Supercritical Kinetic Analysis of Accumulated Fuel Debris in the Fukushima-Daiichi NPS

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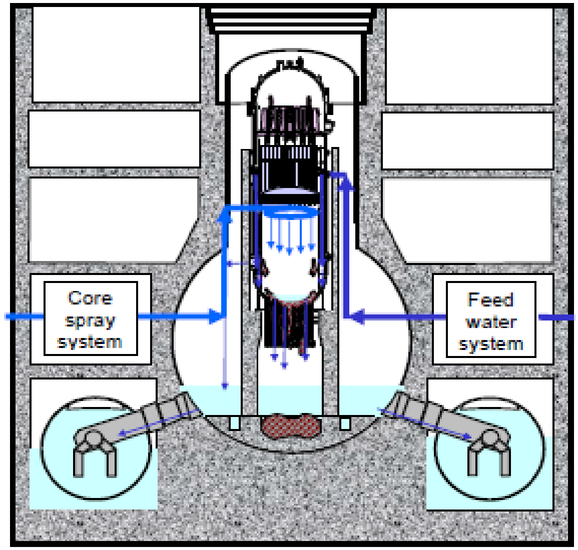
Introduction

Fukushima Daiichi NPS accident and fuel debris retrieval

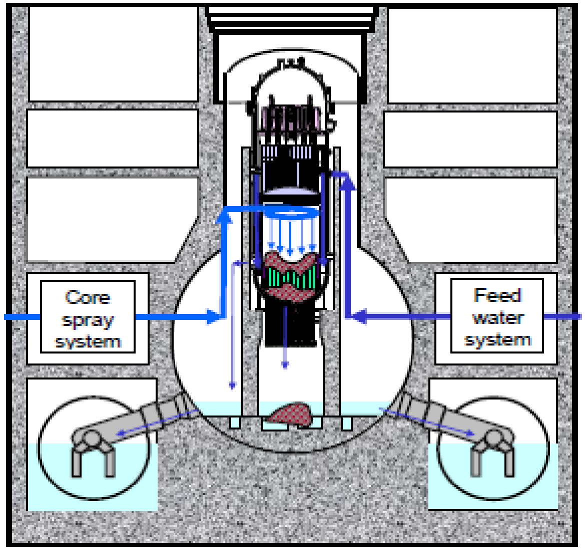
Great East Japan Earthquake and tsunami

1FNPS damaged

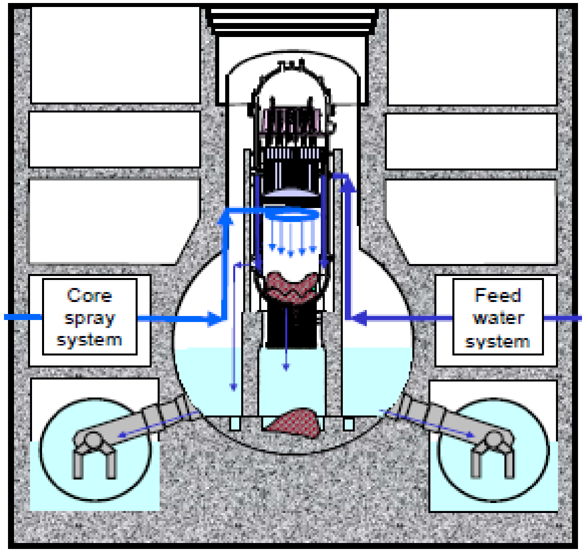
Decommissioning of the 1FNPS (30–40 years)



Estimated condition of
Unit–1



Estimated condition of
Unit–2



Estimated condition of
Unit–3

Source: Evaluation of the situation of cores and containment vessels of Fukushima Daiichi NPS Units-1 to 3 and examination into unsolved issues in the accident progression. TEPCO. 2013

Introduction – Background and Motivation

- Criticality safety in Fukushima-Daiichi NPS decommissioning
    - Not only to prevent a criticality of fuel debris in the core during the fuel debris reloading process.
    - But also to estimate the released energy and expected radiation dose in a re-criticality accident in order to establish safety measures for workers.
    - In the case of a prompt supercritical condition
        - the transient is so fast that it is difficult to take any action at all after the detection of the criticality.
    - essential to estimate the energy and the dose in advance with the highest possible accuracy in order to establish the measures to be taken.

Introduction – Background and Motivation (continued)

- Method for the analysis
  - Point-kinetic analysis
    - not serve this purpose if the fuel debris is large and/or if some fuel debris is coupled weakly from the viewpoint of neutron transportation.
  - space-dependent and time-dependent neutron transport analysis
    - Numerical analysis is theoretically possible, in general impossible
- Space-dependent kinetic analysis code MIK
  - developed for a space-dependent neutron transport kinetic analysis based on the integral kinetic model

Introduction – Purpose

- To show the applicability of MIK code based on the integral kinetic model to an analysis of practical fuel debris geometry in which fuel debris accumulates at the bottom of PCV.

Analysis method in MIK code

Integral kinetic model

$$N_i(t) = \sum_{j=1}^{n} \int_{-\infty}^{t} \alpha_{ij}(t-t')N_j(t')dt' \quad \textbf{(Eq. 1)}$$

$$\left[\frac{\text{fissions@"}i\text{"}}{\text{sec}}\right] \qquad \left[\frac{\text{fissions@"}i\text{"}}{\text{sec} \cdot \text{source fission@"}j\text{"}}\right]$$

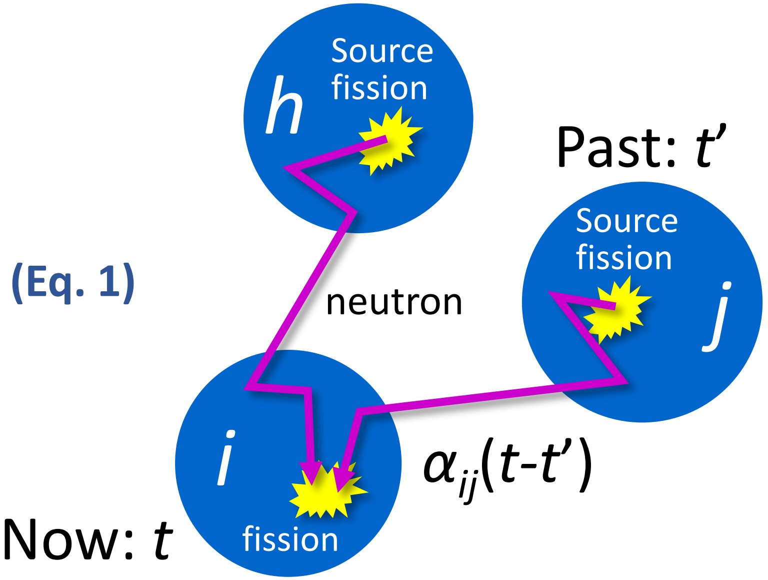


Figure 2: Multi-region system

1. Definitions

- $N_i(t)$: Fission rate at time t in region "*i*".
- $\alpha_{ij}(\tau)$: Fission probability density function in region "*i*" following a source fission in region "*j*" generated in τ seconds before.

2. Physical meaning

- Fission rate in region "*i*" at time *t* is the summation of all "past" fission contributions from other regions to region "*i*".

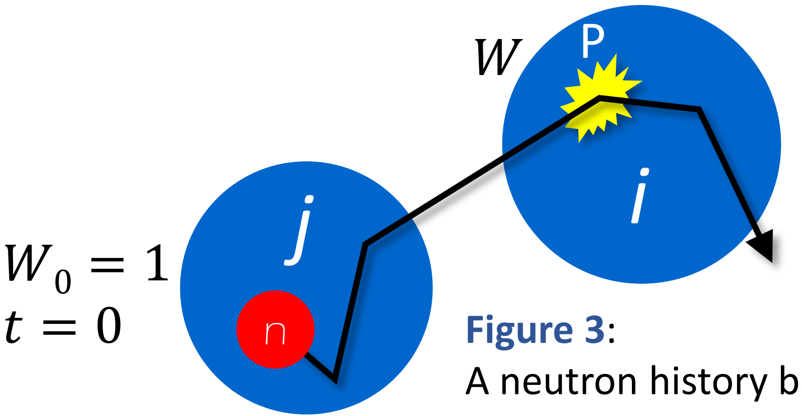
Calculation of $\alpha_{ij}(\tau)$ by Monte Carlo method

1. Introduction of $C_{ij}(\tau)$

$$C_{ij}(\tau) \equiv \int_0^{\tau} \alpha_{ij}(\tau')d\tau' = \frac{\sum_{i,0\le t\le\tau} W_{\text{fission}}}{\sum_{j,t=0} \frac{W_{\text{s}}}{\nu}}$$ **(Eq. 2)**

- Physical meaning
  - Cumulative number of fissions in region "*i*" by time = τ if a fission occurs at time = 0 in region "*j*".
- $C_{ij}(\tau)$ can be estimated by Monte Carlo method

2. Fission weight W_{fission} in non-analog neutron random walk



$$W_{\text{fission}} = \frac{\sigma_{\text{f}}}{\sigma_{\text{t}}} \times W$$ **(Eq. 3)**

Figure 3:
A neutron history born in region "j" and flies to region "*i*"

Calculation methodology

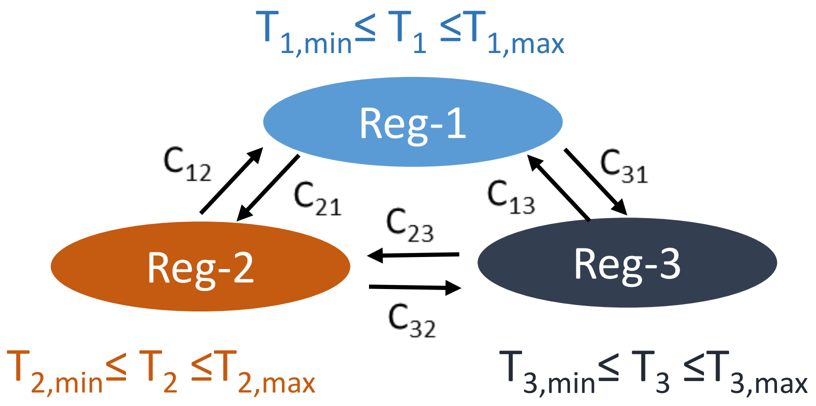
$$N_i(t) = \sum_{j=1}^{n}\int_{-\infty}^{t}\alpha_{ij}(t-t')N_j(t')dt'$$

$$\approx \sum_{j=1}^{n}\left\{\underset{\substack{\text{fission contribution}\\ \text{before reactivity insertion}}}{N_j(0)\left[C_{ij}^{t=0}(\tau')\right]_{k\Delta t}^{k_{\mathrm{cut}}\Delta t}} + \sum_{k'=0}^{k-1} \underset{\substack{\text{fission contribution}\\ \text{after reactivity insertion}}}{N_j(k'\Delta t)\left[C_{ij}^{t=k'\Delta t}(\tau')\right]_{(k-k'-1)\Delta t}^{(k-k')\Delta t}}\right\}$$

1. General features
   - Feedback effects are considered by applying time-dependent $C_{ij}(\tau)$.
   - $C_{ij}(\tau)$ is tallied by contentious energy neutron transport Monte Carlo code MVP2.0 with JENDL-4.0 nuclear data library.
   - No limitation on geometry which the model covers.
2. Limitations and assumptions
   - Delayed neutrons are not considered in the current methodology.
   - The model is applicable to prompt supercritical power excursions from the initial prompt-critical state with very low power.

Feedback modeling

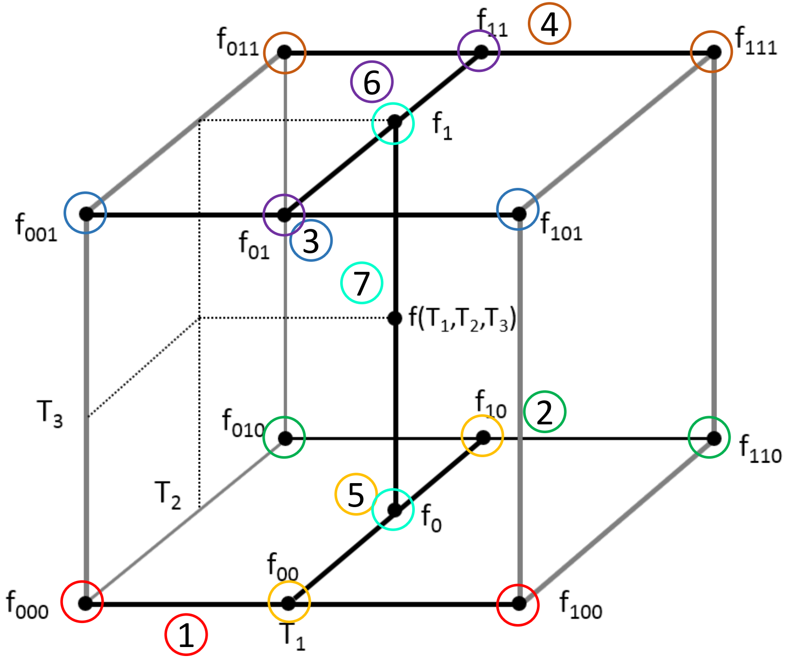
Three-dimensional linear interpolation in case of three regions



T_1	T_2	T_3
$T_{1,min}$	$T_{2,min}$	$T_{3,min}$
$T_{1,min}$	$T_{2,min}$	$T_{3,max}$
$T_{1,min}$	$T_{2,max}$	$T_{3,min}$
$T_{1,min}$	$T_{2,max}$	$T_{3,max}$
$T_{1,max}$	$T_{2,min}$	$T_{3,min}$
$T_{1,max}$	$T_{2,min}$	$T_{3,max}$
$T_{1,max}$	$T_{2,max}$	$T_{3,min}$
$T_{1,max}$	$T_{2,max}$	$T_{3,max}$

$C_{ij}(\tau)$ functions at these 2^3 states are obtained by Monte Carlo method

Effect of feedback included (Doppler broadening)



Denotation:

$f_{000} \equiv C_{ij}(\tau, T_{1,min}, T_{2,min}, T_{3,min})$

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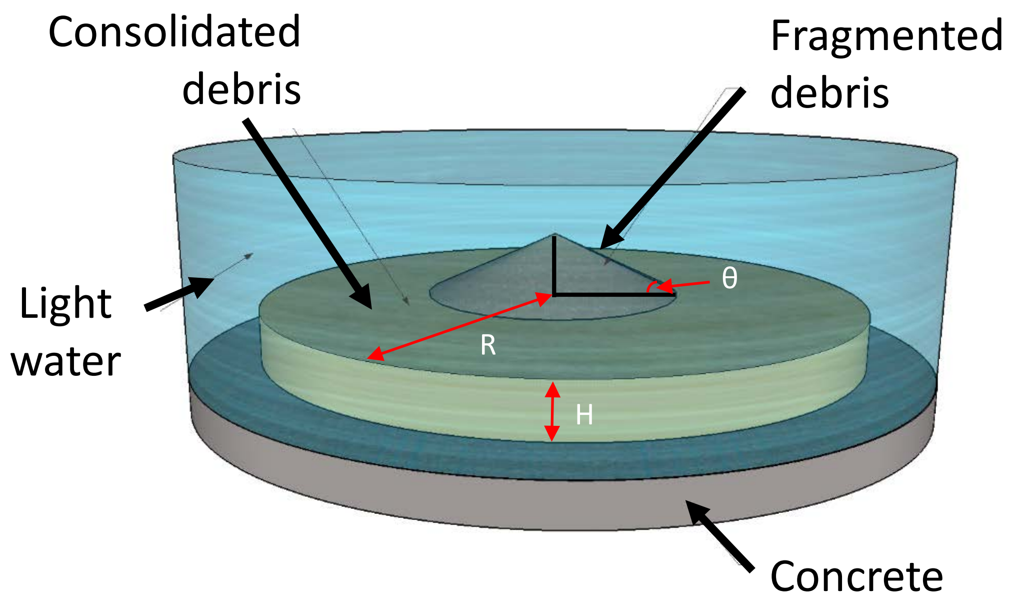
$f_{111} \equiv C_{ij}(\tau, T_{1,max}, T_{2,max}, T_{3,max})$

Analysis condition

Accumulated fuel debris system – Geometry and composition



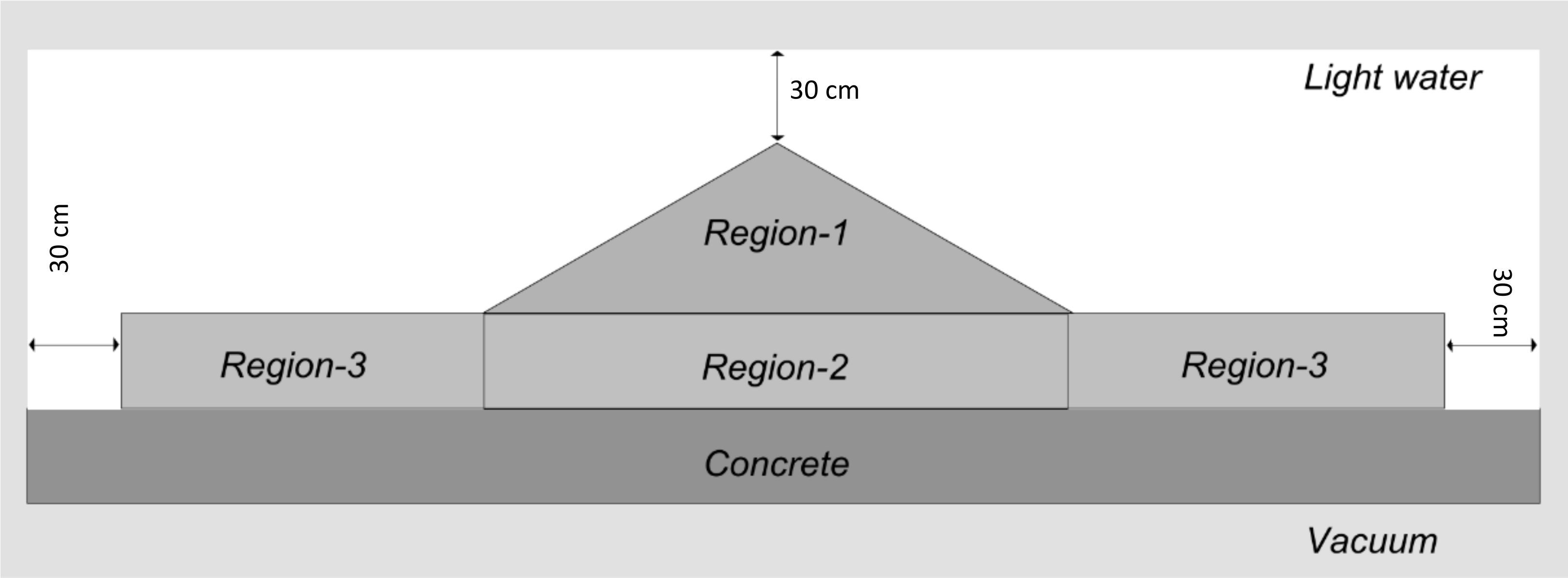
Conical fragmented debris	
Volume of the region	4.7×10^5 cm^3
Particle radius	0.1 cm
Packing fraction	0.6
Height	53 cm
Angle (θ)	30°
Radius	≈ 92 cm
Cylindrical consolidated debris	
Height (H)	5 cm
Radius (R)	150 cm
Cylindrical concrete	
Height	30 cm
Radius	180 cm
Cylindrical light water	
Thickness	30 cm

Composition of fuel debris

Material	Mass %
UO_2	53
Zr	11
ZrO_2	10
Fe	11
Others (Cr, Ni, Si, etc.)	15

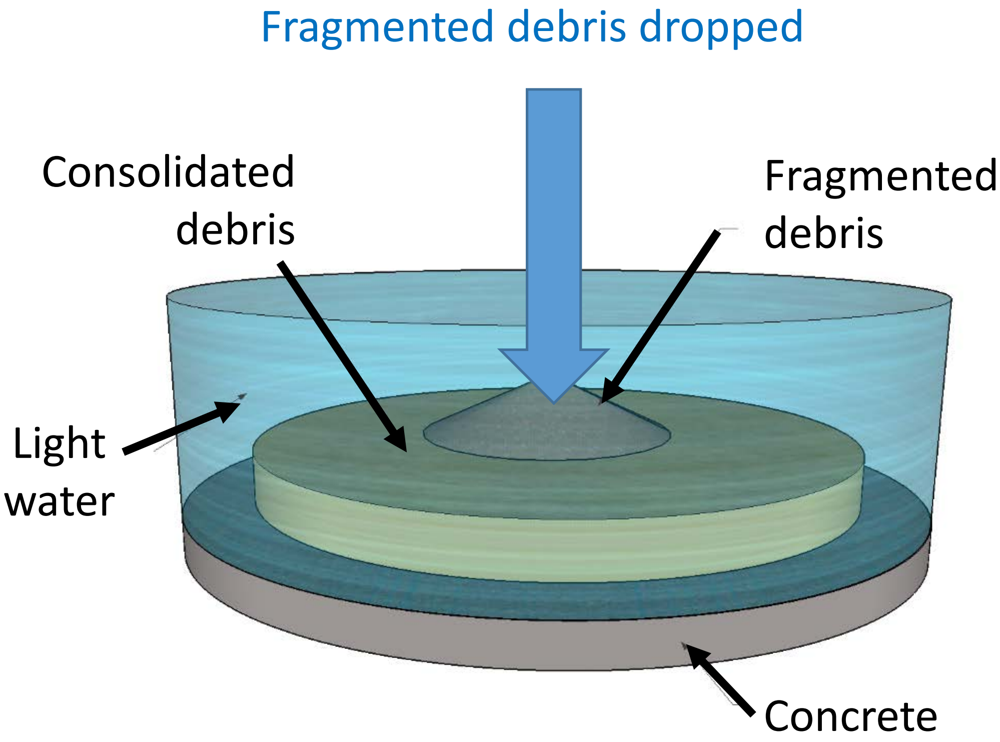
Uranium enrichment: 5%

Accumulated fuel debris system – Modeling in the MIK code



Modeling of hypothetical system in MIK code (3D)

Simulated phenomena



Effective multiplication factor by prompt neutrons

k_p=1.0141 (σ=0.01%)

Initial condition in the analysis:

Critical in very low power (1W)

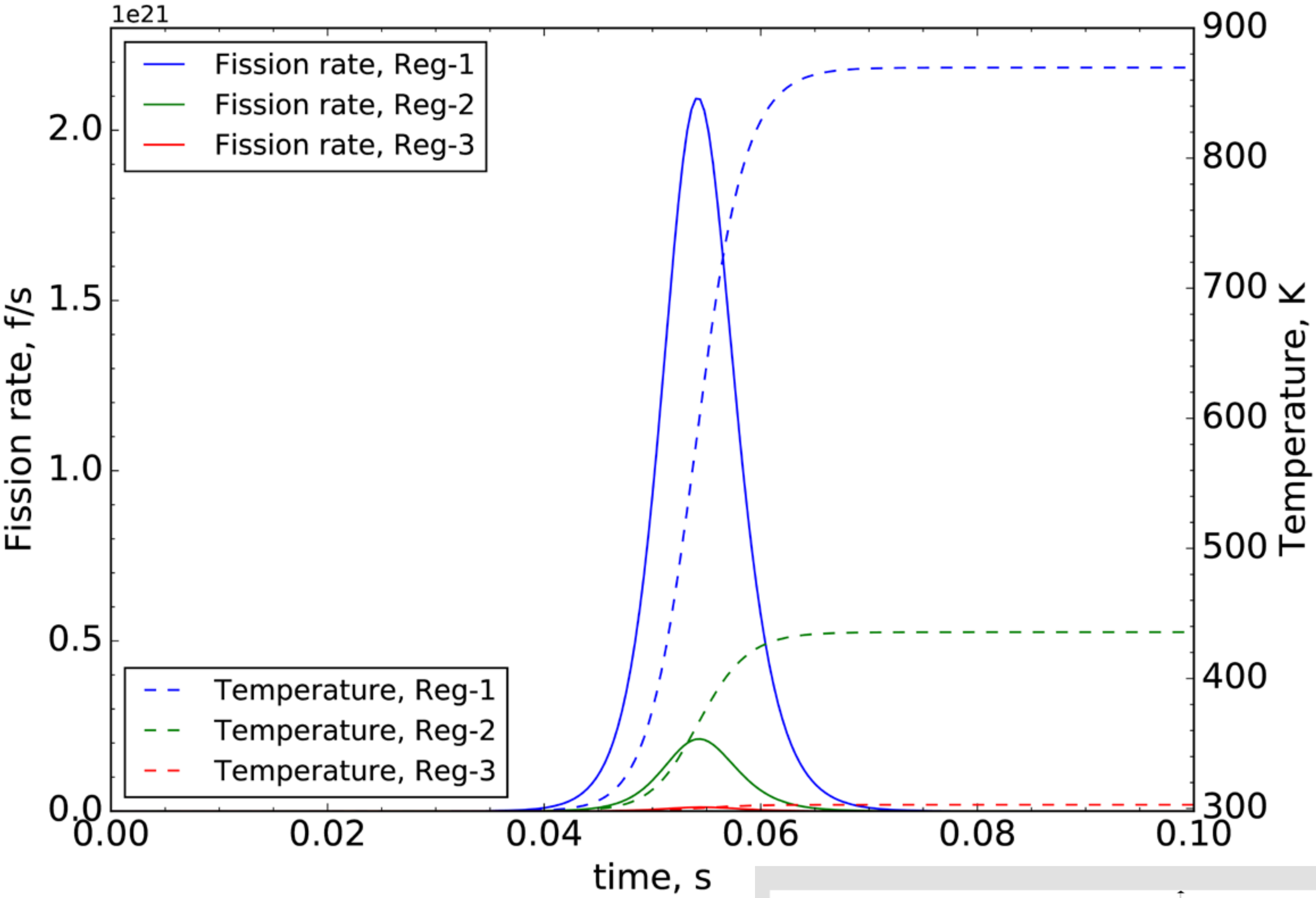
Initial temperature: 25˚C

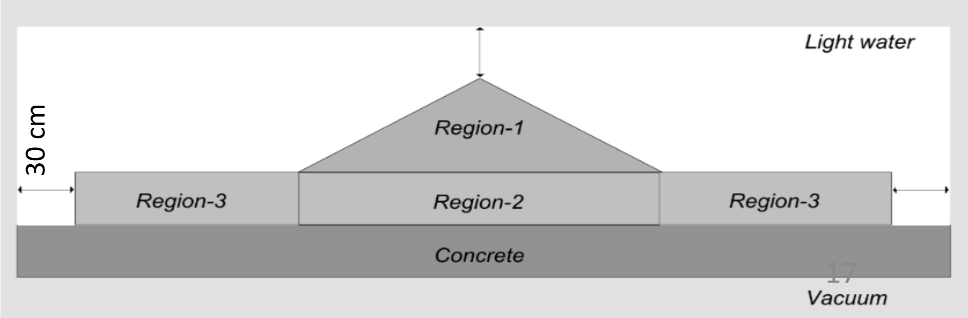
Stepwise reactivity insertion at t =0

Heat transfer from fuel to light water ignored (adiabatic)

Analysis results

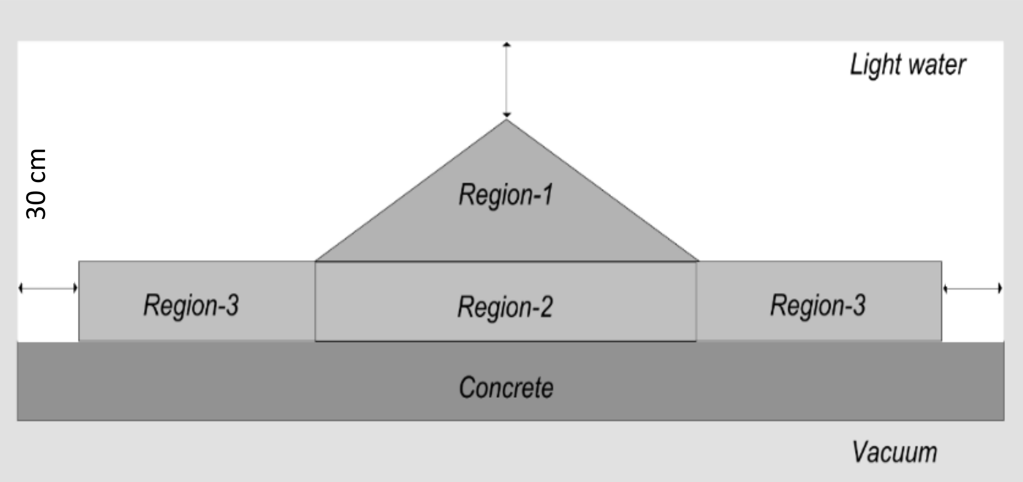
Results - Change of fission rate and temperature in each region





Results – Peak fission rate, Energy release, Temperature

Quantity	Reg-1	Reg-2	Reg-3
Peak fission rate [fissions/s]	2.1×10^{21}	2.1×10^{20}	1.2×10^{19}
Energy release [MJ]	533	54	3
Temperature [˚C]	596	163	30



Conclusions

- A space-dependent kinetic analysis of fragmented debris particles that accumulated on consolidated fuel debris in light water was carried out.
- The results showed that the space-dependent analysis code MIK can provide information about the released energy in each fuel debris region taking into account the reactivity feedback effect by temperature rise properly.
- This provides useful information for the exact estimation of radiation dose in the event of a re-criticality accident.
- More detailed analyses are planed for fuel debris with various geometries and various compositions.