Criticality Safety Research Group 2021

Japan Atomic Energy Agency

August 2021

General Information

- Where in Japan?
  - Nuclear Science Research Institute (Tokai Research Institute), Tokai-mura
- Where in Organization?*:
  - Division of Fuel Cycle Safety Research, Nuclear Safety Research Center (NSRC), Sector of Nuclear Safety Research and Emergency Preparedness, Japan Atomic Energy Agency

* https://www.jaea.go.jp/04/anzen/en/about/organization_e.html

Status of Staff – 19 in total

- Main staff(6):
  - K. Suyama, K. Ueki, S. Gunji, T. Watanabe, S. Araki, K. Fukuda
- Concurrent post(3):
  - Y. Yamane (Fuel Cycle Safety), K. Izawa(Manager of STACY), Y. Nagaya(Author of MVP)
- Posdoc and researcher for the specific topic(2):
  - I. Simanullang, D. Tuya
- Support staff(8):
  - T. Kikuchi, K. Ohkubo, K. Sone, R. Ohuchi, S. Nemoto, M. Sato, K. Kamohara, K. Yonekawa

General Outline of Research Activity

- Criticality Safety of Fuel Debris – Fukushima Daiichi NPS
  - Planning the criticality experiment using new STACY (Gunji)
  - Generic Criticality Parameter - Data Base Development (Araki)
  - Post Irradiation Examination to measure isotopic composition of SNF (Watanabe)
  - Development of New Monte Carlo Solver – Solomon(Ueki)

Schedule of the new STACY project

Items	Status
Construction and Inspections	In action
Operation tests	2nd half of 2022
First Criticality	End of January to February 2023
Fabrication of UO2 fuel rods	Completed
Transportation of fuel rods	TBD
Experiments for basic reactor physics and training	From February 2023
Experiments for pseudo fuel debris	From April 2023 to March 2025

https://snsr.jaea.go.jp/topindex/schedule_5_200401.pdf (Japanese only)

Specifications of the new STACY

Table I. Specifications and Restrictions of the basic experimental cores of STACY

Specifications/Restrictions	Range
(1) Number of fuel rods	up to 900
(2) Enrichment of ^{235}U	5 wt%
(3) Critical water level	40 ~ 140 cm
(4) Restrictions on Reactivity	
Maximum Excess Reactivity (in case of accident)	0.8 $
Maximum Excess Reactivity (normal operation)	0.3 $
Maximum Reactivity Addition Rate	3 ¢/s
(5) Restrictions relevant to Subcriticality	
Reactor Shutdown Margin	k_{eff} < 0.985
One-Rod-Stuck Margin and In Tsunami Case Subcriticality	k_{eff} < 0.995
(6) Restrictions relevant to Reactivity Coefficient and kinetic parameter	
Reactivity Coefficient on Moderator Temperature	$-3.7\times10^{-5} \sim +3.8\times10^{-4}$ Δk/k/°C
Reactivity Coefficient on Moderator Void	$-3.8\times10^{-3} \sim +3.7\times10^{-3}$ Δk/k/vol%
Reactivity Coefficient on Fuel Temperature	$-4.1\times10^{-5} \sim -8.5\times10^{-6}$ Δk/k/°C
Prompt Neutron Lifetime	$6.9\times10^{-6} \sim 8.4\times10^{-5}$ s
Effective Delayed Neutron Fraction	$6.8\times10^{-3} \sim 8.1\times10^{-3}$
Water-level worth	$2.0\times10^{-3} \sim 6.0\times10^{-2}$ $/mm

K. Izawa, et al., "Neutronic design of basic cores of the new STACY," ICNC 2019

Reactor Physics Experiment (January-March 2023)

- Lattice plates; 1.27cm to 1.50cm
- Critical water heights; 40 to 140cm
- Interests;
  - $\frac{d\rho}{dH}$
  - Reproducibility

https://snsr.jaea.go.jp/topindex/schedule_5_200401.pdf (Japanese only)

Experiments for the criticality safety of fuel debris

- Phase I:
  - Small sample (< 30 cents) using loading device
  - Two types of pseudo fuel debris
    - UO2 with concrete or stainless steel
- Phase II:
  - Rod type structural samples (concrete, stainless steel, etc.)
  - Void tubes for the multipurpose insertion
    - Neutron Detectors, activation detectors, neutron sources, etc.
    - Without unsealed fissile.
- Phase III:
  - Rod type pseudo fuel debris (unsealed fissile)

https://www.nsr.go.jp/data/000317923.pdf (Japanese only)

K. Izawa, et al., "Neutronic design of basic cores of the new STACY," ICNC 2019
S. Araki, et al., "A new critical assembly: STACY," RRFM 2020

Motivation of Criticality Map

The fuel debris of Fukushima-Daiichi NNP may have various compositions.

We have computed the criticality characteristics of the fuel debris with various compositions.

- Concrete volume fraction
- Enrichment of fuel
- Moderator-fuel volume ratio
- …

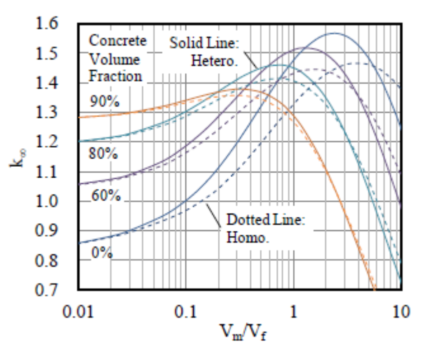


Figure 2 k_∞ of a Composite of an MCCI Product (UO_2, 5 wt% ^{235}U) and Water.

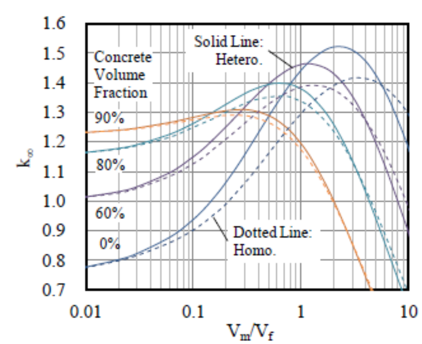


Figure 3 k_∞ of a Composite of an MCCI Product (UO_2, 4 wt% ^{235}U) and Water.

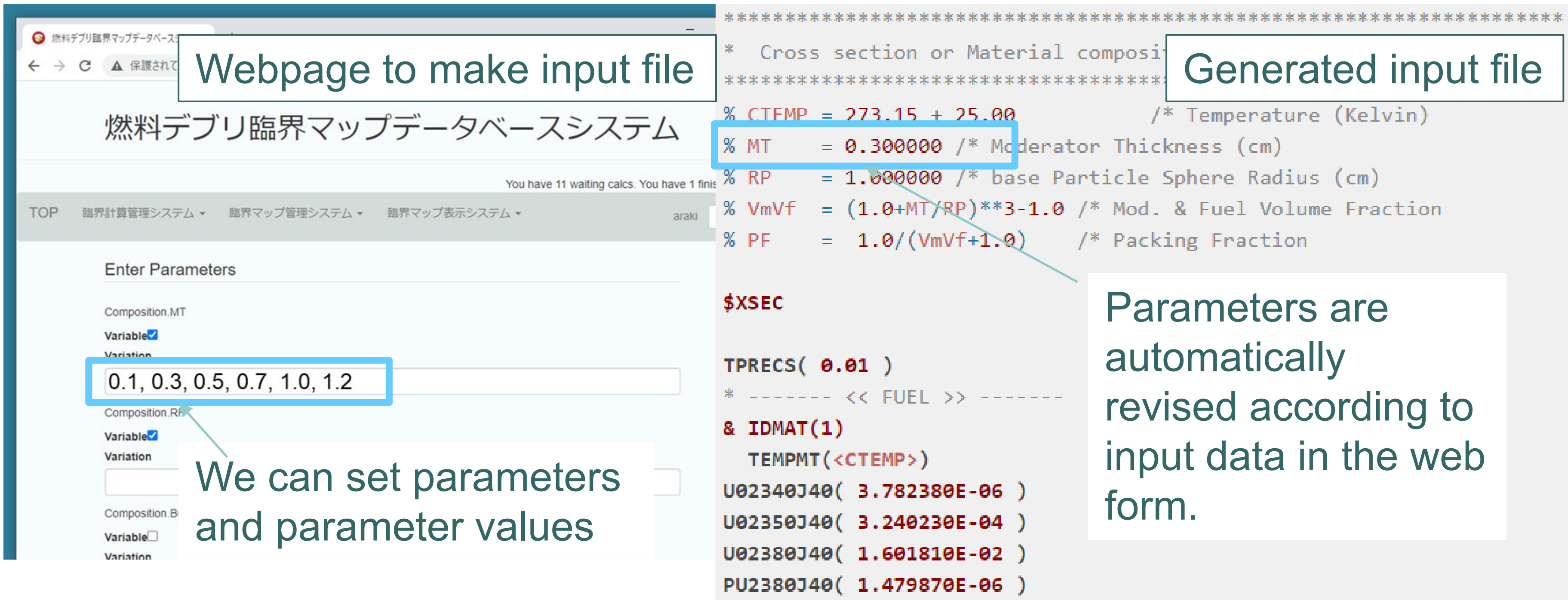
K. Tonoike, et al., ICNC2015

Numerous calculations are required to estimate the characteristics, and analyzing and browsing data is onerous.

We conducted to develop the web application database, “Criticality Map” to support executing criticality calculations and analyzing and browsing them.

Overview of Criticality Map

Make input files for calculation



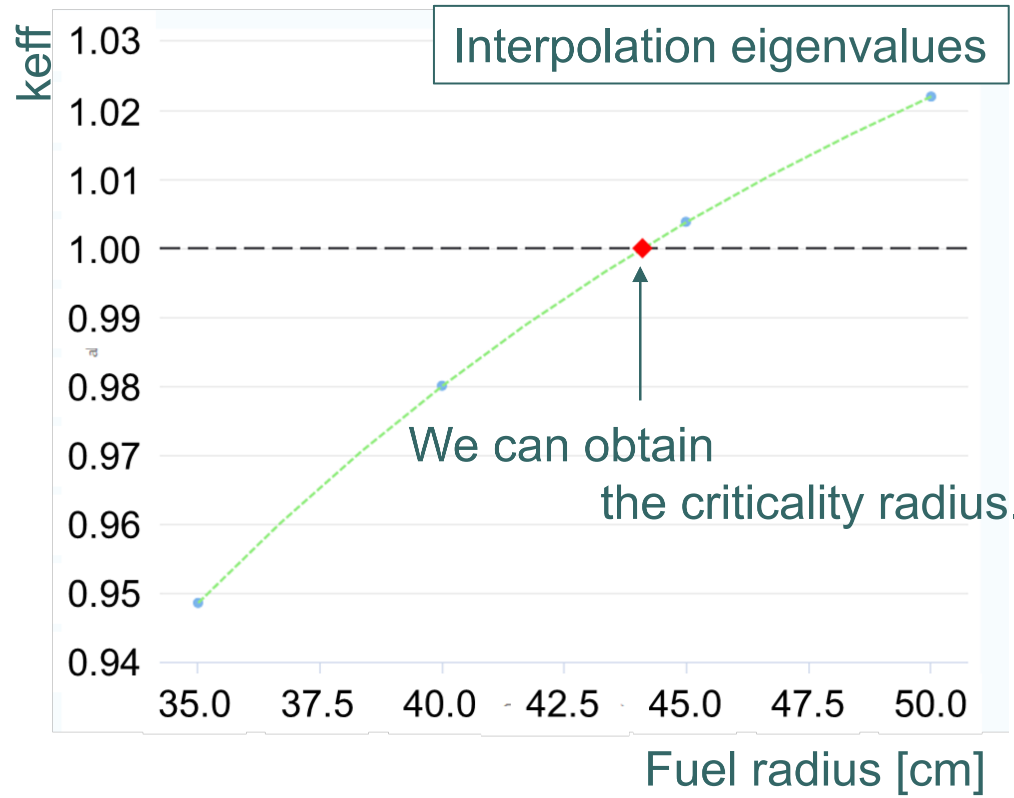
Overview of Criticality Map

Extract an eigenvalue from an output file

Saved eigenvalue data

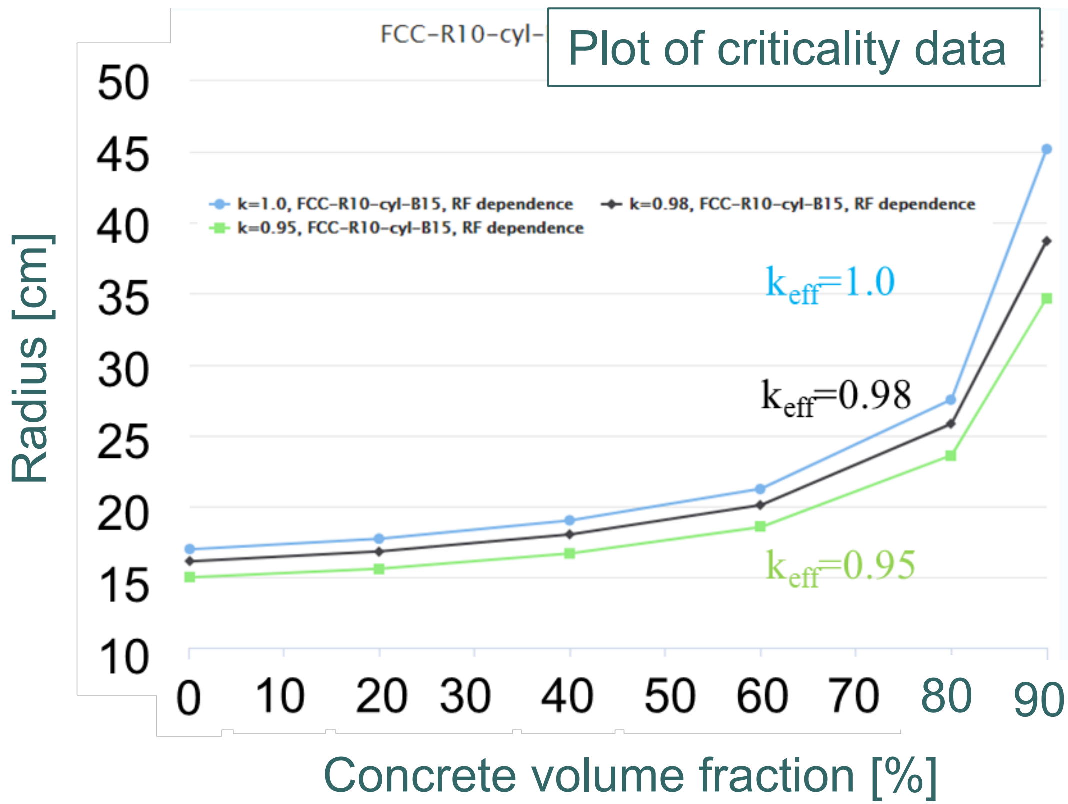
Name	
input	
Composition	[illegible]
Geometry	Sphere, Water reflector
Status	reaped
Comment	
User	
Created	2018/06/07 15:31
Modified	2018/06/25 13:39
Output File1	
Output File2	
Keff	1.017740
Keff Sigma	0.000200
NPART	6000000

An eigenvalue is extracted from output file



Overview of Criticality Map

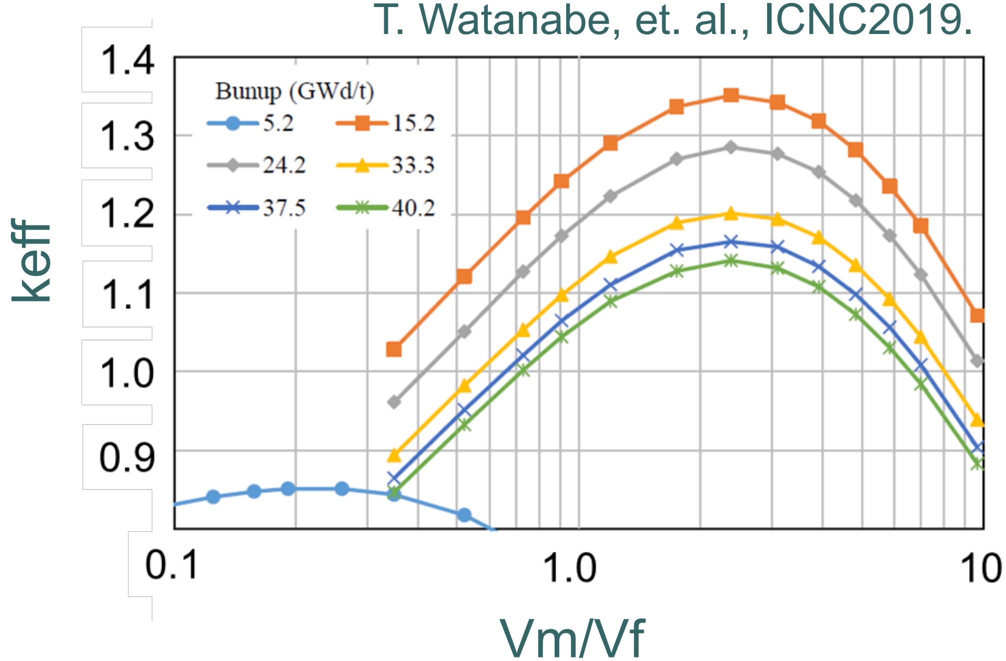
Interpolate the eigenvalues to obtain the criticality radius etc.



Use of Criticality Map and Future plan

Numerous calculations were executed with the Criticality Map.
Criticality characteristics has been investigated in various compositions.

T. Watanabe, et. al., ICNC2019.



Post Irradiation Examination (PIE) and Burn-up Calculation

- Validation of burn-up calculation codes and nuclear data.
- Evaluation of fuel debris' nuclide compositions
- Maintain and improve the PIE technique in JAEA for future PIE and analysis of fuel debris.

Recent PIE in JAEA (2016-2020)

9 samples from Ohi-4 (PWR, ~53 GWd/t)

RFEF

Cutting fuels

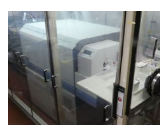
Cut samples

WASTEF

Dissolution

Dilute solution of residue

Dilute solution of fuel



ICP-MS

Lab4

Mass analysis of FP by ICP-MS

Chemically separated samples

TIMS

BECKY

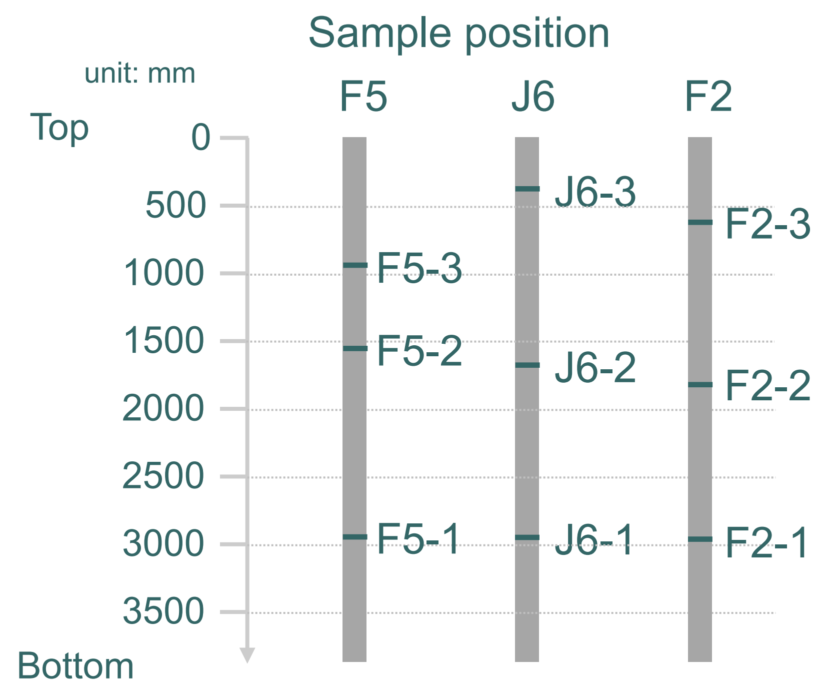
- Mass analysis of U, Pu, Nd by TIMS
- Gamma-ray measurements of Cs, Eu
- Chemical separation

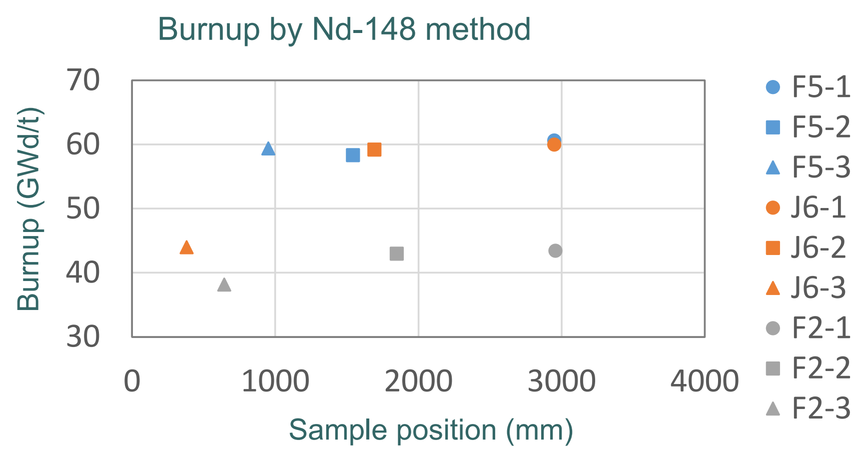
Recent PIE in JAEA (2016-2020)

9 samples from 3 fuel rods

F5, J6 (UO_2) and F2 (UO_2 with Gd_2O_3)

Target nuclides
$^{234}U, ^{235}U, ^{236}U, ^{238}U$
$^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu$
$^{142}Nd, ^{143}Nd, ^{144}Nd, ^{145}Nd, ^{146}Nd, ^{148}Nd, ^{150}Nd$
$^{133}Cs, ^{134}Cs, ^{137}Cs$
$^{151}Eu, ^{153}Eu, ^{154}Eu, ^{155}Eu$
$^{144}Sm, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{150}Sm, ^{152}Sm, ^{154}Sm$
$^{152}Gd, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd, ^{160}Gd$
$^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag$

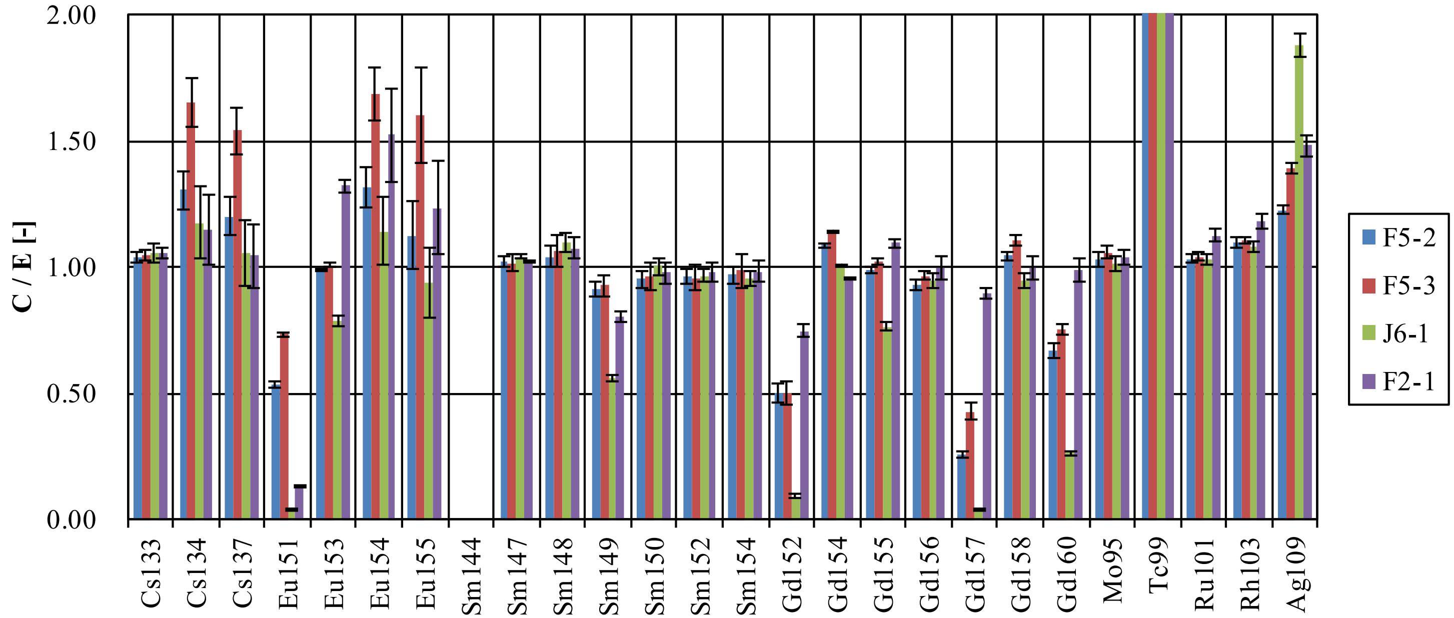




Activities on burn-up calculation

SWAT4 (combination of ORIGEN2 and MVP

Example: C/E of 4 samples by SWAT4 & JENDL-4.0



Evaluation of fuel debris' compositions for "criticality map"

Solomon

- Solver of Monte Carlo
  - Y. Nagaya, T. Ueki, K. Tonoike, SOLOMON: A MONTE CARLO SOLVER FOR CRITICALITY SAFETY ANALYSIS , ICNC 2019
    - Stated on 2015 from scratch
    - Toolkit written in C++14 and newer C++ standards
    - CMake for build environment
    - Designed for usual criticality safety analysis
    - Can build a code package for special applications to random media tailored for fuels debris
  - MVP for general purpose MC code written in FORTRAN

Physics, Geometry & Tracking

- Standard approaches to neutron transport such as:
- Evaluated nuclear data files (ENDF) in ACE format
  - Surface-based geometry
  - Zones defined with pre-defined surfaces
  - Set operations of intersection, union
  - Similar to MCNP (LANL), PHITS (JAEA)
- Two types of particle tracking:
  - Regular tracking for zones filled with uniform materials
  - Delta tracking for zones filled with random media
    - Multi-material mixture under inverse power law power spectrum using randomized Weierstrass function (RWF)

Delta Tracking & Neutron Transport

δ-collision

collide & scatter with
no velocity change

$\mathbf{r}$: position
E : energy
$\boldsymbol{\Omega}$: direction ($|\boldsymbol{\Omega}|=1$)
δ : delta-function

macroscopic cross section of δ-collision

flux

$$\Sigma_\delta(\mathbf{r},E)\phi(\mathbf{r},E,\Omega) = \int_0^\infty \int_{4\pi} \delta(E-E')\delta^2(\Omega-\Omega')\Sigma_\delta(\mathbf{r},E')\phi(\mathbf{r},E',\Omega')d^2\Omega'\,dE'$$

macroscopic total cross section: $\Sigma_T(\mathbf{r},E) + \Sigma_\delta(\mathbf{r},E) = \Sigma_D(E)$ (Set position-independent)

macroscopic differential scattering cross section: $\Sigma_S(\mathbf{r},E\leftarrow E',\Omega\leftarrow\Omega') + \delta(E-E')\delta^2(\Omega-\Omega')\Sigma_\delta(\mathbf{r},E')$

⇒ No change of the solution ϕ of transport equation!

distance-to-collision $= -\frac{1}{\Sigma_D(E)}\ln(\xi)$

always score ⇒

$$(\text{weight})\ \frac{\text{macroscopic cross section of reaction type of interest}}{\Sigma_D(E)}$$

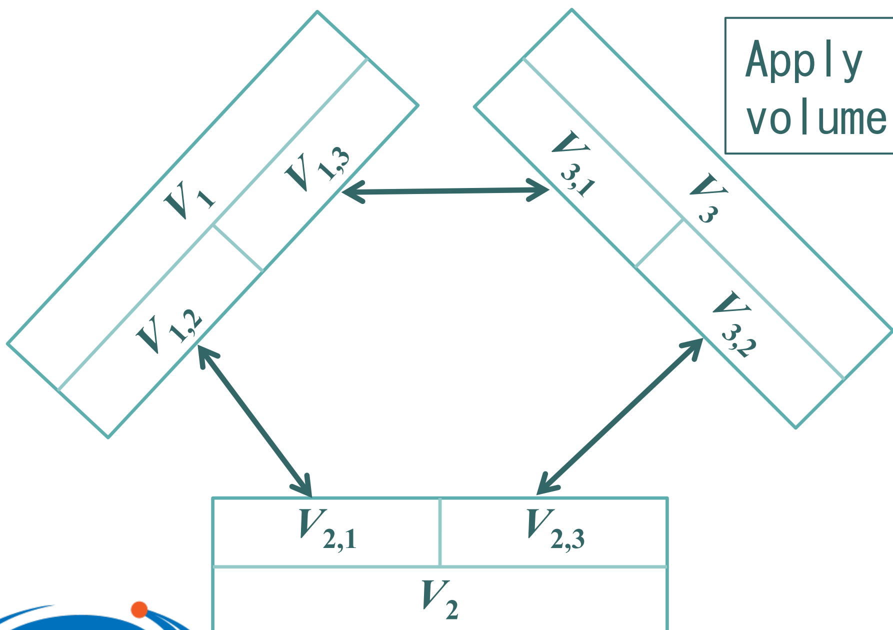
Material Mixture – Case of Three Materials

Mean volume fractions $V_1 + V_2 + V_3 = 1$

Division according to the volume ratio of other materials

$$V_{1,2} + V_{1,3} = V_1 \qquad V_{2,3} + V_{2,1} = V_2 \qquad V_{3,1} + V_{3,2} = V_3$$

$$V_{1,2}: V_{1,3} = V_2: V_3 \qquad V_{2,3}: V_{2,1} = V_3: V_1 \qquad V_{3,1}: V_{3,2} = V_1: V_2$$



Apply RWF methodology to each pairing of volume fractions

RWF: randomized Weierstrass function

$\binom{n}{2}$ pairings for n materials

T. Ueki, Nuclear Science and Engineering, 195, 214-226, 2021.

Formula of Material Mixture

amplitude adjustment | RWF

$$\hat{V}_1(\mathbf{r}) = \overbrace{V_{1,2} + V_{1,3}}^{V_1} + \min(V_{1,2}, V_{2,1})\, z_{1,2,2,1}\, \hat{C}_{1,2,2,1}(\mathbf{r}) - \min(V_{1,3}, V_{3,1})\, z_{3,1,1,3}\, \hat{C}_{3,1,1,3}(\mathbf{r})$$

$$\hat{V}_2(\mathbf{r}) = \overbrace{V_{2,3} + V_{2,1}}^{V_2} + \min(V_{2,3}, V_{3,2})\, z_{2,3,3,2}\, \hat{C}_{2,3,3,2}(\mathbf{r}) - \min(V_{2,1}, V_{1,2})\, z_{1,2,2,1}\, \hat{C}_{1,2,2,1}(\mathbf{r})$$

$$\hat{V}_3(\mathbf{r}) = \overbrace{V_{3,1} + V_{3,2}}^{V_3} + \min(V_{3,1}, V_{1,3})\, z_{3,1,1,3}\, \hat{C}_{3,1,1,3}(\mathbf{r}) - \min(V_{3,2}, V_{2,3})\, z_{2,3,3,2}\, \hat{C}_{2,3,3,2}(\mathbf{r})$$

The hat ^ indicates replica

$\hat{C}_{1,2,2,1}$, $\hat{C}_{2,3,3,2}$, $\hat{C}_{3,1,1,3}$ are constructed from independent sequences of random numbers

$$\hat{\Sigma}_R(\mathbf{r}, E) = \hat{V}_1(\mathbf{r})\Sigma_{R,1}(E) + \hat{V}_2(\mathbf{r})\Sigma_{R,2}(E) + \hat{V}_3(\mathbf{r})\Sigma_{R,3}(E)$$

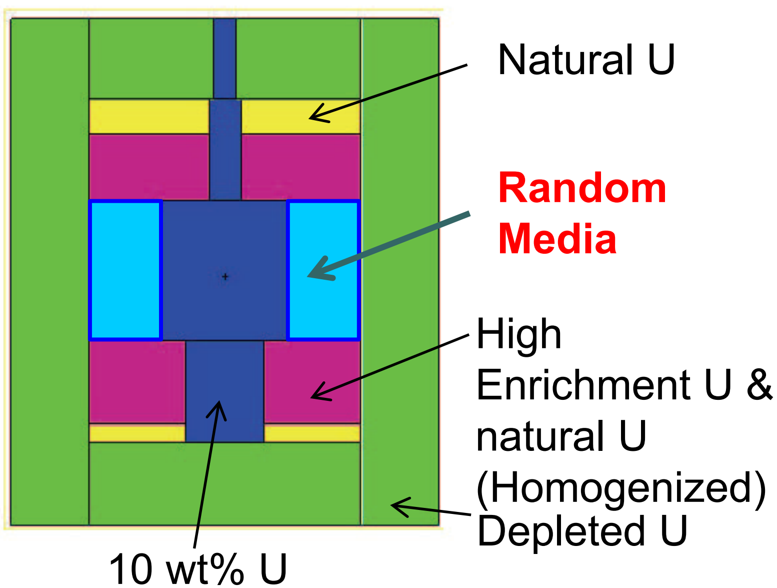
$$\hat{V}_1 + \hat{V}_2 + \hat{V}_3 = V_1 + V_2 + V_3 = 1$$

T. Ueki, Nuclear Science and Engineering, 195, 214-226, 2021.

Preliminary Random Media Result by Solomon

Virtual BIGTEN

Based on HEU-MET-FAST-007 in ICSBEP

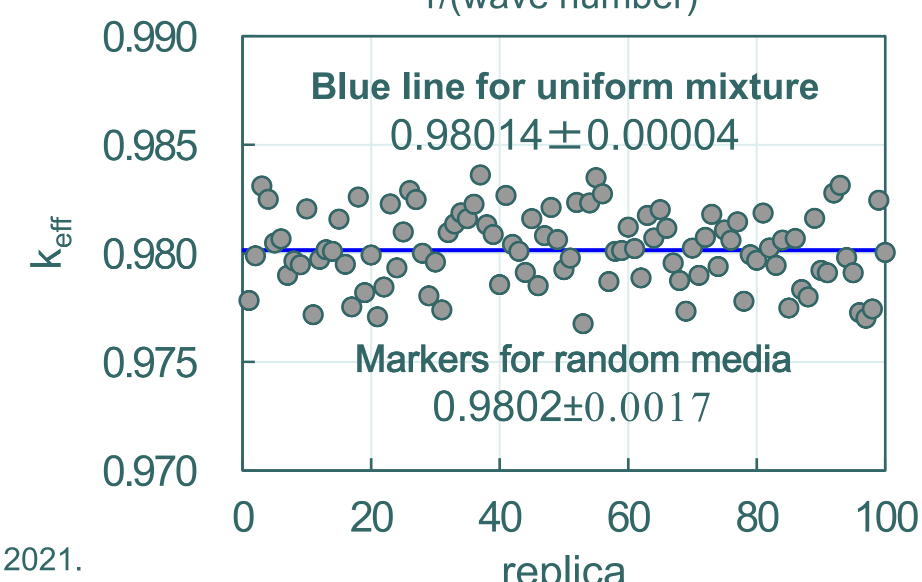


U: Uranium

Three Material Random Media

	mean volume fraction
(1) HEU + Nat U	50%
(2) 10wt% U	40%
(3) Depleted U	10%

Power Spectrum of Mixture: 1/(wave number)^2



https://doi.org/10.1080/00295639.2020.1801000

T. Ueki, Nuclear Science and Engineering, 195, 214-226, 2021.