Preliminary Sensitivity Analyses on the Criticality of Fuel Assembly during Late Phase of a Severe Accident

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1. Introduction

The difference in chemical affinity and the temperature for eutectic formation of control rod absorber material and cladding of the control rods and those of the fuel materials make the molten fuel and control rod absorbers unmixed. Alternative water injection according to the severe accident management guidelines (SAMG) plays role of positive reactivity insertion since it provides a medium to moderate fast neutrons produced by fission reactions to thermal neutrons used for fission reactions. In addition, fission products released from the reactor core provides effects of positive reactivity insertion since they decrease negative reactivity in the reactor core. Therefore, recriticality during severe accidents can be one of the important issues if there are insufficient boron concentrations in the degraded reactor core.

Numerous studies have been performed to evaluate the possibility of recriticality in boiling water reactors (BWRs), such as Fred et al. [1], Monsteller and Rahn [2], EPRI report [3], Darnowski et al. [4], and etc. Based on the previous studies, the authors also performed possibility on the recriticality during the early phase of the severe accident in the PWRs in which fuel rods are not degraded even though control rods are degraded severely and provided sub-critical boron concentrations to prevent recriticality during the early phase [5].

In this study, using Serpent 2, reactor analysis code based on the Monte Carlo method, we perform preliminary sensitivity analyses on the criticality of a degraded single fuel assembly during late phase of a severe accident.

2. Modeling on the Degraded Fuel Assembly

Configurations of the degraded fuel assembly after the melting of the fuel rods can be various, depending on the enrichment of the fuel rods in the intact fuel assembly, composition of the melt, materials occupied in the vacant part of the assembly, amount of blockage, and etc. In this study, we consider the four cases; sensitivity on the enrichment, fractions of uranium (U) and zirconium (Zr), types of the materials occupied in the vacant part, and the amount of blockage.

Case 1 : *Sensitivity on the enrichment of the fuel*

The fuel assembly considered in this study is used in conventional high power PWR [6]. The K0 assembly consists of 184 fuel rods with enrichment of 3.64 w/o, and 52 fuel rods with enrichment of 3.14 w/o. In this sensitivity study, we consider three cases; the enrichment of uranium in the molten fuel materials is 3.64 w/o (high), 3.14 w/o (low), and average of the two enrichment, respectively.

Case 2 : *Sensitivity on the U-Zr fractions*

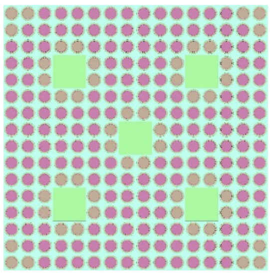
As the fuel rods are being melt, U is mixed with Zr used in the cladding and the configuration of the mixture can be various depending on the accident progression. In this study, we consider five configurations shown in Table 1, considered in Ref. 7.

Table 1. Fractions of U and Zr [7]

Case	U	Zr
2-1	0.82	0.18
2-2	0.59	0.41
2-3	0.52	0.48
2-4	0.48	0.82
2-5	0.26	0.74

Case 3 : *Type of materials in the part of the control rods degraded*

According to the results of Phébus FP tests [8], there are two cases for the materials occupied in the part of the control rods degraded; one with water in the case of water injection, the other with fuel materials. The example of the modeling is shown in Fig. 1.


(a) Fuels in the part of the control rods relocated

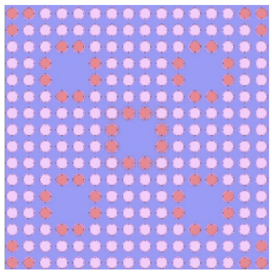

(b) Water in the part of the control rods relocated

Fig. 1. Modeling for sensitivity analyses on the type of materials in the part of the control rods degraded

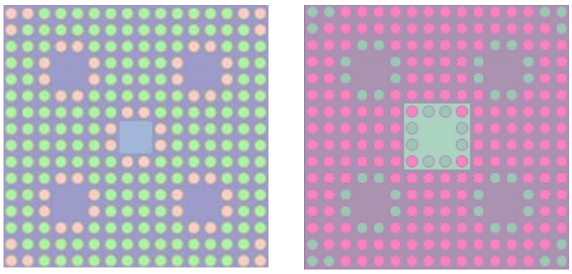
Case 4 : *Sensitivity on the amount of blockage*

In this study, we also calculate the criticality for the various amount of blockage in the unit cell. In this calculation, blockage is defined as

$$BL[\%] = \frac{BA}{s_1^2} \times 100, \quad (1)$$

where
BL : fraction of area blocked in the unit cell,
BA : size of the area blocked in the unit cell,
s_1 : length of the pitch.

Example of the modeling for sensitivity on the amount of blockage are shown in Fig. 2.



(a) Blockage of 8 % at the center part (4x4 rods) (b) Blockage of 100 % at the center part (4x4 rods)

Fig. 2. Modeling for the sensitivity analyses on the amount of blockage

3. Numerical Results

With the modeling of the degraded fuel assembly for the aforementioned cases, we perform the calculation on the criticality of the assemblies. Computation conditions and criticality of the intact fuel assembly with ARO (all rods out) and ARI (all rods in) for comparison are shown in Tables 2 and 3, respectively.

Table 2. Computational conditions used in the Serpent 2

Parameter	Data
Cross section libraries	Continuous energy ENDF/B-VII libraries
# of particles	50,000
# of inactive cycles	300
# of active cycles	300

Table 3. Criticality (k_{inf}) of the intact fuel assembly with ARO and ARI

Control rods	k_{inf}	Std [pcm]
ARO	1.39952	18
ARI	1.06201	17

For case 1, Fig. 3 shows changes of the criticality for high, low, and average enrichment of the fuel melt. The criticality decreases as the fraction of the fuel rods melt increases for all the cases of the enrichment. When the fraction is higher than 60 %, the criticality is lower than that with ARI for intact fuel assembly. Depending on the enrichment of the molten fuel, there are ~300 pcm difference in the criticality, when the fraction is ~20 % and the difference becomes larger as the fraction increases.

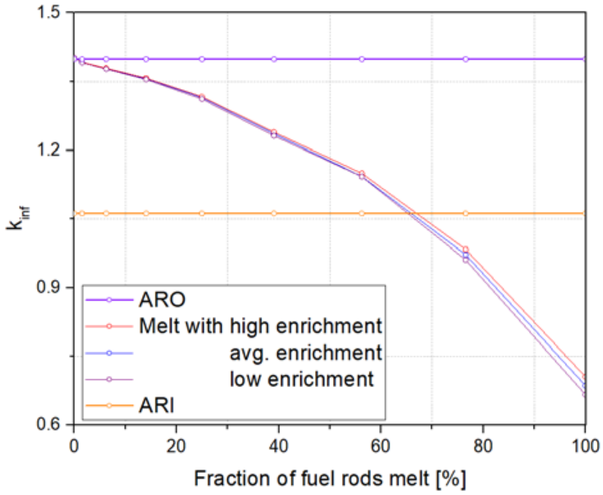


Fig. 3. Sensitivity of the criticality on the various enrichment of the fuel melt (Case 1)

For case 2, Fig. 4 shows the changes for various fractions of the U and Zr used as cladding material. In this case, the criticality increases as the fraction of the U decreases when the fraction is lower than 70 %. It is attributed to that the Zr in the melt seems to play a role of moderator when the melt are located near to intact fuel rods. However, such effect decreases rapidly as the fraction of fuel rods melt increases over 80 %.

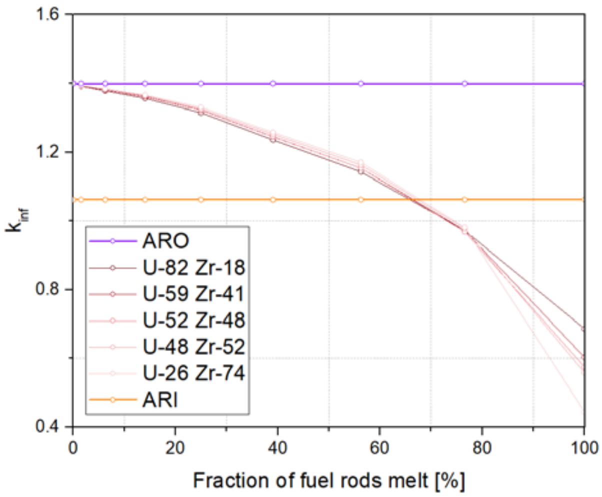


Fig. 4. Sensitivity of the criticality on the various fractions of U and Zr (Case 2)

The changes of the criticality depending on the type of the materials in the rods relocated are shown in Fig. 5. The criticality is higher when the part is filled with water than that when the part is filled with molten fuel, since water is better material to moderate neutrons than molten fuel.

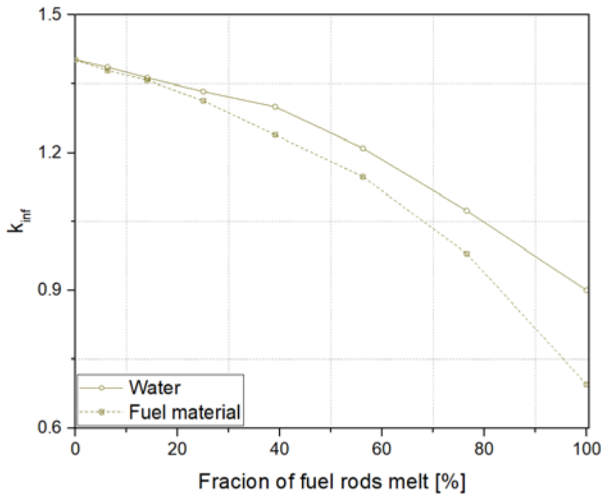


Fig. 5. Sensitivity of the criticality on the type of materials in the parts of the rods degraded (Case 3)

The results of sensitivity analyses on the amount of blockage are shown in Fig. 6. The criticality decreases as the blockage increases. The decrease rate of the criticality is higher when the fraction of fuel rods melt is higher.

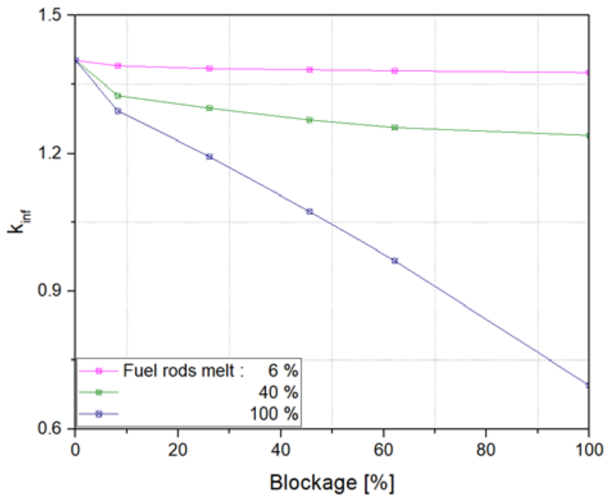


Fig. 6. Sensitivity on the amount of the blockage (Case 4)

For the several cases of the sensitivity analyses on the degraded fuel assembly, we can find that the criticality decreases as the degradation of fuel rods occurs. However, the decrease rate is various depending on the enrichment, fractions of U and Zr in the fuel melt, types of the materials in the part of the rods degraded, amount of blockage in the unit cell, and etc.

4. Conclusions

In this paper, we performed preliminary sensitivity analyses on the criticality of a single fuel assembly during late phase of a severe accident using Serpent 2. From the sensitivity analyses on the enrichment of the degraded assembly, we found that the criticality decreases as the fraction of the fuel rods melt increases for all the cases of the enrichment. Depending on the enrichment of the molten fuel, there are ~300 pcm difference in the criticality, when the fraction is ~20 % and the difference becomes larger as the fraction increases. From the sensitivity analyses on the fractions of the uranium and zirconium, we found that the criticality increases as the fraction of the U decreases when the fraction is lower than 70 %. It is attributed to that the Zr in the melt seems to play a role of moderator when the melt are located near to intact fuel rods.

In the case of the sensitivity analyses on the type of the materials in the parts of the rods degraded, the criticalities were found to be higher when the part is filled with water than that when the part is filled with molten fuel, since water is better material to moderate neutrons than molten fuel. In the case of the sensitivity analyses on the amount of blockage, the criticality was found to decrease decreases as the blockage increases. The decrease rate of the criticality is higher when the fraction of fuel rods melt is higher.

The preliminary sensitivity analyses in this study will be helpful to model the degraded reactor core for the late phase in which there are various configurations of the degraded fuel assembly. With the modeling on the degraded reactor core, we will also perform the whole-core analyses on the potential for recriticality during the late phase and obtain the sub-critical boron concentration for severe accident management.

ACKNOWLEDGEMENTS

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