Supercritical transient analysis in possible fuel debris systems at Fukushima Daiichi NPS by multi-region approach based on integral kinetic model

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Introduction

Shortly after the accident at the Fukushima Daiichi NPS (1FNPS) occurred an effort to safely decommission the damaged reactors has started and been steadily going forward. One of the important topics surrounding the decommissioning activity is criticality safety during a retrieval of fuel debris formed inside the damaged reactors. As a full- or partial-submersion method, in which fuel debris is flooded with water, is likely to be a preferred method for fuel debris retrieval, there is possibility of criticality accident under an appropriate condition that can be formed due to presence of fuel debris and light water.

According to a study by some experts in the nuclear criticality safety field in Japan, a risk-informed criticality control is preferable over a deterministic control, a method that prevents criticality accident by, for example, poisoning a water with strong neutron absorbing materials, which was employed for defueling of Three-Mile Island Unit 2 (TMI-2) (Tonoike et al., 2015). Such risk-informed criticality control of fuel debris allows small possibility of criticality accident and provides a mitigation system should the accident occur. Whether it be the risk-informed criticality control or the deterministic control, for overall criticality control of fuel debris, analyses on possible accident can be important for establishing safety measures against criticality accident in order to eventually protect on-site workers.

To realistically analyze possible criticality accident during fuel debris retrieval, a condition of fuel debris and its possible change in terms of geometry, composition, and amount of water are must be known first. However, currently the condition of fuel debris is unknown and fuel debris retrieval methods are not yet completely determined, making it hard to do any realistic analysis. Secondly, an appropriate method should be used for such analyses. Since it is highly likely that fuel debris contains coupled distinct regions in terms of geometry or composition interacting with one another via neutron transport, a method which takes a space/region-dependency into account is preferred.

Due to the current uncertain condition of fuel debris, we made several simple and hypothetical coupled fuel debris systems that are helpful as a preliminary systems for the 1FNPS. These systems also clarifies the use of the space/region-dependent method. In specific, in the current study, we used a multi-region approach based on the integral kinetic model (IKM), which models a system in region-wise manner by taking their interaction into account using secondary-fission probability density functions (Gulevich and Kukharchuk, 2004; Takezawa and Obara, 2012, 2010). During the time of our analyses on several types of fuel debris systems, we have also been continuously developing and improving the multi-region approach itself. In this study, the earlier version of the multi-region approach was used for supercritical transient analyses in simple fuel debris systems of single or coupled two regions with symmetric and asymmetric geometry, while the latter version, which is the base of **M**ulti-region **I**ntegral **K**inetic (MIK) code that we have developed, was used for supercritical analyses in the hypothetical fuel debris systems with more realistic geometry and composition than the previous systems.

In general, the purpose of this study was to establish the multi-region approach as an applicable method to supercritical transient in various fuel debris systems ranging from the simple systems of two coupled regions with simple composition and geometry to the rather realistic yet hypothetical systems consisting of three coupled regions with more complicated composition and geometry.

As this article is intended as a short introduction of this study, in the remaining part of

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it we will briefly present some of the results and the main conclusion of the study.

Brief results of the study

Here we show the descriptions and analysis results of each type of system briefly along with analysis method. A feedback due to Doppler broadening was considered in all systems except the validation problem of the improved multi-region approach involving Godiva core, in which a feedback due to change in physical density was considered. In addition, in all systems, a heat transfer between the regions was not modeled.

The first systems we analyzed involved single and two symmetrical spherical regions inside of light water. Each region consisted of small spherical fuel debris particles, whose composition is simple UO_2 with 5.0 wt% enrichment of ^{235}U. As for the two-region systems, the regions were separated by certain distances. The distance between the regions was changed while the inserted reactivity kept constant, so that the effect of distance on the transient result could be investigated. In total, we made three two-region systems by changing the distance, plus one single-region system. For each system, the earlier version of the multi-region approach was applied to obtain time- and region-dependent fission rate and temperature profile, and region-wise and total energy release during the first power spike following the step-wise reactivity insertion above prompt-critical level. In short, it was found from the results that as the distance between the regions increased, total energy release decreased in spite of nearly the same inserted reactivity in all systems. More on the results of these analysis can be found in the reference (Tuya and Obara, 2016).

The next systems were consisted of symmetric or asymmetric two spherical regions separated by certain distances inside of light water similar with the previous systems. Again, the regions consisted of small spherical UO_2 particles with 5.0 wt% enrichment. The difference, however, is that the different amount of reactivity was inserted into each system by changing the distance between the regions, while the geometrical size of each region kept constant. The main purpose of the analysis involving these systems was to compare the multi-region approach with a conventional kinetic analysis method known as a one-point kinetics model (PKM). The earlier version of the multi-region approach and the PKM were applied to supercritical transients in these systems. The obtained results were region-wise fission rate and temperature profile as well as region-wise and total energy releases by the multi-region approach; total fission rate and temperature profile and total energy release by the PKM during the first power spike following the step-wise reactivity insertion. In brief, the results showed that in all systems the PKM overestimated energy release compared to that by the multi-region approach. More on these analyses can be found in the reference (Tuya and Obara, 2017).

In the next part of this study, we introduced the improved multi-region approach (i.e., the MIK code) and then attempted to validate it through supercritical transient in simple Godiva core by comparing the results with that of the Godiva experiment. The experimental results were obtained from the work by Wimett *et at* (Wimett et al., 1956). In short, the results by the improved multi-region approach were in reasonably good agreement with the experimental results despite its simpler geometry and feedback models. However, the tail region of the power profile, which was caused by the short-lived delayed neutron precursors, observed in the experiment was not simulated by the improved multi-region approach as it did not take the delayed neutrons into account. The detailed discussion of the improved multi-region approach and the results of these analyses can be found in the reference (Tuya et al., 2017).

And in the last part of this study, we performed supercritical transient analysis in the more practical yet hypothetical fuel debris systems as a preliminary fuel debris system possible at the 1FNPS using the improved multi-region approach. These systems are more practical compared to the previous systems in terms of geometry and composition. The hypothetical fuel debris systems were based on the scenario in which some fragmented small fuel particles drop on top of some consolidated fuel debris region forming supercritical system inside of light water. The composition of fuel debris was homogeneous mixture of fuel, structural materials, and some concrete and was based on the study on fuel debris melting and spreading analysis performed elsewhere (Kevin R. and Matthew W., 2013). The hypothetical systems were modeled as three-region system in the improved multi-region approach. The obtained results included region-wise fission rate and temperature profile, and region-wise and total energy release during the first spike of the transient. It was aimed also in these analyses to evaluate relative impact of certain parameters on the result, specifically on total energy release, of the supercritical transient. In brief, from the results it was found that the enrichment of ^{235}U was the parameter with the highest impact followed by the angle of repose of fragmented conical debris region and the height of consolidated cylindrical debris region.

Brief conclusion

In this study, supercritical transient analyses in various simple and rather complicated fuel debris systems were performed using the multi-region approach based on the integral kinetic model (IKM). In all systems, the feedback due to either Doppler broadening or change in physical density was considered.

In general, this study established the multi-region approach based on the integral kinetic model as an applicable method to supercritical transient in various fuel debris systems that can be possible at the Fukushima Daiichi NPS to some extent, and showed that the multi-region approach can be useful tool to investigate characteristics of supercritical transient involving fuel debris.

While the analyses introduced in this study were being conducted, at the same time we have also been improving and further developing the multi-region approach itself. The latest development of the multi-region approach, referred to as the improved multi-region approach in this study, was named the **M**ulti-region **I**ntegral **K**inetic (MIK) code.

As for the MIK code, several topics such as treatment of delayed neutrons, more realistic feedback mechanisms including heat transfer, and practical reactivity insertion are being considered to be developed and included it in near future.

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