OECD/NEA WPEC/SG46 meeting
Webex Meeting
11 November 2020

Reactivity and Sensitivity Calculation Results with Leakage and Non-leakage Components for Sodium Void Reactivity of the 750MWe JSFR Core

Kenji Yokoyama
Reactor Core Design and Evaluation Group
Fast Reactor Cycle System Research and Development Center
Japan Atomic Energy Agency (JAEA)

Action Agreed at Nov. 2019 Meeting*

- Action on coolant void coefficients with leakage and non-leakage components
  3. [By next meeting] Select, for specific systems, appropriate regions where leakage is the dominant. Separate out the central and leakage regions and perform sensitivity/uncertainty analyses for the different regions

(1) Reactivity with leakage and non-leakage components, and

(2) Component-wise sensitivity coefficients

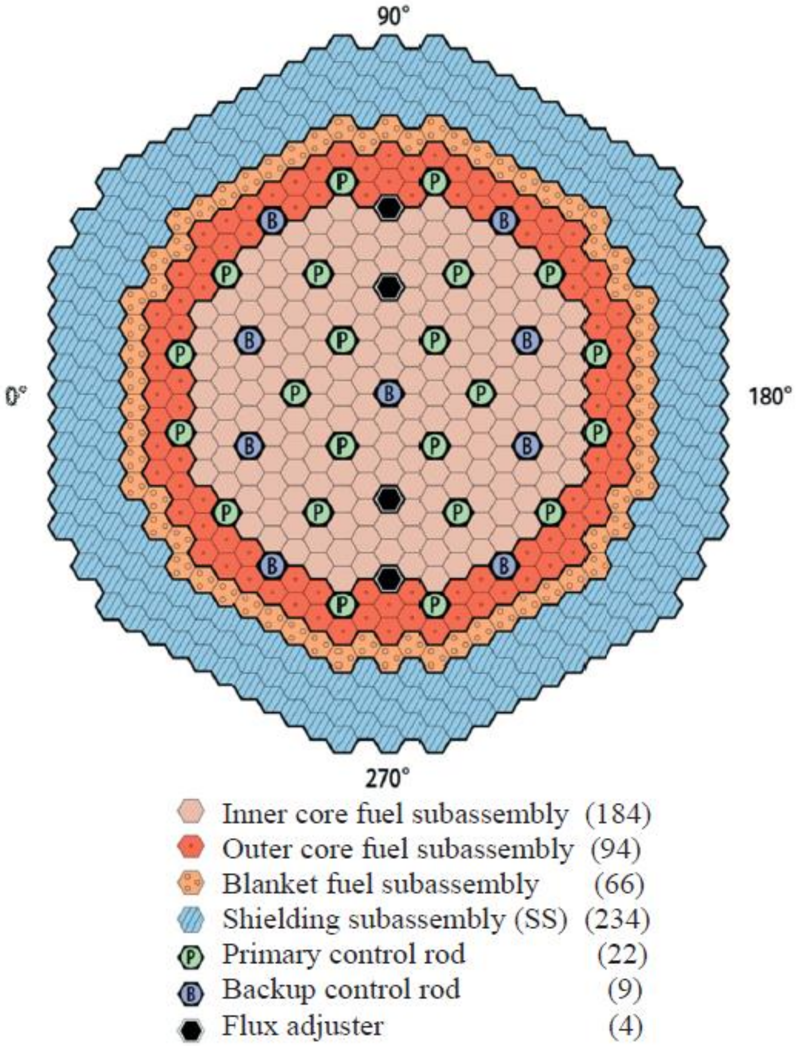
of the sodium void reactivity by using the 750MWe JSFR model**

will be shown in this presentation

*: Summary Record, Meeting of WPEC SG46, 25-26 November 2019, NEA/NSC/WPEC/DOC(2019)13

**: K. Sugino et al., Models of the 750MWe JSFR core, SG46 meeting, 27 November 2018

Review of 750MWe JSFR Model



- A document[1] on 2-D RZ models of 750MWe JSFR[2], which is designed as a demonstration phase fast reactor in Japan, were provided for SG46 TAR exercise
- In the document, two models are included:
  - Simplified model (fresh fuel = BOL) by Table A.2 and Fig. A.2
  - Detailed model (EOEC) by Table A.2 and Fig. A.2

Sodium void reactivity of inner and outer cores and its sensitivity coefficients were calculated by using the detailed model (EOEC)

[1] K. Sugino, et al., Models of the 750MWe JSFR core, SG46 meeting, 27 November 2018

[2] T. Kan, et al, Proc. Int. Conf. of ICAPP2017, April 24-28, 2017, Fukui and Kyoto, Japan

Tools and Data for Analyses

- Sensitivity coefficients:
  - MARBLE/PERKY code system based on exact/first-order perturbation theory
  - MARBLE/SAGEP code system based on GPT (generalized perturbation theory) [1-3] for static integral parameters
  - Modified version of MARBLE/SAGEP for component-wise sensitivity coefficients
- Covariance of nuclear data:
  - JENDL-4.0 [4]
  - Processed by NJOY99.396
- Energy group structure:
  - Equivalent to the 7-group structure proposed in SG46*

Table 7-energy group structure

Group	SG46 proposed (eV)*	This analysis (eV)
1	1.9640E+07	2.0000E+07
2	2.2313E+06	←
3	4.9787E+05	←
4	6.7378E+04	←
5	2.0347E+03	←
6	2.2603E+01	←
7	5.4000E-01	5.3158E-01

[1] L. N. Usachev, J. Nucl. Energy A/B 18, 571-583 (1964)
[2] A. Gandini, J. Nucl. Energy 21, 755-765 (1967)
[3] W. M. Stacey Jr., J. Math. Phys. 13, 1119-1125 (1972)
[4] K. Shibata, et al., J. Nucl. Sci. Technol. 48[1], 1-30 (2011)

*: M. Salvatores, Introduction to TAR, SG46 meeting, 25-26 June 2019

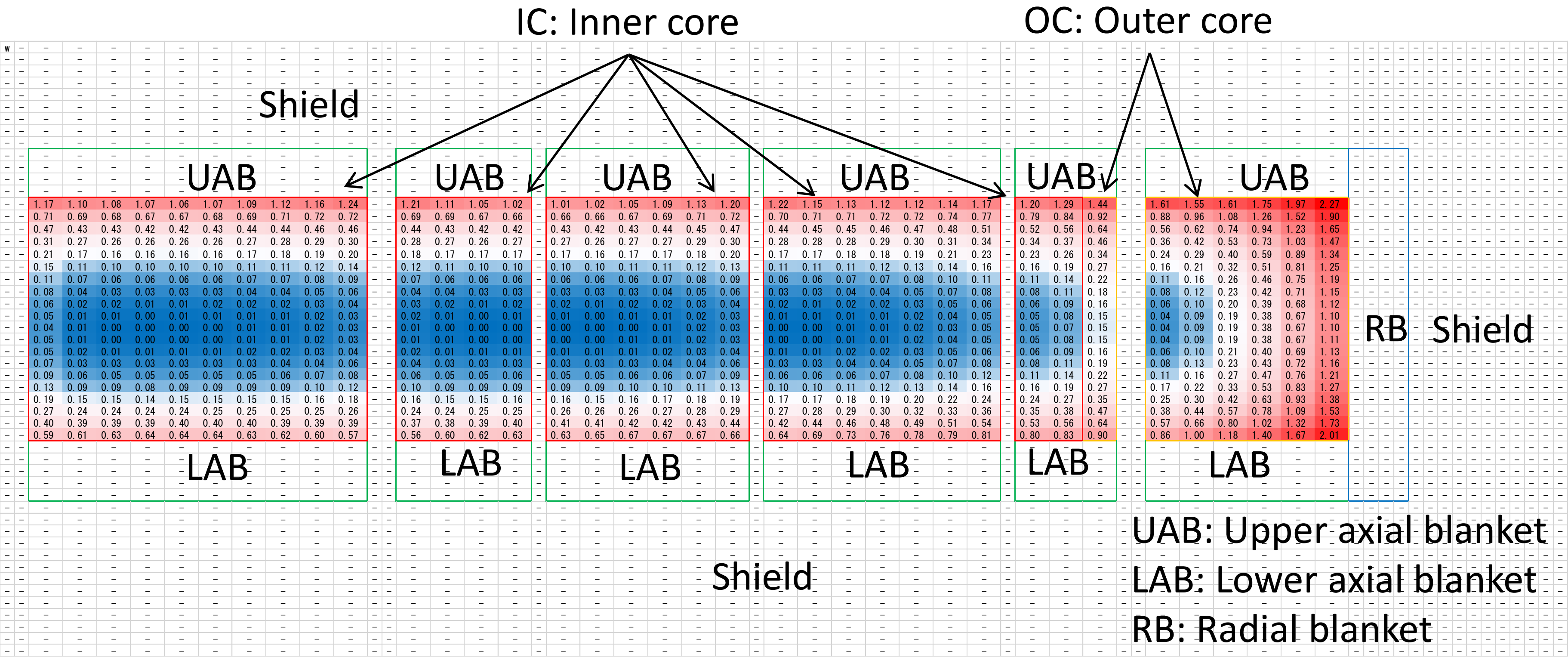
Leakage/Non-leakage Components of Reactivity

Reactivity:

$$
\begin{aligned}
\rho &= \frac{\delta k}{k_{\text{eff}}k_{\text{eff}}^{*}} = \frac{\langle \psi H_{numer}\phi\rangle}{\langle \psi H_{denom}\phi\rangle}\\
&= \frac{1}{\int_V d\vec{r}\sum_g \nu\Sigma_f^g \phi^{g*}\sum_{g'}\chi^{g'}\psi^{g'}}\\
&\quad\times\left[\begin{array}{c}
-\int_V d\vec{r}\sum_g \delta D^g\,\nabla\psi^g\cdot\nabla\phi^{g*}\\
-\int_V d\vec{r}\sum_g \delta\Sigma_a^g\phi^{g*}\psi^g\\
+\int_V d\vec{r}\sum_g \phi^{g*}\sum_g \delta\Sigma_s^{g\to g'}\left(\psi^g-\psi^g\right)\\
+\frac{1}{k_{\text{eff}}^{*}}\int_V d\vec{r}\sum_g \chi^g\phi^g\sum_{g'}\delta\nu\Sigma_f^{g'}\phi^{g'*}
\end{array}\right]
\begin{array}{l}
\left.\vphantom{\int_V}\right\}\ \text{Leakage term}\\
\left.\begin{array}{l}\vphantom{\int_V}\\ \vphantom{\int_V}\\ \vphantom{\frac{1}{k}\int_V}\end{array}\right\}\ \text{Non-leakage terms}
\end{array}\\
&= \frac{\langle \psi H_{numer,L}\phi\rangle}{\langle \psi H_{denom}\phi\rangle} + \frac{\langle \psi H_{numer,NL}\phi\rangle}{\langle \psi H_{denom}\phi\rangle}\\
&= \rho_L + \rho_{NL}
\end{aligned}
$$

- Leakage and non-leakage components of sodium void reactivity are calculated by using the exact perturbation theory

Region-wise Reactivity Components



1.17	1.10	1.08	1.07	1.06	1.07	1.09	1.12	1.16	1.24
0.71	0.69	0.68	0.67	0.67	0.68	0.69	0.71	0.72	0.72
0.47	0.43	0.43	0.42	0.42	0.43	0.44	0.44	0.46	0.46
0.31	0.27	0.26	0.26	0.26	0.26	0.27	0.28	0.29	0.30
0.21	0.17	0.16	0.16	0.16	0.16	0.17	0.18	0.19	0.20
0.15	0.11	0.10	0.10	0.10	0.10	0.11	0.11	0.12	0.14
0.11	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.08	0.09
0.08	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.05	0.06
0.06	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.03	0.04
0.05	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.03
0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03
0.05	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03
0.05	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.04
0.07	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.06
0.09	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.07	0.08
0.13	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.10	0.12
0.19	0.15	0.15	0.14	0.15	0.15	0.15	0.15	0.16	0.18
0.27	0.24	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.26
0.40	0.39	0.39	0.39	0.40	0.40	0.40	0.39	0.39	0.39
0.59	0.61	0.63	0.64	0.64	0.64	0.63	0.62	0.60	0.57

1.21	1.11	1.05	1.02
0.69	0.69	0.67	0.66
0.44	0.43	0.42	0.42
0.28	0.27	0.26	0.27
0.18	0.17	0.17	0.17
0.12	0.11	0.10	0.10
0.07	0.06	0.06	0.06
0.04	0.04	0.03	0.03
0.03	0.02	0.01	0.02
0.02	0.01	0.00	0.01
0.01	0.00	0.00	0.00
0.01	0.01	0.00	0.00
0.02	0.01	0.01	0.01
0.04	0.03	0.03	0.03
0.06	0.05	0.05	0.06
0.10	0.09	0.09	0.09
0.16	0.15	0.15	0.16
0.24	0.24	0.25	0.25
0.37	0.38	0.39	0.40
0.56	0.60	0.62	0.63

1.01	1.02	1.05	1.09	1.13	1.20
0.66	0.66	0.67	0.69	0.71	0.72
0.43	0.42	0.43	0.44	0.45	0.47
0.27	0.26	0.27	0.27	0.29	0.30
0.17	0.16	0.17	0.17	0.18	0.20
0.10	0.10	0.11	0.11	0.12	0.13
0.06	0.06	0.06	0.07	0.08	0.09
0.03	0.03	0.03	0.04	0.05	0.06
0.02	0.01	0.02	0.02	0.03	0.04
0.01	0.00	0.01	0.01	0.02	0.03
0.00	0.00	0.00	0.01	0.02	0.03
0.00	0.00	0.01	0.01	0.02	0.03
0.01	0.01	0.01	0.02	0.03	0.04
0.03	0.03	0.03	0.04	0.04	0.06
0.05	0.05	0.06	0.06	0.07	0.09
0.09	0.09	0.10	0.10	0.11	0.13
0.16	0.15	0.16	0.17	0.18	0.19
0.26	0.26	0.26	0.27	0.28	0.29
0.41	0.41	0.42	0.42	0.43	0.44
0.63	0.65	0.67	0.67	0.67	0.66

1.22	1.15	1.13	1.12	1.12	1.14	1.17
0.70	0.71	0.71	0.72	0.72	0.74	0.77
0.44	0.45	0.45	0.46	0.47	0.48	0.51
0.28	0.28	0.28	0.29	0.30	0.31	0.34
0.17	0.17	0.18	0.18	0.19	0.21	0.23
0.11	0.11	0.11	0.12	0.13	0.14	0.16
0.06	0.06	0.07	0.07	0.08	0.10	0.11
0.03	0.03	0.04	0.04	0.05	0.07	0.08
0.02	0.01	0.02	0.02	0.03	0.05	0.06
0.01	0.01	0.01	0.01	0.02	0.04	0.05
0.00	0.00	0.01	0.01	0.02	0.03	0.05
0.00	0.00	0.01	0.01	0.02	0.04	0.05
0.01	0.01	0.02	0.02	0.03	0.05	0.06
0.03	0.03	0.04	0.04	0.05	0.07	0.08
0.06	0.06	0.06	0.07	0.08	0.10	0.12
0.10	0.10	0.11	0.12	0.13	0.14	0.16
0.17	0.17	0.18	0.19	0.20	0.22	0.24
0.27	0.28	0.29	0.30	0.32	0.33	0.36
0.42	0.44	0.46	0.48	0.49	0.51	0.54
0.64	0.69	0.73	0.76	0.78	0.79	0.81

1.20	1.29	1.44
0.79	0.84	0.92
0.52	0.56	0.64
0.34	0.37	0.46
0.23	0.26	0.34
0.16	0.19	0.27
0.11	0.14	0.22
0.08	0.11	0.18
0.06	0.09	0.16
0.05	0.08	0.15
0.05	0.07	0.15
0.05	0.08	0.15
0.06	0.09	0.16
0.08	0.11	0.19
0.11	0.14	0.22
0.16	0.19	0.27
0.24	0.27	0.35
0.35	0.38	0.47
0.53	0.56	0.64
0.80	0.83	0.90

1.61	1.55	1.61	1.75	1.97	2.27
0.88	0.96	1.08	1.26	1.52	1.90
0.56	0.62	0.74	0.94	1.23	1.65
0.36	0.42	0.53	0.73	1.03	1.47
0.24	0.29	0.40	0.59	0.89	1.34
0.16	0.21	0.32	0.51	0.81	1.25
0.11	0.16	0.26	0.46	0.75	1.19
0.08	0.12	0.23	0.42	0.71	1.15
0.06	0.10	0.20	0.39	0.68	1.12
0.04	0.09	0.19	0.38	0.67	1.10
0.04	0.09	0.19	0.38	0.67	1.10
0.04	0.09	0.19	0.38	0.67	1.11
0.06	0.10	0.21	0.40	0.69	1.13
0.08	0.13	0.23	0.43	0.72	1.16
0.11	0.16	0.27	0.47	0.76	1.21
0.17	0.22	0.33	0.53	0.83	1.27
0.25	0.30	0.42	0.63	0.93	1.38
0.38	0.44	0.57	0.78	1.09	1.53
0.57	0.66	0.80	1.02	1.32	1.73
0.86	1.00	1.18	1.40	1.67	2.01

Fig Ratio of sodium void reactivity components
(Leakage/Non-leakage)

- Sodium void reactivity of IC+OC is evaluated in the design analysis
- It is seen that non-leakage components is dominant

Component-wise Sensitivity Coefficients

Integral parameter:

$$R = \frac{\langle \psi H_1 \phi \rangle}{\langle \psi H_2 \phi \rangle}$$

Sensitivity of integral parameter:

$$S = \frac{dR/R}{d\sigma/\sigma}$$

$$= \left\{ \begin{array}{c} \frac{\psi \frac{dH_1}{d\sigma} \phi}{\langle \psi H_1 \phi \rangle} - \frac{\psi \frac{dH_2}{d\sigma} \phi}{\langle \psi H_2 \phi \rangle} \\ + \frac{\psi H_1 \frac{d\phi}{d\sigma}}{\langle \psi H_1 \phi \rangle} - \frac{\psi H_2 \frac{d\phi}{d\sigma}}{\langle \psi H_2 \phi \rangle} \\ + \frac{\frac{d\psi}{d\sigma} H_1 \phi}{\langle \psi H_1 \phi \rangle} - \frac{\frac{d\psi}{d\sigma} H_2 \phi}{\langle \psi H_2 \phi \rangle} \end{array} \right\}$$

$$= f(H_1, H_2, \phi, \psi, \sigma)$$

Reactivity of leakage components:

$$\rho_L = \frac{\langle \psi H_{numer,L} \phi \rangle}{\langle \psi H_{denom} \phi \rangle}$$

Reactivity of non-leakage components:

$$\rho_{NL} = \frac{\langle \psi H_{numer,NL} \phi \rangle}{\langle \psi H_{denom} \phi \rangle}$$

Sensitivity of leakage components:

$$S_L = f\left(H_{numer,L}, H_{denom}, \phi, \psi, \sigma\right)$$

Sensitivity of non-leakage components:

$$S_{NL} = f\left(H_{numer,NL}, H_{denom}, \phi, \psi, \sigma\right)$$

- Sensitivity coefficients of leakage/non-leakage components are calculated by using Generalized Perturbation Theory (GPT)

Dominant Sensitivity Coefficients

Sensitivity coefficients of sodium void reactivity with respect to the following nuclides and reactions are large for 750MWe JSFR:

- U-238 capture
- U-238 inelastic
- Pu-239 capture
- Pu-239 fission
- Pu-239 nu
- Pu-239 fission spectrum
- Pu-240 capture
- Pu-241 fission
- Pu-241 nu
- …

Component-wise sensitivity coefficients of these nuclides and reactions will be shown in the next slides

$$S_{original} = \frac{d\rho/\rho}{d\sigma/\sigma}$$

$$S_L = \frac{d\rho_L/\rho_L}{d\sigma/\sigma} \qquad \widetilde{S_L} = \frac{S_L\rho_L}{\rho_L + \rho_{NL}}$$

$$S_{NL} = \frac{d\rho_{NL}/\rho_{NL}}{d\sigma/\sigma} \qquad \widetilde{S_{NL}} = \frac{S_{NL}\rho_{NL}}{\rho_L + \rho_{NL}}$$

$$S_{N+NL} = \frac{S_L\rho_L + S_{NL}\rho_{NL}}{\rho_L + \rho_{NL}} = \widetilde{S_L} + \widetilde{S_{NL}} = S_{original}$$

Sensitivity: U-238 capture and inelastic

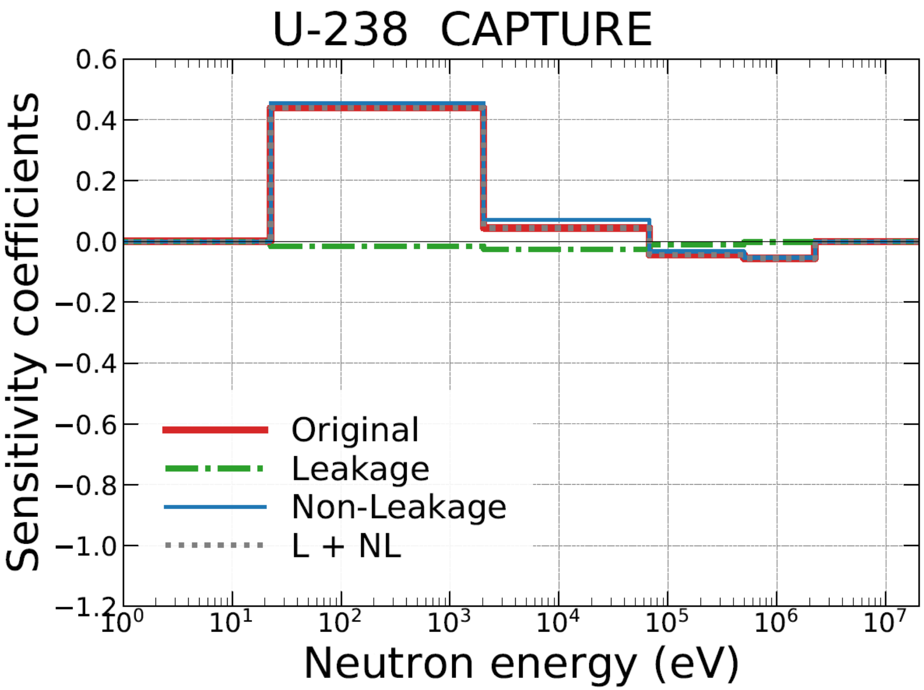
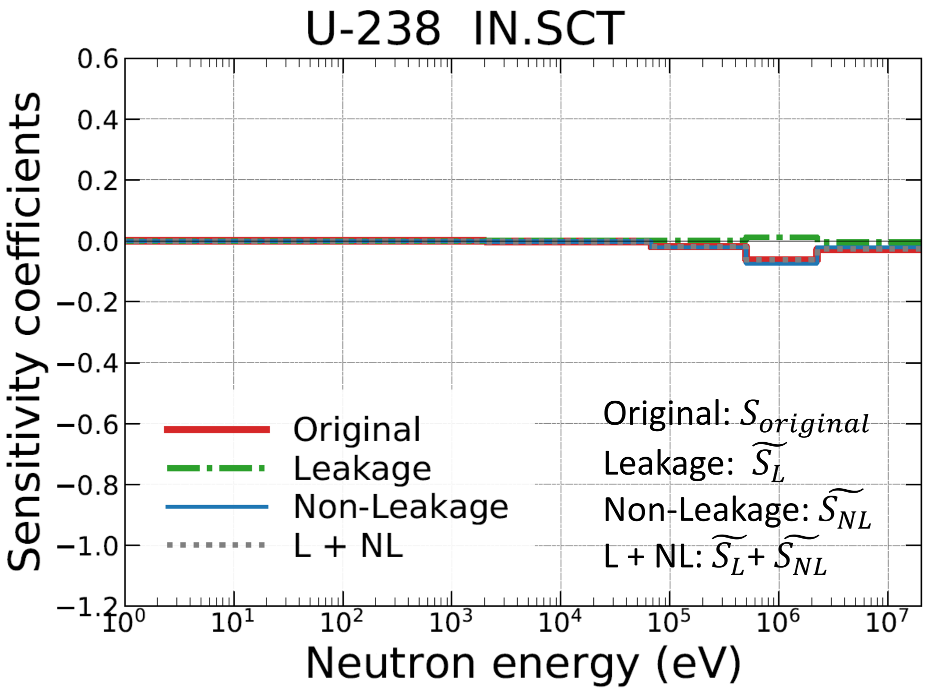


Fig. Sensitivity coefficients of sodium void reactivity with respect to U-238 capture



Original: $S_{original}$
Leakage: $\widetilde{S_L}$
Non-Leakage: $\widetilde{S_{NL}}$
L + NL: $\widetilde{S_L} + \widetilde{S_{NL}}$

Fig. Sensitivity coefficients of sodium void reactivity with respect to U-238 inelastic scattering

- Sensitivity of non-leakage component is dominant

Sensitivity: Pu-239 capture and fission

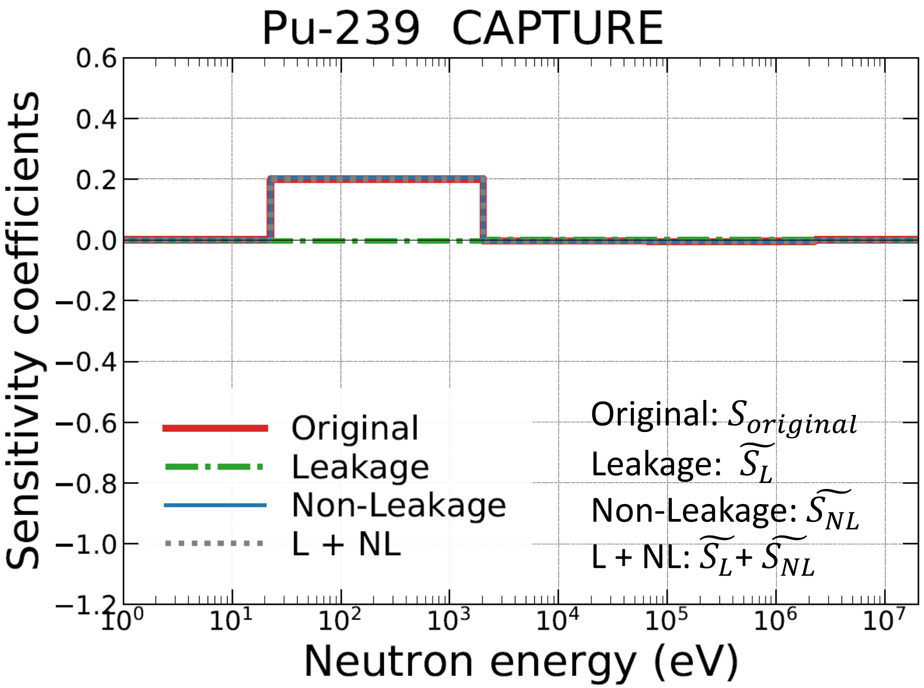


Fig. Sensitivity coefficients of sodium void reactivity with respect to Pu-239 capture

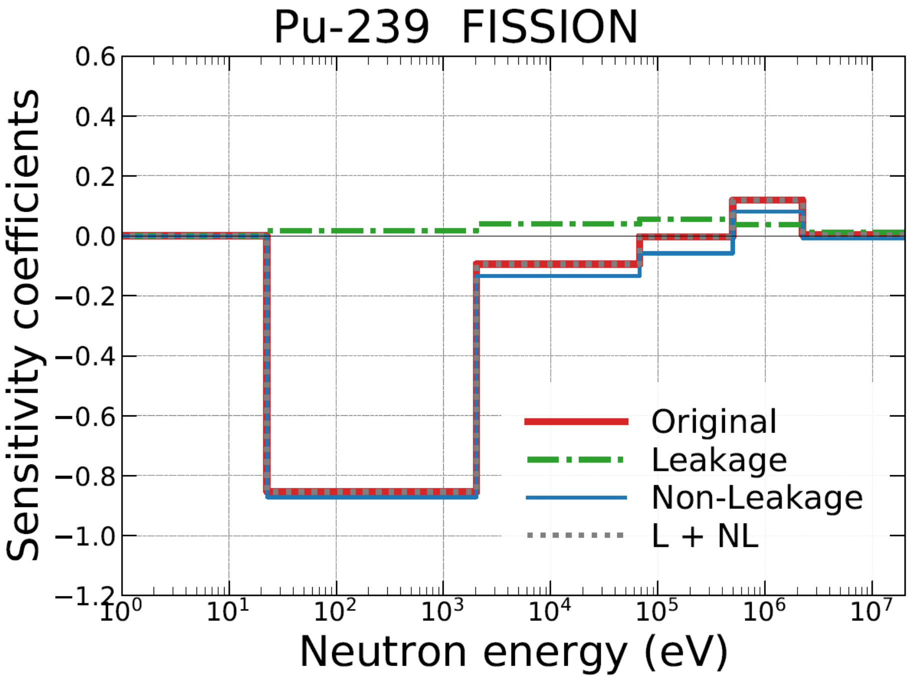


Fig. Sensitivity coefficients of sodium void reactivity with respect to Pu-239 fission

- Sensitivity of non-leakage component is dominant

Sensitivity: Pu-239 nu-bar and fission spectrum

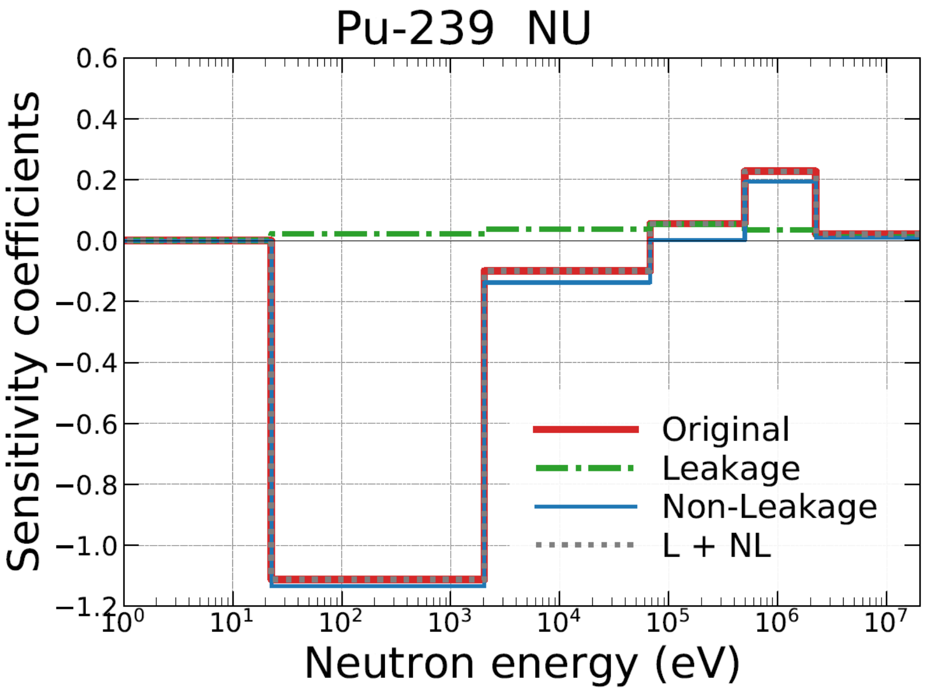


Fig. Sensitivity coefficients of sodium void reactivity with respect to Pu-239 nu-bar

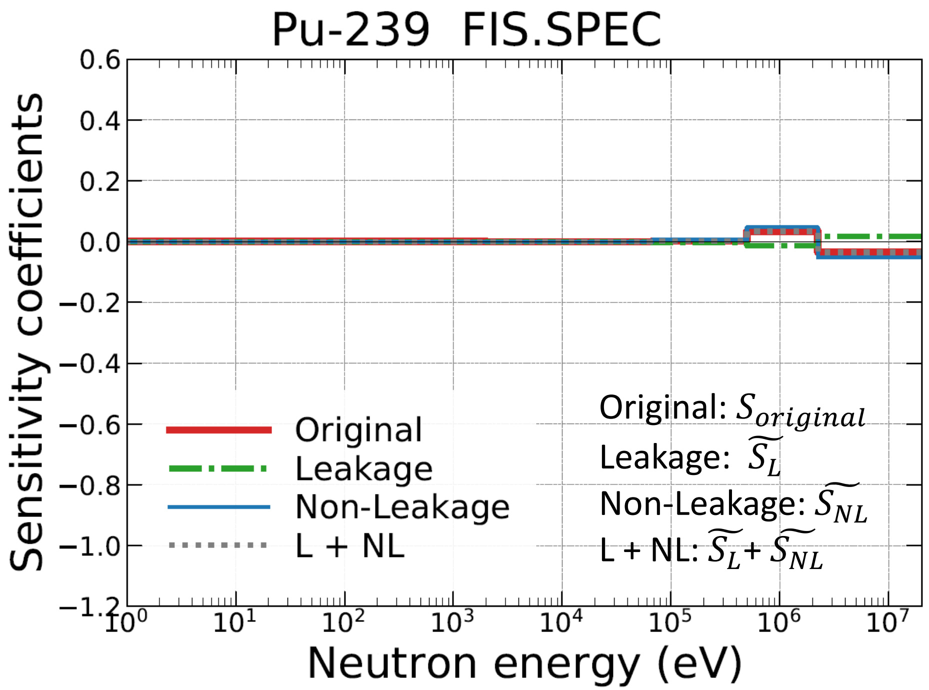


Fig. Sensitivity coefficients of sodium void reactivity with respect to Pu-239 fission spectrum

- Sensitivity of non-leakage component is dominant

Sensitivity Coefficients in SG33 Format

```
# Date: 29 October 2020
# Lab: JAEA
#
# Data: Sensitivity of I=JSFRtable2 SVR (leakage=-6.71173e-03 dk/kk') to p=B-10
#
#                       Capt.       Mu-bar       N2n         Elas.       Inel.
# Grp upper E(eV)    MF3/MT102-117 MF3/MT251    MF3/MT16    MF3/MT2     MF3/MT4
#     lowest=1E-5      (no-dim)    (no-dim)    (no-dim)    (no-dim)    (no-dim)
#
#-I2-------E12.4-----------E12.4-------E12.4-------E12.4-------E12.4-------E12.4
   1  2.0000E+07      6.5881E-04  1.0327E-04 -1.0719E-07 -1.7901E-04  1.8938E-05
   2  2.2313E+06      4.2604E-03  2.2798E-04  0.0000E+00  4.5884E-04  5.2348E-05
   3  4.9787E+05      2.1248E-02  1.2009E-04  0.0000E+00  1.4169E-03  0.0000E+00
   4  6.7380E+04      1.4850E-02  5.0703E-05  0.0000E+00 -2.8815E-05  0.0000E+00
   5  2.0347E+03     -2.4573E-04  7.4903E-06  0.0000E+00 -9.3410E-05  0.0000E+00
   6  2.2603E+01     -2.0601E-06  1.9430E-09  0.0000E+00 -2.5296E-08  0.0000E+00
   7  5.3158E-01     -2.2474E-09  3.6534E-13  0.0000E+00 -4.6964E-12  0.0000E+00
# Sum over energy --------------------------------------------------------------
                      4.0770E-02  5.0953E-04 -1.0719E-07  1.5745E-03  7.1286E-05
#
# Data: Sensitivity of I=JSFRtable2 SVR (non-leakage=3.29434e-02 dk/kk') to p=B-10
#
#                       Capt.       Mu-bar       N2n         Elas.       Inel.
# Grp upper E(eV)    MF3/MT102-117 MF3/MT251    MF3/MT16    MF3/MT2     MF3/MT4
#     lowest=1E-5      (no-dim)    (no-dim)    (no-dim)    (no-dim)    (no-dim)
#
#-I2-------E12.4-----------E12.4-------E12.4-------E12.4-------E12.4-------E12.4
   1  2.0000E+07     -1.3668E-05 -1.9401E-05  2.8719E-08  5.0093E-05  5.2766E-06
... (continued) ...
```

ρ_L

S_L

ρ_{NL}

S_{NL}

- Numerical data of the 7-group sensitivity coefficients are stored in the SG33 format for the SG46 TAR exercise

Concluding Remarks

- Sodium void reactivity and its sensitivity coefficients with leakage and non-leakage components were calculated
  - By using the 750MWe JSFR model provided in the November 2018 meeting
  - With 7-group energy structure proposed in SG46

- Numerical data of the 7-group sensitivity coefficients of sodium void reactivity with leakage and non-leakage components are available in the SG33 format
  - For the SG46 TAR exercise