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Sensitivity Analysis of Basemat Melt-Through for PSA Success Criteria of Ex-vessel Debris Coolability in OPR-1000

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1. Introduction

Ex-vessel debris coolability (EDC) is the one of the major issues threatening containment integrity during core melt accidents, inducing molten core concrete interaction (MCCI) in the reactor cavity and then a large release of fission product to the environment. Nuclear safety law revised in 2015 specified the safety goal of "Cs-137 release", for which a safety research on EDC possibility is in progress in KAERI. As one of severe accident management strategies, pre-flooding of coolant into the reactor cavity for both ex-vessel corium cooling and stabilization is adopted in most operating Korean NPPs. If the molten corium were not coolable, MCCI phenomena would happen in the reactor cavity, which can be a big threat to the containment due to over-pressurization and basemat melt-through (BMT). In this paper, uncertainty factors in BMT are studied, based on the success criteria of EDC in the Level-2 PSA (Probabilistic Safety Assessment) and their impact on BMT. From the sensitivity analysis results of related parameters in BMT, the most important and uncertain parameters are selected and suggested to be taken into further EDC/BMT study in the future.

2. Preliminary Evaluation of Existing Success Criteria for EDC in Level-2 PSA

Cooling failure of the core debris in the reactor cavity is important in terms of the containment building failure that can be caused by BMT and/or non-condensable gas (and steam) overpressurization, but this study is limited to the BMT only. Especially, in this preliminary evaluation, through the EDC success criteria review and sensitivity analysis of the BMT in the existing OPR-1000 Level-2 PSA [1], the largest uncertainty factors of the existing EDC/BMT analysis are derived.

According to the Level-2 PSA (CET/DET modeling, see Fig.1 and Fog.2) of the standard nuclear power plant (OPR-1000), EDC success (EXVCOOL) and BMT occurrence (BMT-MELT) in the severe accidents are determined by three conditions, (1) the amount of core melt/debris ejected out of cavity, which is the opposite of remained corium in the reactor cavity (CRM-EJECT), (2) the thickness of the core melt remaining in the reactor cavity floor (DB-DEPTH), and (3) reactor cavity immersion state (CVT-WATER). The base value for each condition is as follows:

- CRM-EJECT: classified as 'HIGH' (less than 60% (representative value =50%) of all core melts are remained), 'MEDIUM' (60%-80% (representative value =70%)), and 'LOW' (80% or more (representative value =90%))
- DB-DEPTH: classified as "VERY SHALLOW" (the debris thickness of the thickest part is less than 10 cm), "SHALLOW" (10-25cm), and "DEEP" (25 cm or more)
- CVT-WATER: classified as 'YES' (reactor cavity is wet) or 'NO' (dry)

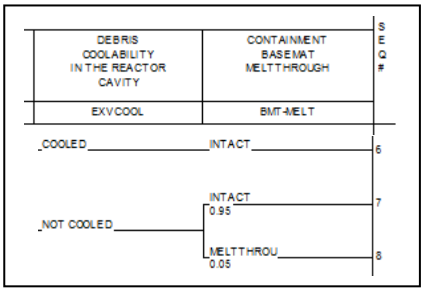

Fig. 1 CET top heading of EDC/BMT modelling in OPR-1000 plant

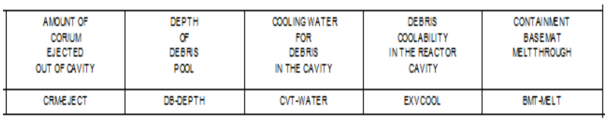

Fig. 2 DET for CET top heading "BMT-MELT"

Table.1 shows the basic PSA analysis cases. Look at the last column (BMT-MELT) of the table meaning whether the BMT occurred or not. If the core melt is cooled or the core melt in the reactor cavity remains in small amounts, BMT is determined not occurred (N/A) regardless of the cooling of the core melt, and BMT occurring possibilities are not taken into account.

Table. 1 PSA analysis cases for BMT

CRM-EJECT	DB-DEPTH	CVT-WATER	EXVCOOL	BMT-MELT
HIGH	-	-	-	N/A
MEDIUM	SHALLOW	YES		N/A
MEDIUM	SHALLOW	NO	NOT COOLED	Case-A
MEDIUM	DEEP	YES	COOLED	N/A
MEDIUM	DEEP	YES	NOT COOLED	Case-B
MEDIUM	DEEP	NO	NOT COOLED	Case-C
LOW	SHALLOW	YES	COOLED	N/A
LOW	SHALLOW	NO	NOT COOLED	Case-D
LOW	DEEP	YES	COOLED	N/A
LOW	DEEP	YES	NOT COOLED	Case-E
LOW	DEEP	NO	NOT COOLED	Case-F

On the other hand, if there is a possibility of BMT, there is a need to derive the occurrence fraction, the reference value is derived from the engineering judgment from the evaluator experience referring to the USNRC data (NUREG/CR-4551 [2]) and/or domestic MAAP calculations [3]. For example, according to NUREG/CR-4551, (1) if MCCI is progressed by a large amount of core melt, BMT possibility is 0.25 (wet cavity) or 0.4 (dry cavity), (2) if MCCI is progressed by a medium amount of core melt, BMT possibility is 0.05 (wet cavity) or 0.2 (dry cavity), (3) if MCCI proceeds by a small amount of core melt, BMT is evaluated not occurred regardless of cavity water conditions. In the OPR-1000 base results (default) for six cases (Case-A/B/C/D/E/F) defined in Table.1, BMT fractions are as follows:

- Case-A: P (not occurring) = 0.95, P (occurring) = 0.05 (engineering judgment by evaluator experience)
- Case-B: P (not occurring) = 0.95, P (occurring) = 0.05 (NUREG/CR-4551 basis)
- Case-C: P (not occurring) = 0.90, P (occurring) = 0.10 (engineering judgment by evaluator experience)
- Case-D: P (not occurring) = 0.95, P (occurring) = 0.05 (engineering judgment by evaluator experience)
- Case-E: P (not occurring) = 0.75, P (occurring) = 0.25 (NUREG/CR-4551 basis)
- Case-F: P (not occurring) = 0.60, P (occurring) = 0.40 (NUREG/CR-4551 basis)

According to the Level 2 PSA results (evaluating the soundness of the reactor building), the probability of the BMT occupying the reactor building damage frequency appears very different depending on the nuclear power plant. For example (see Table.2 and Table.3), whereas the BMT probability was very high to 40-60% in Kori unit 2 (the reactor cavity is always dry), the BMT probability appeared to be about 1-2% in OPR-1000 such as Hanul 3,4 (the cavity flooding state (wet) is well maintained).

Table. 2 OPR-1000 (Hanul 3,4) failure probability by reactor building failure mode (for internal events)

No CF	ECF	LCF	BMT	CFBRB	Isolation Failure	Bypass Failure
57%	0.8%	8.1%	0.7%	19.8%	0.3%	13.3%

(Note)
- No CF: No Containment Failure
- ECF/LCF: Early/Late Containment Failure
- CFBRB: Containment Failure before Reactor Vessel Breach

Table. 3 OPR-1000 (Hanul 3,4) BMT probability by internal/external Events

Event Type	External (Seismic)	External (Flooding)	Internal
BMT Probability	1.9%	0.7%	0.7%

According to existing domestic PSA results, even if the flooded water in the cavity (= wet cavity) does not cool the core melt, BMT possibilities were not large. This is because not only the melt erosion phenomenon into the concrete is endothermic itself but also the heat removal is made continuously by the cavity cooling water. This also implies that the liner plate under the reactor cavity floor (by a depth of 3ft) is not likely to be penetrated during the Level-2 PSA mission time (3 days).

3. Sensitivity Study for EDC

In order to derive the important uncertainty factors of the the existing OPR-1000 PSA related with BMT analysis, a sensitivity analysis of the nine cases are performed for five success criteria composed of three DET headings (CRM-EJECT, DB-DEPTH, CVT-WATER) and two CET headings (EXVCOOL, BMT-MELT) appeared in the CET, as shown in the Table.4 below.

Table. 4 Sensitivity analysis cases for BMT

Case	Definition
S1	‘LOW’ branch value is 1 in ‘CRM-EJECT’ top event
S2	'SHALLOW' branch value is 1 in 'DB-DEPTH' top event, when 'CRM-EJECT' top event is predefined as 'MEDIUM' or 'LOW'
S3	'SHALLOW' branch value is 0 in 'DB-DEPTH' top event, when 'CRM-EJECT' top event is predefined as 'MEDIUM' or 'LOW'
S4	'YES' branch value is 1 in 'CVT-WATER' top event
S5	'YES' branch value is 0 in 'CVT-WATER' top event
S6	'COOLED' branch value is 1 in ‘EXVCOOL’ top event
S7	'COOLED' branch value is 0 in ‘EXVCOOL’ top event
S8	All 'INTACT' branch values are 1 in ‘BMT-MELT’ top event
S9	'INTACT' branch value is 0.1 in 'BMT-MELT' top event, when 'CRM-EJECT' top event is predefined as 'LOW' and 'EXVCOOL' as 'NOT COOLED'

The main results of the sensitivity analysis, shown in the Table.5, are as follows:

- S3-case: The thickness of the corium (debris) layer in the reactor cavity is always assumed to be 'DEEP'. In this case, the probability of BMT increases due to the lack of cooling of the corium.
- S4-case: This assumes that there is always water in the reactor cavity. The probability of BMT is reduced because the possibility of the corium cooling increases if there is water in the reactor cavity. In other words,

having a facility that can fill the reactor cavity in any condition means that BMT can reduce the likelihood of occurrence.

- S6- and S7- cases: They were treated with the 'COOLED' branch value of 1 or 0, respectively, for the 'EXVCOOL' heading, which did not affect BMT probability. The reason is that the bifurcation of 'COOLED' / 'NOT COOLED' branches in the 'EXVCOOL' heading is only provided for the 'DEEP' branch (of the 'DB-DEPTH' heading) which value is very small like 0.01 or 0.05. The corium depth is divided into "DEEP" and "SHALLOW" based on the amount of corium falling into cavity and the cavity floor area, while the probability of distribution in a non-uniform thickness to the cavity floor is estimated from engineering judgment of evaluator experience.
- S8-case: As all values for 'INTACT' branch in the 'BMT-MELT' heading are treated as 1 (i.e., "MELTTHROUGH" branch value is 0), BMT does not occur naturally.
- S9-case: The "INTACT" branch value in the 'BMT-MELT' heading is decreased from 0.6~0.95 (base case) to 0.1 (i.e., "MELTTHROUGH" branch value is increased to 0.9), which greatly increases the BMT probability.

Table. 5 Sensitivity analysis results for BMT

	No CF	ECF	LCF	BMT	CFBRB	Iso. Fail	Bypass
Base	57.0	0.8	8.1	0.7	19.8	0.3	13.3
S1	56.9	0.8	8.1	0.7	19.8	0.3	13.3
S2	57.1	0.8	8.1	0.5	19.8	0.3	13.3
S3	53.6	0.8	8.1	4.0	19.8	0.3	13.3
S4	57.5	0.8	8.1	0.1	19.8	0.3	13.3
S5	56.9	0.8	8.1	0.7	19.8	0.3	13.3
S6	56.9	0.8	8.1	0.7	19.8	0.3	13.3
S7	56.9	0.8	8.1	0.7	19.8	0.3	13.3
S8	57.6	0.8	8.1	0.0	19.8	0.3	13.3
S9	48.3	0.8	8.1	9.2	19.8	0.3	13.3

4. Conclusion

In the current PSA technique for obtaining the BMT probability, the reactor cavity bottom concrete is eroded and the reactor cavity bottom is penetrated to determine whether the core melt (or fission product) is released to the outer soil of the reactor building. Derived from the above sensitivity results using these PSA techniques, the impact of large uncertainty factors is as follows:

- Currently, even if the cavity residue of the corium is more than 80%, there is only a 5% chance that the thickness of the corium layer is more than 25cm. This is due to the lack of information about the corium/debris configuration on the cavity floor in the existing PSA, while using only the total amount of corium falling into cavity together with the cavity floor area as a factor to determine the thickness of the (evenly distributed) corium layer. In practice, including the case where the cavity is pre-flooded, both the floor occupied area by corium and the stacked shape of the corium layer (e.g., cylinders, cones, etc.) are unknown factors that affect the EDC. Thus as the thickness prediction is variable and the influence is quite large (see S3-case), these uncertainties should be resolved.
- Currently, even if the corium layer is thick (i.e., EDC fails), BMT occurring fractions (within 3 days after the accident) are 0.4 for the dry cavity and 0.25 for the wet cavity. This is mainly based on engineering judgments that take into account the results of the analysis and the uncertainty of the existing severe accident codes (MAAP, MELCOR, etc.). When the corium layer is thick, the cooling should be not good and the impact on the possibility of BMT occurrence is the largerst (see S9-case). In other words, if you can evaluate the dryout heat flux according to the debris layer configuration and predict the temperature change in the cavity floor below the debris layer, the initial conditions of the MCCI can be provided more exactly and the uncertainty for BMT occurrence can be greatly reduced.

In conclusion, under severe accident conditions, it is essential both to be able to always supply water to the cavity and to make the corium layer in the cavity spread evenly from the design standpoint. Therefore, in the phenomenological study, it is important to provide PSA branch informations such as (1) the cumulated shape associated with the thickness of the corium layer in the reactor cavity, (2) the condition that the corium is not cooled despite of the wet or flooded cavity, and (3) the initial conditions (within 3 days or in the long term) for BMT occurrence under situations imposed by (2) and (3).

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REFERENCES

[1] KAERI, "Extreme Risk Factors Comprehensive Risk Assessment and Accident Management Technology Development," KAERI/RR-4225/2016, p.152 (2016).
[2] USNRC, "Evaluation of Severe Accident Risks: Quantification of Major Input Parameters," NUREG/CR-4551, Vol. 2, Rev. 1, Part 2, Chapter (1991. 4).
[3] KAERI, MELCOR and MAAP code core and concrete reaction analysis model comparative analysis, Park Soo-Yong, KAERI/TR-1255/99 (1999).