Sensitivity Study with PSA Branch Probability for Ex-vessel Debris Coolability in OPR-1000

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1. Introduction

Ex-vessel debris coolability (EDC) and stabilization under severe accident conditions is one of the important phenomena closely associated with molten core concrete interaction (MCCI) and then containment integrity issues. The strategy of pre-flooding into the reactor cavity is adopted in the SAMG (Severe Accident Management Guidance) of most operating Korean PWRs. If the molten corium is not coolable even with this strategy, MCCI phenomenon will happen in the cavity and it can be a grave threat to the containment integrity due to basemat melt-through (BMT) together with steam (and non-condensable gas) over-pressurization. KAERI has been performing the EDC research for this situation in an experimental (DEFCON[1]) and a modeling (COLAS[2]) ways.

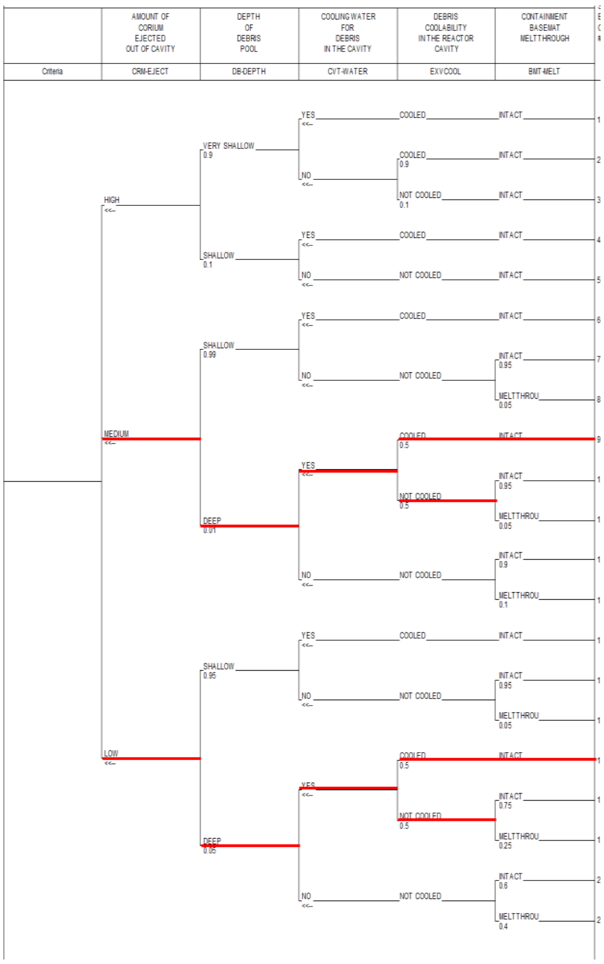

Fig. 1 Basis BMT DET in OPR-1000

As an effort to apply the research achievements to the practical improvement of the current SAMG, sensitivity analyses for the BMT factors are performed in the PSA viewpoint by changing EDC branch Probabilities in OPR-1000 plants.

2. BMT Review for Basis Case

In the Level-2 PSA, DET (Decomposition Event Tree) has been developed [3] to evaluate the possibility of EDC and BMT (see Fig. 1). In the DET, the following five factors (or headings or top events) are modeled for the basis case and the resulting BMT probability appeared to be 0.7% in Hanul 3/4 OPR-1000 plant [4].

- CRM-EJECT: amount of corium ejected out of cavity (= amount of cavity residue corium after reactor vessel bottom failure)
- DB-DEPTH: depth (= thickness) of debris pool or layer (= cake + particle debris bed)
- CVT-WATER: existence of cavity water enough for 3-day (Level-2 PSA mission period) lasting cooling
- EXVCOOL: EDC probability in the cavity
- BMT-MELT: BMT probability in the cavity

The last heading of the DET, BMT-MELT, determines BMT, i.e., whether the containment fails (with certain probability) from the erosion of the cavity basemat by MCCI. It becomes an EDC DET if the BMT-MELT heading is deleted, which also means BMT is determined by 4 precedent factors like CRM-EJECT, DB-DEPTH, CVT-WATER and EXVCOOL.

3. Sensitivity Analysis for BMT-MELT

The BMT occurs only for medium/low amount of corium ejected out of cavity and the branch probability of the EDC in the wet (= deep pool) cavity was 0.5 (=50%) as highlighted by red line in Fig. 1. As the probability of 0.5 means it is the most uncertain branch path with no knowledge from a PSA perspective, this study brings it into main focus by sensitivity analyses.

3.1 Selection of three sensitivity parameters

Among 4 EDC factors, the severe accident scenario first determines the factor of CRM-EJECT which then affects the DB-DEPTH in the dry cavity. Basically, the (cavity) corium pool thickness is determined by the corium amount and the spreading area in the dry cavity.

In this study, the spreading area is assigned as a floor area even for the wet cavity considering the large amount of corium, which was noted in the MELTSPREAD simulation [5][6]. By using SAMG, a deep water pool is envisaged from the pre-flooding strategies of the OPR-1000 cavity. When corium is ejected into the flooded cavity with a deep pool, a part or all of hot corium becomes small fragments (= particle debris), while the corium without undergoing fragmentation in a deep pool (including in the dry or shallow-pool) becomes a cake layer in the cavity floor. According to our study, the DB-DEPTH can be higher in this wet cavity where voids are formed in the particle debris layer. That is, the thickness of the debris layer becomes thicker, even if the same amount of corium is placed in the cavity. Therefore, these voids deteriorate the EDC by the thickness increase of the debris bed. In the meantime, the enhancing effect in the EDC by the increase in the water peneteration distance (from the top of the debris layer) is neglected in this study [4], considering the large volume of corium spread over the whole cavity floor. Like this, the void effect (by the thickness increase of the particle debris bed) is chosen as one of three sensitivity cases (= Case-S2).

Next, from the DEFCON experiments, it is found the corium fragments are not uniformly distributed in the cavity but distributed like a cone shape having an inclination angle at the edge [3]. A new heading is added to the basis DET to reflect the effect of the inclination angle as the cooling property of the debris layer (or bed) is expected to vary according to this angle [4]. Like this, the inclination angle effect is chosen as one of three sensitivity cases (= Case-S1).

For the last, CVT-WATER means corium immersion status in the cavity asking the existence of cavity water enough for 3-day lasting cooling before water depletion. In OPR-1000 plants, cavity flooding is possible with the injection of coolant from two safety measures, the passive one using SIT (Safety Injection Tank) and the active one using RWST (Refueling Water Storage Tank). In the basis DET, the insufficient flooding which results in water depletion before 3 days (like the case of a successful SIT injection without RWST injection) was included into 'No' branch of CVT-WATER. But a new branch is added for CVT-WATER to reflect the effect of the insufficient flooding as this insufficient flooding enhances the EDC according to the COLAS analysis [4]. Like this, the temporary flooding effect is chosen as one of three sensitivity cases (= Case-S3).

3.2 Sensitivity Analysis Case-S1

DB-SHAPE is added as an additional top event when there is water in the cavity and the depth of debris pool is deep (as highlighted by red line in Fig. 2). There are three different branches (divided by inclination angles of 10˚ and 20˚) for which branch fraction together with unsuccessful EDC probability is assigned as follows, using the DEFCON and COLAS researches so far.

- ANGLE-L (<10˚): 0.6 (EDC 'not cooled' = 0.4)
- ANGLE-M (10~20˚): 0.3 (EDC 'not cooled' = 0.2)
- ANGLE-H (>20˚): 0.1 (EDC 'not cooled' = 0.5)

Using this, the probability of the COOLED branch, which was 0.5 (meaning no knowledge for this branch probability) in the basis case, was allocated differently according to DB-SHAPE for top event EXVCOOL. That is, 0.6 was assigned to ANGLE-L, 0.8 to ANGLE-M, and 0.5 to ANGLE-H. These new probabilities implies that (1) a cone shape enhances the EDC compared with the cylindrical (or rectangular) shape assumed in the basis case, and (2) a certain optimal angle can exist that maximize the enhancement. These findings are based on a new model (COLAS) which is under development at this stage. The probability of the INTACT branch for top event BMT-MELT was assigned according to CR-EJECT regardless of DB-SHAPE for simple comparison, which is the same value with the basis case.

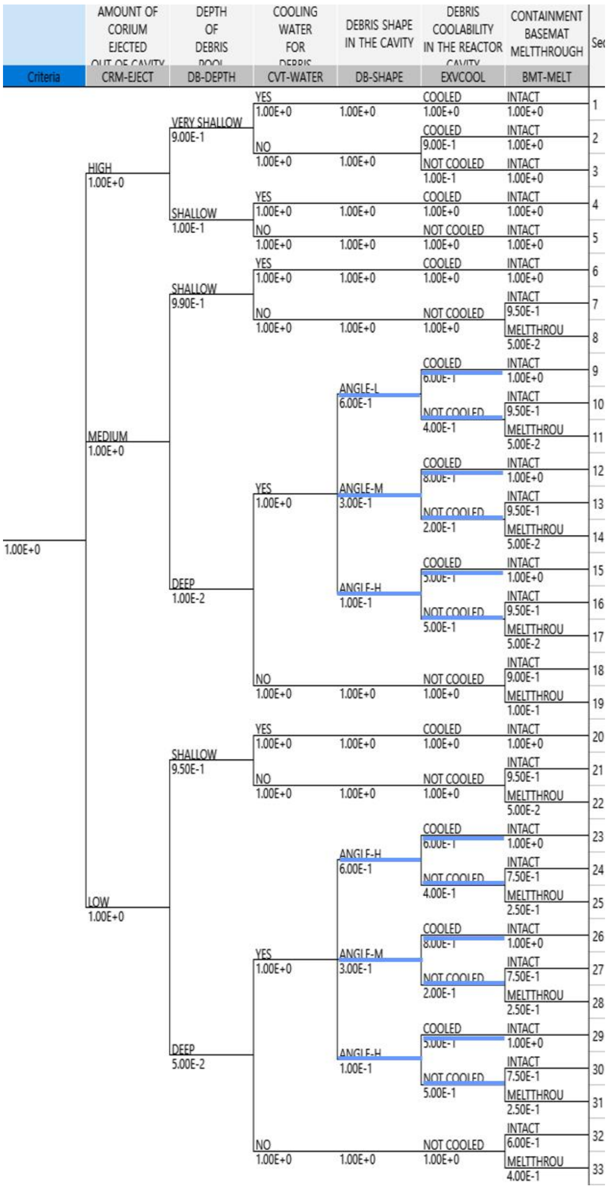

Fig. 2 Modified BMT DET for Case-S1

The branch probability for each branch is shown in Fig.2, and non-zero BMT probabilities among the unsuccessful EDC cases are summarized in Table 1.

Table 1: BMT probabilities in Case-S1

CRM-EJECT	DB-DEPTH	CAV-WATER	DB-SHAPE	EXV COOL	BMT
MEDIUM	SHALLOW	NO		NOT COOLED	0.05
	DEEP	YES	ANGLE-L		0.05
			ANGLE-M		
			ANGLE-H		
		NO			0.1
LOW	SHALLOW	NO			0.05
	DEEP	YES	ANGLE-L		0.25
			ANGLE-M		
			ANGLE-H		
		NO			0.4

3.3 Sensitivity Analysis Case-S2

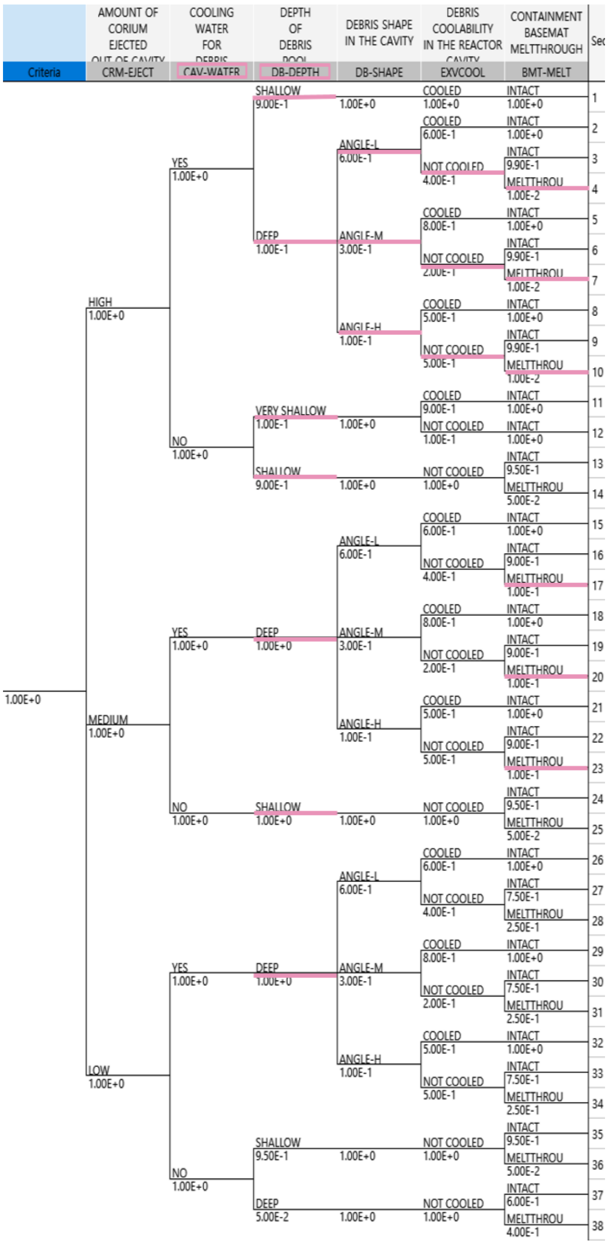

Fig. 3 Modified BMT DET for Case-S2

Two modifications are made in this sensitivity case.

First, the analysis of the particle debris layer thickness is improved (as highlighted by pink line in Fig. 3). For this, the two followings are taken into account (in addition to the basic assumptions that 100% of the core melt is discharged into the cavity and the spreading area uses 100% of the cavity floor area).

1. Add core support structures (to the basis composition of 100% core melt) like the below:
   - Total corium mass: 137 tons (= 115 tons (assuming 50% Zr oxidation) + 22 tons (assuming 50% melting of the support))
   - Total corium volume: 15.45 m^3 (= 12.65 m^3 (assuming 50% Zr oxidation) + 2.8 m^3 (assuming 50% melting of the support))
2. In case of pre-flooding of the reactor cavity (including the case of inflow of coolant along with the core melt in case of reactor vessel failure), the thickness of the debris layer (DB-DEPTH) is doubled in consideration of the voids (in which the porosity due to voids are randomly assumed as 50% by volume ratio)

Second, in order to remove unnecessary 3 branches and enhance the understandings (but no change in final BMT probability), two headings (CAV-WATER and DB-DEPTH) in sequence are interchanged in Case-S2 (as highlighted by pink rectangle in Fig. 3).

Excluding DB-DEPTH, the branch probabilities for the remaining top events were assigned as in Case S1, and non-zero BMT probabilities among the unsuccessful EDC cases are summarized in Table 2.

Table 2: BMT probabilities in Case-S2

CRM-EJECT	CAV-WATER	DB-DEPTH	DB-SHAPE	EXV COOL	BMT
HIGH	YES	DEEP	ANGLE-L	NOT COOLED	0.01
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
MEDIUM	YES	DEEP	ANGLE-L		0.1
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
LOW	YES	DEEP	ANGLE-L		0.25
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
		DEEP			0.4

3.4 Sensitivity Analysis Case-S3

In Case-S3, one more branch ‘TEMP’ for the CAV-WATER event is added to the DET of Case-S2 (as highlighted by green line in Fig. 4). This is for the situation when only SIT water without RWST water was injected as a safety measure, which results in temporary flooded cavity before dryout within 3 days of the Level-2 PSA mission time. The modified BMT DET is shown in Fig.4 and and non-zero BMT probabilities among the unsuccessful EDC cases are summarized in Table 3.

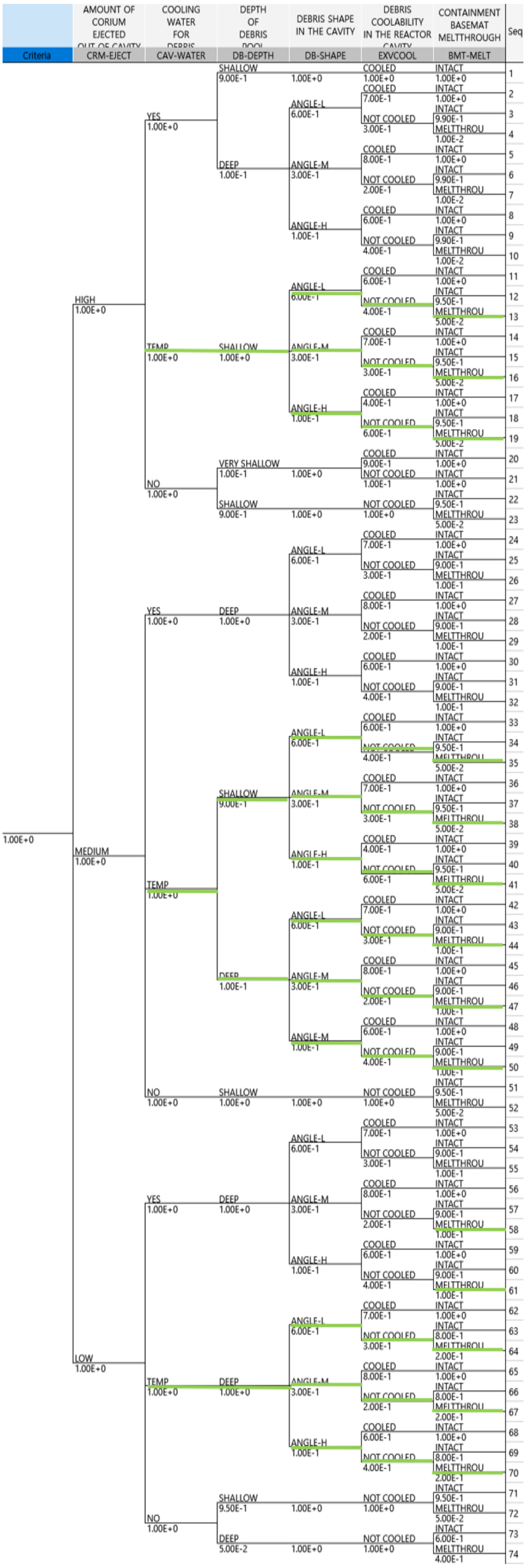

Fig. 4 Modified BMT DET for Case-S3

Table 3: BMT probabilities in Case-S3

CRM-EJECT	CAV-WATER	DB-DEPTH	DB-SHAPE	EXV COOL	BMT
HIGH	YES	DEEP	ANGLE-L	NOT COOLED	0.01
			ANGLE-M		
			ANGLE-H		
	TEMP	SHALLOW	ANGLE-L		0.05
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
MEDIUM	YES	DEEP	ANGLE-L		0.1
			ANGLE-M		
			ANGLE-H		
	TEMP	SHALLOW	ANGLE-L		0.05
			ANGLE-M		
			ANGLE-H		
		DEEP	ANGLE-L		0.1
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
LOW	YES	DEEP	ANGLE-L		0.1
			ANGLE-M		
			ANGLE-H		
	TEMP	DEEP	ANGLE-L		0.2
			ANGLE-M		
			ANGLE-H		
	NO	SHALLOW			0.05
		DEEP			0.4

3.5 Branch probability for Case-S1/S2/S3

The basis branch probabilities is shown in Table 4 while the changes such as newly assigned or adjusted probabilities for sensitivity cases are summarized in Table 5. These changes are based on the COLAS analysis so far and the changes are added to the prior case, in an accumulating manner, like (1) the blue part is applied to Case-S1, (2) the blue and pink parts are applied to Case-S2, and (3) the blue, pink and green parts are applied to Case-S3.

Table 4: Branch Probability in Basis DET of OPR-1000

CRM-EJECT	DB-DEPTH		CAV-WATER	EDC Not cooled	BMT
HIGH **(>40%) (~50%)**	Very SHALLOW **(<10cm)**	0.9	YES **(wet≥3day)**	0.0	0.0
			NO **(dry)**	0.1	0.0
	SHALLOW	0.1	YES	0.0	0.0
			NO	1.0	0.0
MEDIUM **(20-40%) (~30%)**	SHALLOW **(10-25cm)**	0.99	YES	0.0	0.0
			NO	1.0	0.05
	DEEP **(>25cm)**	0.01	YES	0.5	0.05
			NO	1.0	0.1
LOW **(<20%) (~10%)**	SHALLOW	0.95	YES	0.0	0.0
			NO	1.0	0.05
	DEEP	0.05	YES	0.5	0.25
			NO	1.0	0.4

Table 5: Changes in Case-S1(blue)/S2(pink)/S3(green)

CRM-EJECT	CAV-WATER	DB-DEPTH	DB-SHAPE	EDC Not cooled	BMT

HIGH (>40%) (~50%)	YES (wet ≥3day)	SHALLOW	0.9			0.0	0.0
		DEEP	0.1	ANGLE-L (<10°)	0.6	0.3	0.01
				ANGLE-M (10~20°)	0.3	0.2	
				ANGLE-H (>20°)	0.1	0.4	
	TEMP (wet <3day)	SHALLOW	1.0	ANGLE-L	0.6	0.4	0.05
				ANGLE-M	0.3	0.3	
				ANGLE-H	0.1	0.6	
	NO (dry)	Very SHALLOW (<10cm)	0.1			0.1	0.0
		SHALLOW	0.9			1.0	0.05
MEDIUM (20-40%) (~30%)	YES	DEEP (>25cm)	1.0	ANGLE-L	0.6	0.3	0.1
				ANGLE-M	0.3	0.2	
				ANGLE-H	0.1	0.4	
	TEMP	SHALLOW (10-25cm)	0.9	ANGLE-L	0.6	0.4	0.05
				ANGLE-M	0.3	0.3	
				ANGLE-H	0.1	0.6	
		DEEP	0.1	ANGLE-L	0.6	0.3	0.1
				ANGLE-M	0.3	0.2	
				ANGLE-H	0.1	0.4	
	NO	SHALLOW	1.0			1.0	0.05
LOW (<20%) (~10%)	YES	DEEP	1.0	ANGLE-L	0.6	0.3	0.1
				ANGLE-M	0.3	0.2	
				ANGLE-H	0.1	0.4	
	TEMP	DEEP	1.0	ANGLE-L	0.6	0.3	0.2
				ANGLE-M	0.3	0.2	
				ANGLE-H	0.1	0.4	
	NO	SHALLOW	0.95			1.0	0.05

4. Results

The sensitivity analysis results are shown in Fig. 5.

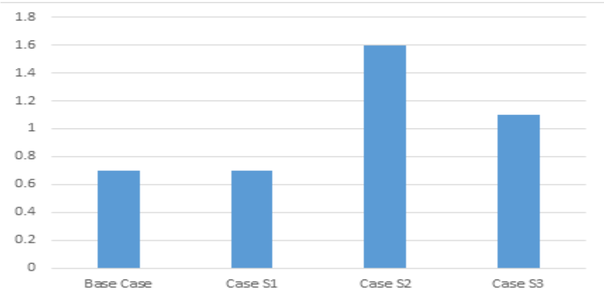

Fig. 5 Sensitivity Analysis Results for BMT [%]

Case-S1 is based on the experimental observation that EDC vary depending on the inclination angle at the edge of debris bed having a cone (or the roof part of a Mongolian tent) shape when the core debris forms a layer of particle on the bottom of the reactor cavity. According to the model evaluation so far, (when 100% of the core melt is discharged into the cavity) the maximum angle was 20°, and the maximum EDC was estimated at the angle between 10° and 20°. In other words, it is judged that there is an optimal angle with maximum coolability.

When looking at the result of Case-S1 in Fig. 5, the BMT probability is almost the same compared to the basis case. This is because the precedent DB-DEPTH probabilities (for high/medium amount of the core melt) were very small, 5% and 1% respectively (see Fig. 2), which makes the BMT probability to change meagerly though the unsuccessful EDC probability was decreased from 50% to 35%.

Case-S2 is mainly based on DEFCON experimental observations with the COLAS evaluation that the debris porosity is 0.5 (draft value at this stage) when the core debris forms a debris layer at the bottom of the reactor cavity. In addition to this, a half of core support structures is added to the basis composition of core melt. These increase the thickness of the debris bed (DB) layer, which then results in EDC decrease with BMT increase. When looking at the result of Case-S2 in Fig. 5, the BMT probability increased significantly (about 2.3 times) compared to the basis case.

In detail, in the wet cavity (when applying the increase of DB thickness by debris porosity and mass addition of core support structure),

- If there is a large (90%) amount of cavity residue, most (95%) of the basis case have a shallow DB height without BMT, whereas all (100%) of the modified case have a deep DB height with BMT probability of 25%
- If there is a medium (70%) amount of cavity residue, almost all (99%) of the basis case have a shallow DB height without BMT, whereas all (100%) of the modified case have a deep DB height with BMT probability of 10%.

And in the dry cavity (when applying the increase of DB thickness only by mass addition of core support structure),

- If there is a small (50%) amount of cavity residue, most (90%) of the basis case have a very shallow DB height without BMT, whereas most (90%) of the modified case have a shallow DB height with BMT probability of 5%.

Case-S3 is mainly based on the model evaluation that temporary flooded cavity (with expected dryout within 3 days) has better coolability compared with dry cavity. When looking at the result of Case-S3 in Fig. 5, the BMT probability increased moderately (about 0.5 times) compared to the base case.

In detail, in the wet cavity (when reflecting the porosity of the core debris layer),

- If there is a large (90%) amount of cavity residue, all (100%) of this case have a deep DB height with BMT probability of 10% (replacing 25% in Case-2).

And, in the temporarily wet cavity (when reflecting the porosity of the core debris layer),

- If there is a large (90%) amount of cavity residue, all (100%) of this case have a deep DB height with BMT probability of 20%
- If there is a medium (70%) amount of cavity residue, 90% of this case have a shallow DB height with BMT probability of 5% while 10% of the modified case have a deep DB height with BMT probability of 10%.

5. Conclusion

BMT impacts are evaluated by changing EDC branch Probabilities in the Level-2 PSA (Probabilistic Safety Assessment) for Korean standard OPR-1000 plants. In this study, the core debris layer cooling properties may vary depending on the inclination angle and porosity of the debris layer deposited on the bottom of the reactor cavity, whose effects were not considered in the existing PSA.

The present results show that the increase in the thickness of the debris layer due to the void porosity deteriorates the cooling property of the debris layer and increases the BMT probability, while the inclination angle improves the cooling property of the debris layer and reduces the BMT probability. Though the total impact (on the containment failure) resulting from the balance between two factors is preliminary, a negatively affecting porosity thickness appeared to have more impact than a positively affecting inclination angle.

Lastly, this study is for the cavity that was previously submerged to a sufficient depth (before corium relocation into cavity floor), and the cooling characteristics of the debris layer for the cavity that was not submerged, which must have a greater effect on BMT, require a separate research.

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