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Implementation of Reactor Regulating System in Safety Analysis of Research Reactor

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ABSTRACT

A reactor regulating system (RRS) is implemented in the safety analysis of research reactor to simulate the realistic reactor behavior during accidents. The RRS controller is integrated into the RELAP5/MOD3.3 input file based on the algorithm of RRSSIM (RRS SIMulator), which is the RRS simulator program excluding thermal hydraulic systems. Since the RELAP5/MOD3.3 modeling includes the reactor core, primary cooling systems and RRS, it enables a simulation of reactivity induced events coupled with thermal hydraulics including the reactor power control by the RRS. The implementation of RRS is validated by comparing the reactor power behavior under various reactivity insertions with those calculated by RRSSIM. A cold water-induced reactivity insertion event by an abrupt pump operation is then analyzed for a 5-MW pool type research reactor, to demonstrate the effect of RRS on safety analyses.

1. Introduction
1.1. Objectives

For conservative safety analysis, reactor regulating system (RRS) has not been considered because it usually mitigates the consequences of accidents. However, more realistic approach is helpful when establishing emergency operation procedures or a probabilistic safety assessment. Although RRSSIM (RRS Simulator) is developed to simulate the performance of RRS and to educate reactor operators [1], it is not adequate for safety analyses because it has no capability to model thermal hydraulic systems.
In this study, the RRS is implemented into the RELAP5/MOD3.3 using the control variable inputs and the power control capability is validated in various reactivity insertion cases by comparing the RRSSIM. Then, a reactivity insertion event is analyzed with and without the RRS modeling and the results are discussed.

1.2. Reactor Regulating System

The RRS controls the reactor power with four control absorber rods (CARs) to regulate neutron power within a predetermined level in the range of 10^{-8}%Full Power (FP) to 100%FP. In an auto control mode, the RRS receives the current power signals from the neutron monitoring system (NMS) and compares the power with the power demand (PDM) set by an operator. The RRS transfers signals to control rod drive mechanism (CRDM) via internal control logic to move up and down the CARs every execution cycle (200ms), then the reactor power reaches the power demand.

RRSSIM is a simulation package with the same control algorithm as RRS, which is developed to optimize the RRS. To simulate the kinetic and dynamic behaviors of reactor, the point kinetics and lumped thermal hydraulic model on the reactor core are implemented into the RRSSIM.

2. Implementation of RRS into RELAP5 Input

To consider the RRS in safety analyses, the control logic of RRS is implemented in the RELAP5/MOD3.3 using control variable inputs.

Figure 1 shows the feedback power control algorithm of RRS. The RRS first builds the error structure composed of the PDM to power ratio and the power log rate terms as below.

$$\text{ERROR} = \langle (G1) Log(\frac{PDM}{N}) \rangle_{[-1,1]} - (G2)\frac{1}{N}\frac{dN}{dt}, \tag{1}$$

where G1 and G2 are the controller gains regarding characteristics of RRS. The first term, the ratio of PDM to the neutron power N, is for a proportional control according to the difference between PDM and the current power. Depending on the power level, the RRS takes either linear or log power signal from NMS. The logarithm of this ratio is zero at the steady state (PDM=N). The second term which is the power log rate is added to limit a fast power change during the control. Even though the current power is smaller than the PDM, the ERROR can be zero depending on the power log rate. Therefore, the error balances the power and power log rate to limit the CAR movements during power transients.

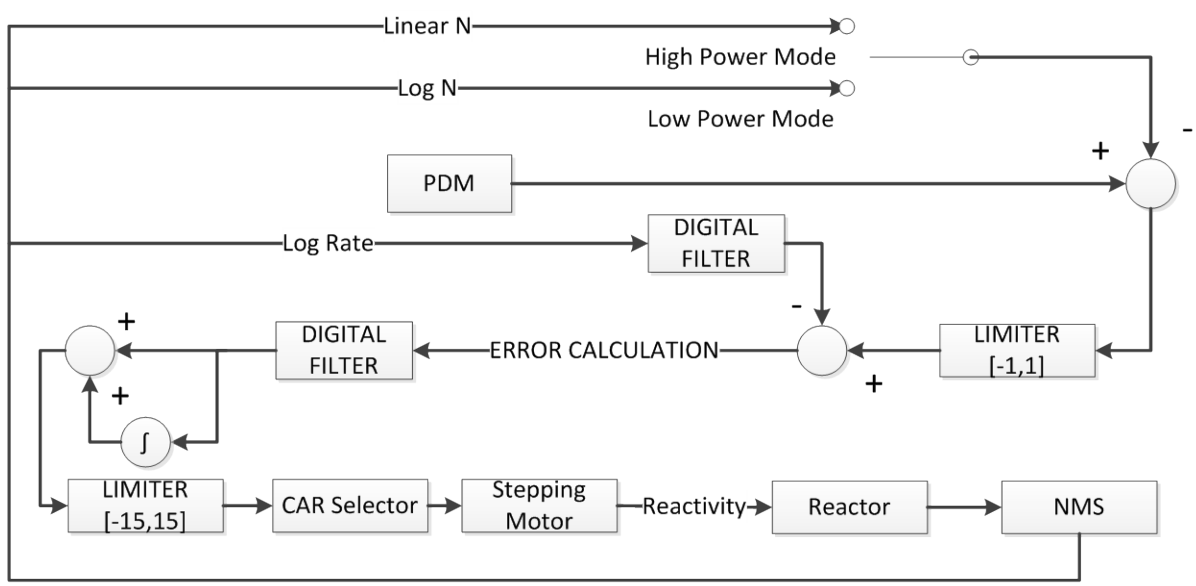


Figure 1 Reactor power control algorithm

The power log rate passes through a z-transform filter before combining with the left term of equation (1). The filter is reproduced by an equivalent Laplace transform provided as a control variable in RELAP5/MOD3.3 input.
Calculated error then passes another z-transform filter once again which is also replaced by an equivalent Laplace transform. After a gain is multiplied to the error, a small portion of the error is integrated and added to the error to accelerate the control speed. The step number per cycle corresponding to the final error is transferred to the step motor controller, which is limited between -15 and 15. Then, the output is rounded to be digitalized into 4-bit integer and transferred through four independent hard wires. Once the step number is finalized, RRS selects one CAR of which the height is the lowest in increasing the power and the highest in decreasing the power. And then only the selected CAR moves up or down in a cycle of 200ms. In the RELAP5/MOD3.3 modeling of the RRS, however, the four CARs are assumed to move simultaneously with 25% of the output. Then the reactivity insertion by CAR movement is calculated from the relation between the CARs position and the worth.

3. Comparison of the RELAP5/MOD3.3 Modeling on the RRS with RRSSIM

3.1. Conditions of Comparison

A series of investigations are performed to check whether the RRS is properly implemented in the RELAP5/MOD3.3 using the control variable inputs. Two kinds of reactivity insertions shown in Figure 2 are considered in a 5-MW open pool-type research reactor.
In the case of ramp insertions, four different reactivity insertion rates such as 1mk/10sec., 1mk/15sec., 1mk/20sec. and 1mk/30sec. are considered. On the other hand, in the case of step insertions, three different amounts of positive reactivity are inserted in the same insertion time, 0.1seconds.
It is assumed that the reactor is operating at the steady-state of 100%FP where the critical position of the CARs is 600mm from the bottom of core. To minimize the effect of other parameters, the feedbacks of coolant and fuel temperature are not used for this comparison.

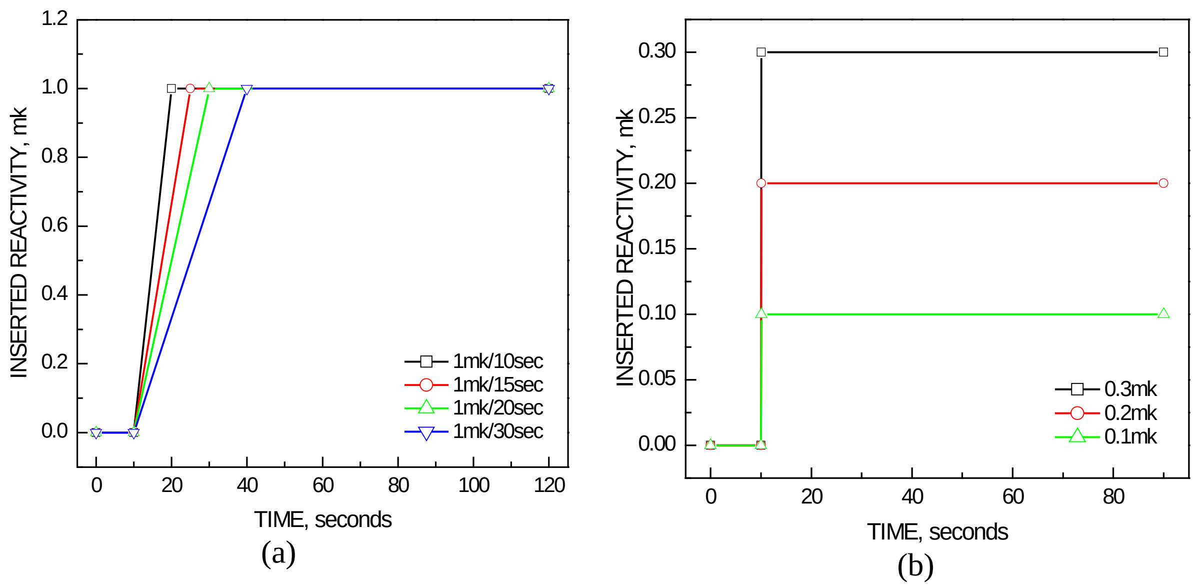
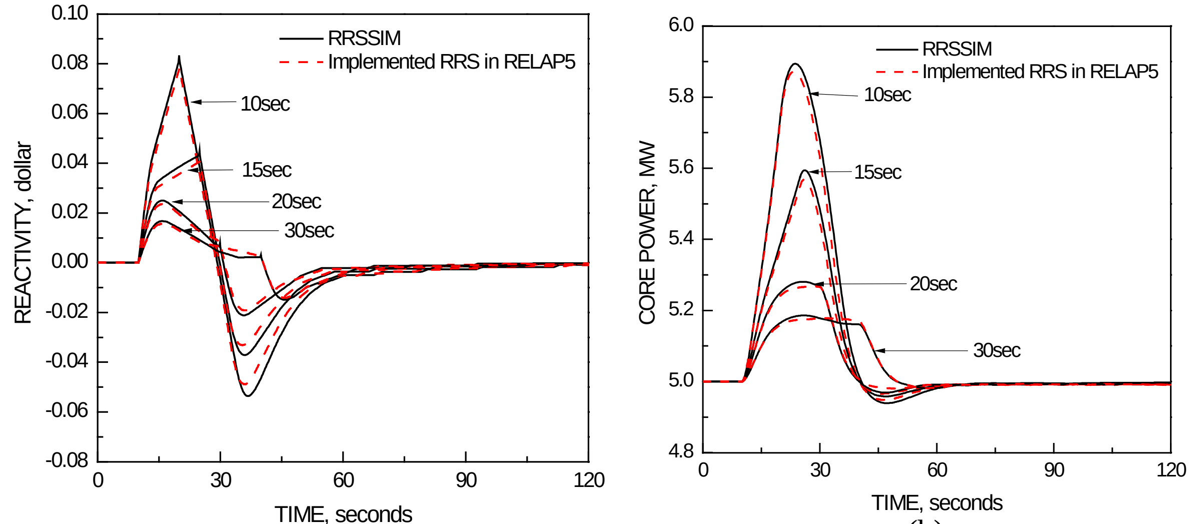


Figure 2 Reactivity insertion rates for ramp insertion (a) and step insertion (b)

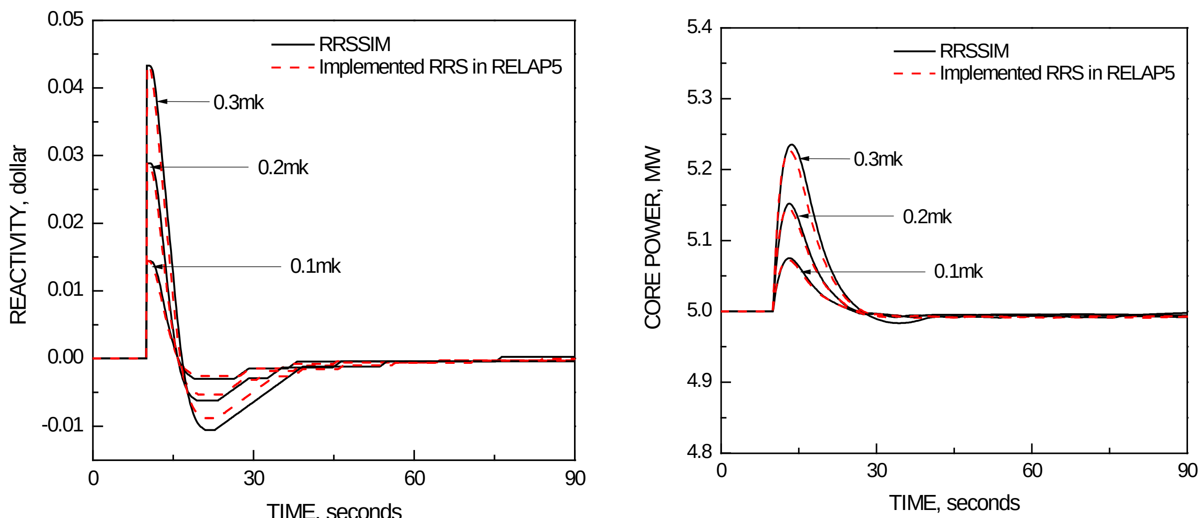
3.2. Discussion of Comparison

Figure 3 and Figure 4 show the comparisons of reactivity and power in the cases with the ramp insertions and step insertions, respectively. The inserted reactivity and the power profiles matches well each other, with the maximum power difference of 2.7% in the case of ramp insertion of 1mk/10sec. and with the maximum difference of 1% in the case of step insertion of 0.3mk. The differences between the results are mainly originated by the deviations between the z-transform and the Laplace transform in the modeling. Since the power change is steeper in the cases of faster and larger reactivity insertion, the largest deviation is shown in the cases of 1mk ramp insertion in 10seconds and 0.3mk step insertion. Overall, the control logic of RRS is confirmed to be implemented successfully in the RELAP5/MOD3.3.



(a) (b)

Figure 3 Comparisons of reactivity and power in the ramp insertions of reactivity (Reactivity (a), Core power (b))



(a) (b)

Figure 4 Comparisons of reactivity and power in the ramp insertions of reactivity (Reactivity (a), Core power (b))

4. Safety Analysis with Implemented RRS

4.1. Cold Water-Induced Reactivity Insertion Event

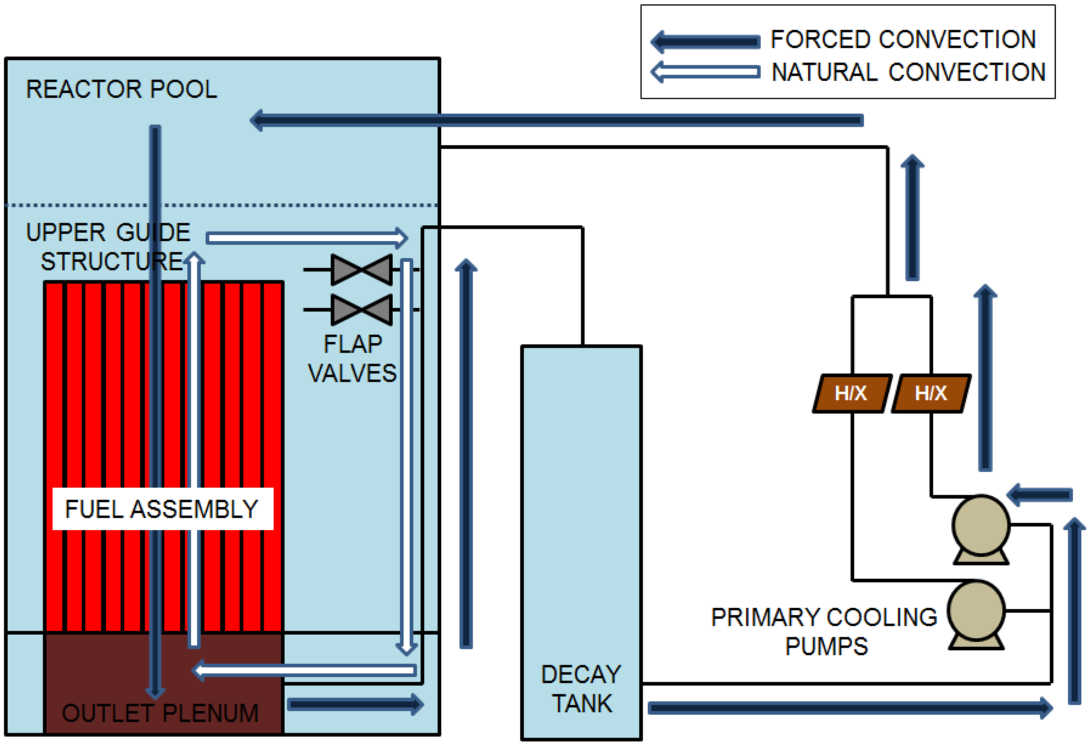


Figure 5 Schematic diagram of forced convection and natural convection mode

A cold water-induced reactivity insertion event is demonstrated including the reactor power control by the RRS during the event. An insertion of cold water causes reactivity feedbacks of coolant and fuel temperature when the primary cooling pump starts suddenly during the natural convection mode [2]. Figure 5 shows the schematics of two different cooling modes at the reactor; the natural convection mode and the forced convection mode by primary cooling pumps. During the natural convection mode, the temperature at the upper guide structure is higher than that of reactor pool since the hot water flows up by natural circulation. When a primary cooling pump starts to operate suddenly in a critical state, the hot water at the upper guide structure enters the core first and the relatively cold pool water enters soon after a few seconds. Then the reactor power increases by the reactivity feedbacks of coolant and fuel temperature. The insertion of cold water is the most complicated event among Reactivity Induced Accidents (RIAs) since the thermal hydraulic variables and the reactor kinetic variables are coupled and change together during the event. Therefore, the insertion of cold water event is calculated to investigate the effect of the RRS on the event.

4.2. Results of Analyses

Figure 6 shows the reactivity, CAR height and core power during the transient, respectively. Right after the event initiation, as the hot water enters the reactor core due to the abrupt start of primary cooling pump, negative reactivity by temperature feedback is inserted and then the CARs are withdrawn to compensate the negative reactivity. After a few seconds, cold water in the pool enters the reactor core.

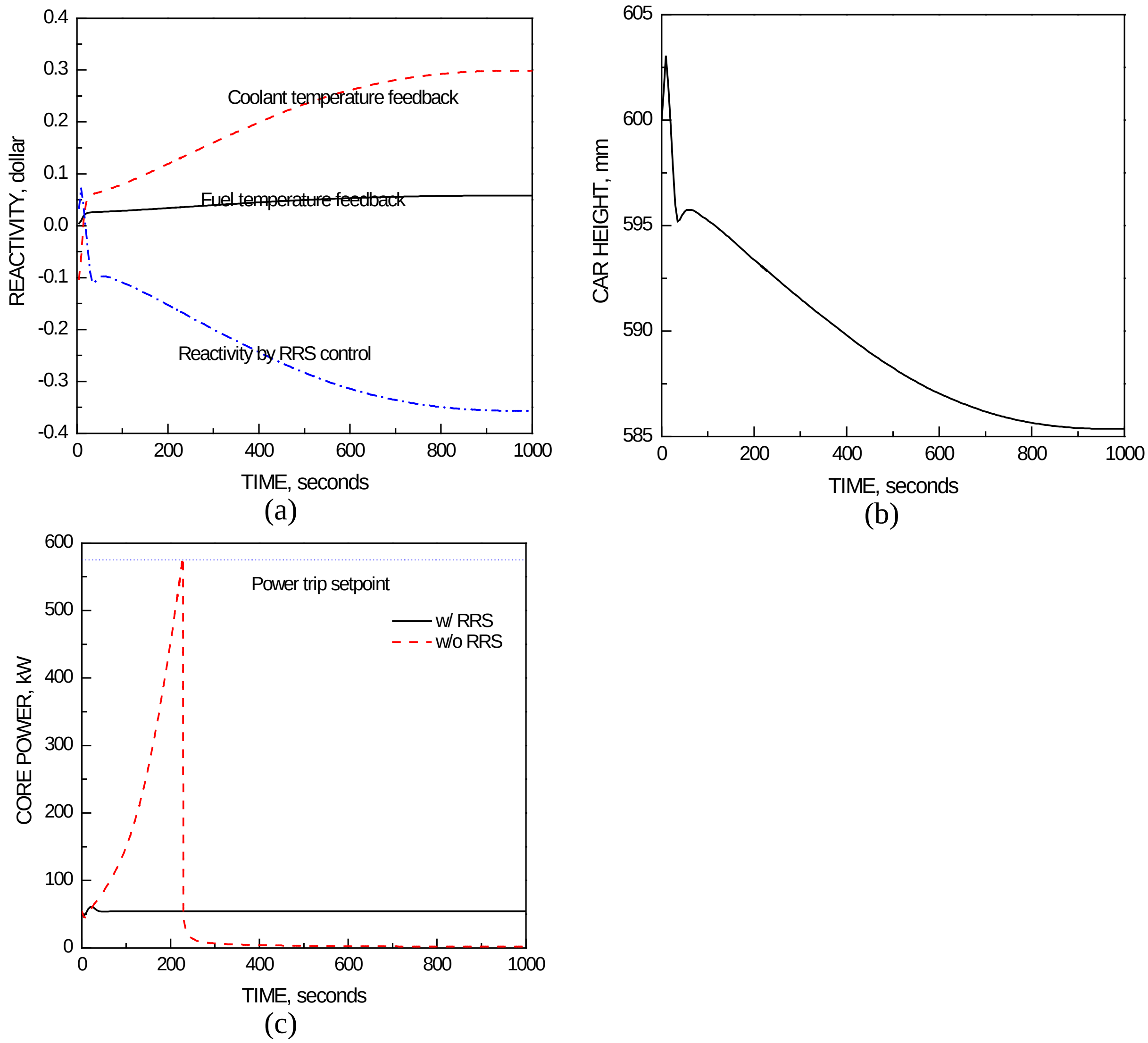


Figure 6 Results of cold water insertion accident with respect to RRS action

((a): Reactivity, (b): CAR height, (c): Core power)

Accordingly, positive reactivity by temperature feedback is inserted due to the cold water and the CARs are inserted to compensate the positive reactivity.

Therefore, the core power is controlled back to an initial value in the natural circulation mode. On the other hand, the core power increases and reaches the trip setpoint when the RRS is not considered in the analysis (Figure 6-(c)). The results show that the reactor response is completely different depending on the actuation of RRS. The results are helpful when establishing an emergency operation procedures or a probabilistic safety assessment, which consider all possible counteraction of reactor systems regardless of their safety category.

5. Conclusion

In this study, a reactor regulating system (RRS) is implemented in the safety analysis of research reactor to simulate the realistic reactor behavior during accidents. The implemented RRS in

RELAP5 is validated with comparing the results from RRSSIM for both ramp and step insertion of positive reactivity. In addition, the implementation of RRS in safety analysis was demonstrated with a cold water insertion accident. The implementation of RRS into RELAP5/MOD3.3 input shows that the methodologies of safety analyses can be expanded beyond the deterministic approaches, to the performance oriented one including complicated controls.

6. References

[1] H.I.Kim, S.K. Park, C.Park, "Simulation of Power Maneuvering Using Coupled Analysis of Kinetics and Thermal-Hydraulics in a Research Reactor", Proceedings of the International Group Operating Research Reactors 2014, Bariloche, Argentina, November, 17-21, 2014.

[2] S.B.Yum, S.K. Park, "Uncertainty Assessment for Reactivity Induced Accident of 5-MW Pool-Type Research Reactor," Proceedings of the European Research Reactor Conference 2015, Bucharest, Romania, April, 19-23, 2015.