Plant Application of SPACE-mTRAN Coupled Code System

Seung Wook Lee [a*], Hyo Chan Kim [a], Yong Sik Yang [a], Kyung-Doo Kim [a] and Jin-Hyuk Hong [b]
[a]*Korea Atomic Energy Research Institute, 111 Daedeok-Daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea*
[b]*Engineering Driven Technologies, 20 Daedeok-Daero 512 Beon-gil, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: nuclist@kaeri.re.kr*

1. Introduction

SPACE-FRAPTRAN coupled code system has been developed by KAERI (Korea Atomic Energy Research Institute) for a realistic safety analysis preserving the analyzing capability of each code [1]. FRAPTRAN used for coupling was simplified by removing the needless function such as a finite element module for detailed deformation analysis and the various functions for calculating the convective heat transfer coefficient (HTC). Such a modulized FRAPTRAN was named 'mTRAN', therefore, the coupled code system of SPACE and FRAPTRAN is also called as 'SPACE-mTRAN'. In addition, a capability for multiple-rod analysis has been implemented into the coupled code. Using this feature, multiple fuel rods can be simulated with single mTRAN DLL.

In the previous study [2], IFA-650.5 experiment, which is a kind of the separate effect test, was simulated to validate the basic performance of SPACE-mTRAN for the single rod only. In this study, a postulated large break loss of coolant accident (LBLOCA) of the APR1400 was simulated by using multiple-rod analysis function to investigate the effect of the fuel burn-up for the transient of a real plant.

2. Improvement of SPACE-mTRAN

There are two kinds of the improvements in the SPACE-mTRAN coupling scheme. One is the manual memory loading library (MMLL) method to enable a multiple-rod analysis with single DLL and the other is the heat structure and fluid deformation model to apply the effects of the rod deformation to the heat structure and fluid system of SPACE.

2.1 Manual Memory Loading Library (MMLL)

For the multiple-rod analysis, the MMLL method is applied to SPACE. As shown in Fig. 1, whenever the mTRAN DLL is called, SPACE searches the free memory space and allocates the different memory to the current DLL image. If the free memory space is not enough to allocate the memory for the remaining DLL images, an error message is generated and the process is also terminated. The size of memory allocation depends on the number of the coupled fuel rods, therefore, the free memory size is very important to determine how many rods will be coupled in a calculation. Such memory allocation procedure is not related with an operating system but performed by SPACE assigning the memory manually, so that this procedure is called as the manual memory loading library.

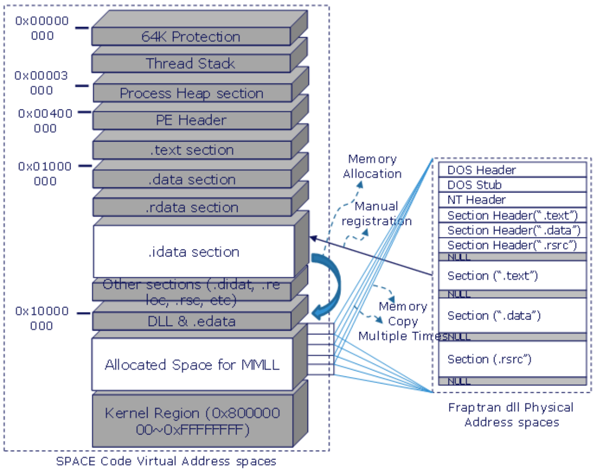

Fig. 1. Memory structure of MMLL scheme

2.2 Heat Structure & Fluid Deformation Model

The fuel cladding radius is changed every time as a result of the fuel deformation predicted by mTRAN and the geometric deformation of the adjacent hydraulic cell arises. To simulate such effects, heat structure and fluid deformation model based on rectangular coolant channel has been developed [3]. The assumptions used for the model are as follows:

(1) Rectangular coolant channel is assumed.
(2) Coolant channel is adjacent to no other heat structures than fuel rods.
(3) Deformation is symmetric circumferentially.
(4) Pitch of channel is not changed by deformation.

Using the assumptions above, the flow area change, ΔA and hydraulic diameter, D_h of coolant channel can be expressed as follows, respectively:

$$\Delta A = \sum_{k=1}^{N} \pi R_{k,0}^2 \left(1-\frac{R_k^2}{R_{k,0}^2}\right) N_k \cong \pi R_0^2 N_T \sum_{k=1}^{N} \left(1-\frac{R_k^2}{R_{k,0}^2}\right)\frac{N_k}{N_T} = A_{rod}^2 \sum_{k=1}^{N} \left(1-\frac{R_k^2}{R_{k,0}^2}\right) w_k \tag{1}$$

$$\frac{D_h}{D_{h,0}} = \left(1+\frac{\Delta A}{A_0}\right) \Big/ \left(\frac{1}{R_0 N_T}\sum_{k=1}^{N} R_k N_k\right) \cong \left(1+\frac{\Delta A}{A_0}\right) \Big/ \left(\sum_{k=1}^{N} \frac{R_k}{R_{k,0}} w_k\right) \tag{2}$$

where N is the number of heat structures adjacent to the same coolant channel, N_k is the number of fuel rods in the k-th heat structure, R is an outer cladding radius, $N_T = \sum_{k=1}^{N} N_k$, and $w_k = N_k/N_T$. Subscript 0 means that it is the initial value.

For the heat structures, similar correction for the deformation is applied to the surface area, S_k and heated diameter, $D_{ht,k}$ as follows:

$$S_k = S_{k,0}\frac{R_k}{R_{k,0}} \tag{3}$$

$$\frac{D_{ht,k}}{D_{ht,k,0}} = \left(1+\frac{\Delta A}{A_0}\right)/\frac{R_k}{R_{k,0}} \tag{4}$$

For complete implementation of the fluid deformation model, the term of the time-dependent porosity which can be calculated by Eq. (1) and its rate was added to the governing equations. If the fluid deformation model is activated without considering time-dependent porosity, the mass error of fluid system will become extremely large [4].

When the heat structure deformation model is not used, the ratio of deformed outer diameter to the initial outer diameter should be considered in the calculation of the wall heat flux to preserve the total transferred energy between SPACE and mTRAN.

3. Plant Application

For the plant application of SPACE-mTRAN coupled system, a postulated APR1400 LBLOCA was simulated by SPACE-mTRAN. The base input deck for APR1400 is almost same as the input deck used for licensing the methodology of the LBLOCA analysis developed by Korea Electric Power Corporation – Nuclear Fuel Company (KEPCO-NF) except for some modifications. Main differences from the original input are as follows:

- Heat structures which represent the average core (H130), hot assembly (H140) and hot rod (H141) are coupled with mTRAN using the MMLL.
- Number of axial nodes of the core is reduced to 20 from 40 in the original input considering the capability of mTRAN.
- Coolant channel (C141) and related crossflow faces for the hot rod are added.
- Heat structure and fluid deformation model is applied to the coupled heat structures and adjacent coolant channels, respectively.
- 2-D heat conduction model and reflood heat transfer option for those heat structures are neglected due to the absence of 2-D conduction model in mMRAN.

Average core was assumed to be in the fuel burn-up of 30 MWd/kgU but hot rod (HR) and hot assembly (HA) were assumed to be in four different burn up cases (0, 30, 45 and 57 MWd/kgU) according to the currently licensed methodology for LBLOCA analysis.

For mTRAN initialization, FRAPCON calculation was also performed and the result of fuel burnup versus effective full-power days (EFPD) is shown in Fig. 2.

Table 1 shows the fuel burn-up of each region in the simulation cases.

Table. 1 Summary of simulation cases

Case No.	Fuel Burnup (MWd/kgU)		
	Avg. Core (H130)	HA (H140)	HR (H141)
0	30	0	0
1	30	30	30
2	30	45	45
3	30	57	57

Steady-state runs for all cases were performed for 200 seconds coupled with mTRAN before the transient calculation. Then, restart calculation for the transient run was performed using the restart file of SPACE. However, mTRAN has no restart capability, so that all variables of mTRAN was initialized with input value at the starting time of transient run. Therefore, null-transient runs were required for 100 seconds in all cases to stabilize the mTRAN calculation before the initiation of the LBLOCA.

Fig. 3 shows the axial temperature distribution of the cladding surface and fuel center in the HR during the steady-state. Whereas the cladding surface temperatures are almost same as each other due to the similar convective HTCs and coolant temperatures, the fuel center temperatures are quite different because of both different gap conductance and thermal conductivity degradation of pellet as function of fuel burnup.

Fig. 4 shows the cladding temperature of the 15th node of the HR (H141), where the fuel temperature is highest, during the steady-state. After the initiation of the LBLOCA at 100 seconds, the blowdown peak cladding temperature (PCT), blowdown quenching and reflood PCT occur successively. The highest blowdown PCT (1370 K) and reflood PCT (1430 K) occur in Case-3 where the initial stored energy is largest due to the highest fuel temperature.

Fig. 5 shows the equivalent cladding reacted (ECR) of the 15th node of the HR predicted by mTRAN in all cases. The ECR of the highest burnup case (Case-3) predicts the highest value (8.5%) but the difference between steady-state value and transient value is largest (1.7%) in Case-1 due to the combined effect of initial oxide thickness, the PCT and thinning clad induced by ballooning.

Fig. 6 and 7 show the outer radius and surface area, respectively, of the clad at the 15th node of the HR. As the clad surface expands due to ballooning, both the outer radius and the surface area increase. The largest deformation is predicted in Case-1 where the clad rupture occurs at the 15th node unlike the other cases.

Fig. 8 and 9 show the porosity and hydraulic diameter of the cell adjacent to the 15th node of the hot assembly (H140) in all cases. As the clad balloons, flow area is reduced and wetted perimeter of the channel is increased, therefore, both cell porosity and hydraulic diameter are reduced. The variation of Case-1 is smallest because no cladding rupture of the HA occur in that case.

From the results above, it is found that heat structure and fluid deformation models of SPACE have been implemented as intended. Major results of simulation are summarized in Table 2.

Table. 2 Summary of simulation results

Case	PCT (K)	Rupture node (time)	
		Hot Rod	Hot Assembly
0	1360	18 (116 s)	15 (164 s)
1	1350	15 (106.5 s)	No rupture
2	1380	16 (106 s)	15 (167 s)
3	1430	16 (106 s)	15 (139 s)

4. Conclusions

For more realistic plant simulation such as a LOCA, SPACE-mTRAN coupled code has been upgraded by implementing the MMLL for multiple-rod analysis and developing the heat structure & fluid deformation model for SPACE. The MMLL is an essential function to simulate a lot of the fuel rods with different fuel burnup. In addition, deformation of fluid as well as fuel should be simulated to consider the wall heat transfer and flow resistance correctly when the fuel surface area and flow blockage increases due to the ballooning or rupture. From the results of steady-state simulation, it was found that the fuel burnup effects were simulated well quantitatively using the multiple-rod analysis with the MMLL. It was also found that heat structure and fluid deformation model for SPACE worked correctly as intended.

ACKNOWLEDGEMENT

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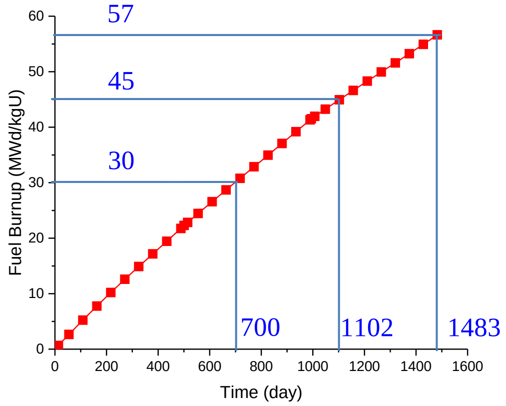

Fig. 2 Fuel burnup vs. EFPD

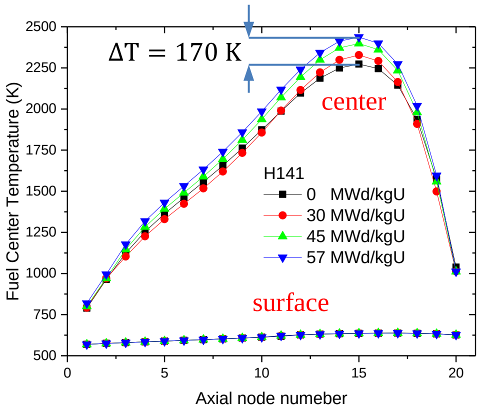

Fig. 3 Axial temperature distribution during steady-state

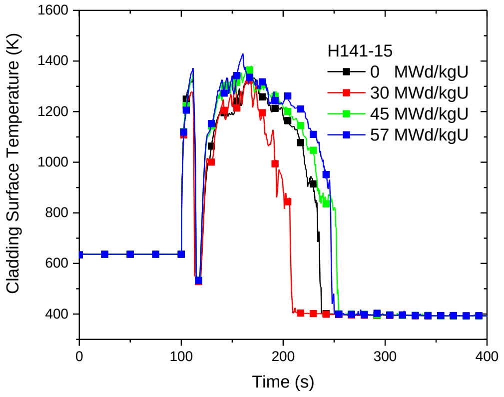

Fig. 4. PCT at the 15th node during LBLOCA

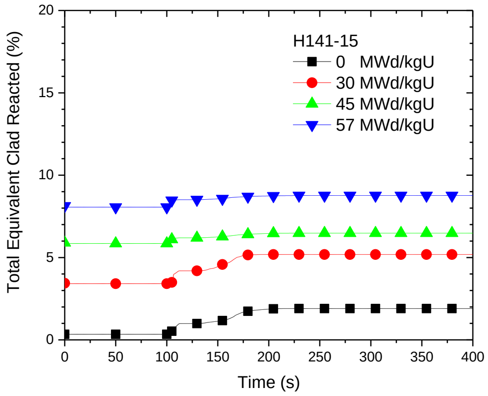

Fig. 5. ECR (HR)

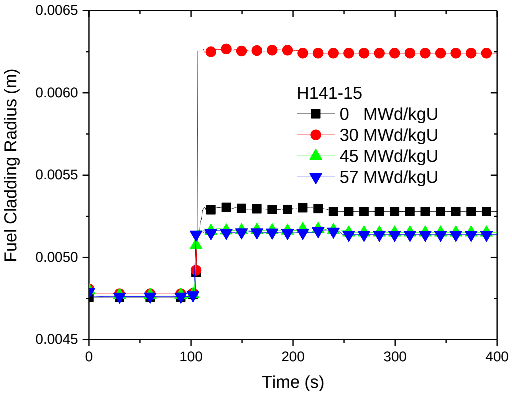

Fig. 6. Outer cladding radius (HR)

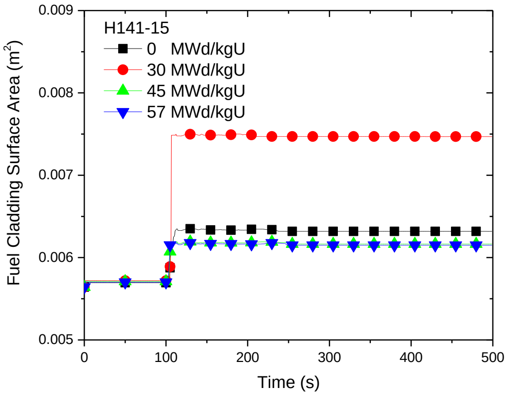

Fig. 7. Cladding surface area (HR)

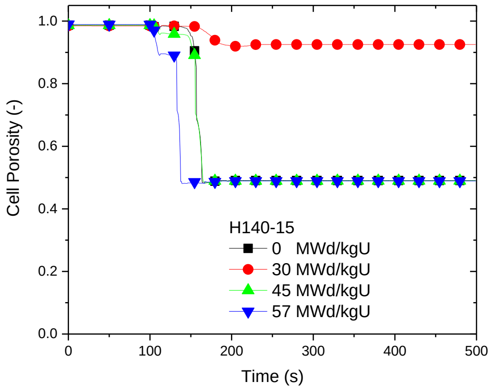

Fig. 8. Cell porosity (HA)

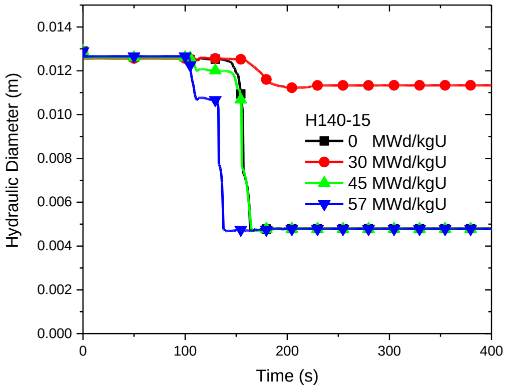

Fig. 9. Hydraulic diameter (HA)