# Development and Verification of MAAP5.0.3 Parameter file for APR1400

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## 1. Introduction

After the Fukushima accident, EPRI has continuously upgrade the MAAP5 (Modular Accident Analysis Program version 5) that is expected to expand the limitation of MAAP4. As a result of those efforts, the MAAP5.0.2 (Build 5020000) was released officially in December, 2013. Also, in August, 2014, the newest version of MAAP5, MAAP 5.0.3 (Build 5030000), was officially released. The representative characteristics of MAAP 5.0.3 version are the upgrades of the "Lower head plenum model" and the "Melt eruption model in Molten Core Concrete Interaction (MCCI)".

According to the fast upgrade of MAAP code, KHNP has made a great effort to catch up with technical basis of MAAP5, and to develop the base deck, named as Parameter files for domestic NPPs. The parameter file development is essential for severe accident analysis using MAAP code for specific plant.

In 2014, KHNP developed the first draft version of MAAP 5.0.2 parameter file for APR1400 type NPP and had tested for some basic severe accident sequence. And, until now, KHNP has continuously complemented the first draft version of APR1400 type NPP parameter file for MAAP 5.0.2 and 5.0.3.

In this study, we analysis the MCCI phenomena using MAAP 5.0.3 version with the 2$^{nd}$ draft version of APR1400 parameter file developed by KHNP. The purpose of this study is to compare the major difference in MAAP 5.0.2 and 5.0.3 MCCI model and to verify the appropriateness of the 2$^{nd}$ draft version of parameter file.

## 2. Methods and Results

### *2.1 MAAP code and the Parameter file*

From now on, MAAP4 code has been used to analysis the severe accident phenomena in the plant specific PSA and to assess the SAMG strategies in Korea. But, after the Fukushima accident, there were so many requests that the capability of MAAP should be enlarged. According to these requests, after the version of MAAP 5.0.2, MAAP code enlarged its capabilities to the analysis of phenomena in SFP and the accident progression in LPSD operation mode. The RCS model of MAAP5 is expanded from 7 flow nodes and 13 water nodes in MAAP4 to 29 flow nodes and 49 water nodes. And the momentum equations are partly introduced in some sub models. Also, the containment nodalization is expanded from 39 compartments in MAAP4 up to 199 compartments in MAAP5. In addition, the major models are upgraded based on the studies related to Fukushima accident.

Therefore, there are so many new parameters are introduced, and some parameters are changed or deleted for the detailed analysis in MAAP5. For example, the number of parameters for MAAP 5.0.2 is compared with that of MAAP4 in Table 1.

Table 1. Comparison of MAAP Parameter

| Section | MAAP5 | MAAP4 |
|---|---|---|
| Control | 714 | 451 |
| Specific Features (MAAP5 only) | 1311 | 0 |
| Core | 605 | 274 |
| Primary system | 591 | 294 |
| ESF | 606 | 509 |
| Containment /Aux. Building | 6386 | 4573 |
| Total | 10213 | 6101 |

The parameter values in the model parameter sections are mainly used the default value recommended by the code developer, FAI. However, the parameter values in the plant specific parameter sections should be calculated based on the design documents such as the Final Safety Analysis Report.

KHNP had developed the 1$^{st}$ draft version of MAAP 5.0.2 parameter file for APR1400 type plant in 2014. The parameter file for MAAP 5.0.2 can be compatible with MAAP 5.0.3 without some change. So, KHNP developed the 2$^{nd}$ draft version of MAAP 5.0.2 and 5.0.3 parameter file in 2015 that complemented the 1$^{st}$ draft version.

### *2.2 Accident Scenario Selection*

In order to find the improvement in MCCI Model of MAAP 5.0.3, we select the Large Loss of Coolant Accident sequence because this accident sequence is fast sequence for reactor vessel failure. The selected sequence is initiated by the Double Ended Guillotine Break in the cold leg, and all safety injections including Aux. Feedwater system are not available except Safety injection Tank. The analyses are performed for 72 hours as a MAAP time step. Also, this sequence was one of the cases selected in the previous study in order to verify the appropriateness of the 1$^{st}$ draft version parameter file for APR1400 using MAAP 5.0.2. So, we can find the differences in MAAP4, MAAP 5.0.2, and MAAP 5.0.3 as comparing the analysis results.

### *2.3 Sensitivity Factor Selection*

Based on the LLOCA sequence, we classified the analysis cases into 16 cases according to the 4 major factors which can affected the MCCI phenomena.

(1) Concrete Type

Generally, it is known that the MCCI phenomena are greatly affected by the concrete composition. In the MAAP code, 4 options (Basaltic, Limestone, Limestone commonsand, and user specific) were provided for the concrete type based on the composition. The basaltic concrete is known to be much more vulnerable for concrete ablation by molten corium. Since the concrete composition for domestic NPP is close to the basaltic concrete composition, the BMT (basemat melt-through) by MCCI was the one of the main issues. To solve this issue, the limestone concrete was reinforced for cavity floor in APR1400 NPP design. So, the limestone concrete composition becomes the base case, and the Basaltic concrete composition is used for sensitivity study in this study.

(2) Cavity Flooding Status

The existence of water in the cavity at the time when the reactor vessel fails greatly affects the debris coolability and the MCCI progression. In APR1400 design, the coolant poured into the RCS during LOCA is gathered in the In-containment Refueling Water Storage Tank (IRWST). This is the unique design features in APR1400 because the coolant is gathered in cavity in the case of previous OPR 1000 design. So, in the base case, we opened the junction from IRWST to Cavity at the time when the severe accident management guideline (SAMG) entry conditions are met before the reactor vessel fails. And, in the sensitivity case, those junctions are forced to close after 100 sec later when those junctions are opened.

(3) Melt Eruption Model

During MCCI, the off-gas happens due to concrete ablation. This off-gas is considered to entrain into the corium pool in the reactor cavity and to carry molten mass with it. The molten mass then becomes added to the particle bed. It is known that this off-gas can cool down the molten corium, so the concrete ablation due to MCCI can be delayed, especially in the case of limestone concrete. Also, it is known that the effect of the Melt Eruption Model for Basaltic concrete is much smaller than that of Limestone concrete. In this study, we use the Melt Eruption Model as the base case.

(4) FCHF Value

The parameter “FCHF”[3] is the flat plate critical heat flux (CHF) Kutateladze number. This number applies to the case of pool levitation of droplets from a heated surface in contact with an overlying water pool. It is used for ex-vessel debris heat transfer only. Large values (on the order of 0.1) represent efficient water ingression, resulting in coolable debris. Small values (on the order of 0.036 to 0.0036) represent impermeable debris. The uncoolable debris transfers energy to concrete, resulting in concrete erosion and subsequent pressurization of the containment. Hence, the value of FCHF has a strong influence on containment failure. The default value recommended by code developer is 0.1. To evaluate the sensitivity of reduced heat transfer between a debris bed and an overlying water pool, it is recommended to reduce FCHF to 0.02. This will greatly decrease the heat flux into the water pool, and as a result, greatly increase the heat flux into the concrete. The sensitivity study for FCHF value had been performed during the APR 1400 SAMG development project, and the effect of the FCHF value was reported as negligible one [4]. However, we performed this sensitivity study to assess the appropriateness of the 2nd draft version of MAAP 5.0.3 parameter file.

In Table 2, every case for this sensitivity study is classified using above 4 major factors.

Table 2. Case Classification

| MAAP version | Concrete type | Cavity Flooding | Melt Eruption model | FCHF Value | Case Number |
|---|---|---|---|---|---|
| 4.0.7 | Specific | No | N/A | 0.1 | M4 |
| 5.0.2 | Limestone | No | N/A | 0.1 | M52L |
| | Basaltic | No | N/A | 0.1 | M52B |
| 5.0.3 | Limestone | Yes | Yes | 0.1 | M53L1 |
| | | | | 0.02 | M53L2 |
| | | | No | 0.1 | M53L3 |
| | | | | 0.02 | M53L4 |
| | | No | Yes | 0.1 | M53L5 |
| | | | | 0.02 | M53L6 |
| | | | No | 0.1 | M53L7 |
| | | | | 0.02 | M53L8 |
| | Basaltic | Yes | Yes | 0.1 | M53B1 |
| | | | | 0.02 | M53B2 |
| | | | No | 0.1 | M53B3 |
| | | | | 0.02 | M53B4 |
| | | No | Yes | 0.1 | M53B5 |
| | | | | 0.02 | M53B6 |
| | | | No | 0.1 | M53B7 |
| | | | | 0.02 | M53B8 |

Case M4 is performed by MAAP 4.0.7 using the parameter file developed during APR1400 PSA. And Case M52L and M52B means that the concrete type is limestone and basaltic concrete, and the analysis is performed by MAAP 5.0.2. The base case is M53L1, which is performed by MAAP 5.0.3 and the concrete parameters are used as the limestone default value. Also, the cavity is flooded before RV failure and the Melt Eruption model is used with 0.1 FCHF value

### *2.4 Analysis Results*

The representative major event occurrence time for each case are summarized in Table 2.

Table 3. Major Accident Progression

| Case | Core Uncover (S) | RV Fail (S) | CV Fail in 72hr (S) | Eroded Depth (M) |
|---|---|---|---|---|
| M4 | 11.25 | 9081.81 | No Fail | 4.12 |
| M52L | 2.5 | 8543.93 | No Fail | 0.894 |
| M52B | 2.5 | 8709.76 | No Fail | 0.895 |
| M53L1 | 2.5 | 8568.25 | 171307.41 | 0.166 |
| M53L2 | 2.5 | 8568.25 | 172550.59 | 0.166 |
| M53L3 | 2.5 | 8568.25 | 245585.67 | 3.141 |
| M53L4 | 2.5 | 8568.25 | 245464.27 | 3.140 |
| M53L5 | 2.5 | 8561.41 | No Fail | 3.582 |
| M53L6 | 2.5 | 8561.41 | No Fail | 3.582 |
| M53L7 | 2.5 | 8561.41 | No Fail | 3.676 |
| M53L8 | 2.5 | 8561.41 | No Fail | 3.676 |
| M53B1 | 2.5 | 8568.25 | 186414.89 | 2.631 |
| M53B2 | 2.5 | 8568.25 | 188903.71 | 2.615 |
| M53B3 | 2.5 | 8568.25 | 241561.81 | 3.921 |
| M53B4 | 2.5 | 8568.25 | 241666.83 | 3.922 |
| M53B5 | 2.5 | 8561.41 | No Fail | 4.115 |
| M53B6 | 2.5 | 8561.41 | No Fail | 4.115 |
| M53B7 | 2.5 | 8561.41 | No Fail | 4.157 |
| M53B8 | 2.5 | 8561.41 | No Fail | 4.157 |

First of all, we compare the changes of the major parameters, such as primary system pressure and containment pressure, concrete eroded depth, due to the difference of code version.

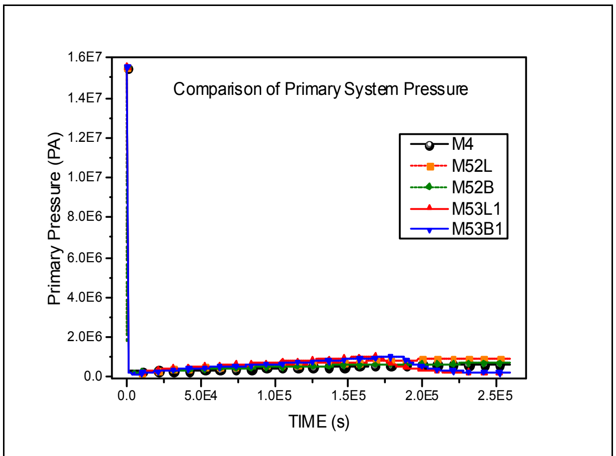


Fig 1. Primary System Pressure Change in LLOCA

Figure 1 shows the change of primary system pressure for different code version and concrete type. Since this study focus the MCCI phenomena after RV fail, it is natural that there is no big difference in the primary system behavior.

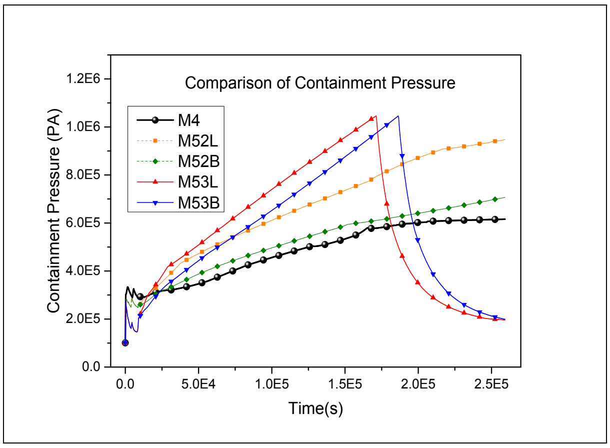


Fig 2. Containment Pressure Change in LLOCA

Figure 2 shows the change of containment pressure for each cases. In the previous study, the containment did not fail until 72 hrs. However, in this study, the containment fails due to overpressurization. The main reason for this difference is the error correction of the heat sink thickness in 1st draft parameter file used in MAAP 5.0.2. For the case of M52L and M52B, we determined the cavity floor heat sink thickness as from the floor to the linar plate. We corrected this thickness as from the floor to the basement.

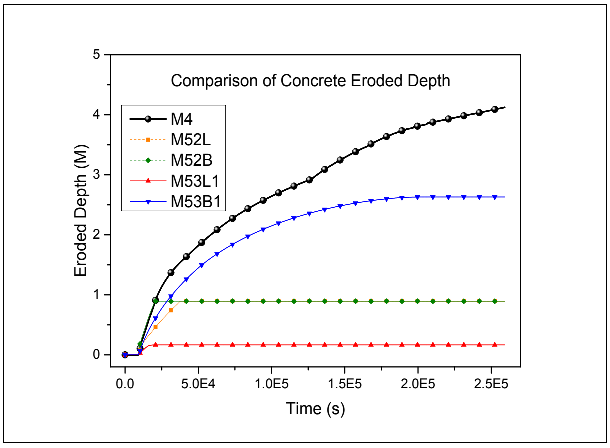


Fig 3. Concrete Eroded Depth Change in LLOCA

Figure 3 shows the concrete eroded depth due to MCCI for each case. In the case of M52L and M52B, since the thickness of cavity floor heat sink was wrong as described above, the concrete ablation is stopped. In the case of M53B1, the general trend is similar to that of MAAP 4.0.7. But it shows the less conservative trend because the cavity is flooded in case of M53B1. In case of M53L1, it is considered that the Melt Eruption model greatly affect the MCCI progression. The concrete ablation is limited to very small thickness since the large amount of off-gas was generated. And as a result, it is judged that the containment failure time is faster than that of M53B1 case as shown in Fig 2.

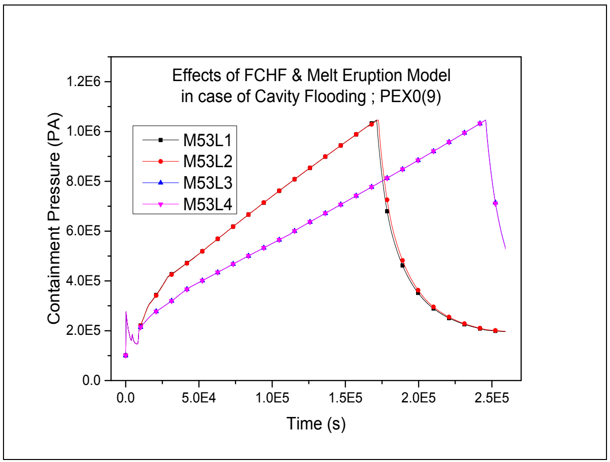


Fig 4. Containment Pressure Change due to FCHF Value and Melt Eruption Model (Wet Cavity)

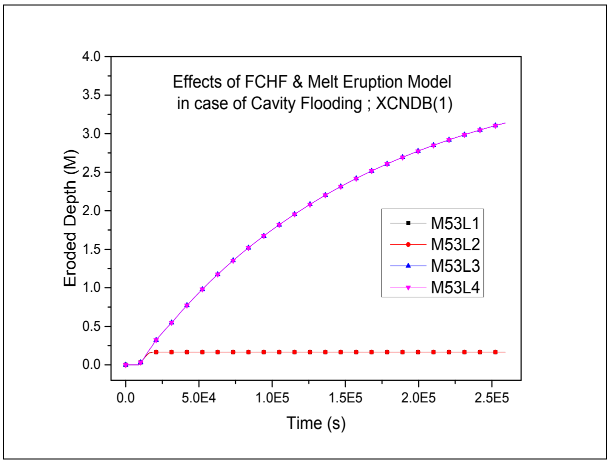


Fig 5. Concrete Eroded Depth Change due to FCHF Value and Melt Eruption Model (Wet Cavity)

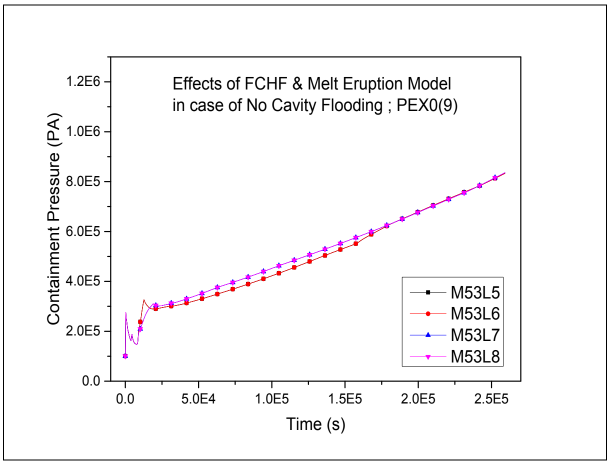


Fig 6. Containment Pressure Change due to FCHF Value and Melt Eruption Model (Dry Cavity)

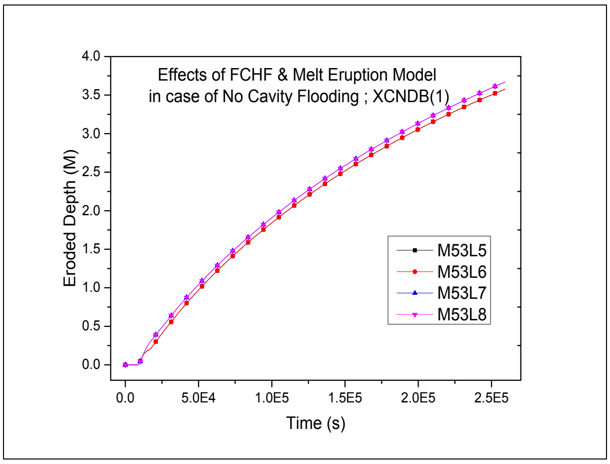


Fig 7. Concrete Eroded Depth Change due to FCHF Value and Melt Eruption Model (Dry Cavity)

Figure 4 and 5 shows the change of containment pressure and concrete eroded depth for sensitivity case 1. The purpose of the sensitivity case 1 study is to assess the effect of FCHF value and the Melt Eruption Model for limestone concrete when the cavity is flooded.

As shown in the figures, we know that the effect of the change in FCHF value is negligible. This result coincides with the previous study [4].

The Melt Eruption model has dramatically affected the MCCI progression for the wet cavity and limestone concrete condition since the eroded depth is limited to 0.166m (M53L1). However, the effect of the Melt Eruption Model is limited and the concrete ablation keeps going on in the case of the basaltic concrete case even though the cavity is flooded (M53B1). The large amount of off-gas due to the Melt Eruption Model in limestone concrete became the main factor for the faster containment failure as shown in Figure 4.

Figure 6 and 7 shows the change of containment pressure and concrete eroded depth for sensitivity case 2. The purpose of the sensitivity case 2 study is to assess the effect of FCHF value and the Melt Eruption Model for limestone concrete when the cavity is not flooded.

As shown in Figure 6 and 7, in the case of dry cavity condition, it is observed that there is no effect for the Melt Eruption Model even in the limestone concrete. So, the concrete ablation is continuously progressed. However, the amount of off-gas generation is much less than that in the wet cavity condition, the containment does not fail in the analysis time (72hrs).

Figure 8 and 9 shows the change of containment pressure and concrete eroded depth for sensitivity case 3. The purpose of the sensitivity case 3 study is to assess the effect of cavity condition (wet or dry) and the Melt Eruption Model for limestone concrete when the FCHF value is fixed as 0.1.

As shown in Figure 8 and 9, in the case of wet cavity condition, the Melt Eruption model greatly affects the concrete ablation progression and generates the large amount of off-gas which becomes the main cause of the containment failure. However, in the case of dry cavity, even though the concrete ablation is much more than that of the wet cavity condition, the amount of off-gas generation is smaller. So, the containment did not fail in the analysis time (72hrs).

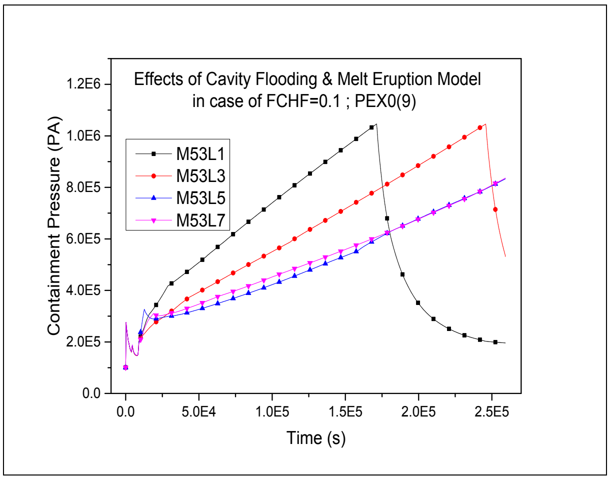


Fig 8. Containment Pressure Change due to Cavity condition and Melt Eruption Model

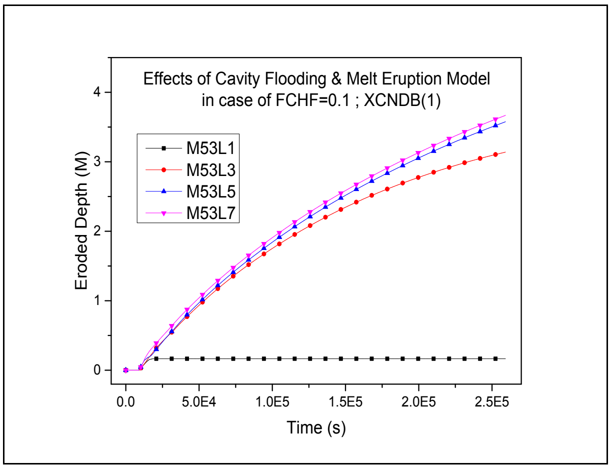


Fig 9. Concrete Eroded Depth Change due to Cavity condition and Melt Eruption Model

Figure 10 and 11 shows the change of containment pressure and concrete eroded depth for sensitivity case 4. The purpose of the sensitivity case 4 study is to assess the effect of cavity condition (wet or dry) and the concrete type (limestone and basaltic) when the FCHF value is fixed as 0.1 and the Melt Eruption Model is used.

As shown in Figure 10, containment pressure behavior shows the different trend according to the cavity condition, not the concrete type. In the case of limestone concrete, the pressure increase rate is faster than that of the basaltic concrete case because the generation of off-gas in limestone is much more than that of the basaltic concrete. Also, we know that the containment failure time in the wet cavity condition is faster than that in the dry cavity condition. As shown in Figure 11, in the case of basaltic concrete, the concrete ablation is continuously progressed even though the Melt Eruption Model is used. However, the concrete ablation depth in case of the wet cavity is some smaller than that in case of the dry cavity.

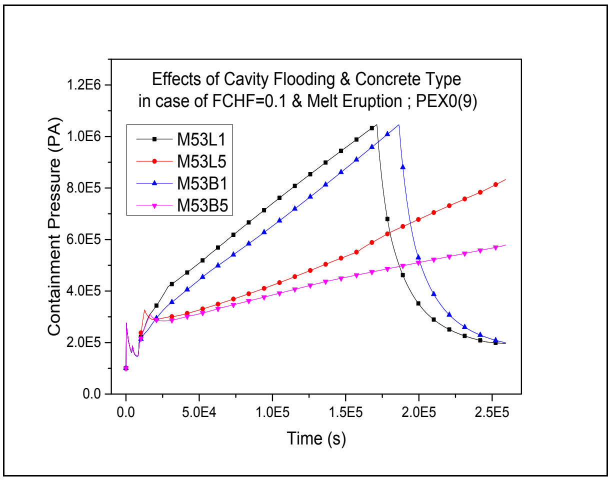


Fig 10. Containment Pressure Change due to Cavity condition and Concrete Type

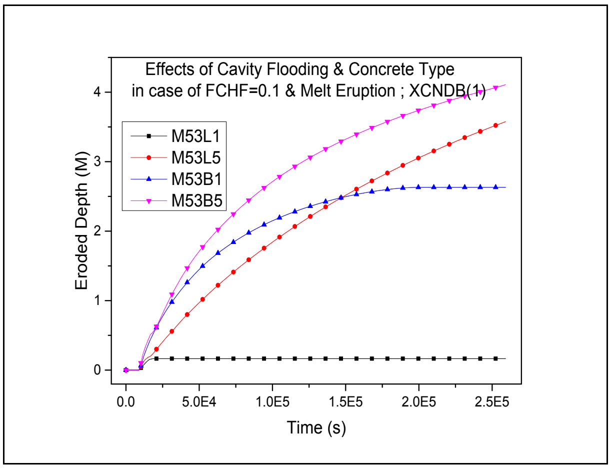


Fig 11. Concrete Eroded Depth Change due to Cavity condition and Concrete Type

Figure 12 and 13 shows the change of containment pressure and concrete eroded depth for sensitivity case 5. The purpose of the sensitivity case 5 study is to assess the effect of the Melt Eruption Model and the concrete type (limestone and basaltic) when the FCHF value is fixed as 0.1 and the cavity is flooded.

As shown in Figure 12, containment pressure behavior shows the different trend according to the Melt Eruption Model, not the concrete type. In the case of using the Melt Eruption Model, the containment pressure increase rate is some faster than that in the case of not using the Melt Eruption Model. Also, we know that the containment failure time in case of limestone concrete is some faster than in the case of basaltic concrete. This result coincides with other previous analysis results. As shown in Figure 13, in the case of basaltic concrete, it is observed that the concrete ablation rate when the Melt Eruption Model is used is some slower than that for not using the Melt Eruption Model. So, in case of the wet cavity, we know that the Melt Eruption Model can affect the concrete ablation rate in some degree, but cannot stop the concrete ablation like the case for limestone concrete.

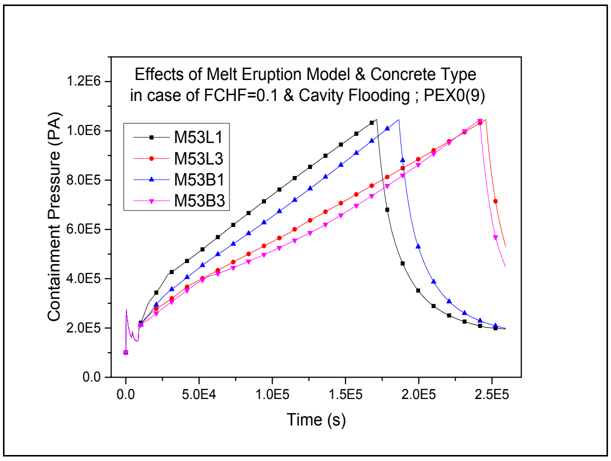


Fig 12. Containment Pressure Change due to Melt Eruption Model and Concrete Type (Wet Cavity)

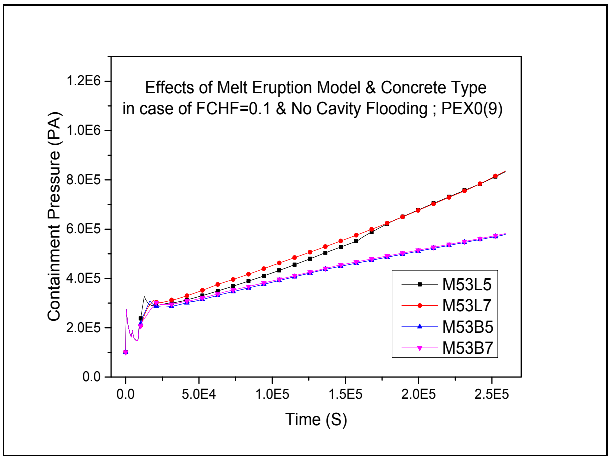


Fig 14. Containment Pressure Change due to Melt Eruption Model and Concrete Type (Dry Cavity)

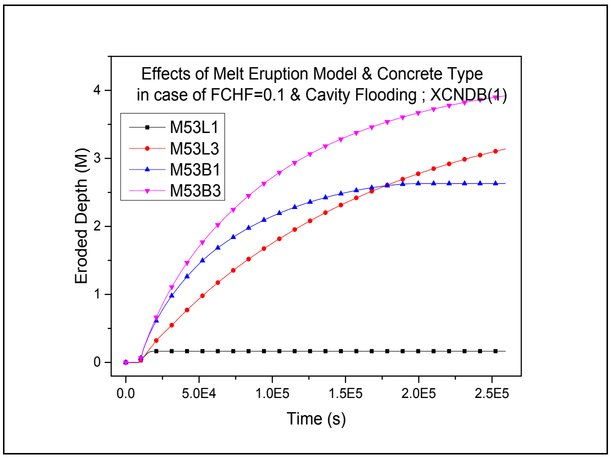


Fig 13. Concrete Eroded Depth due to Melt Eruption Model and Concrete Type (Wet Cavity)

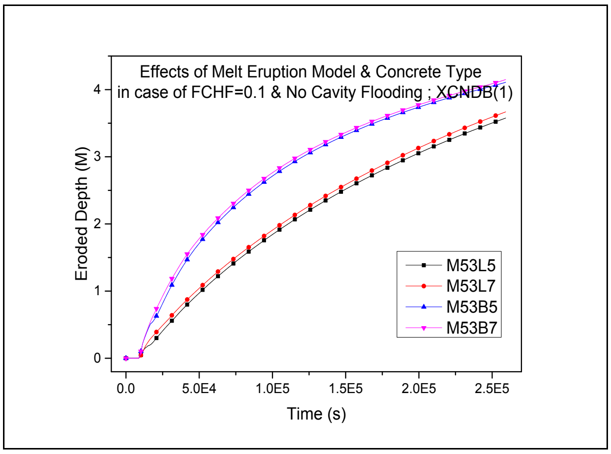


Fig 15. Containment Pressure Change due to Melt Eruption Model and Concrete Type (Dry Cavity)

Figure 14 and 15 shows the change of containment pressure and concrete eroded depth for sensitivity case 6. The purpose of the sensitivity case 6 study is to assess the effect of the Melt Eruption Model and the concrete type (limestone and basaltic) when the FCHF value is fixed as 0.1 and the cavity is not flooded.

As shown in Figure 14 and 15, in the case of dry cavity condition, the concrete ablation is continuously progressed and the effect of Melt Eruption Model is negligible. Since the amount of off-gas generation is much smaller than that in the case of wet cavity, the containment pressure increase rate is much slower than that in the case of wet cavity. As a result of that, the containment does not fail in the analysis time (72hrs). As we already knows, the concrete ablation rate of the basaltic concrete is some higher than that of the limestone concrete, and the containment pressure increase rate in the case of limestone concrete is some higher than that in the case of basaltic concrete.

## 3. Conclusions

The MCCI phenomena have been controversial issues in the severe accident progression, so there have been great efforts to solve them until now. As the part of these efforts, EPRI published MAAP 5.0.3 version which is known that the "Lower head plenum model" and the "MCCI model" was upgraded.

KHNP have the plan in order to upgrade the old parameter file based on MAAP4 to that based on MAAP5.0.2 or higher version for all domestic nuclear power plants. So, we have continuously developed the MAAP 5.0.2 and 5.0.3 parameter file for APR1400 type NPP.

In this study, we analyzed the MCCI phenomena using MAAP 5.0.3 and 2$^{nd}$ draft version parameter file. And we found some insight as belows;

(1) The Melt Eruption Model can greatly affect the MCCI progression only in the case of limestone concrete in the wet cavity condition.

(2) In the wet cavity condition, the large amount of off-gas generated in MCCI became the main factor for

the faster containment failure even though the BMT can be mitigated.

(3) In the dry cavity condition, the BMT should be happened even though the containment failure cannot happen during the mission time.

(4) In the case of basaltic concrete in the wet cavity, both the BMT and the containment failure due to overpressurization are the threat for the containment integrity.

(5) The effect of the change in FCHF value is negligible

(6) The $2^{nd}$ draft version parameter file is appropriate for severe accident analysis.

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