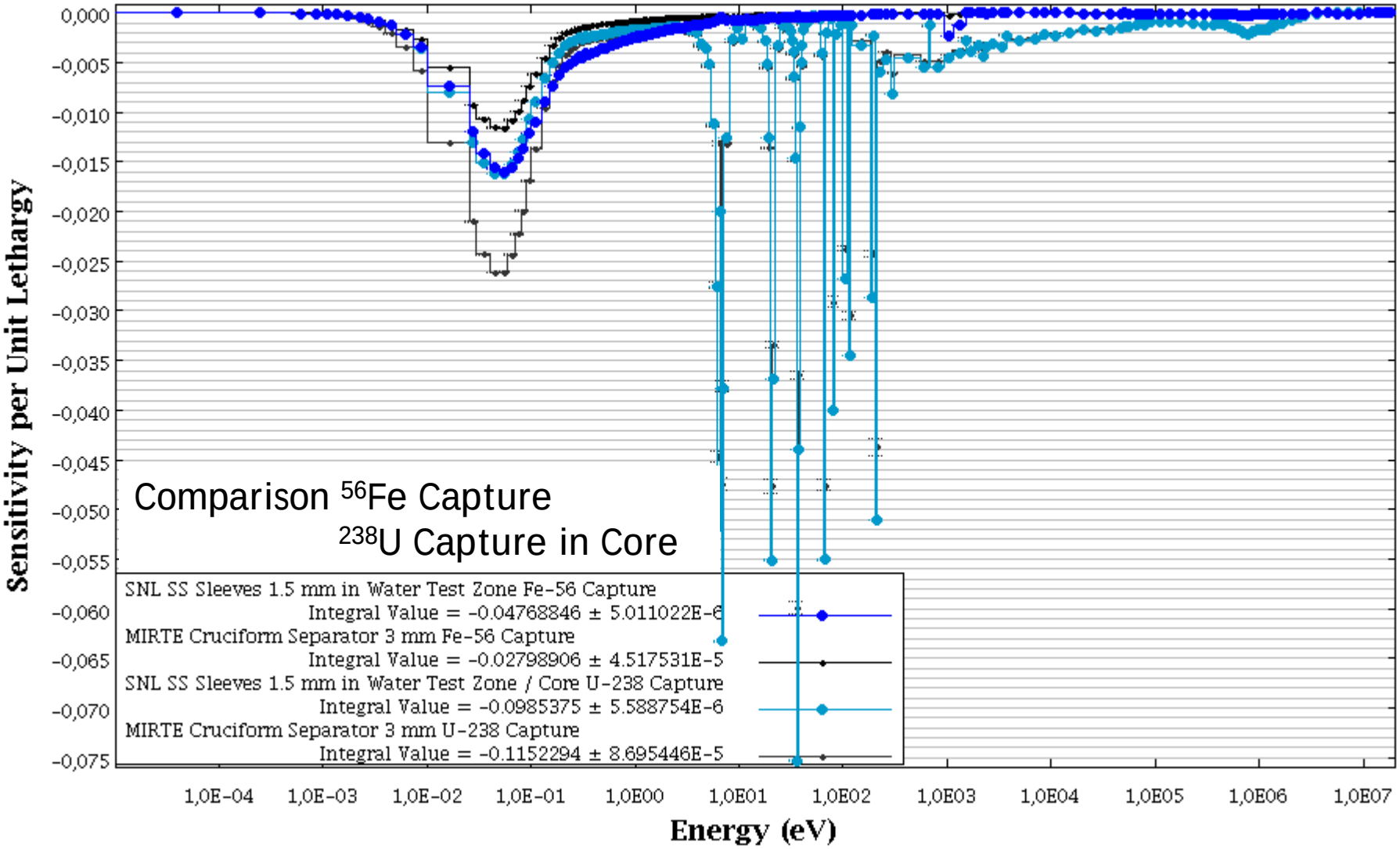
Sensitivities for "Thermal" Configurations



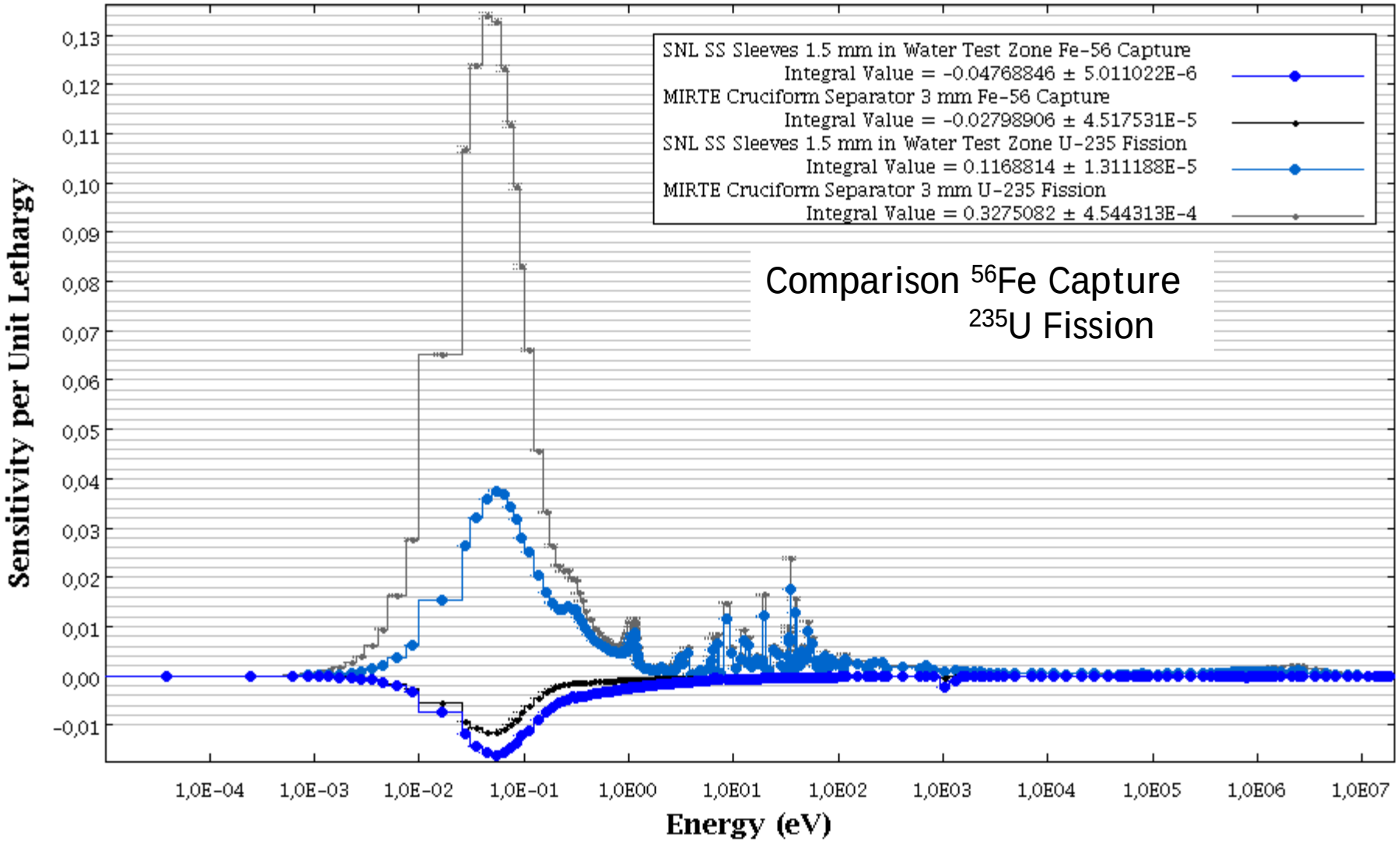
Sensitivities for “Thermal” Configurations



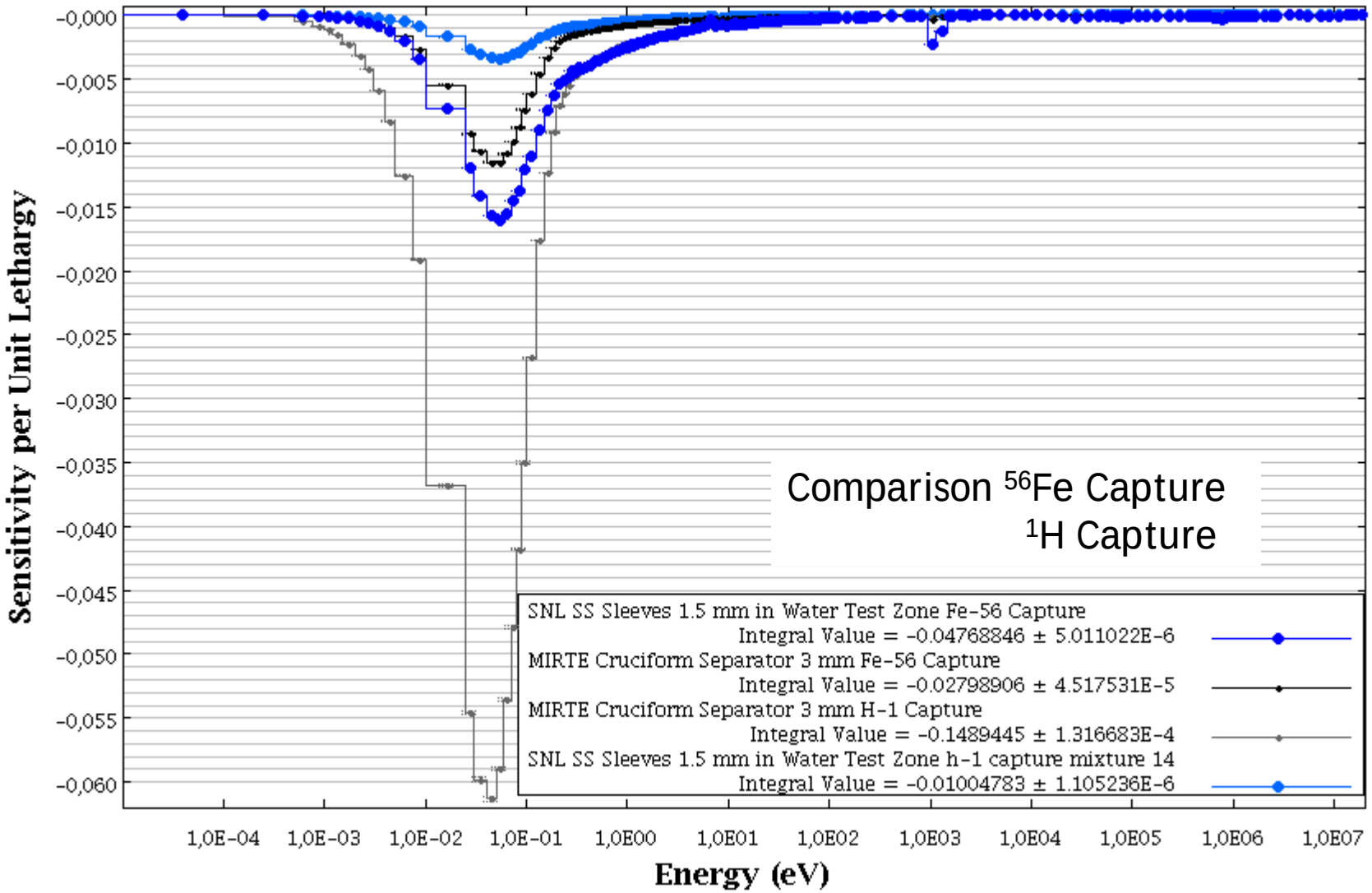
Sensitivities for “Thermal” Configurations



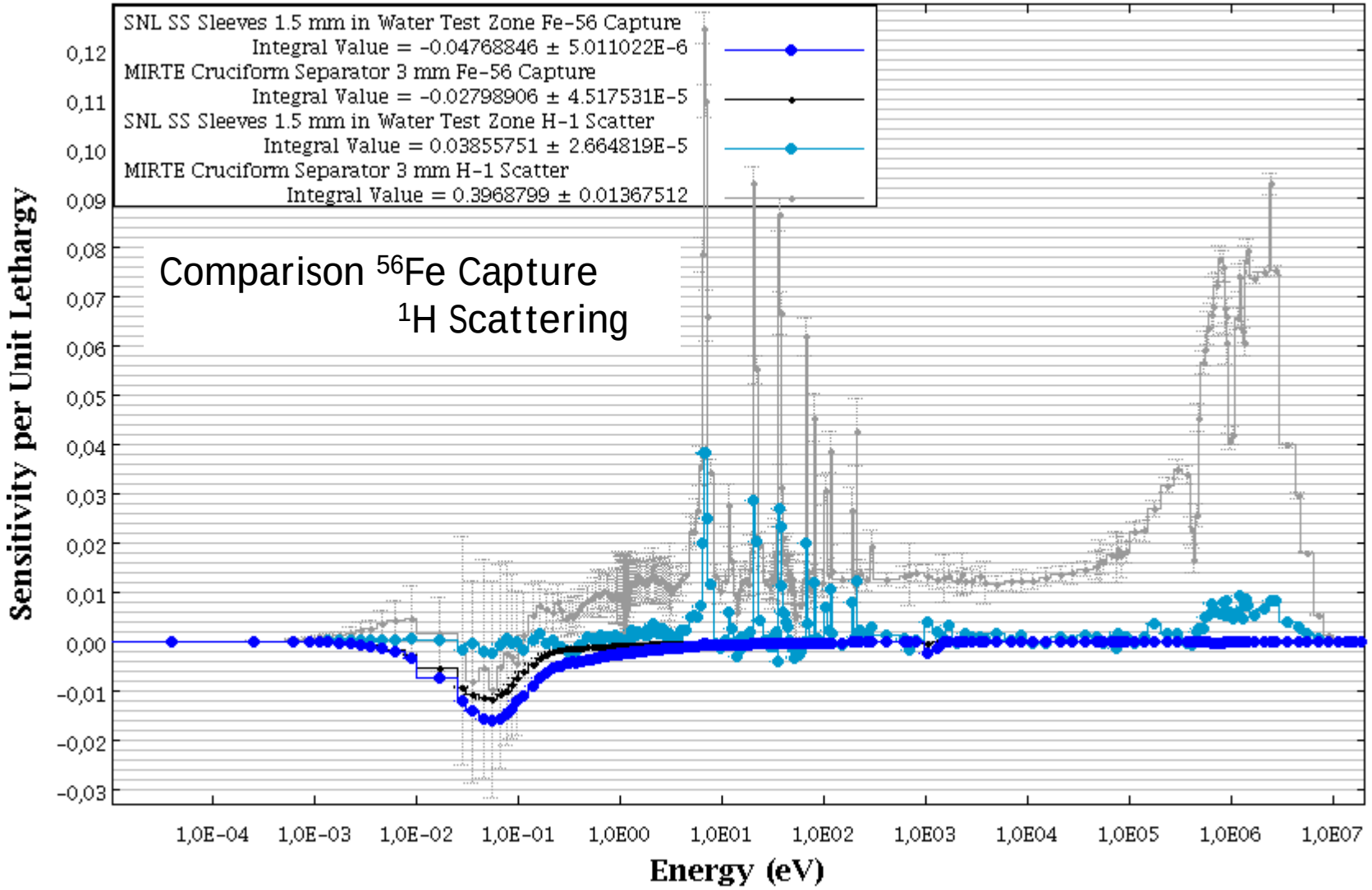
Sensitivities for "Thermal" Configurations



Sensitivities for "Thermal" Configurations



Sensitivities for "Thermal" Configurations



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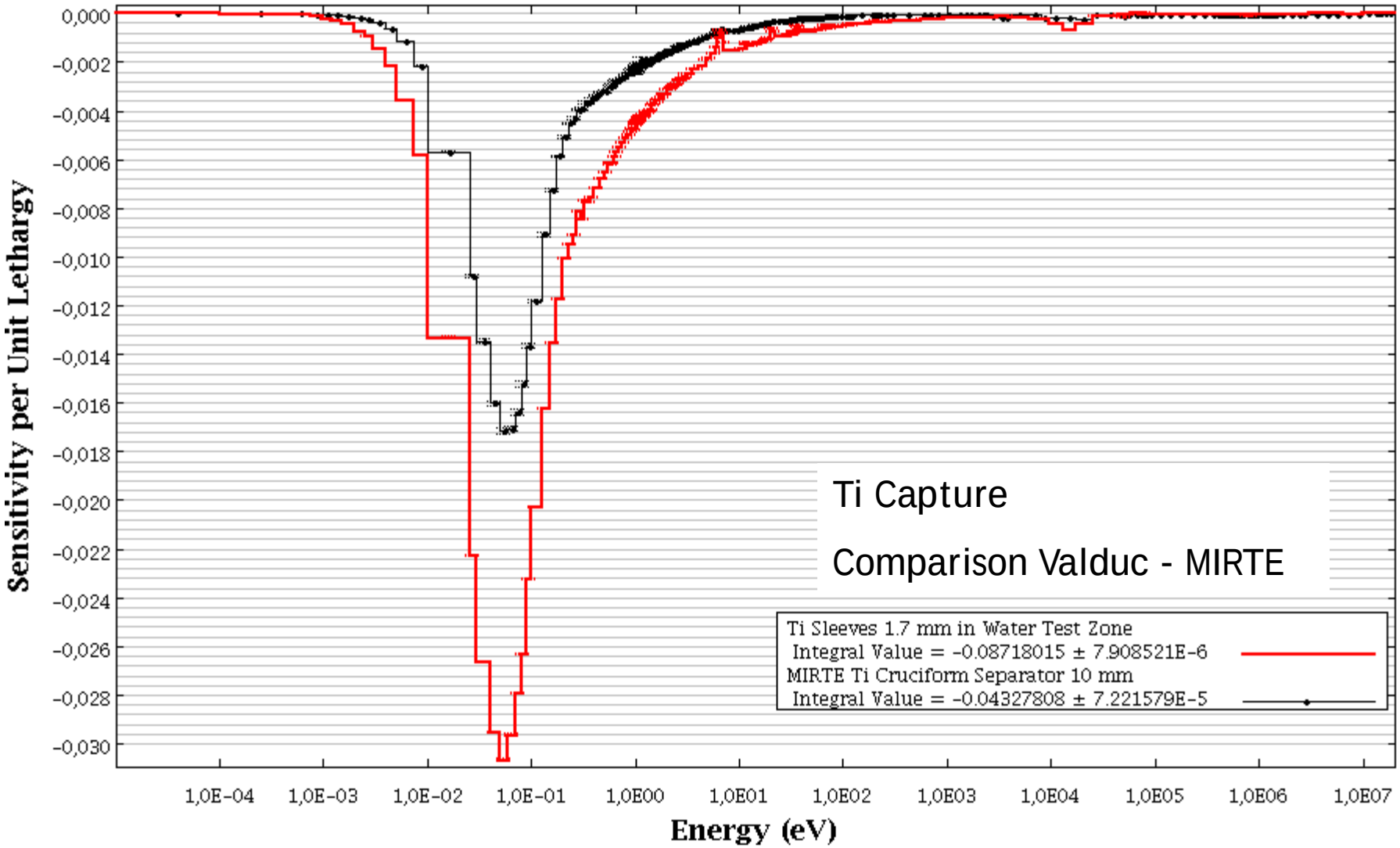
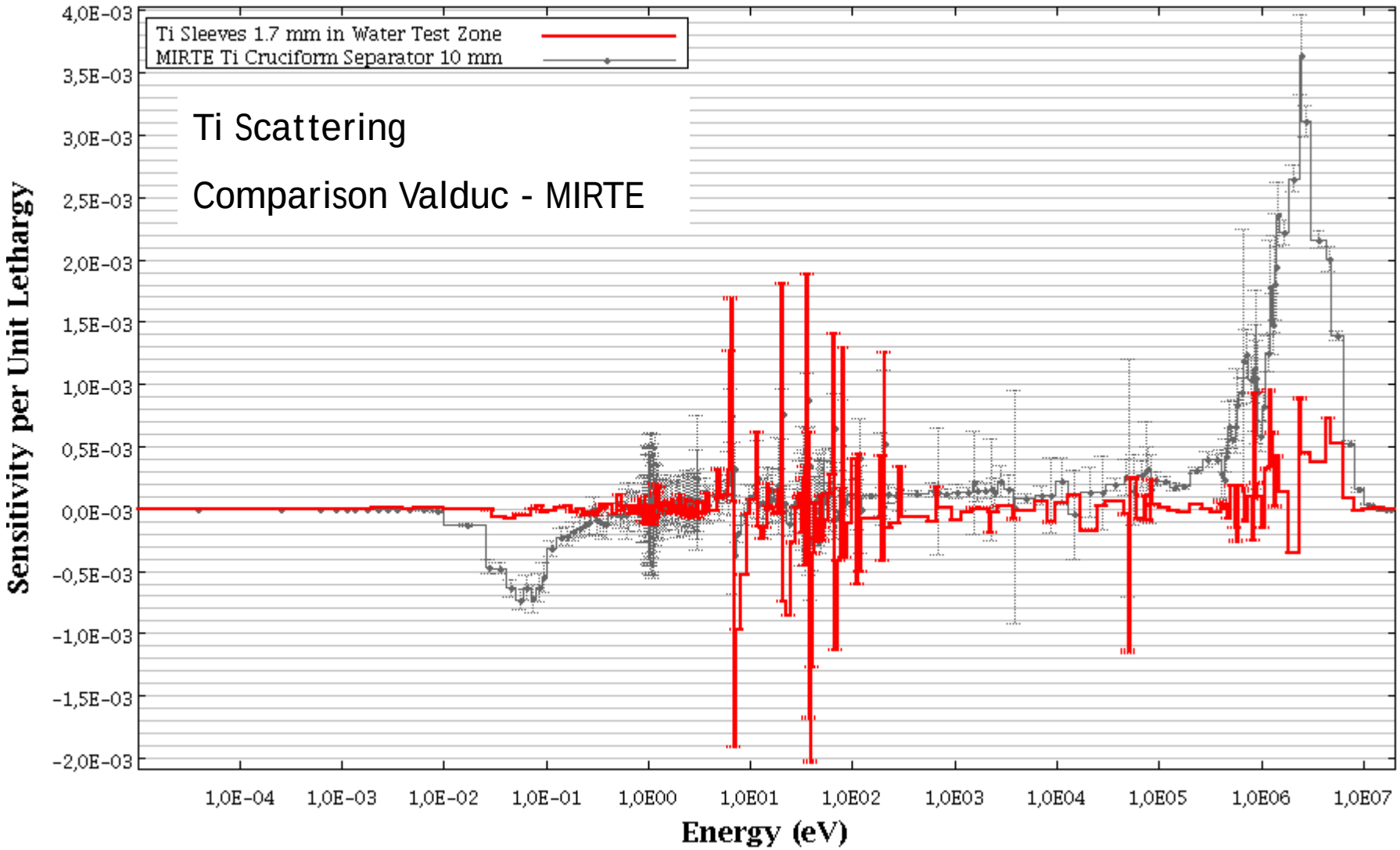


Sensitivities for "Thermal" Configurations



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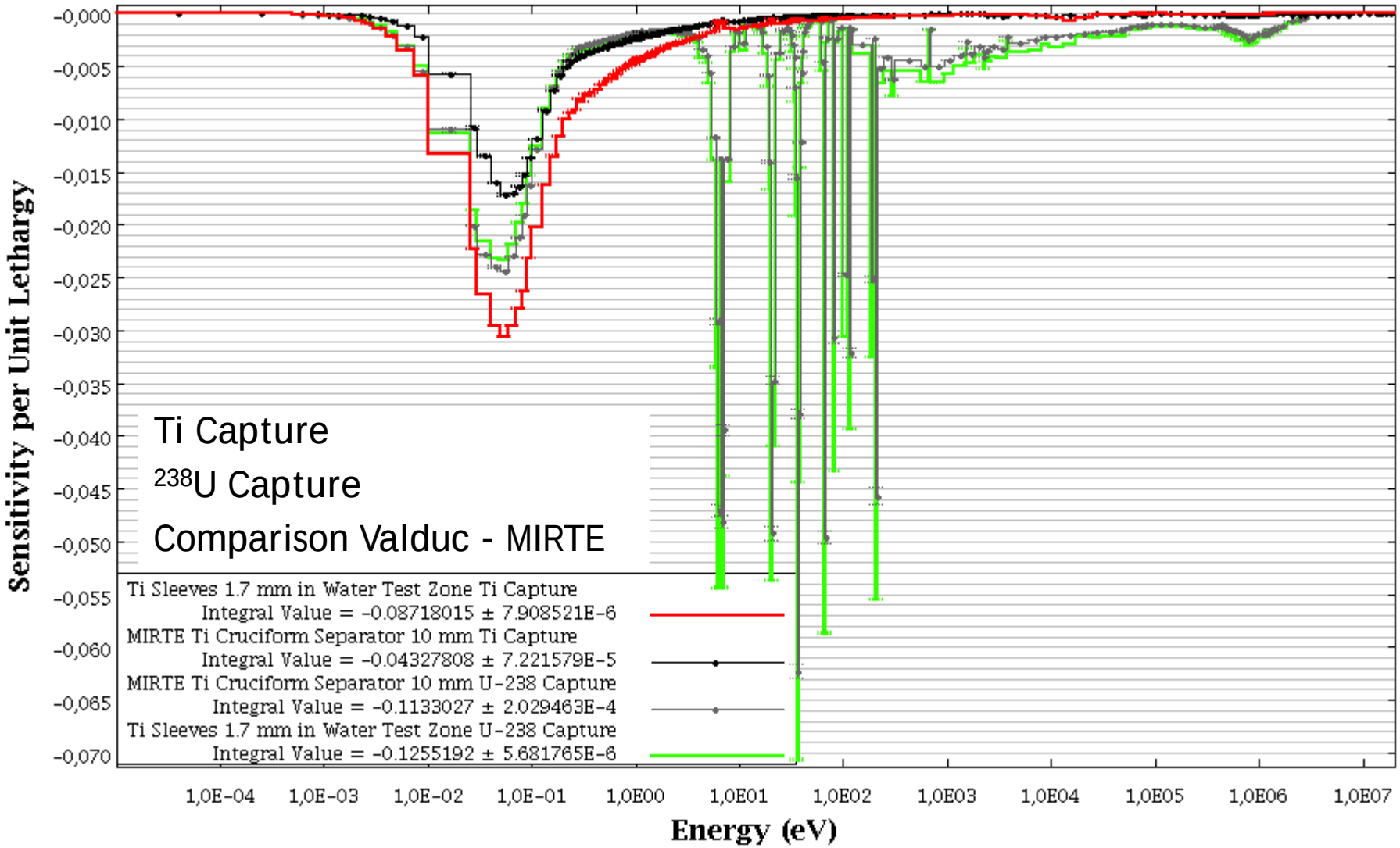
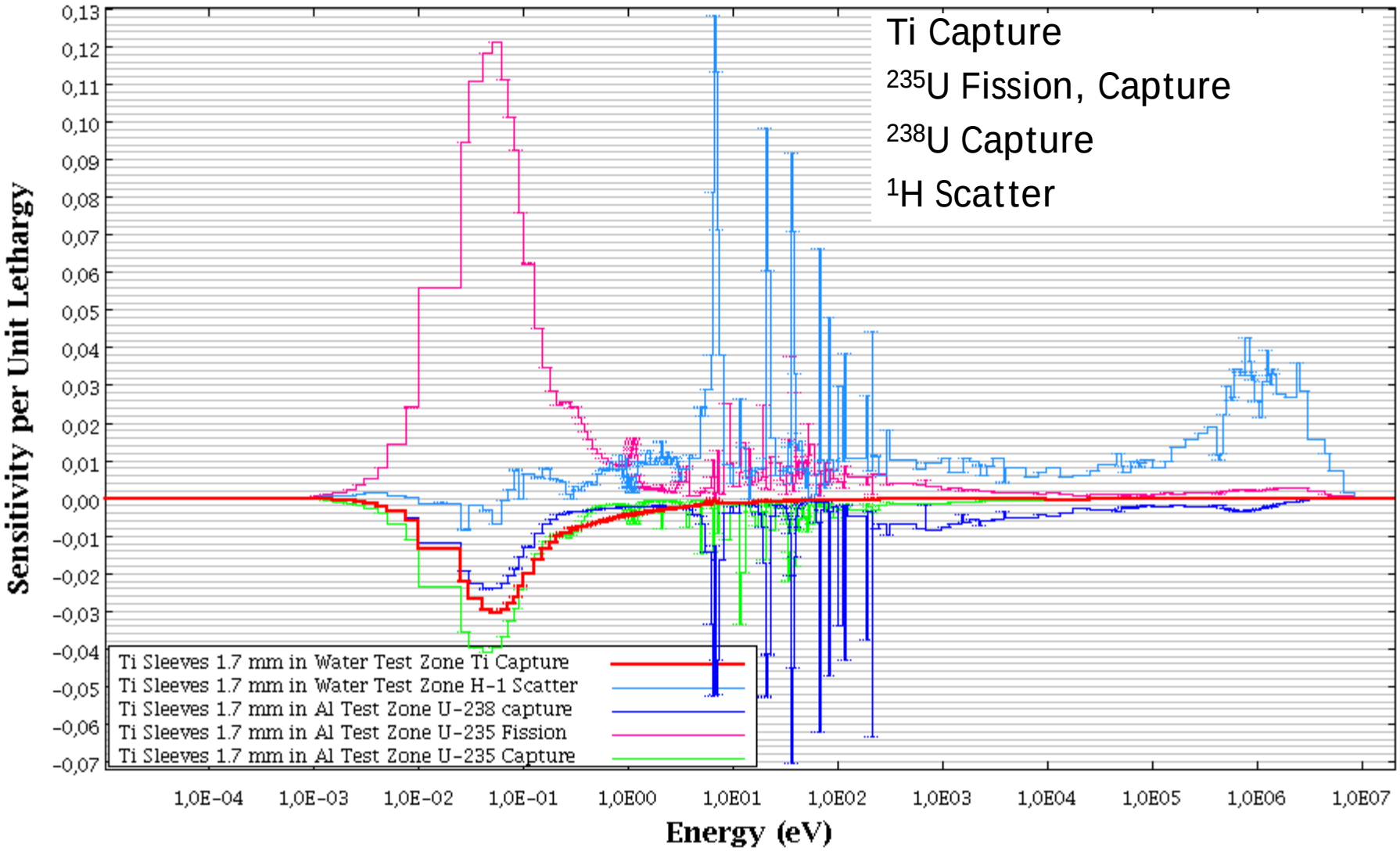
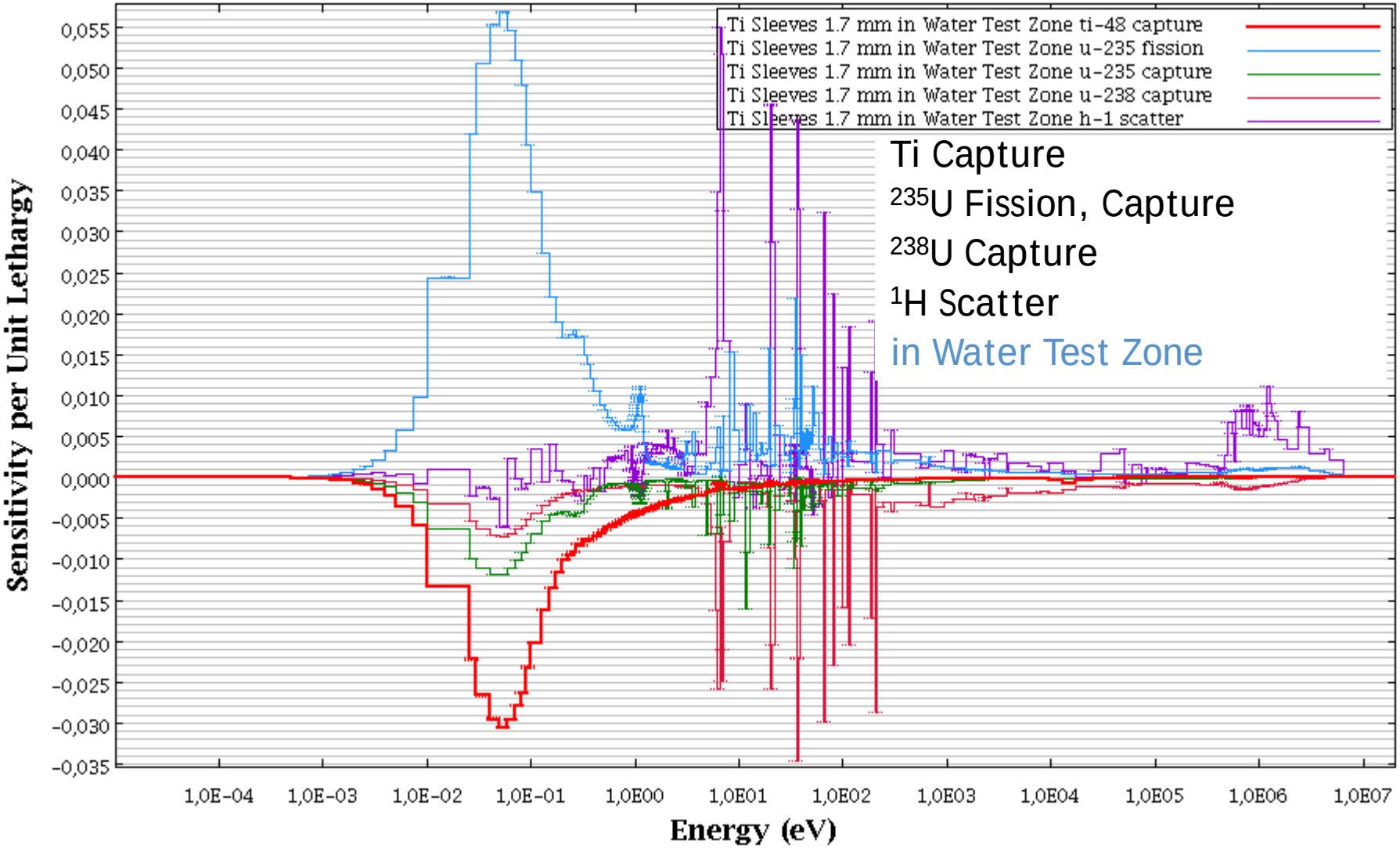


Sensitivities for "Thermal" Configurations



Sensitivities for "Thermal" Configurations

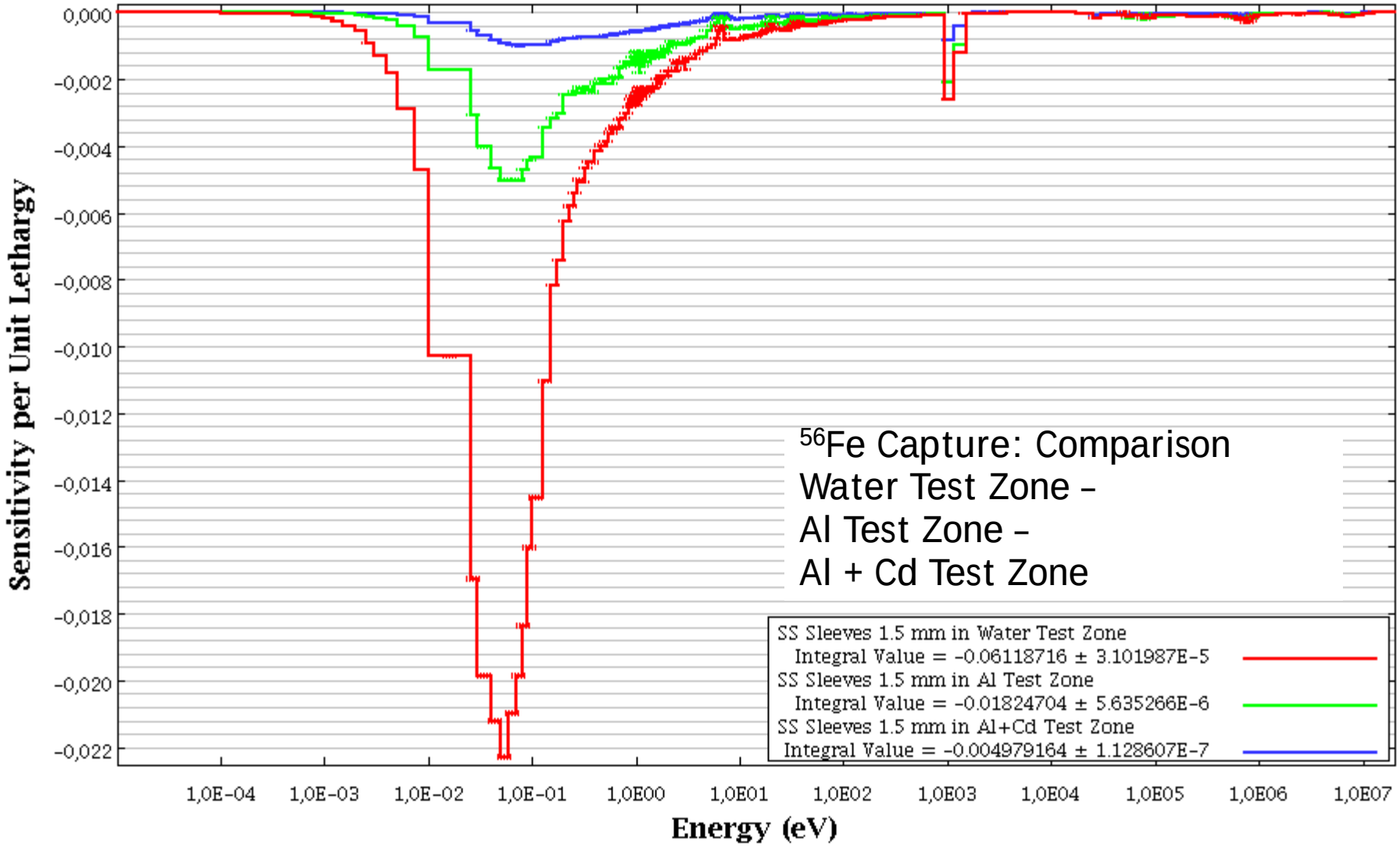


“Thermal” Configurations: Conclusions

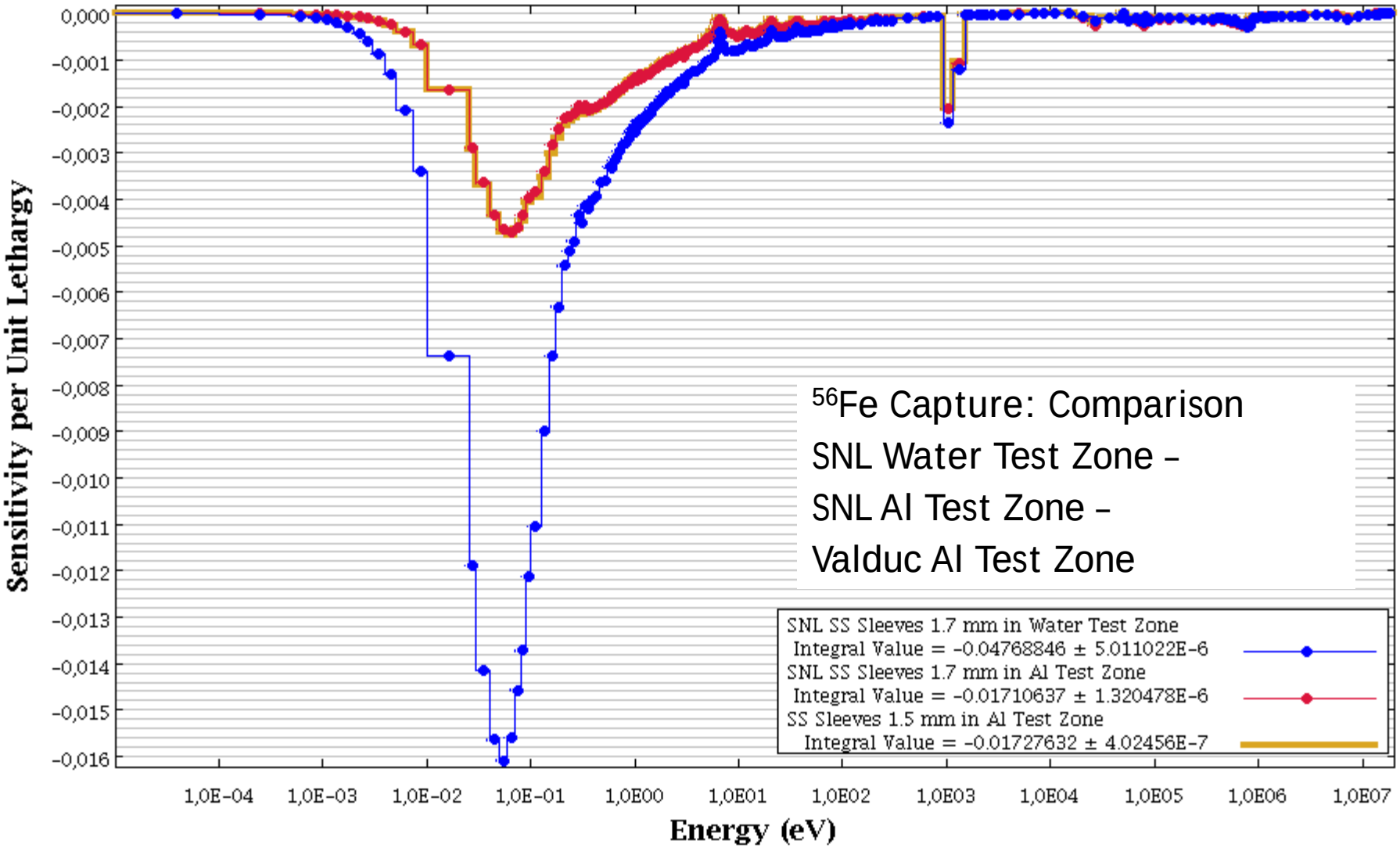
Sleeved configurations versus MIRTE experiments:

- Provide higher worth and sensitivities for structural materials;
- Magnitude sensitivities for uranium in resonance range;
- Provide better agreement in sensitivities for structural materials and fuel/moderator materials;
- *Do not correlate* in experimental uncertainties;
- Exhibit *different spatial self-shielding effect* that can provide better coverage for applications with distributed structural material;
- Structural material *reactivity measurements* in test zone would increase value of the experimental data

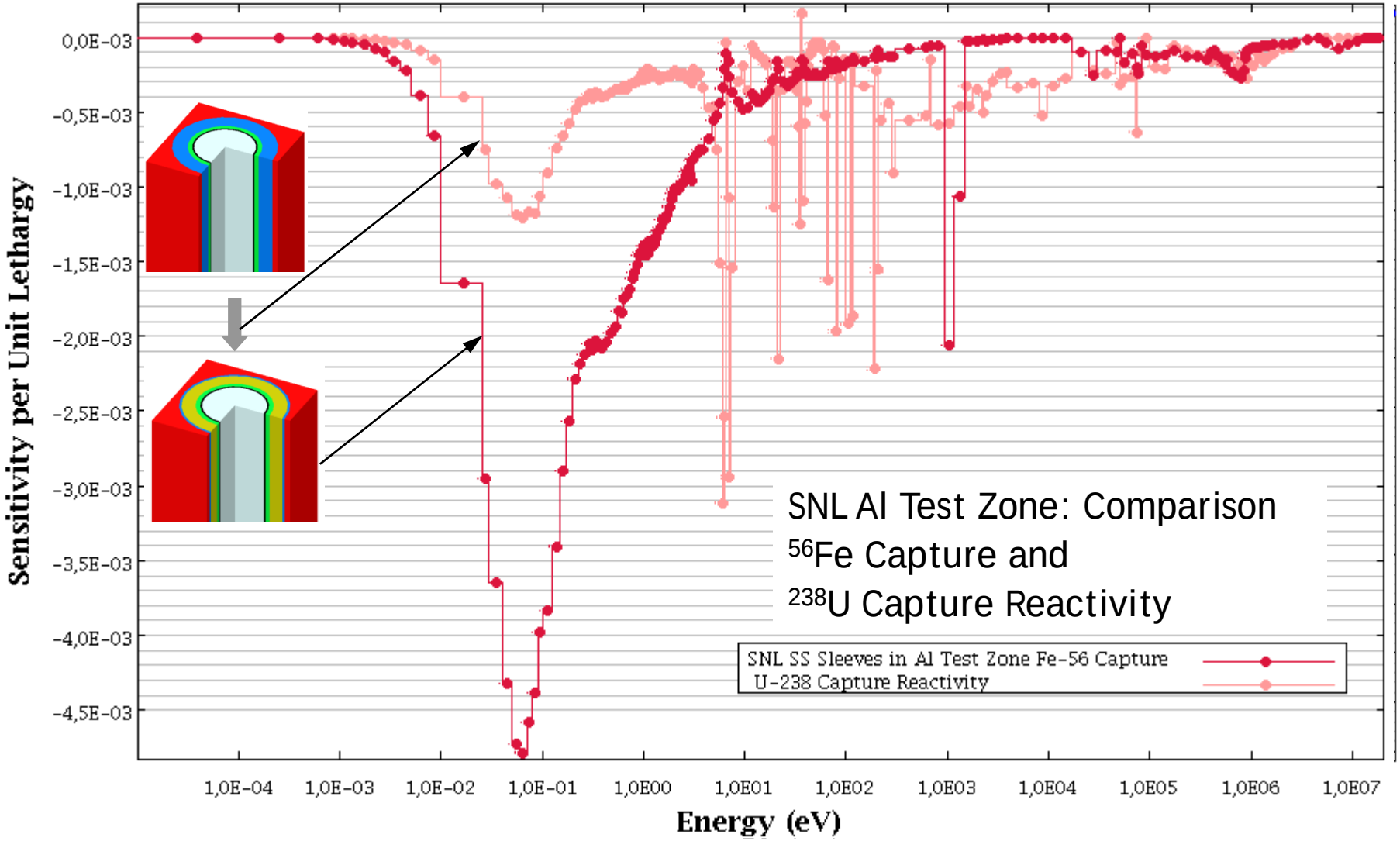
Sensitivities for "Epithermal" Configurations



Sensitivities for "Epithermal" Configurations



Sensitivities for "Epithermal" Configurations



“Epithermal” Configurations: Conclusions

Sleeved configurations in Al Test Zone:

- Provide lower sensitivities for structural materials compared to “thermal” configurations, but
- Magnitude sensitivities in the resonance energy range;
- Require efforts on design optimization to provide higher sensitivities;
- To provide data valuable to for cross-sections examination, test material reactivity measurements is the best experimental approach.
- Requires advanced uncertainty analysis methods to use the experimental data;
- Allow modeling water density variation (steam) in the scenarios for criticality assessment.

Outline

- Need
- Existing experimental hardware
- Proposal on experiment designs
- Calculations
- Material replacement worth
- Sensitivity analysis
- Simulation of uncertainty analysis
  - *Methods*
  - *Results*
- Some proposals on design optimization
- General conclusions

Data Adjustment: Basic Equations

$$S^2 = P^t W^{-1} P + (\Delta k - HP)^t U^{-1} (\Delta k - HP)$$

$$P = (W^{-1} + H^t U^{-1} H)^{-1} H^t U^{-1} \Delta k$$

$$W' = (W^{-1} + H^t U^{-1} H)^{-1}$$

Bias = DP **Bias Uncertainty = DW'D^t**

W – cross-section covariances

U – experimental uncertainty covariances

H – k_{eff} sensitivities for experiments

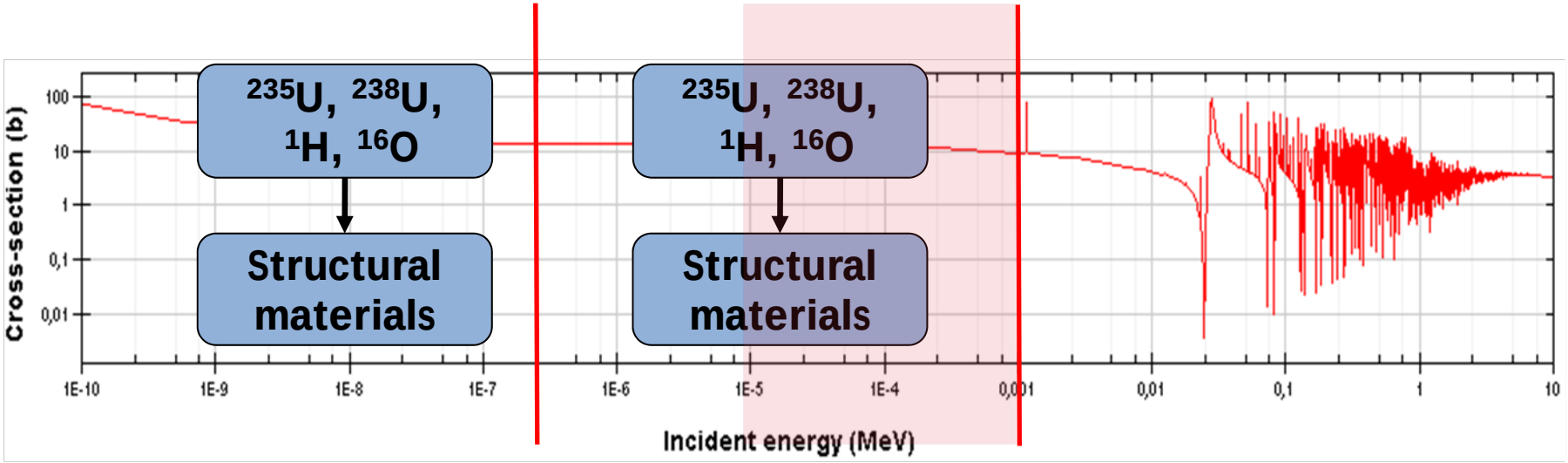
D - k_{eff} sensitivities for application

P – vector of corrections to cross sections

$\Delta k = k_c - k_e$

Principal of Uncertainty Analysis

Iterative Data Adjustment*



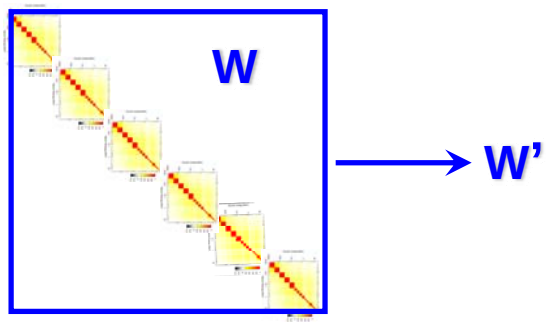
"Thermal" configurations

"Epithermal" configurations

* Proposed and used for analysis of the Fission Product experiments (NSE and NCSD-2009 publications)

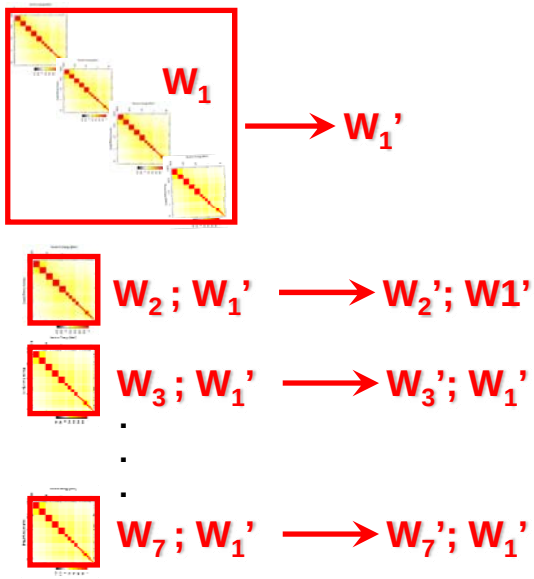
Iterative Adjustment: Example for ND Covariances

Adjustment



W: ^{235}U, ^{238}U, ^{1}H, ^{16}O, Test materials

Iterative Adjustment



W_1: ^{235}U, ^{238}U, ^{1}H, ^{16}O

W_2: Test materials…

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Input Data for Adjustment

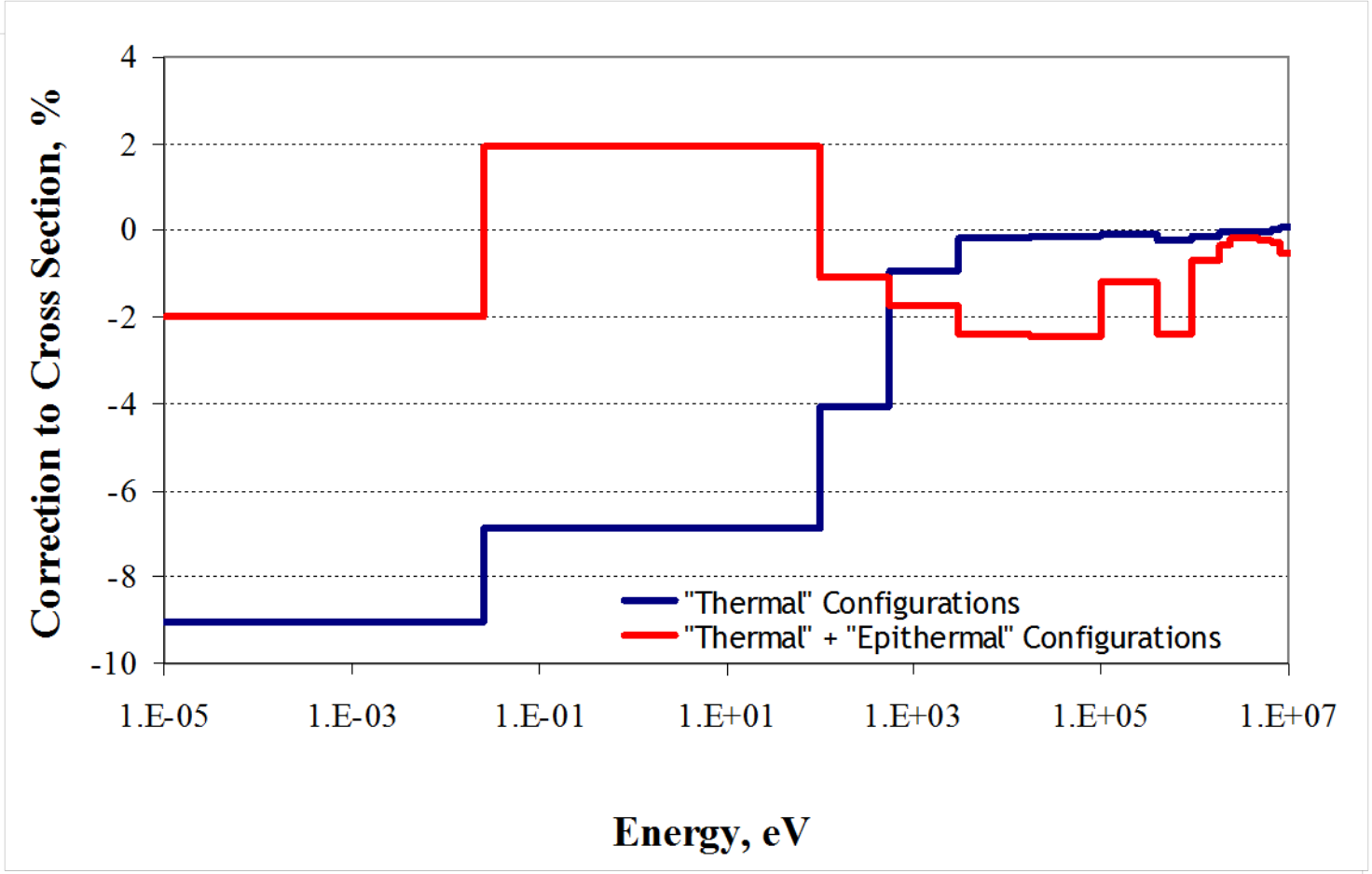
Calculated k_{eff} and 238-group sensitivity coefficients for
20 "Thermal" configurations and
15 "Epithermal" configurations

Assumptions for experimental data:
$k_{eff} = 1$
Uncertainty of k_{eff} = 0.2% ("thermal") and 0.3% ("epithermal")
Correlation in k_{eff} uncertainties
= 60% for all Valduc/SNL "thermal" – "thermal"
= 40% for all Valduc/SNL "thermal" – "epithermal"
= 20% for "thermal"/"epithermal" Valduc – SNL

SCALE5.1 covariance data 44group v6 rec

Data for application system are not available

Results of Uncertainty Study Simulation



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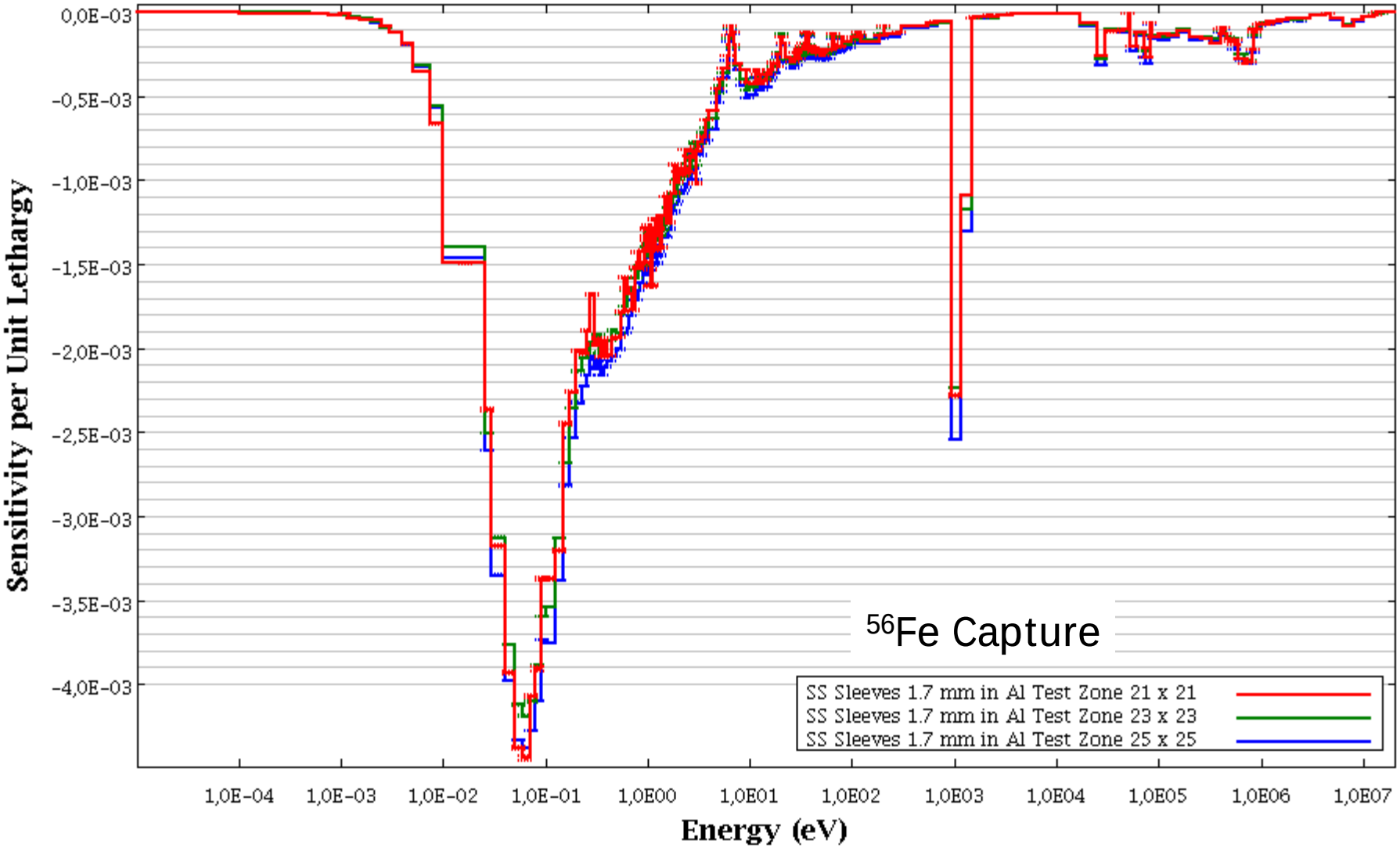
Proposal on Design Optimization

- Increase importance of test zone:
  - Pitch;
  - Test zone dimension (for “epithermal” configurations).

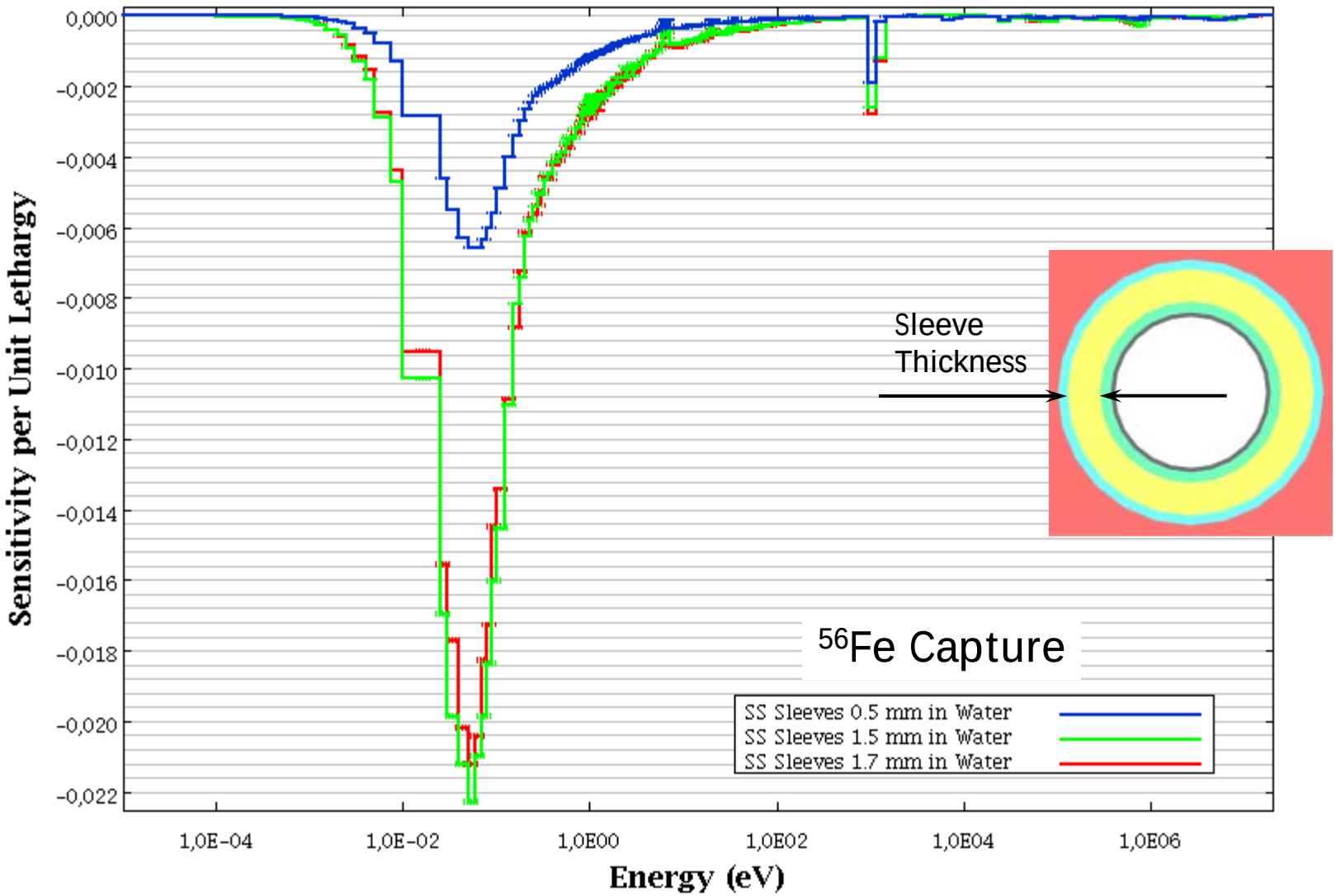
- Optimize position and dimension of test material:
  - Sleeve thickness;
  - Sleeve length;
  - Water gap between sleeve and Al (for “epithermal” configurations).

- Test different design for Al zone

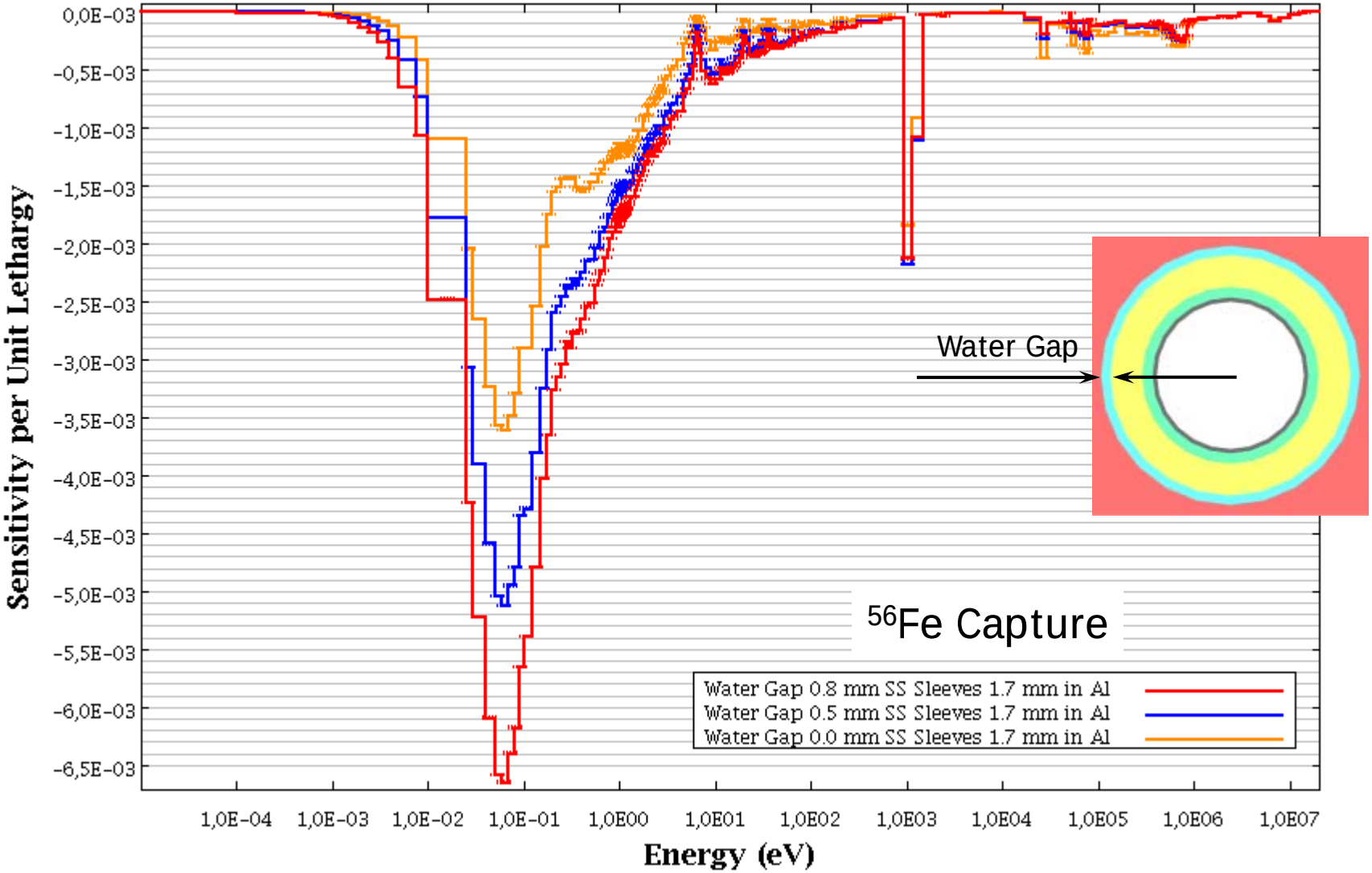
Design Optimization: Test Zone Dimension



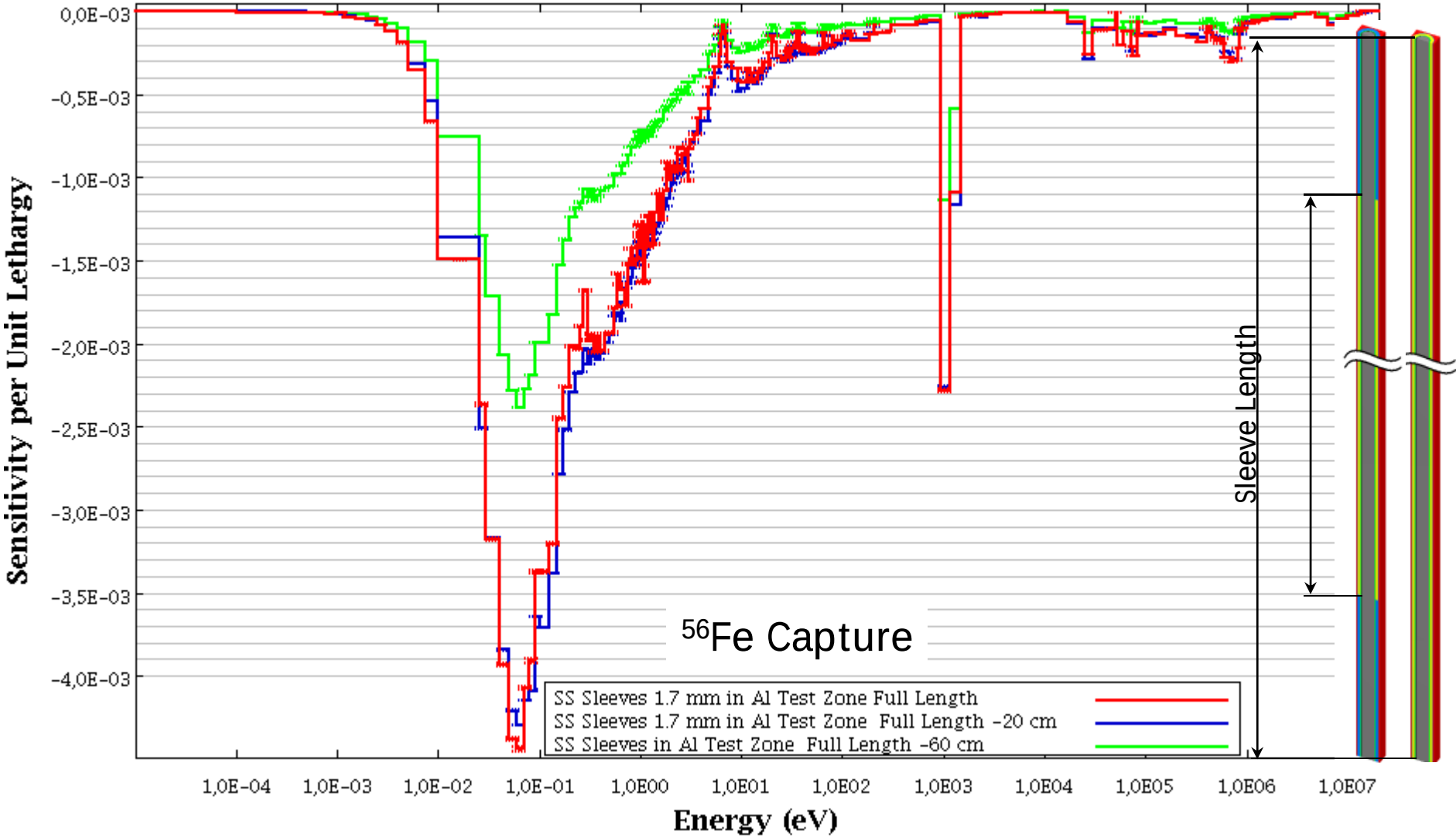
Design Optimization: Sleeve Thickness



Design Optimization: Water Gap

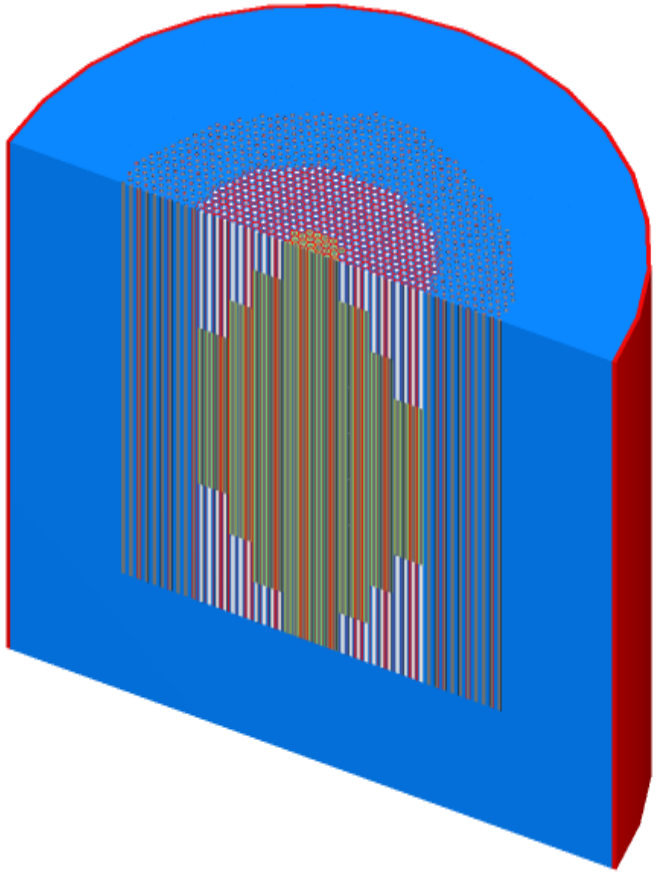


Design Optimization: Sleeve Length



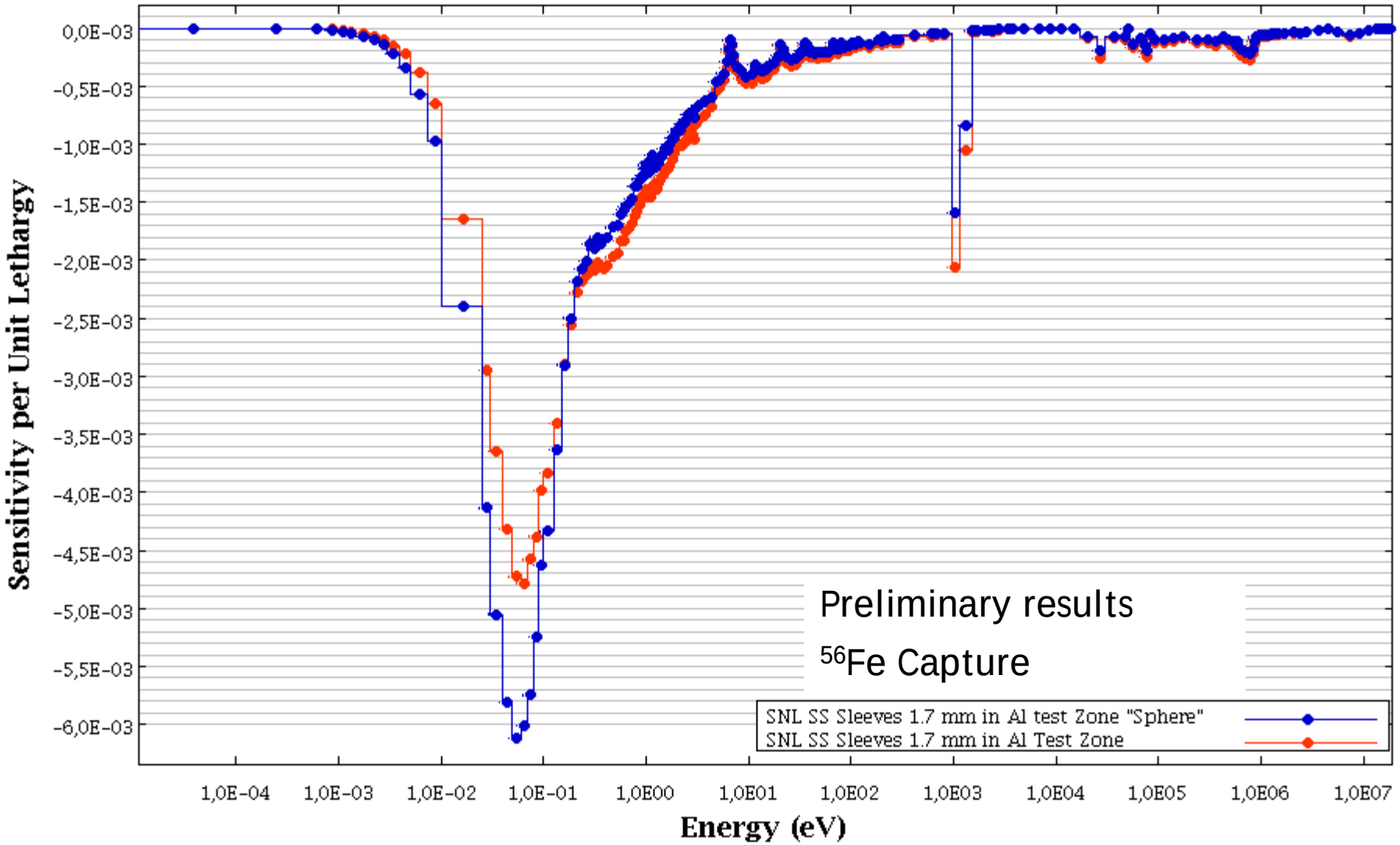
Design Optimization: Test Zone Dimension (1/2)

Model "Sphere" made of fuel rods for more efficient use of the fissile material and experimental tank available



Assumption: Fuel pellets can be reloaded into longer tubes

Design Optimization: Test Zone Dimension (2/2)



Design Optimization: Conclusions

Parameters to be studied to optimize the potential "thermal" and "epithermal" configurations:

- Minimize pitch
- Maximize test zone dimension
- Optimize sleeve thickness
- Optimize sleeve length (for "epithermal" configurations)
- Minimize water gap between sleeve and Al (for "epithermal" configurations)

Outline

- Need
- Existing experimental hardware
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- Calculations
- Material replacement worth
- Sensitivity analysis
- Simulation of uncertainty analysis
  - *Methods*
  - *Results*
- Some proposals on design optimization
- General conclusions

General Concluions (1/2)

- The proposed design:

  - Has potential to provide valuable data for nuclear data examination in both thermal and epithermal energy ranges;

  - Allows modeling water density variation (steam) in scenarios for criticality safety assessment;

  - Requires advanced uncertainty analysis methods to better use the experimental data;

- Series of replacement experiments with different sleeve materials and thicknesses, progressive introduction of water replacement materials would allow to harden spectrum incrementally and to provide better results for uncertainty analysis.

General Concluions (2/2)

- Test material reactivity measurements is the best experimental approach to magnitude sensitivity in epithermal energy range;

- The experiments to be planned based on the method used for further analysis along with the needs, material inventory, experimental methods; technological feasibility, financial aspects.