Reactivity Coefficient Calculation for a Low-Power LEU Research Reactor

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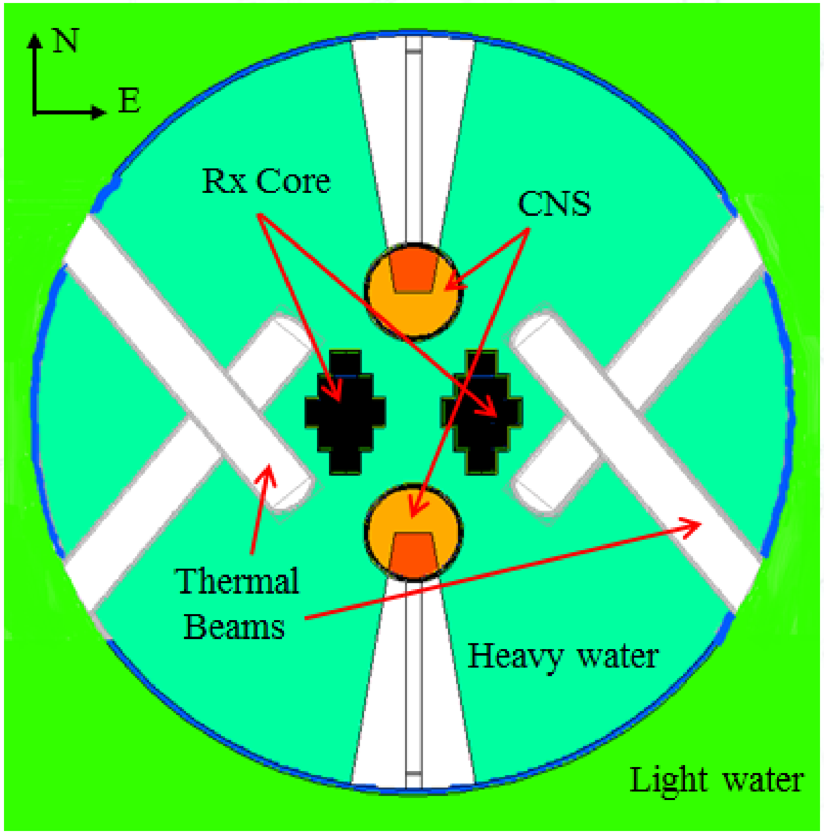
Outline

- Introduction of the Split Core Design for a Reactor Replacement at NIST
- Reactivity Coefficient Calculations
  - Moderator Temperature Coefficient (MTC)
  - Fuel Temperature Coefficient (FTC)
  - Void Coefficient (VC)
- Global Negative Reactivity Effects Evaluation
- An Example of ‘Best-Estimate’ Transient Analysis with Reactivity Feedback Incorporated
- Summary

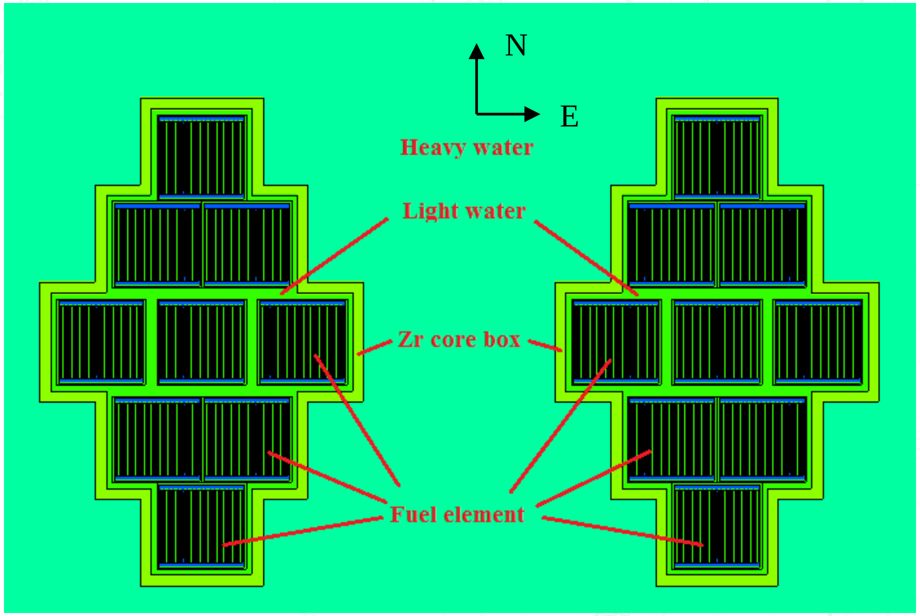
Schematics of the Split-Core Design



Reactor Size (m)	Value
Heavy water tank diameter	2.5
Heavy water tank height	2.5
Light water pool diameter	5.0
Light water pool height	5.0

The mid-plane of the split core reactor. Two cold neutron source (CNS) are placed in the north and south side of the core, and four thermal beam tubes are located in the east and west side of the core at different elevations.

Horizontally Split Core With 18 Fuel Elements

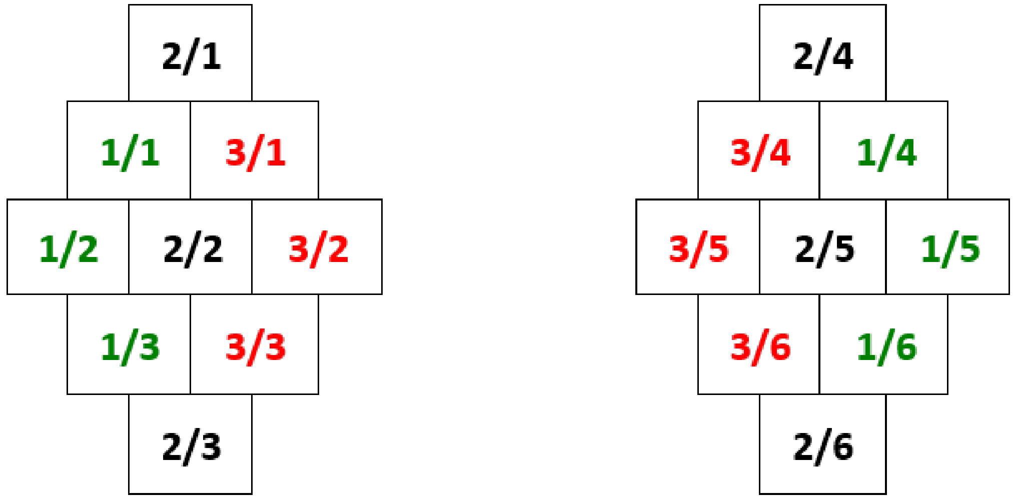


A close view of the horizontally split-core. The core consists of total 18 fuel elements which are evenly distributed into two horizontal split regions.

Core Design Information

Parameter	Data
Thermal power rate (MW)	20
Fuel cycle length (days)	30
Active fuel height (cm)	60.0
Fuel material	U_3Si_2/Al
U-235 enrichment in the fuel (wt. %)	19.75
Fuel mixture density (g/cc)	6.52
Uranium density (g/cc)	4.8
U-235 mass per fuel element (gram)	399
Number of fuel elements in the core	18

Startup (SU) and End-of-Cycle (EOC) Core



Three-batch Fuel Management Schemes of the Core

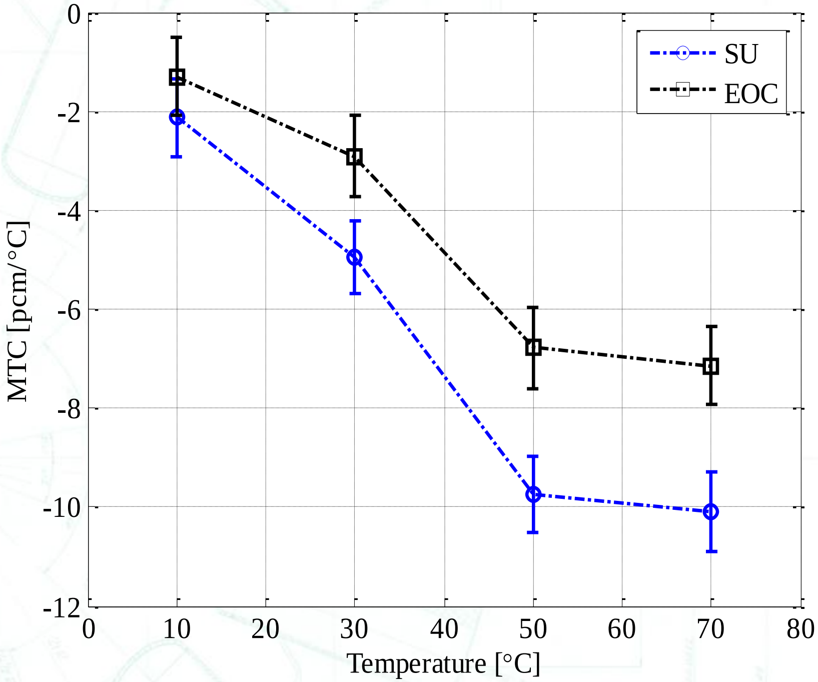
- The **green** color indicates fresh fuel at SU, and the **red** color indicates discarded fuel at EOC. The **first** number indicates the batch number, and the **second** number indicates the FE index in the batch.
- 6 fuel elements are replaced after the 30-day cycle.
- SU and EOC represents two limiting core status for safety analysis as SU has the most reactive fuel configuration while EOC has control rods all out positions.

Moderator Temperature Coefficient (MTC)

- The MTC accounts for the reactivity change when the temperature of the moderator varies.
- The underlying mechanism of MTC is due to the moderator density changes because of thermal expansion or contraction.
- MTC is the main factor that contributes to the *temperature defect* of reactivity, which is the change of reactivity that occurs in the reactor core from the fuel-loading temperature to the operating temperature.
- The moderator temperature is reflected in MCNP in three ways:
  - Moderator density
  - $S(\alpha,\beta)$, thermal neutron scattering kernel
  - TMP card to specify temperature for every cell

MTC Calculation and Results

- The light water is assumed to be 43 °C with the density 0.9914 g/cm³ at reference.
- The MTC is calculated by modifying the water density associated with temperature from 0 °C to 80 °C in 20 °C increments.
- The TMP card for the coolant cells are also changed correspondingly whereas the scattering kernel remains unchanged
- The k_{eff} for each perturbed case is calculated and the corresponding MTC is evaluated by dividing the reactivity change to the temperature difference.



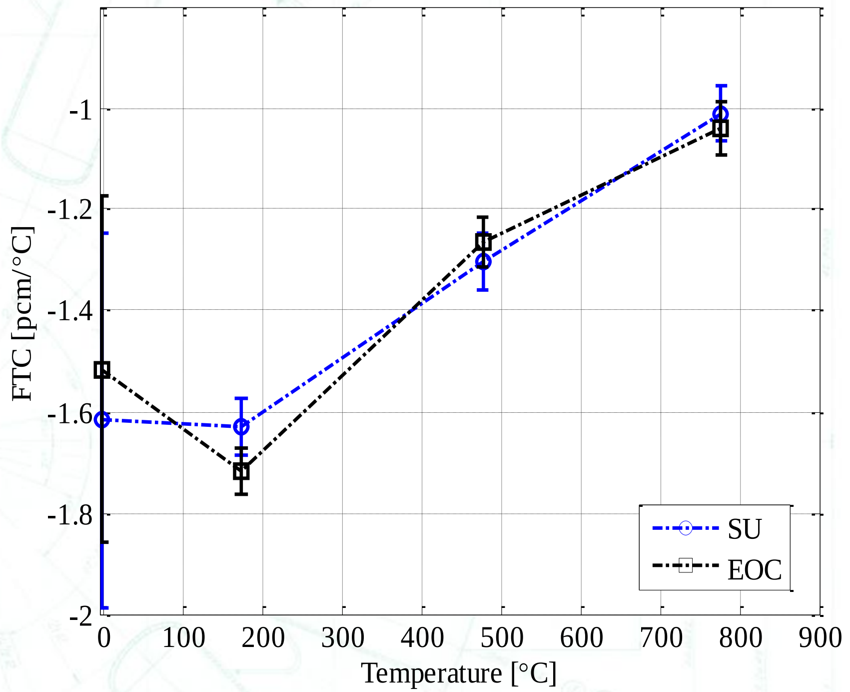
The MTC has negative effect and an slightly *increasing* trend with the temperature. The average MTC is about −6.7 for SU and −4.5 for EOC in the unit of pcm/°C.

Fuel Temperature Coefficient (FTC)

- The FTC accounts for the reactivity change due to the fuel heat up or cool down.
- The primary physics that dominates FTC is the Doppler broadening of the resonance peaks of the U-238 in the fuel.
- The FTC would have negligible effect on high enriched uranium (HEU) fuel as weight percentage of U-238 in HEU is very small, but the large amount of U-238 in the LEU core may result in a significant FTC effect.
- FTC is a significant factor that contributes to the *power defect* of reactivity, which is defined to be the change in reactivity taking place between hot zero power (HZP) and hot full power (HFP).

FTC Calculation and Results

- The FTC is calculated by perturbing the fuel temperature and Doppler-broadened cross-section to determine the reactivity changes in the perturbed cases.
- With the available data in MCNP6, a set of ENDF-B7.1 libraries generated for 250 K (.86c), 293.75 K (.80c), 600 K (.81c), 900 K (82.c), and 1200 K (.83c) are used for the perturbation.
- The TMP card for fuel is modified accordingly whereas the thermal expansion is neglected.
- The k_{eff} is calculated and the corresponding FTC is determined by dividing the reactivity change to the temperature difference.



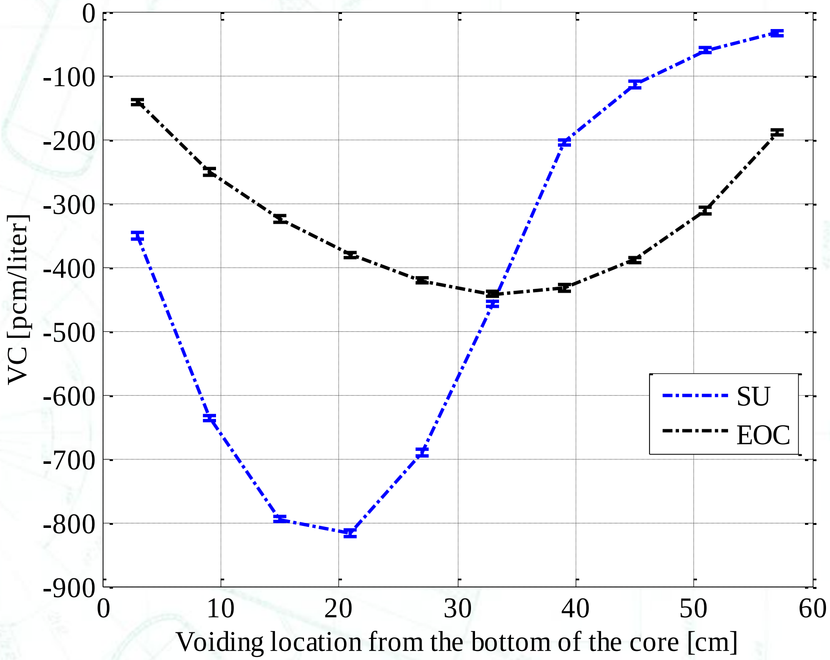
The FTC has a very slight negative effect and an insignificant *decreasing* trend with the temperature. The average FTC is about -1.27 for SU and -1.26 for EOC in the unit of pcm/°C.

Void Coefficient (VC)

- The VC accounts for the reactivity change due to voiding in coolant, moderator, or reflector.
- Voiding could take place in the coolant channel, for example, through boiling because of flow blockage, or in the heavy water reflector tank through leakage.
- A negative void coefficient is definitely needed to ensure negative feedback to the power level.
- The void reactivity coefficient generally has spatial dependence due to the fact that neutrons in different areas of the core exhibit different importance to the criticality.

VC Calculation and Results

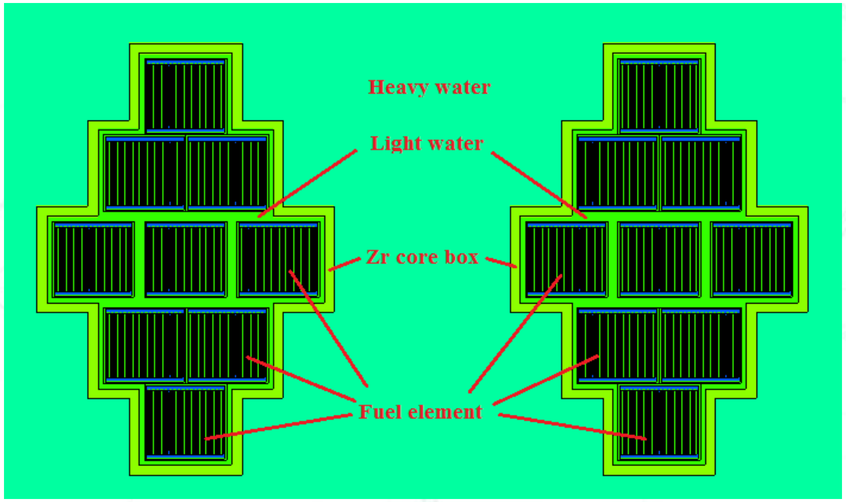
- Perturbed cases are generated with voids created at different axial zoning of the coolant channels examine the spatial characteristic of the coolant void coefficient.
- The reactivity change is calculated for each voided case, and the corresponding VC is determined by dividing the reactivity change by the volume of void.
- The VC at any axial voiding zone shows a negative effect on the reactivity, and has a magnitude of few hundred pcm per liter of coolant volume for both SU and EOC.



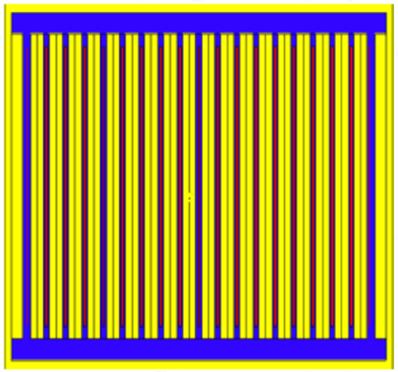
The axial dependence of the VC has demonstrated appreciable difference from SU to EOC due to the neutron importance variations.

Global Negative Reactivity Effects

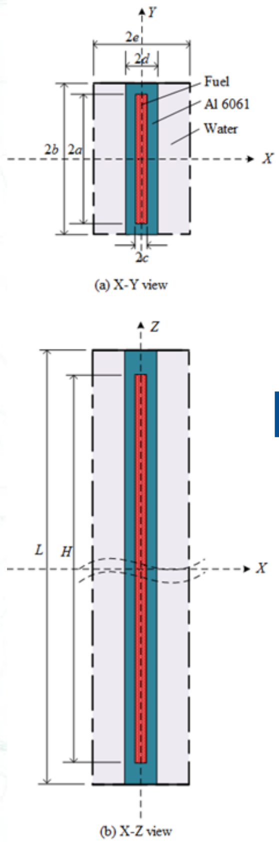
	Core Status	SU	EOC
Case	Case Description	Δρ (pcm)	Δρ (pcm)
1	Moderator Density Changed	-309	-267
2	Moderator S(α, β) Changed	-43	-92
3	Combine 1 & 2 Effects	-352	-359
4	Fuel Temperature Changed	-391	-379
5	Water between FEs Voided	-3841	-2478
6	Water within FEs Voided	-32904	-27013
7	Heavy Water Tank Voided	-36306	-35112



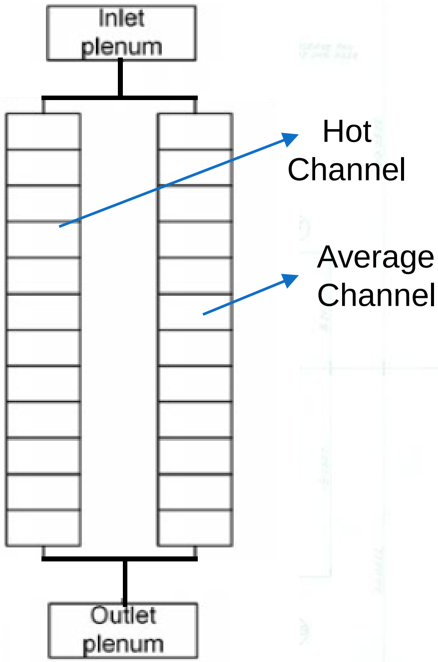
Transient Safety Analysis Code and Modeling



Fuel Element



Single-Channel Model



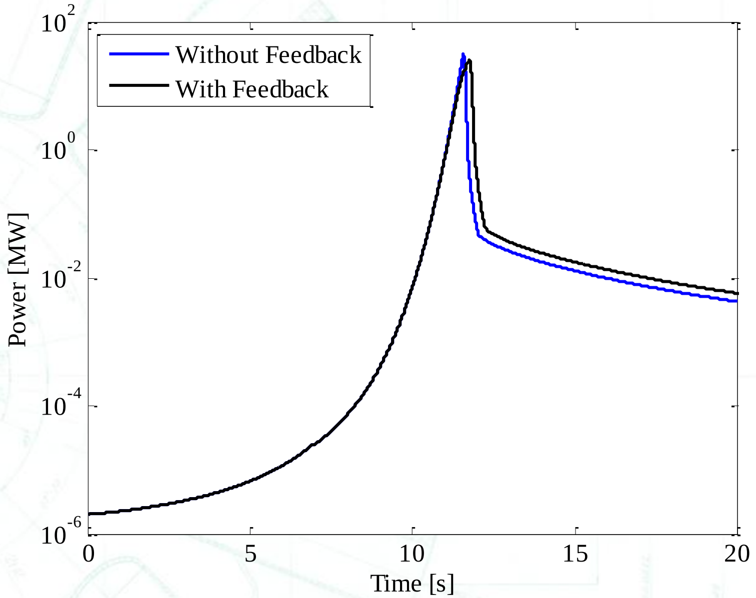
PARET-ANL Two- Channel Model

The PARET-ANL code is appropriate for safety analysis of research and test reactors that use plate-type fuel elements or round fuel pins.

Slow Reactivity Insertion Accident Analyses

Hypothetical Conditions:

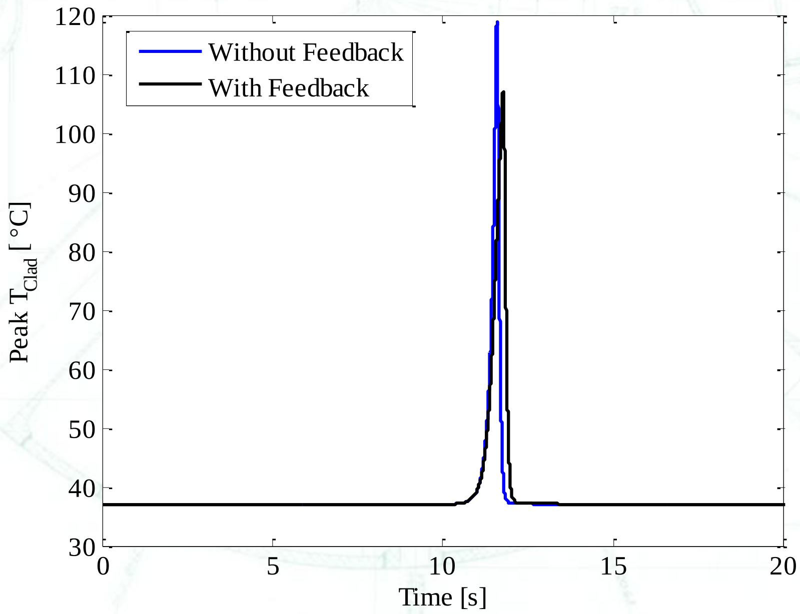
- The reactor is initially critical and operated at an power of 2 Watts
- Reactivity insertion at a slow ramp rate $0.1/s to mimic the slow reactor start-up procedure
- The reactor scram occurs at 120% full power (24 MW)
- Time delay constant is 25 ms before control rods are fully inserted
- Control rod constant move rate 1.2 m/s for the scram
- The reactor period trip is neglected.



The power response during slow start-up transient.

Slow Reactivity Insertion Accident (continued)

Cases	No Feedback	w/ Feedback
Peak Power [MW] (Time [s])	31.0 (11.6)	25.2 (11.7)
Power Trip Time [s]	11.51	11.7
Peak Clad Temp. [°C] (Time [s])	118.7 (11.6)	106.9 (11.8)
Max. Coolant Temp. [°C] (Time [s])	63.5 (11.6)	59.73 (11.8)
MCHFR (Mirshak DNB) (Time [s])	2.2 (11.6)	2.6 (11.8)



Summary

- Core design studies are underway at NIST to develop a low-power LEU fueled beam reactor to advance the neutron source capability at NCNR for the next century.
- The reactivity effect caused by moderator temperature, fuel temperature and void is investigated though a direct perturbation approach using the MCNP code.
- The MTC, FTC, and VC for the SU and EOC core is obtained and the negative effect characteristics of these coefficients are observed.
- The global negative feedback to the reactivity at each situation is confirmed.
- The reactivity feedback effects are demonstrated in postulated reactivity insertion accidents under 'best-estimate' safety analysis category.

Thank you!