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# Initial Core Start-up Model of the JRTR Simulator

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## 1. Introduction

KAERI has been developing the simulator for the JRTR (Jordan Research & Training Reactor) integrating the best-estimate code, MARS into the commercial simulator program, 3KeyMaster [1] for the purpose of operator training. The JRTR simulator was also used as a dynamic test bed (DTB) to validate the control logics in RRS (reactor regulating system) [2]. However, the initial condition of the simulator aims at the full-power operation and the equilibrium decay heat is assumed with the infinite operation time. Therefore, a start-up operation of the initial core cannot be simulated appropriately under this condition because a significant decay heat exists for a very long time even if the reactor is scrammed. A significant amount of the decay heat cannot be ignored and plays an important role during start-up operation of the fresh core. In order to eliminate the effect of the decay heat during a fresh core operation, an initial condition of zero-decay heat is required. For this purpose, we have made nearly zero-decay heat condition by using the point kinetics of the MARS code and applied it into the JRTR simulator environment.

## 2. Overview of the JRTR Simulator

### *2.1 Primary Cooling System (PCS)*

Overall system layout of the JRTR primary cooling system (PCS) model is described in the previous study [2] but the boundary volumes and junctions are modified compared with the previous model. Fig. 1 and 2 show the overall layout of the previous and current PCS model, respectively. In the figures below, the red symbols represent the break flow path and the blue ones are the interface time-dependent volumes and junctions between the MARS and 3KeyMaster.

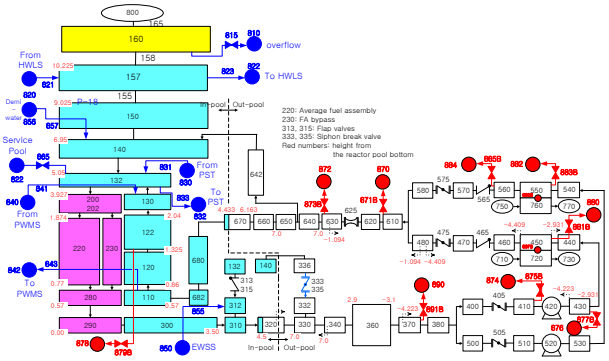


Fig. 1. Previous PCS model of the JRTR

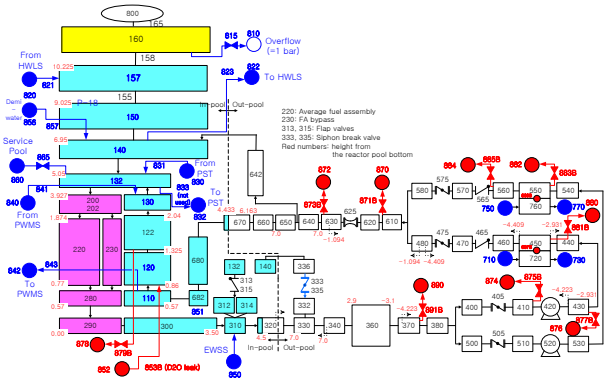


Fig. 2. Current PCS model of the JRTR

Most of the break boundaries are always treated as the atmosphere except for the internal leakage in the heat exchangers.

### *2.2 MARS-3KeyMaster Interface Functions*

The interface functions between the MARS and 3KeyMaster are required to simulate plant operation. Through the interface function, it is possible to transfer the variables to the other side. The general concept of variable interface between the MARS and 3KeyMaster is shown in Fig. 3.

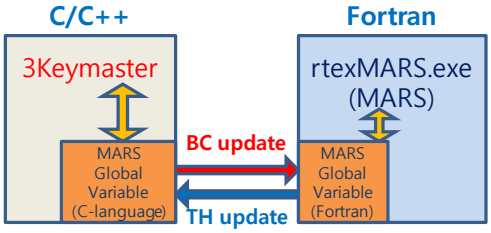


Fig. 3. Variable interface function

### *2.3 Point Kinetics Model*

We considered delayed neutron groups and neglected the photo-neutron groups of the JRTR because the point kinetics of MARS has six delayed neutron groups only. The effective delayed neutron fraction $\beta_{eff}$ is 0.00685.

The reactivity model of MARS is as follows:

$$r(t) = r_o - r_B + \sum_{i=1}^{Ns} r_{si}(t) + \sum_{i=1}^{Nc} r_{ci}(t) + r_{fb}(t) \qquad (1)$$

where,

$r(t)$ : total reactivity,

$r_o$ : User-specified initial reactivity,

$r_B$ : Bias reactivity,

$r_{si}(t)$ : User-specified tabular reactivity,

$r_{ci}(t)$ : User-specified control variable reactivity,

$r_{fb}(t)$ : Feedback reactivity,

$Ns$ : Number of $r_{si}(t)$,

$Nc$ : Number of $r_{ci}(t)$.

The bias reactivity $r_B$ is defined as follows:

$$r_B = \sum_{i=1}^{Ns} r_{si}(t_0) + \sum_{i=1}^{Nc} r_{ci}(t_0) + r_{fb}(t_0) \qquad (2)$$

where,

$t_0$ : First time that point kinetics input entered.

From Eq. (2), the bias reactivity is defined as the summation of all reactivity except for the user-specified initial reactivity at the initial time.

The initial reactivity is determined at the code initialization stage and does not change during the transient. The bias reactivity is also determined at the initialization stage but it can be modified in order to change the critical rod position. The others such as tabular, control variables and feedback reactivity change according to the change of rod worth, fluid and fuel temperature as the code calculation goes on.

Rod worth is the most important reactivity source because of its large reactivity. There are four CARs (control absorber rods) in the JRTR. Each CAR worth is simulated by a control variable reactivity ($r_{ci}$) in Eq. (1). Once the RRS control logics in 3KeyMaster determine each CAR position, MARS will calculate the each CAR worth by using a tabular relationship between position and worth as shown in Fig. 4. Currently, the critical rod position is assumed to be 430 mm from the bottom of the core. Every CAR worth is added by assuming the superposition principle. In the all rod-in (ARI) state, therefore, total CAR worth is about -50 $.

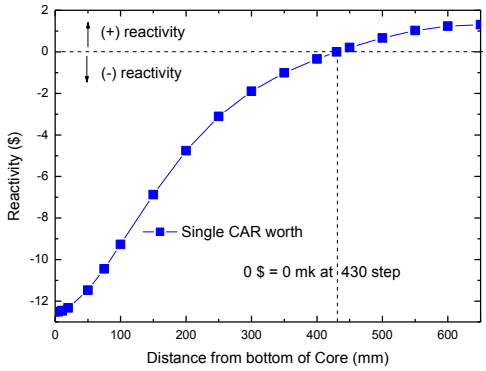


Fig. 4 Single CAR position vs. integral CAR worth

MARS also has a simple xenon poison model [2] but it is not used in our study.

## 3. Zero-Decay Heat Condition

To get the zero-decay heat condition by using the MARS code, two-step calculation is required. The first step is a steady-state calculation by neglecting the decay heat and feedback reactivity. The second step is a transient calculation considering both the decay heat and the feedback reactivity.

### *3.1 First Step: Steady-state without Decay Heat*

During a steady-state calculation, it is possible to neglect the decay heat by using 'no-gamma' option of the point kinetics model. In this case, all reactor power is generated by fission and the decay heat is not calculated. From the first step calculation, we can get the normal fluid and heat structure condition at the full-power operation. To ignore the feedback reactivity, zero-temperature coefficients are used for the moderator and heat structure. The first step is important in that the reference temperatures of fluid and heat structures, which will determine the feedback reactivity in the 2nd step calculation, are determined in this step. And then the feedback reactivity will not be changed during a next calculation because all feedback factors are stabilized at the full-power condition.

### *3.2 2nd Step: Reactor Scram with Decay Heat*

The second step is a restart calculation by using the restart-plot file from the first step calculation. In the JRTR simulator, however, the decay heat should be simulated, so that 'no-gamma' option is not available any longer. Therefore, in the 2nd stage, 'gamma' option is used to simulate the decay heat due to fission product. Because the initial decay heat should be zero, 'power history data' option is used, i.e., zero-reactor operation time is assumed. If 'power history data' option is not used, the maximum or equilibrium decay heat is assumed [3].

Feedback reactivity should also be considered appropriately in this stage. Therefore, all temperature feedback coefficients which were reset to zero in the first step are restored during the 2nd step calculation.

The most important thing in the 2nd step is that a reactor scram should be invoked at the beginning of the restart calculation. The fission product decay heat is proportional to the fission rate or power. If the reactor power maintains the full-power level, fission product decay heat would be increased drastically and reach a significant level in short time. This is why the reactor should be scrammed at the beginning of the restart calculation. Even if the reactor is scrammed immediately, the fission power does not decrease to zero but exponentially and a little of decay heat could be generated during that time. However, the amount of decay heat would be negligible if problem time is enough to ignore the decay heat.

## 4. Results

### *4.1 Two-step Calculation for Zero-Decay Heat*

The first step has been performed for 1000 seconds. The results of fluid temperature are shown in Fig. 5. The core inlet and outlet temperature slightly decrease but can be considered as almost steady-state. Fig. 6 shows the fission and FP decay power. As mentioned above, no feedback and decay heat are assumed in the first step, so that fission power is maintained at the full power level of 5 MW and decay power is zero.

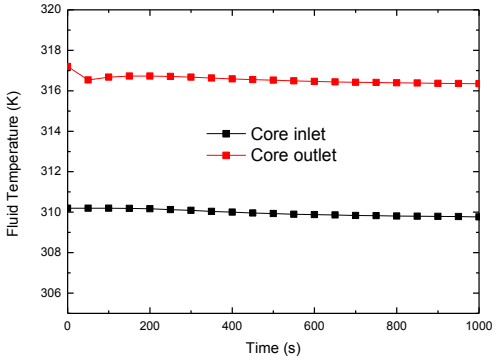


Fig. 5 Core inlet and outlet temperature in the first step

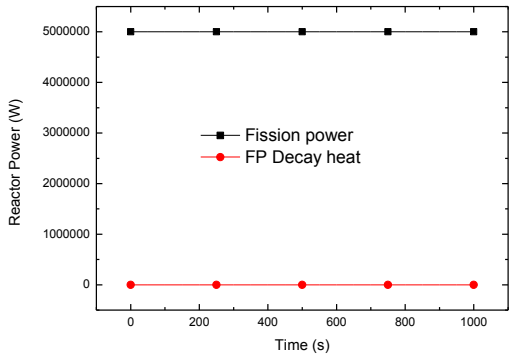


Fig. 6 Fission and decay power in the first step

The 2nd step calculation has been performed from 1,000 seconds to 10,000 seconds by using the restart-plot file from the first step run. In this step, all feedback reactivity and FP decay power were taken into account. In order to set initial FP decay heat to zero, 'power history data' option was also used with zero-operation time. The most important factor in the 2nd step is the reactor scram at the beginning of the transient as mentioned earlier. To simulate the reactor scram, the CARs were fully inserted into the core at the beginning of transient. And then, the CARs reactivity was inserted according to the reactivity function of the CAR position as shown in Fig. 4.

The log of fission and FP decay power in the 2nd step run is shown in Fig. 7. As soon as the CAR reactivity was inserted, the fission power decreased and reached the minimum power level of $5\times10^{-4}$ W after 2,200 seconds. This minimum power is introduced by modifying source of MARS to simulate the neutron source for the start-up operation of the fresh core. At the beginning of the 2nd step calculation, the FP decay power increased by 325 W due to a large fission rate but decreased continuously as the fission power decreased. Finally the FP decay power is less than 0.4 W ($10^{-5}$ % of the full-power) which is negligible enough to simulate the start-up operation.

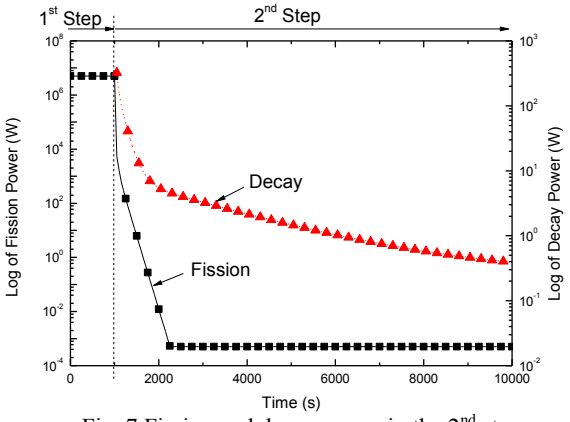


Fig. 7 Fission and decay power in the 2nd step

According to the text book [4], it takes $1\times10^{9}$ seconds for the FP decay power to decrease to $2\times10^{-2}$ % of the full-power assuming the infinite reactor operating time. Therefore, two-step calculation method suggested in this study is very effective way to simulate the start-up operation.

### *4.2 Start-up Simulation*

We used the JRTR simulator to simulate the start-up operation for the zero-decay heat condition. The initial condition for the simulation was determined by the final restart-plot file from the two-step calculation described in the previous section. The restart-plot file of the MARS code can be used directly as an initial condition (IC) file of the 3KeyMaster. The initial condition and assumptions used in simulation are as follows:

(1) Using IC based on the restart-plot file
(2) Withdrawing all CARs to critical position (=430 mm from bottom of the core) for the start-up operation
(3) All reactor control systems including RRS and RPS are not used.
(4) Xenon poison is not considered.
(5) Secondary cooling system (SCS) is under normal operation.
(6) 3 times faster than real-time

Once the CARs were moved to the critical position, net positive reactivity was inserted into the core by +0.008 $ due to the feedback from the moderator and the fuel and then, the fission power increased. The FP decay power decreased slowly at first but increased again when the fission power exceeded the decay power. Fig. 8 and 9 show the fission and decay power during start-up operation. The time format of the x-axis in the figure is hh:mm:ss and the unit of the y-axis is the watts. During start-up operation, the reactor power overshoots

the nominal reactor power (5 MW) due to a large initial reactivity but in actual operation, small overshoot like this can be overcome by the RRS control. The maximum reactor power reaches the value of 5.3 MW but, as the FP decay power continuously increases, the fission power decreases and becomes stable by the feedback reactivity (Fig. 10).

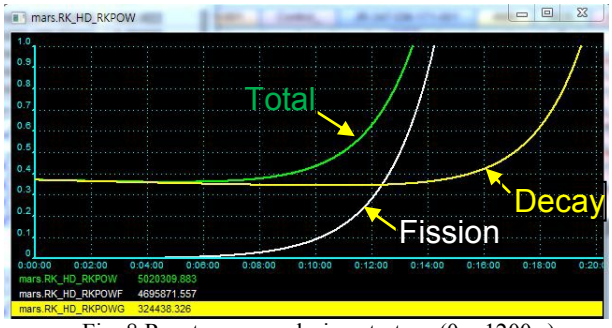


Fig. 8 Reactor power during start-up (0 ~ 1200 s)

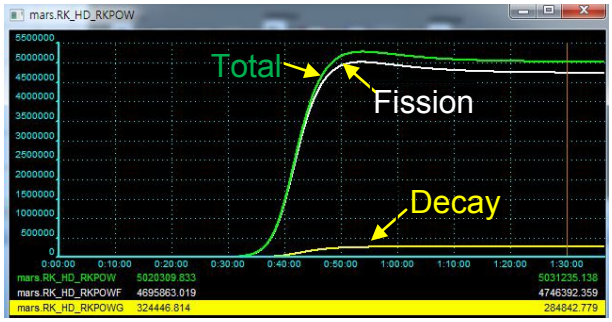


Fig. 9 Reactor power during start-up (0 ~ 5400 s)

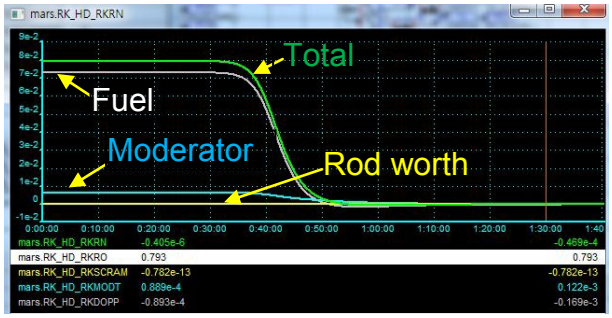


Fig. 10 Reactivity ($) during start-up (0 ~ 5400 s)

Fig. 11 shows the fluid temperature at the core inlet and outlet region. The temperature difference between two regions is almost zero due to extremely low reactor power at first but as the reactor power increases, the temperature difference increases and becomes stable. Comparing Fig. 11 with Fig. 5, the temperatures are almost restored to the value of the full-power operation.

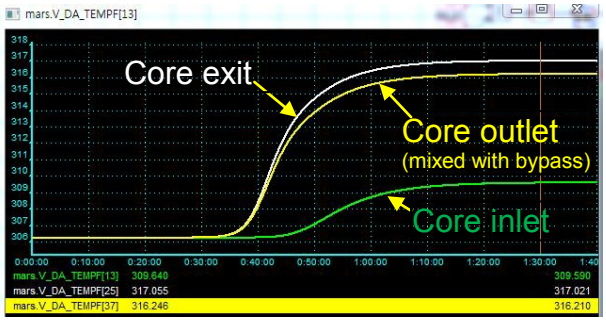


Fig. 11 Fluid temperature (K) during start-up (0 ~ 5400 s)

## 5. Conclusions

To simulate the start-up operation of the fresh core, nearly zero-decay heat condition has been generated with two-step calculation method by using the MARS code. This method is very effective way to simulate the start-up operation because the decay power which can affect the temperature of the coolant and fuel during the operation is at extremely low level. As for simulator application, this method has been successfully applied into the JRTR simulator. Moreover, this method will be applicable to not only the simulator but also general safety analysis for the initial core by using the MARS code.

## REFERENCES

[1] 3KEYMASTER Analyst and Developer Guide, Western Services Corporation, Sep. 2011.
[2] S. W. Lee, *et al*., "Development of the Dynamic Test Bed of JRTR Based on MARS", KNS Spring Meeting, Korean Nuclear Society, May 2013.
[3] MARS Code Manual Volume II: Input Requirements, KAERI/TR-2811/2004, KAERI, Dec. 2009.
[4] John R. Lamarsh, "Introduction to Nuclear Engineering", 2nd edition, Addison-Wesley Publishing Company, 1983.