Safety Assessment of Reactivity Insertion Accidents for a Conceptual Upward-Flow Research Reactor

Donghyun Kim*, Suki Park
Korea Atomic Energy Research Institute,111, Daedeok-Daero 989 Beon-Gil, Yuseong-Gu, Daejeon, 34057, Korea
**Corresponding author: dhkim1113@kaeri.re.kr*

***Keywords :** research reactor, reactivity insertion accident, safety analysis

1. Introduction

High-power open-pool research reactors typically employ an upward forced flow during normal operation. This core cooling configuration satisfies the net positive suction head (NPSH) requirements of primary cooling pumps and facilitates natural circulation for decay heat removal upon a loss of forced flow. In the conceptual design stage of an upward-flow research reactor, verifying core cooling capability and thermal margins under anticipated operational occurrences and design basis accidents is essential[1].

Among these, reactivity insertion accidents (RIAs)−postulated to occur by inadvertent control rod withdrawal or effects of experiments and experimental devices−can cause a prompt increase in reactor power. The rapid power excursion may lead to excessive core thermal loads and critical heat flux (CHF) violation, potentially challenging the fuel cladding integrity.

This paper presents preliminary numerical analyses of reactivity insertion accidents for a 20 MW conceptual open-pool research reactor with an upward core flow using the RELAP5/MOD3.3 code[2]. Transient thermal-hydraulic responses and safety margins are investigated to support the safety assessment and establish design criteria for the reactor protection system.

2. System modelling and initial conditions

2.1 RELAP5 modelling

The overall reactor system consists of the reactor structure assembly (RSA), open reactor pool, the primary cooling system (PCS), and the secondary cooling system (SCS). The primary coolant flows into the inlet plenum beneath the core, passes upward through the fuel assemblies, and enters the chimney to return to the PCS.

Figure 1 illustrates the RELAP5/MOD3.3 nodalization scheme developed for this system. The primary loop includes the primary cooling pumps, heat exchangers, decay tank, flap valves, and check valves. The reactor core is discretized into three parallel hydraulic channels: a hot channel (210) incorporating peaking factors, an average channel (220) representing the core average power, and a bypass gap channel (230). Point kinetics with reactivity feedback models (fuel doppler and moderator temperature/density coefficients) is coupled to simulate core power dynamics during reactivity transients.

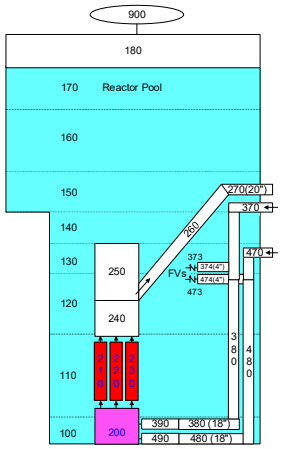


Fig. 1. RELAP5 Nodalization Diagram.

2.2 Initial and transient conditions

The initial steady-state parameters summarized in Table I conservatively include design uncertainties. The reactor trip is set to actuate at 130% FP with an appropriate scram delay time.

For the transient simulation, step reactivity insertions are applied to evaluate the core thermal response. Parametric analyses are performed by varying the inserted reactivity and feedback conditions using conservative minimum coefficients (Fuel Temperature Coefficient (FTC) = -0.01 mk/K, Coolant Temperature Coefficient (CTC) = -0.1 mk/K) to evaluate their impacts on safety margins.

Table I: Initial conditions

Parameter	Values
Reactor power	21.2 MW
Flow rate	582 kg/s
Core inlet temperature	36 ℃
Pool water level	11.8 m

3. Analysis results

Parametric sensitivity analyses were conducted under various step insertion magnitudes and feedback conditions. Figure 2 shows the transient core power for a representative step insertion of 2.0 mk with three feedback cases. Due to the prompt positive reactivity insertion, reactor trip initiation occurs almost identically across all cases. However, during the scram delay time, negative reactivity feedbacks suppress the power excursion, leading to the lowest peak power in the case with both FTC and CTC and the highest without feedback, which directly affects the core thermal margin.

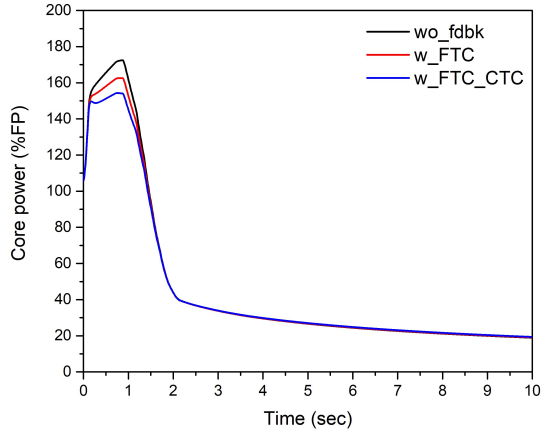


Fig. 2. Transient core power for a 2.0 mk step reactivity insertion.

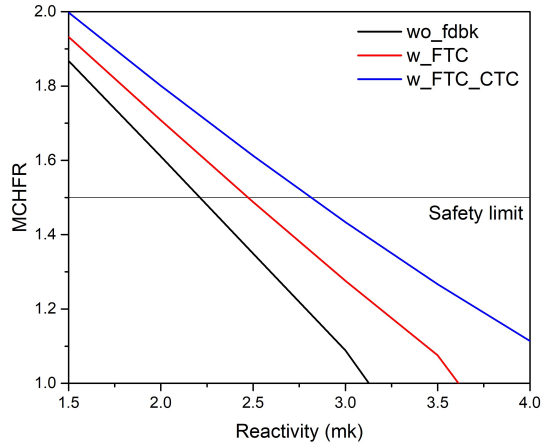


Fig. 3. Minimum CHFR as a function of inserted step reactivity.

Critical heat flux ratio (CHFR) is essential to evaluate core thermal margins during reactivity insertion accidents. Figure 3 shows the minimum CHFR (MCHFR) as a function of the inserted step reactivity for the three feedback cases, along with the safety limit criteria of MCHFR = 1.5[3]. As the inserted reactivity increases, the MCHFR decreases almost linearly across all cases. The threshold reactivity satisfying the safety limit is approximately 2.2 mk for the case without feedback, 2.5 mk with minimum FTC, and 2.8 mk with both FTC and CTC. These results demonstrate that the negative reactivity feedbacks significantly expand the allowable step reactivity margin while maintaining fuel integrity.

4. Conclusions

Safety assessments of reactivity insertion accidents for a conceptual 20 MW upward-flow research reactor were performed using RELAP5/MOD3.3. Based on the current conceptual design and conservative assumptions, the allowable step reactivity limit to satisfy the safety criterion (MCHFR > 1.5) was determined to be approximately 2.0 to 3.0 mk depending on the reactivity feedback conditions. This reactivity limit defines the maximum allowable reactivity worth of irradiation targets that can be loaded during reactor operation. The thermal margin can be further enhanced by reducing the scram delay time of the reactor protection system, whereas increases in the power peaking factors and instrument decalibration factors would decrease the margin. These results provide fundamental design bases for establishing the core protection system setpoints and operational limits for irradiation facilities in the conceptual design.

ACKNOWELGEMENTS

This work was supported by the Ministry of Science and ICT (MSIT) of the Republic of Korea (Grant No. RS-2025-02313658).

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