*Transactions of the Korean Nuclear Society Autumn Meeting*
*Changwon, Korea, October 20-21, 2022*

# Pin-wise Fuel Behavior in Non-LOCA by Multi-Scale and Multi-Physics Approach

Jae Ryong Lee[a*] and Han Young Yoon [a]
[a]*Korea Atomic Energy Research Institute, 111, 989 beon-gil, Daedeokdae-ro, Yuseong-gu, Daejon, Korea*
[*]*Corresponding author: jrlee@kaeri.re.kr*

## 1. Introduction

During the past decades, 1D-based system thermal-hydraulics code has been widely used for safety analysis where simple hot channel modeling has been applied to evaluate conservative DNBR margin in steam line break accident (SLB) in the nuclear reactor. Since the system safety analysis codes consider an axial flow only, the radial convection and thermal mixing cannot be resolved. In addition, a simple assumption for neutron power using point kinetics and simplified geometric parameters must be assigned.

In order to examine a realistic safety margin, the MSMP approach is applied in this study. Both conventional 1D and 3D resolution are simultaneously implemented as a multi-scale concept. For the region of interest such as the reactor core, 3D spatial resolution is applied to predict the 3D flow behavior. 1D resolution is applied for the rest of the RCS. For a multi-physics approach, 3D neutron kinetics code and fuel performance code are coupled to obtain a pin-wise power distribution and realistic fuel behavior.

## 2. Numerical Methodology

### *2.1 System modeling*

| Region | features | Code | Coupling |
|---|---|---|---|
| RCS | System-scale T/H | MARS | |
| RPV | Subchannel-scale T/H | CUPID-RV | Source-to-source |
| Reactor core | Fuel performance | FRAPTRAN | |
| | 3D neutron diffusion | MASTER | Dynamic Link Library (DLL) |

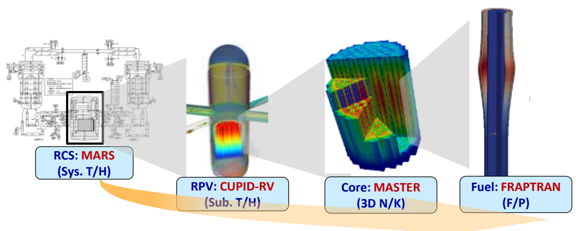


Fig. 1. System configuration for MSMP

In this SLB safety analysis by the MSMP approach, the entire reactor coolant system (RCS) is taken into account. 1D system TH code covers most of the RCS except the reactor pressure vessel (RPV) which is resolved in 3D subchannel-scale. The system-scale code, MARS, and subchannel-scale code, CUPID-RV are implicitly coupled at the source level. To obtain the 3D power distribution, neutron kinetics code is compiled as a dynamic link library (DLL) and explicitly coupled. The fuel performance code is also coupled with the subchannel T/H code at the source level. Since many codes are coupled for the MSMP safety analysis, it is necessary to make a platform for easy access.

### *2.2 MARU Platform*

The MARU platform is a tool for the MSMP safety analysis. As the current status, the MARU contains four codes. All the codes except the fuel performance code were developed by KAERI. It provides a co-simulation capability as users would like to couple such as multi-physics with neutron kinetics code and multi-scale thermal-hydraulics analysis. Combining the system thermal-hydraulics and neutron kinetics code, the SLB accident has been simulated [1]. The MARU platform is operated by TCP/IP socket communication. In a general coupled simulation widely used in the nuclear society, TCP/IP socket communication is used for data transfer among the independently compiled codes. The MARU platform, however, uses TCP/IP communication between the server and client. Users can handle a user-interface such as a desktop app in a Windows system, whereas the coupled codes are activated in a HPC environment. Therefore, a single executable program compiled at the source level can be operated in the server.

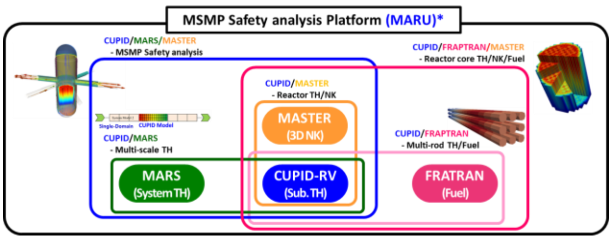


Fig. 2. Code configuration in MARU platform

### *2.3 Pin-wise Fuel Performance code Coupling*

In our MARU platform for MSMP safety analysis, we use the US NRC F/P code, FRAPTRAN which can handle a single fuel rod behavior. This code has been widely used for coupled simulation, especially with system TH codes.

The first thing to be done is a mapping of computing cells of the fuel rod between CUPID and FRAPTRAN. Since CUPID has its own heat structure model, the computing cells between two codes can be easily coupled. In order to match the CUPID heat structure nodes with the FRAPTRAN computing cell, the coupling variables should be modified with consideration of the number of fuels. Furthermore, the source code also should be modified according to the increase of multiple fuels. CUPID then calls the FRAPTAN part as many times as the number of fuels to be solved instead of calling the heat structure model.

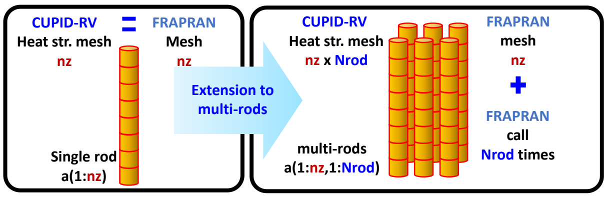


Fig. 3. Schematics of multi-rod extension in CUPID-FRAPTRAN coupling

## 3. Results

For verification of pin-wise coupled code, LWR full core steady state is simulated. Since the subchannel-scaled resolution is applied, total number of mesh is about 1 million in which 20 meshes are employed in axial direction. For a parallel computation, the entire domain is arbitrarily partitioned by METIS library, and 100 processors are used. Figure 4 shows the contours of major output of coupled simulation. The neutron power is calculated by neutron kinetics code. By using core power as a source term, the coolant behavior and fuel information are obtained by CUPID and FRAPTRAN, respectively.

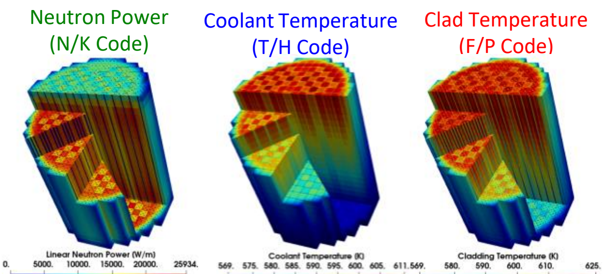


Fig. 4. Verification of CUPID/MASTER/FRAPTRAN Coupled code – Steady state of OPR1000

By coupling F/P code, the SLB accident scenario is simulated. Since the accident procedure in this study does not include a relocation or failure of fuel rod, the radial conduction of the fuel rod is a dominant phenomenon. Therefore, the fuel behavior from FRAPTRAN code is similar with that from the simple heat structure model of CUPID-RV code.

As cold coolant is injected from the cold leg into the fuel assembly region, the power increases due to the negative reactivity. After reaching the setpoint, the control rod is inserted and consequently the power suddenly decreases. At about 30 seconds, a void occurs at the upper plenum due to flashing. Since the fuel assembly region is resolved in subchannel-scale, the detailed information such as the power distribution, and coolant temperature can be shown.

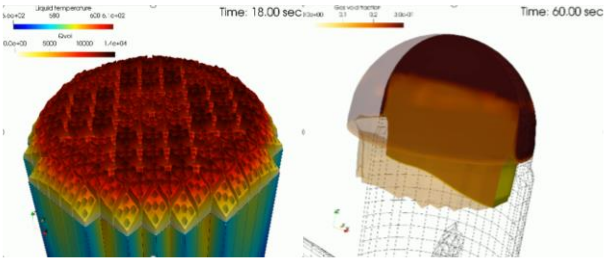


Fig. 5. Key phenomena in the RPV during SLB accident: Left – Overpower distribution prior to setpoint, Right – Occurrence of void fraction in upper head

As pointed out in the introduction part, MDNBR is the one of the important parameter to ensure the safety margin. The MDNBR for various methodologies is summarized in this table 1. Compared with a 1D safety analysis code, the MSMP approach can produce an enhanced MDNBR of about 30%. Compared with 1D approach, we would like to suggest three factors regarding why the MDNBR is improved for the MSMP approach. That is, radial flow mixing, realistic pin-by-pin power distribution, and channel-by-channel geometric parameters.

Table 1. Comparison of minimum DNBR

| Methodology | MDNBR |
|---|---|
| 1D System-scale TH | 2.020 |
| MSMP (with w/o FRAPTRAN) | 2.615 |
| MSMP (with w/i FRAPTRAN) | 2.563 |

The first factor is the 3D coolant flow. Since the 1D safety analysis code cannot consider radial flow mixing, excessive assumptions should be considered to obtain the minimum DNBR. However, the 3D MSMP approach can handle radial coolant flow including turbulent mixing and makes it possible to enhance the coolability of the reactor core.

The second factor is realistic fuel power obtained by the NK code simultaneously. The hot pin has been assumed to have the minimum DNBR in 1D safety analysis codes. However, the MSMP simulation reveals that the minimum DNBR does not always satisfy the hot pin assumption. Therefore, what we have expected is that we can secure the additional safety margin by itigating conservative 1D assumption.

The last factor we have considered is the various geometric parameters. In the MSMP approach, however, subchannel-scale resolution provides various geometric parameters. Since the DNBR is dependent on the CHF correlation, which is a function of these geometric parameters, the CHF can be locally evaluated according to the subchannel type. Consequently, additional safety margin can be obtained.

Finally, calculation performance of coupled code is examined. Since the OPR1000 reactor has about 42,000 fuel rods, FRAPTRAN code is called 42,000 times at every time-marching step. A computation time is about 120min without FRAPTRAN code. By coupled FRAPTRAN code, the computation cost increases at about 30% and we are still working on optimizing coupled code to reduce the computation cost.

Table 2. Performance of coupled code

| Performance | |
|---|---|
| **Problem time** | **100 sec** |
| Resources | Intel® Xeon® Gold 6230R CPU @ 2.10GHz |
| Number of Procs | 300 |
| **Computing time** | **160 min (w/I FRAPTRAN)** |
| | 120 min (w/o FRAPTRAN) |

## 4. Conclusion

For the SLB safety analysis, the multi-dimensional MSMP approach has been applied. The body-fitted RPV mesh is applied for the 3D thermal-hydraulic behavior. The system-scale TH and N/K code are coupled for a co-simulation. Through the simulation, we can visualize the coolant behavior and the power distribution during the sequence of the accident in detail. Furthermore, the enhancement of safety margin was quantitatively investigated by obtaining a realistic DNBR distribution. In addition, Pin-wise F/P code is coupled and reproduces the SLB accident.

## REFERENCES

[1] H. Yoon, et al., A Multiscale and Multiphysics PWR Safety Analysis at a Subchannel Scale, Nuclear Science and Engineering, Vol. 194, pp.633-649 (2020).