Nuclear Data Sensitivity and Uncertainty Analysis for Fusion

Bamidele Ebiwonjumi[1], Ethan Peterson[2]

[1]Plasma Science and Fusion Center, MIT, Cambridge MA, USA
[2]Department of Nuclear Science and Engineering, MIT, USA

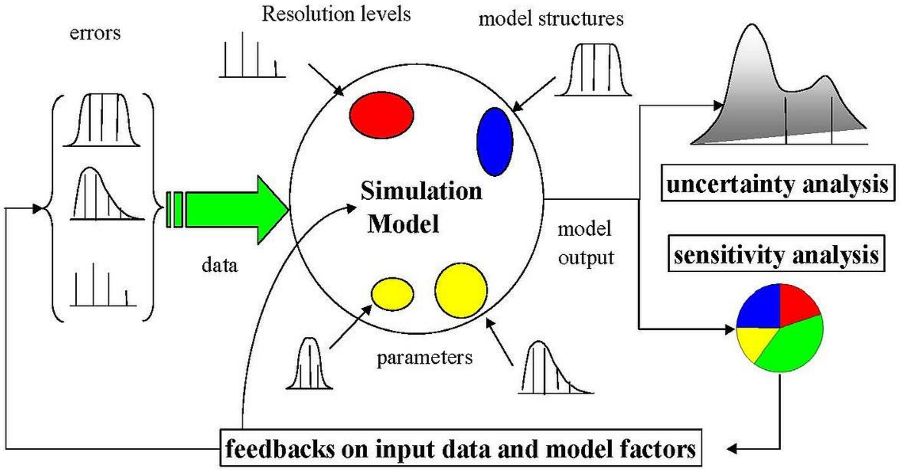
Workshp for Applied Nuclear Data Activities (WANDA 2026) February 9-12, 2026, Arlington, VA, US.

Outline

- Sensitivity and uncertainty analysis for fusion
- Needs, gaps and possible solutions
  - Uncertainty analysis of gamma heating
  - Uncertainty analysis of shutdown dose
  - Uncertainty analysis of radiation damage

Sensitivity & Uncertainty Analyses

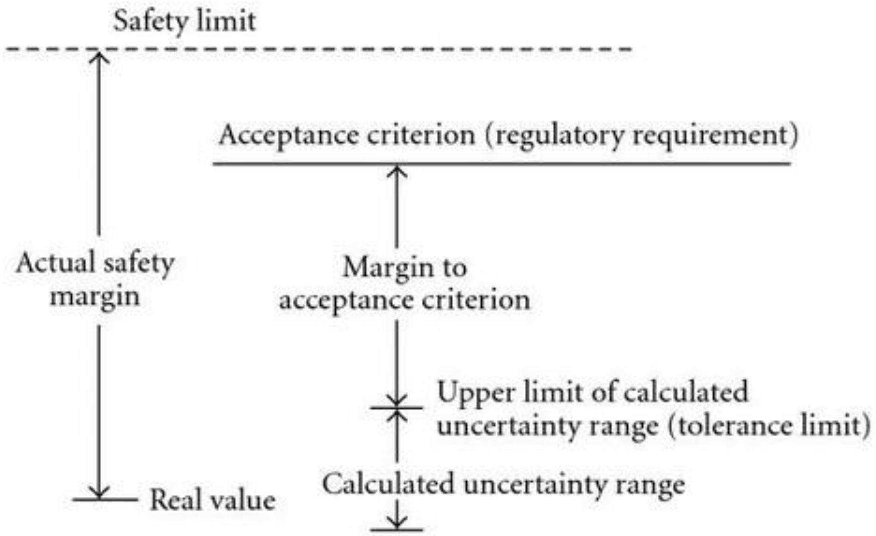
- Response uncertainty is caused by **uncertain input parameters**
- Propagation of input parameter uncertainties through code calculations is necessary:
- To breakdown response uncertainty into input parameter contributions
- To identify important input parameters (isotopes, reactions, energy ranges) contributing the most to the response uncertainty



Ref: Wikipedia "sensitivity analysis"

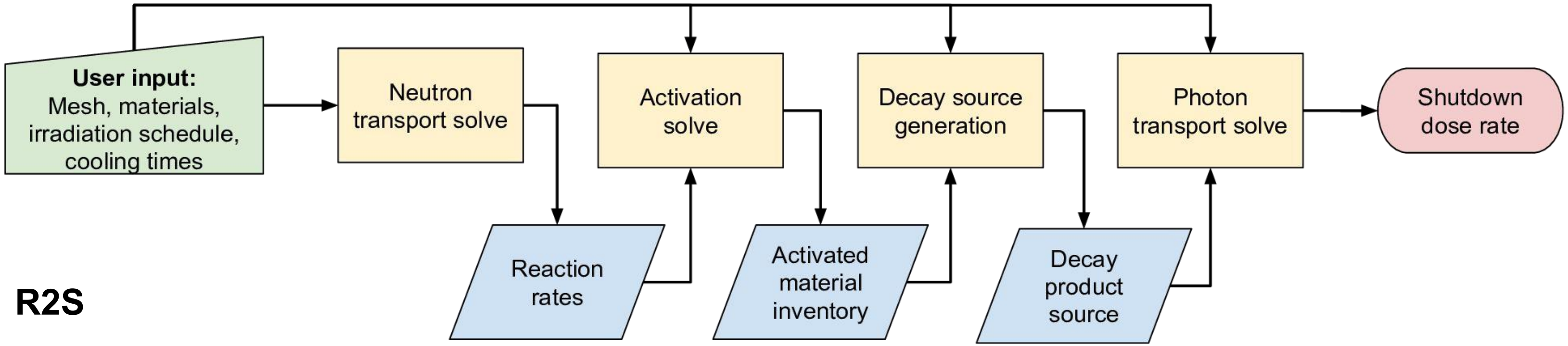
Motivation for Uncertainty Analysis

- Confidence in calculated quantities demand the uncertainty analysis of simulation responses
- Regulatory requirement: safety parameters must lie within acceptable criteria
- Conservatism in safety margins (traditional approach to safety analyses) has been minimized
- Current approach: Best Estimate Plus Uncertainty (BEPU) – best estimate acceptable if accompanied by uncertainty evaluation.



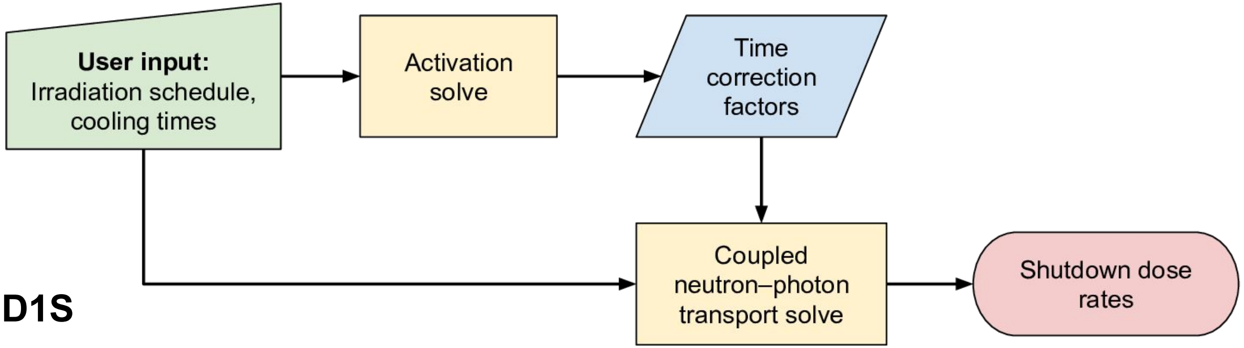
Glaeser, Horst, GRS Method for Uncertainty and Sensitivity Evaluation of Code Results and Applications, *Science and Technology of Nuclear Installations*, 2008, 798901

Rigorous 2-Step & Direct 1-Step SDR Workflows



R2S

Peterson et al., Development and validation of fully open-source R2S shutdown dose rate capabilities in OpenMC, *Nucl. Fusion* 64 (2024) 056011



D1S

Romano et al., Implementation of the D1S methodology for shutdown dose rate calculations in the OpenMC Monte Carlo particle transport code, *Fus. Sci. Tech.*, (2025). https://doi.org/10.1080/15361055.2025.2567099

Uncertain Input Parameters

- Nuclear data
  - Activation data
  - Neutron cross-sections
  - Secondary particles:
    - energy distribution
    - angular distribution
  - Photo-atomic interaction data
  - Damage/displacement cross-sections
  - KERMA
  - ~~Fission product yield~~
  - Decay data (Q-values, half-lives)
    - Small effect on k_{eff}, inventory, decay heat
- Non-nuclear data
  - Material compositions, Design specifications
  - Operating conditions, Statistical errors

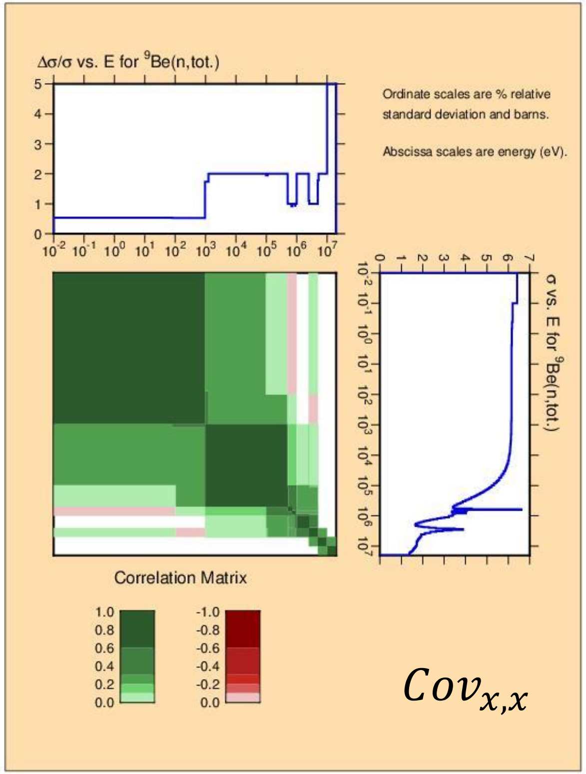
Library	Number of nuclides w/covariance
ENDF/B-VIII.0	182
JENDL-5	105
JEFF3.3	447
FENDL-3.1	58
TENDL	2,850
CENDL-3.2	70 (fission products)

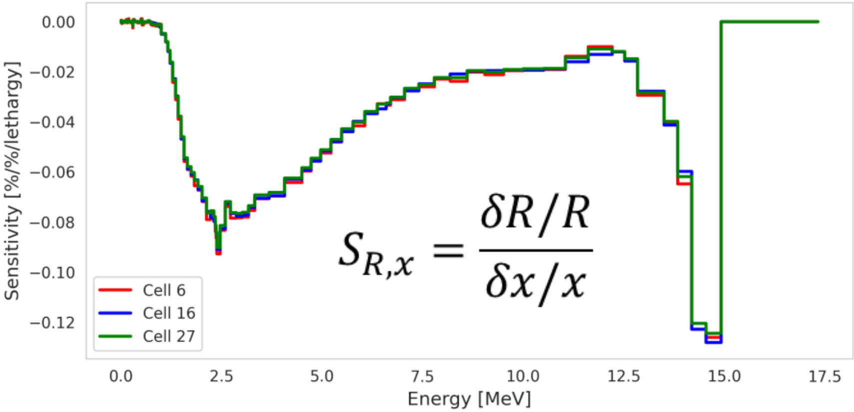
Photo-atomic cross-section data
no covariance in ENDF/B library (NJOY)
Covariance location exist in GNDS (FUDGE)

KERMA/Displacement/Damage cross-section
no covariance in ENDF/B library (NJOY)

Nuclear Data Uncertainty Propagation

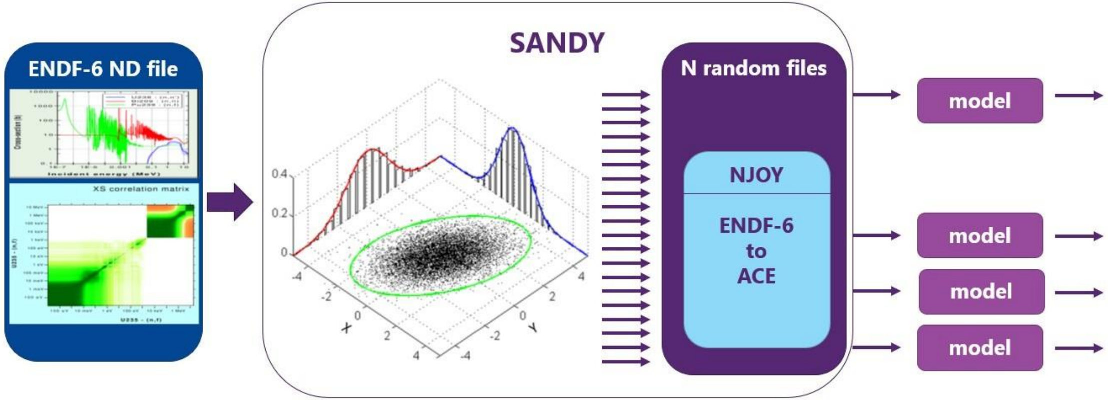
MIT PSFC





Sandwich Rule

$$\sigma_R^2 = S_{R,x} Cov_{x,x} S_{R,x}^T$$



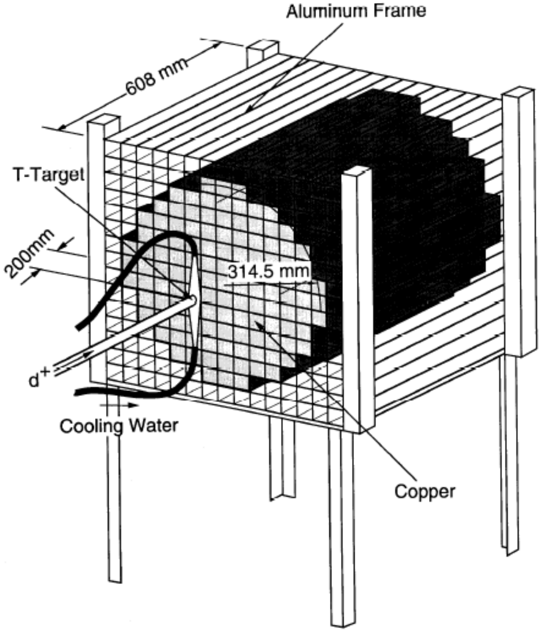
E. Belfiore, Sensitivity and uncertainty analysis for nuclear data of relevance in spent nuclear fuel characterization, MSc Thesis, Politecnico di Torino, 2023.

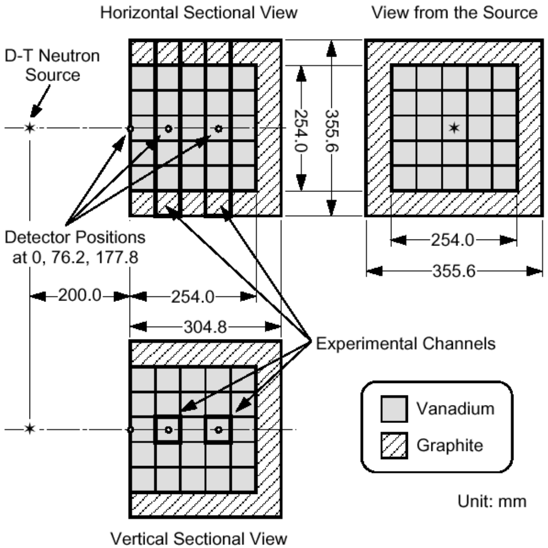
Uncertainty Analyses of Gamma Heating

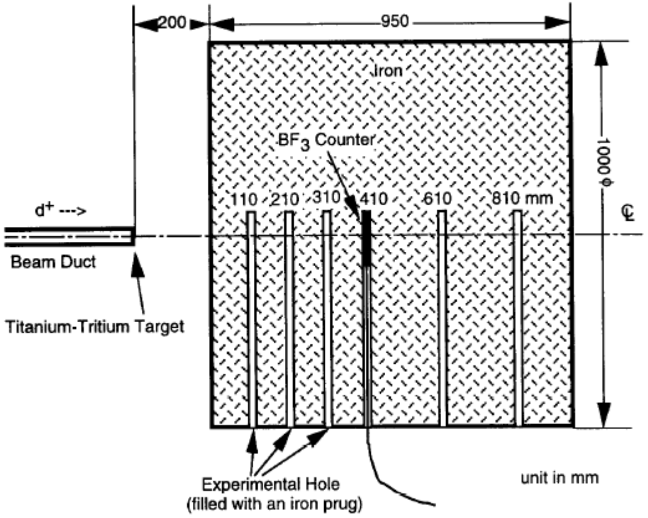
- JAEA FNS Clean Benchmark Experiments
  - Fe Cylinder, quasi-cylinder (W, Cu, C), V cube

Table 2 Nuclear heating rates and their required accuracy at various position for neutron wall loading of 1MW/m² in typical experimental fusion reactor.

positions	maximum nuclear heating rate	required accuracy
the first wall	~15 W/cm³	~20 %
inside blanket	~10 W/cm³	10~20 %
surface of divertor	~5 W/cm³	~20 %
vacuum vessel	~0.1 W/cm³	~50 %
toroidal coil	~0.001 W/cm³	~30 %

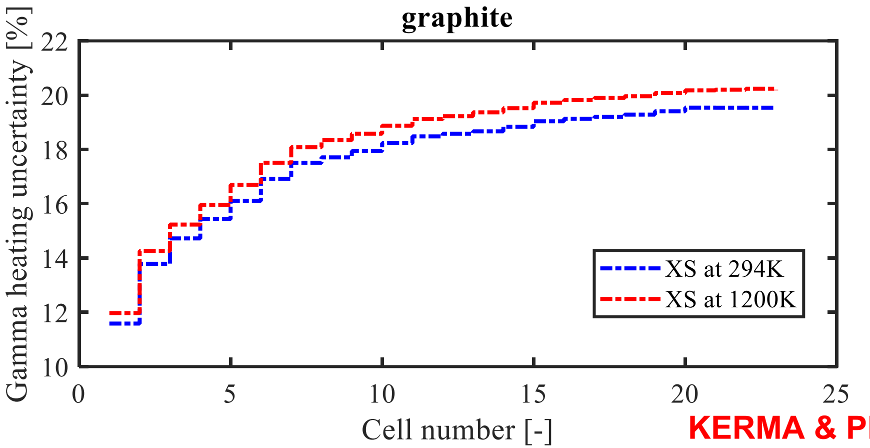


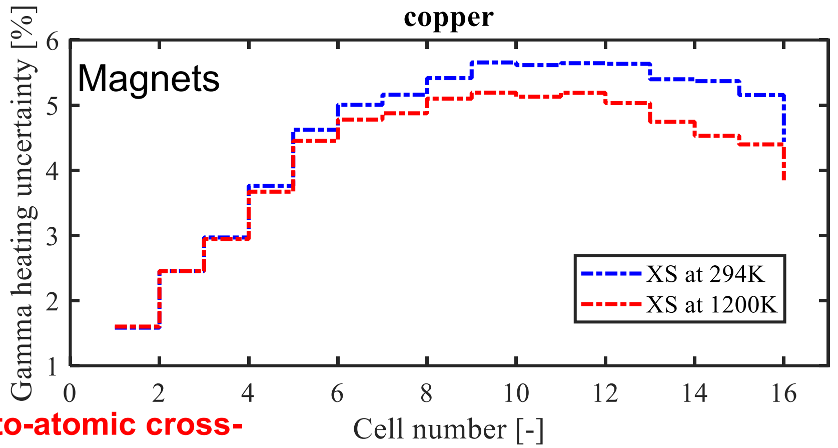




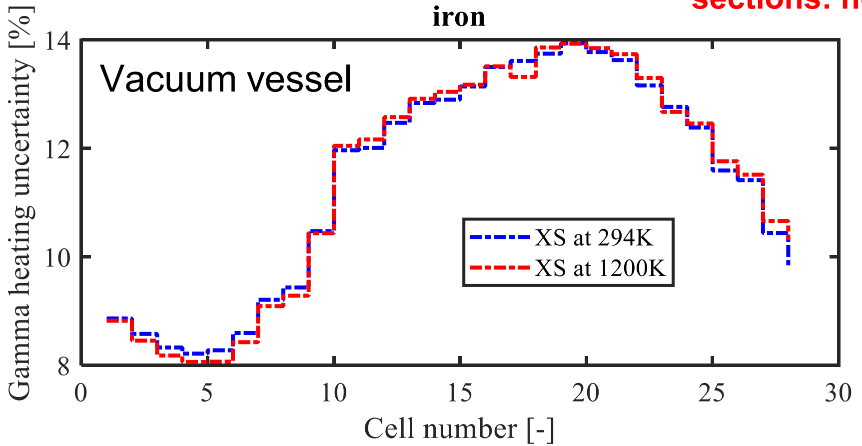
F. Maekawa, et al., Data collection of fusion neutronics benchmark experiment conducted at FNS/JAERI. JAERI-Data/Code 98-021, Japan Atomic Energy Research Institute, 1998.

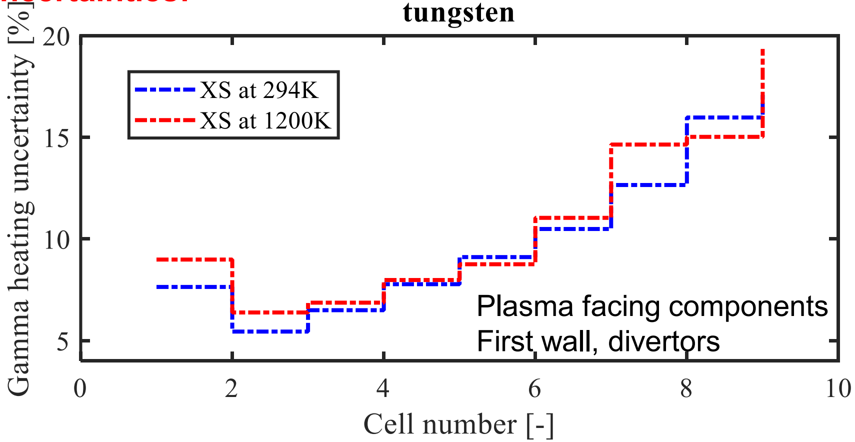
Incomplete Uncertainty Analyses of Gamma Heating





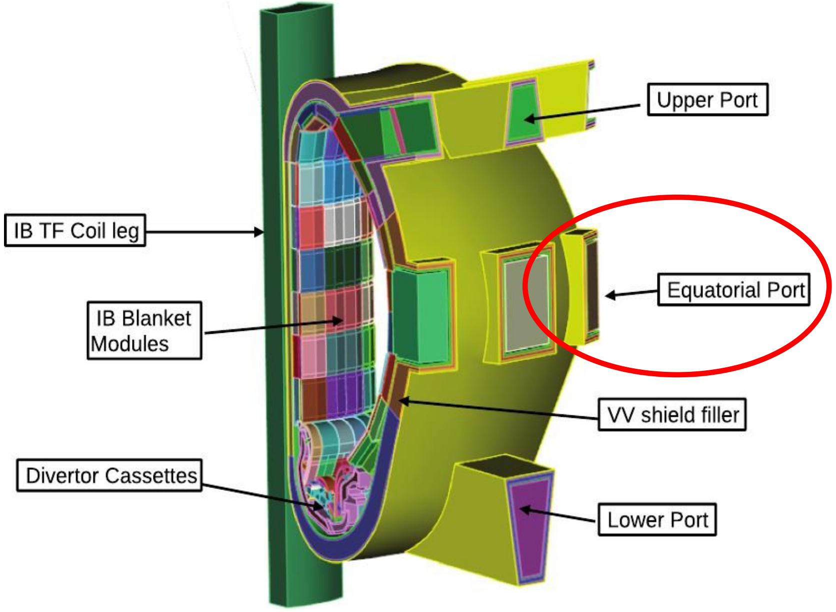
KERMA & Photo-atomic cross-sections: no uncertainties!





Incomplete Uncertainty Analysis of Shutdown Dose Rate

Nuclides	Covariance library
^{54}Cr, ^{62}Ni, ^{58}Fe, W, V, Cu, ^{39,40,41}K, ^{122,124}Sn, ^{32,33,34,36}S, ^{31}P, ^{93}Nb	JEFF3.3
^{61,64}Ni, ^{55}Mn, ^{112,114,115,116,117,118,119,120}Sn, ^{181}Ta	TENDL-2019
^{1,2}H, ^{10,11}B, ^{15}N, ^{46,47,48,49,50}Ti, ^{59}Co, ^{90,91,92,94,96}Zr, ^{92,94,95,96,97,98,100}Mo, ^{206,207,208}Pb, ^{209}Bi	ENDF/B-VII.1
^{12}C	ENDF/B-VIII.0
^{14}N	JENDL-5



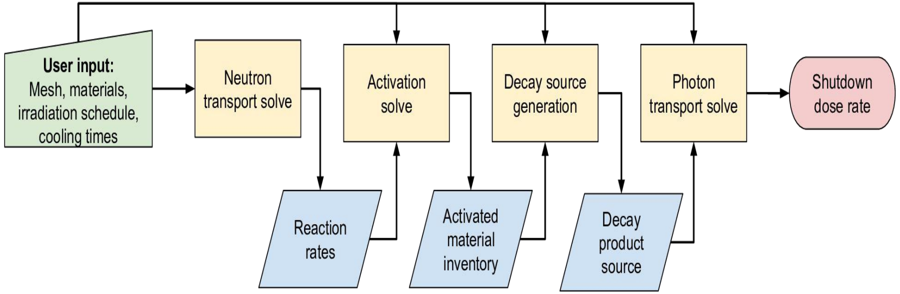


Photo-atomic cross-section uncertainties not available!

Uncertainty Analysis of Radiation Damage

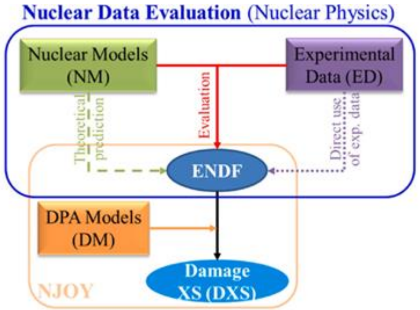
- Challenging uncertainty analysis for radiation damage, displacement cross-section (Fe, W)

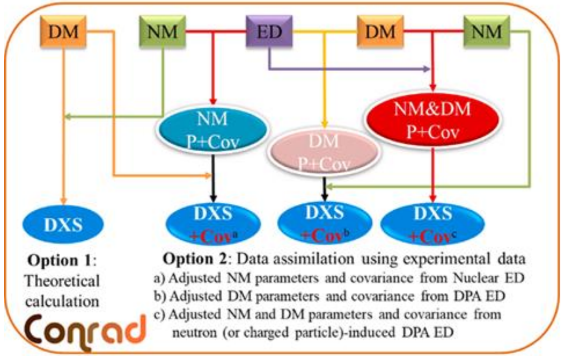
BEKED
- Random files from cov-data
- Random sampling parameters

NJOY
- HEATR
- ACER

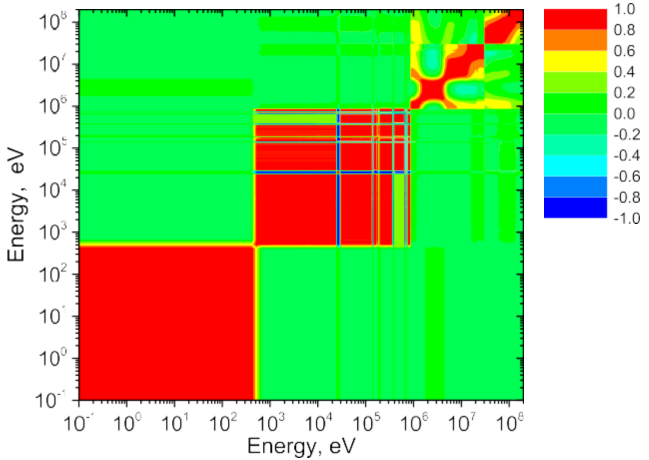
PREPRO other
- Displacement cross section covariances
- MF33, MT900, MT901

A.Y. Konobeyev & D. Leichtle, Status of complete neutron-induced displacement damage cross section data, WANDA 2024.





S. Chen et al., Results in Physics, **17** (2020) 103023.



Simakov et al., Iron NRT- and arc-displacement cross sections and their covariances, Nucl. Mat. Ene., 15 (2018).

European effort to provide recommended nuclear data library for nuclear response files such as displacement damage

Issues & Needs

- Photo atomic cross-section, KERMA, damage/displacement cross-sections lack covariances
- No nuclear data random sampling code can sample photo atomic cross-section data, KERMA, damage/displacement cross-sections, using their covariances
- Nuclear data random sampling codes mostly have been developed for neutron cross-section data
- Complete sensitivity and uncertainty analysis isn't possible currently for nuclear heating, shutdown dose rate, and radiation damage calculations
- Currently, uncertainty quantification isn't a priority in FENDL, will be in future.
- Comprehensive assessment of target accuracy of fusion reactor responses is pending
- In evaluated file 'A', taking data from evaluated file 'B' for some specific utilization, may destroy consistency among data.

Summary

- Uncertainty analysis in fusion is limited due to nuclear data among other things
- Gaps in nuclear data makes S/U analysis challenging in fusion
- For responses with limited and incomplete uncertainty data
  - Radiation damage/dpa (damage energy, displacement cross-section, gas production uncertainties N/A)
  - Shutdown dose rates (photo-atomic cross-section, flux-to-dose conversion factors uncertainties N/A)
  - Nuclear heating (photo-atomic cross-section & KERMA uncertainties N/A)
  - *e.g.*, damage, randomly sample model parameters (TALYS, BEKED, CONRAD)
    - Combine random cross-sections with random model parameters (NJOY HEATR/GAMINR/GASPR)
    - Uncertainty propagation, statistical analysis

Thank you!

This work is supported by
Commonwealth Fusion Systems