Consequence analysis of a postulated nuclear excursion in BWR spent fuel pool using 1/f$^{\beta}$ spectrum model of randomization

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Background

Severe Nuclear Accident

- The Fukushima Accident in 2011.
  - The SFP cooling system was lost in the Unit 1 to Unit 4 SFPs.
- Loss of spent fuel pool cooling function.
  - Fuel meltdown[1].

CRITICALITY EVENT → **Number of fissions in the first peak power** → **To estimate the scale of accident and employees' dose**

Challenge

The uncertainty of composition distribution in fuel debris

Conventional Method

Conservative assumptions → Unrealistic overestimation

- Highest neutron multiplication
- Weakest temperature feedback, etc.

- High cost, unfeasible design, etc.

New idea

Introduction of random media model [Randomized Weierstrass Function (RWF) and 1/f spectrum]

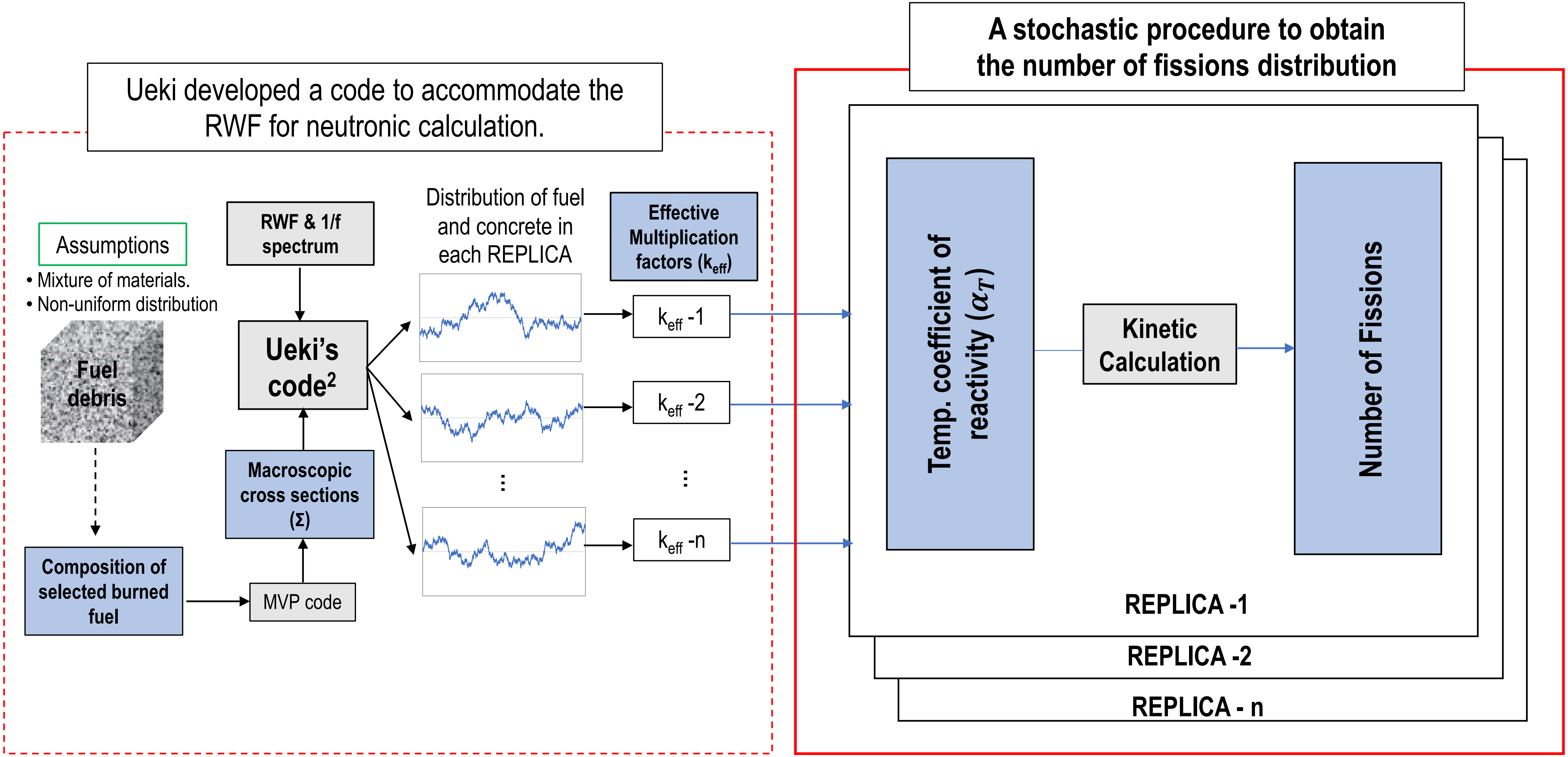
- Burned fuel assumption.

Purpose

To obtain a realistic distribution of the number of fissions.

[1] S.Carlos, et.al, "Use of TRACE best estimation code to analyze spent fuel storage pools safety," *Prog. Nucl. Energy*, vol. 77,224-238,2014

Concept of random media model & New calculation procedure

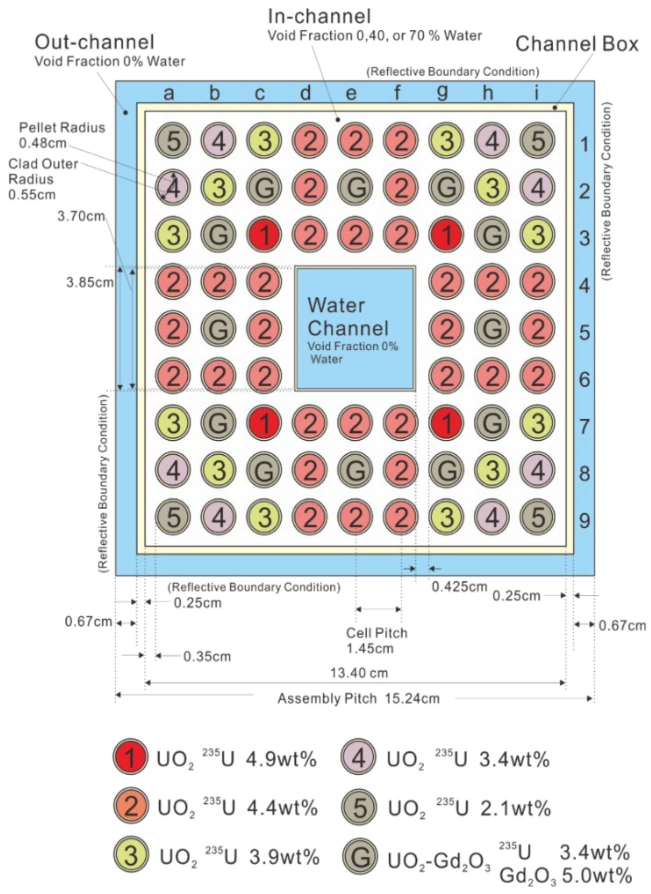


[2] T. Ueki, "Monte Carlo criticality analysis under material distribution uncertainty," *J. Nucl. Sci. Technol.*, vol. 54, no. 3, pp. 267–279, 2017.

1. Selection of Burned Fuel Compositions

Objective

To obtain the nuclide compositions at 15.2 and 33.3 GWd/t.



Fuel Assembly of BWR STEP3 model [4]

Burnup Calculation

- SWAT4 code
- JENDL-4.0.
- Cooling: 5 years
- 70% void fraction

2. Cross section information for building a random media model

Objective

To generate:

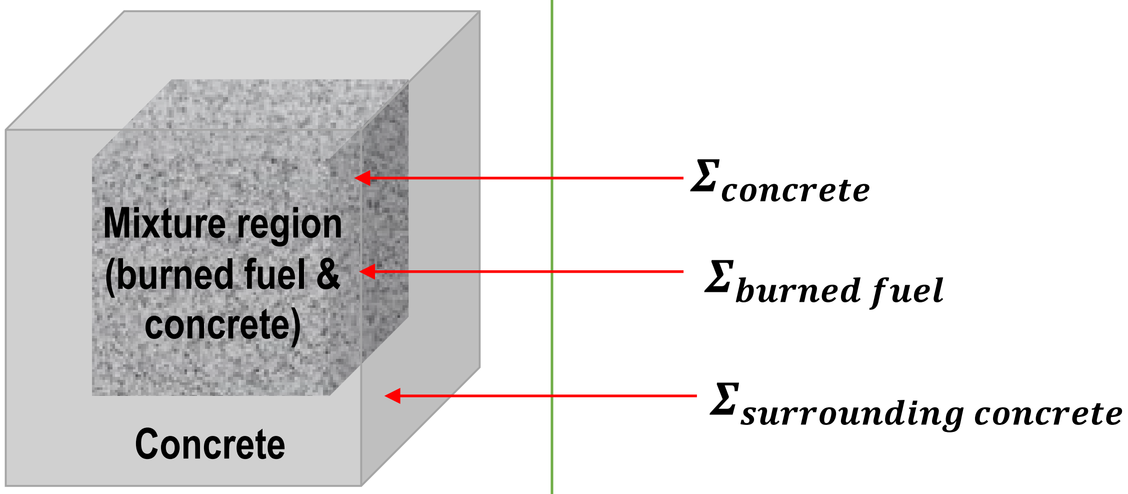
- $\Sigma_{burned\ fuel}$
- $\Sigma_{concrete}$
- $\Sigma_{surrounding\ concrete}$

Calculation method

- MVP code
- JENDL-4.0

- For initial temp. : 25 °C
- To postulated temp. : 1,000 °C

Geometry of random media model



[4] OECD/NEA, "Burn-up credit criticality safety benchmark phase III-C," no. NEA/NSC/R/(2015)6, 2015.

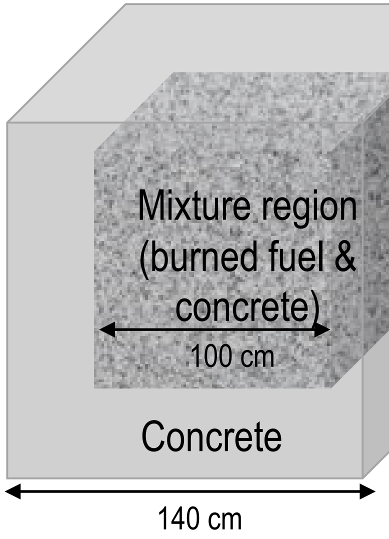
3. Distribution of Effective Multiplication Factors (k_{eff})

Objective

To obtain k_{eff} distribution under the random model.

Calculation

Ueki's code



Inner cube: Mixture region

- **Case 1: burned fuel at 15.2 GWd/t**
- **Case 2: burned fuel at 33.3 GWd/t**

Outer cube: Concrete

Randomized Weierstrass Function (RWF)

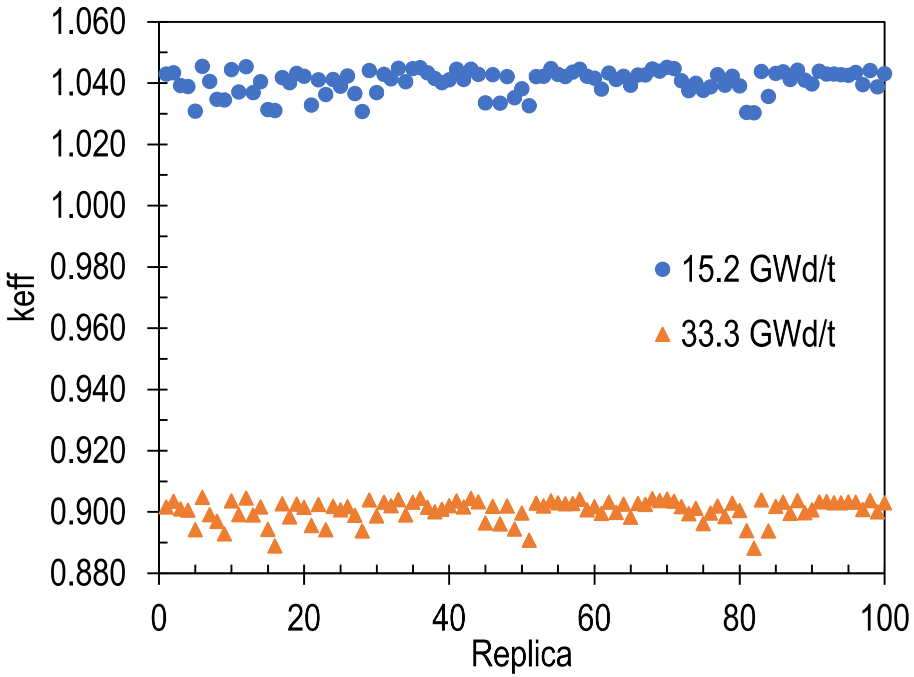
$$V^{RWF}(r) = \sigma \sum_{j=1}^{\infty} B_j \lambda^{-\alpha j} sin(\lambda^j \boldsymbol{r} \cdot \boldsymbol{\Omega}_j + A_j)$$

$S(f) \propto 1/f^{1+2\alpha}$, where $\beta = 1+2\alpha$; $0 \leq \alpha \leq 0.5$

$S(f)$ = power spectrum
f = frequency
β = parameter related to randomness ($1 \leq \beta \leq 2$)

- RWF is the sum of sine functions and is an approximate representation of the dynamical system state reached via extreme disorder.
- The spatial distribution of fuel debris is expected under the extreme physical disorder ("$1/f$ spectrum" model[4]).
- In this study, β = 2 (Brownian motion) was assumed.
- 100 replicas were generated using the RWF.

Results



The 15.2 GWd/t shows the possibility of criticality where k_{eff} was distributed between 1.03 and 1.05

[4] B. R. Frieden, "Spectral 1/f noise derived from extremized physical information," vol. 49, no. 4, 1994.

4. Distribution of temperature coefficient of reactivity (α_T)

Objective

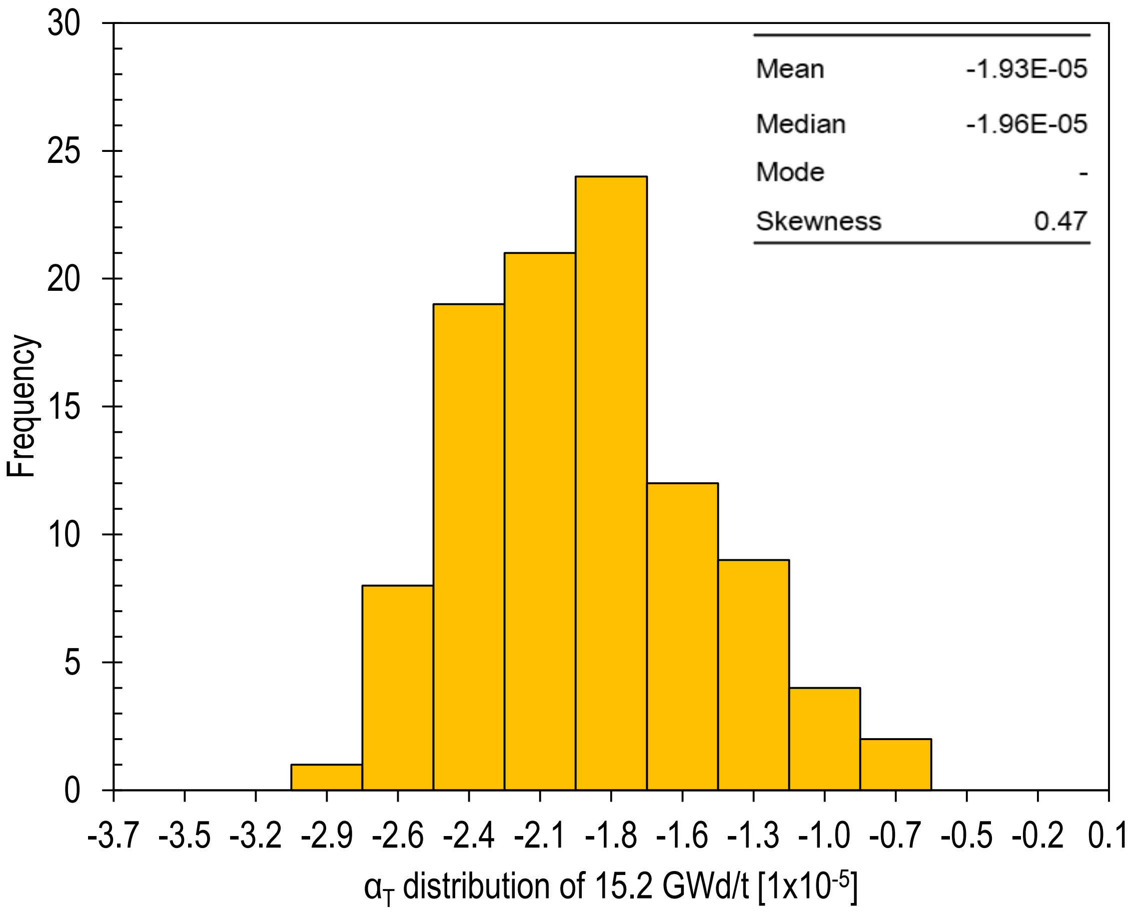
To obtain α_T distribution under the random media model.

- The number of fissions can be determined from the temperature coefficient of reactivity.
- A uniform temperature coefficient was proposed to simplify the calculation.
- The temperature was varied from 25 to 1000 °C for each replica.

$$\alpha_T = \frac{\rho_2 - \rho_1}{T_2 - T_1} = \frac{\frac{1}{k_1} - \frac{1}{k_2}}{T_2 - T_1}$$

α_T: uniform temperature coefficient [1/K]
T_1, T_2: temperature [K]
ρ_1, ρ_2 : reactivity at T_1 and T_2
k_1, k_2 : effective multiplication factors at T_1 and T_2

Results



α_T is categorized as symmetrical distribution (skewness < 0.5).

5. Distribution of the number of fissions

Objective

To obtain the number of fissions distribution under the random media model.

Nordheim-Fuchs (N-F) Model

- An analytical approximation to obtain the number of fissions in the first peak power.
- Based on one point kinetics equation (only prompt neutron is considered).
- Initial reactivity insertion (ρ_0) > 1$.
- α_T values are obtained from the previous step.
- K is assumed to be constant.

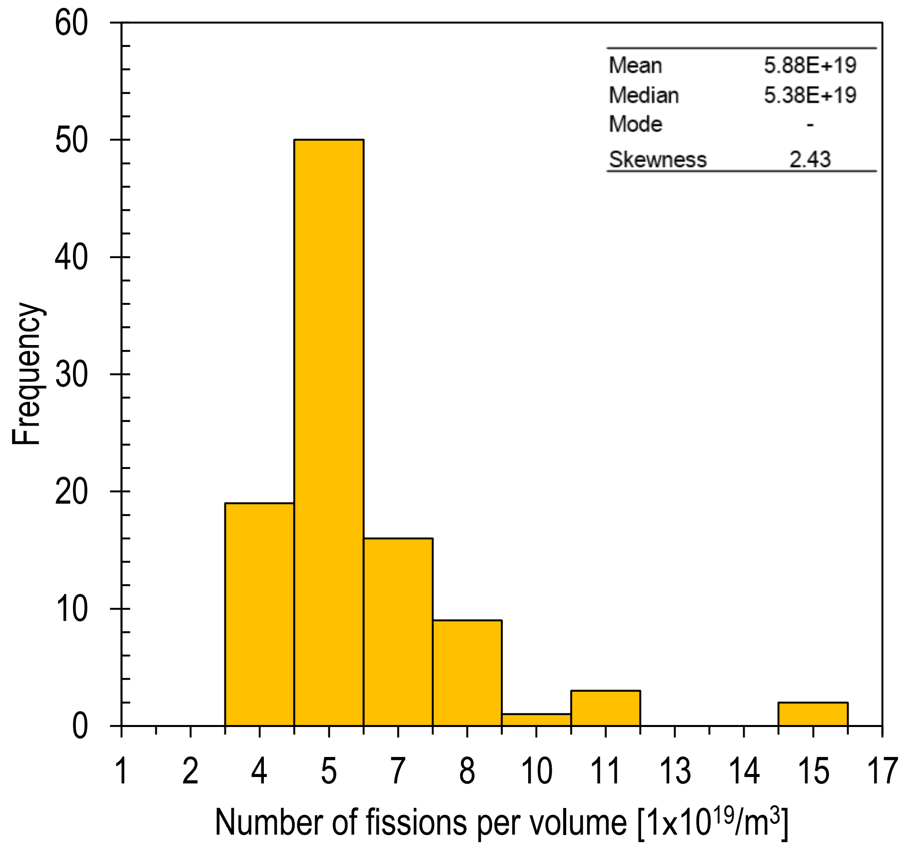
Energy production[6]

$$E(J) = \frac{2(\rho_0 - \beta)}{\alpha_T K}$$

β = delayed neutron fraction
K = inverse heat capacity

Energy released per fission ≈ 200 MeV
$1\ \text{MeV} = 1.602 \times 10^{-13}\text{J}$

Distribution of the number of fissions



Results

- The number of fissions per volume fluctuated from 4 x 10^{19} to 15 x 10^{19} fissions/m^3.
- It has positive skewness, therefore there is a small possibility of an incredibly high number of fissions.

[6] Hetrick, D., 1971. Dynamics of Nuclear Reactors. University of Chicago Press.

THANK YOU