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Assessment of Recent Research on Ex-vessel Debris Bed Formation and Coolability

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1. Introduction

If a core fuel meltdown severe accident occurs and there are no appropriate measures such as in-vessel corium cooling and ex-vessel reactor vessel cooling, molten corium should lead to the reactor vessel failure and corium release into a reactor cavity. In such a postulated accident, BMT (basemat melt-through) resulting from MCCI (molten core concrete interaction) can threaten the containment integrity significantly [1]. As Korean NSA (nuclear safety act) was amended in 2015, it requires submission of AMP (accident management plan) including severe accident management at the time of the operating license application for new units and within 3 years for existing units. Also, the mitigation measures of MCCI should be included in the AMP. Therefore, from a regulatory point of view, the research on the ex-vessel melt coolability is of high importance in that the post MCCI progression is obviously contingent on the ex-vessel melt cooling.

All Korean PWRs (pressurized water reactors) adopt a pre-flooding (or wet cavity) as the forth strategy in the diagnostic flow chart of SAMG (severe accident management guidance) [2]. According to the recent assessment report for all Korean NPPs (nuclear power plants), a few meters of deep water pool can be secured optimistically in the cavity using the equipped several flow paths and water inventories. Thus, we are focused on the accident scenario of ex-vessel melt release under the deep water pool condition, where it is quite probable that a melt jet is fragmented completely and a particulate debris bed is formed at the bottom of the cavity. Debris agglomeration and ‘cake’ formation due to incomplete melt jet fragmentation or agglomeration by fragmented particles can significantly deteriorate the debris bed coolability [3-6], and it is beyond the scope of our research.

When corium is released into a deep water pool, FCI (fuel coolant interaction) is accompanied by very complicated phenomena such as melt jet breakup and fragmentation, steam spike or explosion, particulate debris sedimentation, and debris bed formation on the cavity basemat. Figure 1 represents a schematic diagram of the phenomena, and flow chart of the relevant events. The bed coolability is influenced by many parameters such as accident scenario parameters (e.g. containment pressure, decay heat power), water pool conditions (pool depth & temperature), debris properties (e.g. porosity, particle size distribution etc.), and geometrical configuration of the bed [3, 7-8]. Recently, many researchers are paying attention to the debris bed formation and coolability, and they found that the debris bed coolability can be enhanced significantly by multi-dimensional infiltration of water into the debris bed, and it depends on the geometrical configuration of the bed [9-15].

This paper describes the assessment on the recent researches on ex-vessel debris bed formation and coolability, and introduces our experimental research plan for further development.

2. Assessment of Recent Research

Recently, many researches on ex-vessel debris bed formation and coolability have been conducted mainly in European countries. Nordic BWRs (boiling water reactors) has the design features of deep cavity and abundant water source, and thus adopt ex-vessel debris cooling as a severe accident mitigation strategy [3, 8]. Table I shows the representative researches on the debris bed formation and coolability using various simulant particulate debris.

2.1 Debris Bed Formation

As shown in Fig. 1, the debris bed formation is affected by debris particle transport after settlement on the debris bed, and in the water pool above the bed [8]. The former is related to ‘self-leveling’, and the latter ‘convective flow’. Both phenomena are induced by steam generation within the debris bed during the process of decay heat removal. Two-phase coolant flow escaping from the bed through its top layer is a source of mechanical energy to move the debris particles along the slope, spreading and flattening the debris bed. This process is called ‘self-leveling’ phenomenon. On the other hand, the large-scale two-phase ‘convective flow’ may affect the particle sedimentation in the pool and accordingly debris bed formation.

The parametric studies have been carried out experimentally to investigate the ‘self-leveling’, and its effect on the debris bed coolability was analyzed using an empirical model of the bed shape [3, 16-20]. They used non-heated mono-disperse metallic and/or ceramic particles, and simulate the steam generation by using depressurization method or air injection from the bottom. The effect of large-scale natural ‘convective flow’ above the bed on the particle sedimentation was investigated similarly by injecting air from the bottom of the debris bed [8, 22-23]. They observed the particle spreading by convective flow in the pool, and developed the empirical models of the bed shape.

The researches described before were focused on the

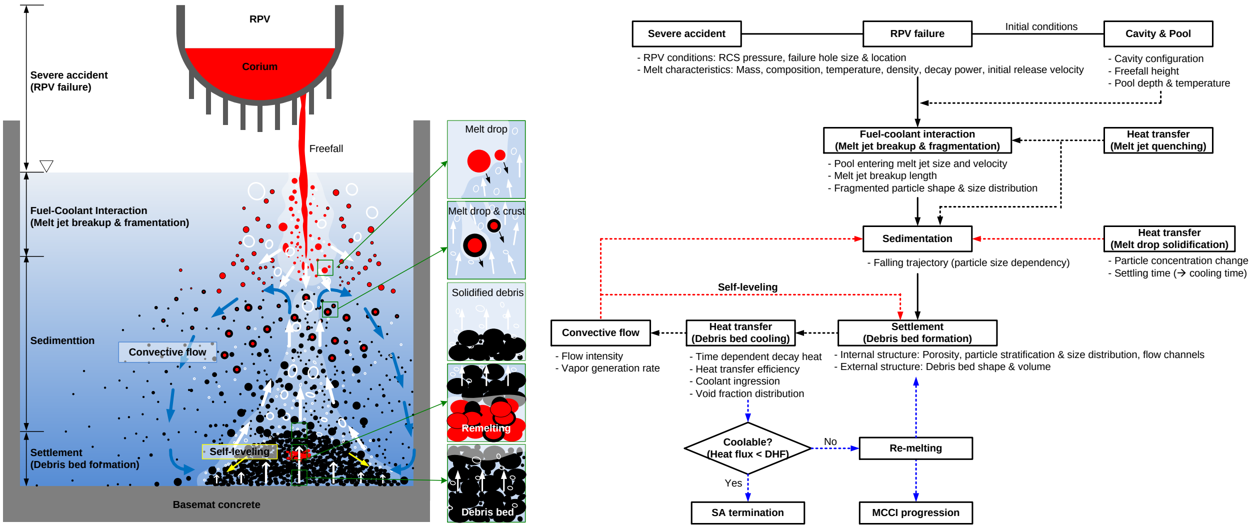

Fig. 1. A schematic diagram of phenomena of melt release into a deep pool, and flow chart of the relevant events

Table I: Recent research on debris bed formation and coolability using simulant particulate debris

Debris bed formation		Two-phase flow pressure drop in a debris bed	Debris bed heat transfer	
Self-leveling	Convective flow		Reflooding & quenching	Long-term coolability - DHF
PDS-C [3, 16-19] Zhang et al. [20] Cheng et al. [21]	PDS-P [8, 22] DAVINCI [23,24]	POMECO-FL [10,11] PICASSO [26]	PRELUDE (PEARL) [29-30] QUENCH-DEBRIS [31]	POMECO-HT [12-14] DEBRIS [32, 33] COOLOCE [15] STYX [34]

effects of 'self-leveling' and 'convective flow' on the debris bed formation. In those researches, they used air to simulate the steam generation, and considered only the decay heat power of the settled debris bed to estimate the steam generation rate. However, in a real accident situation, even more steam is expected to be generated during the melt jet breakup and fragmentation processes owing to melt jet quenching and a surge in the heat transfer area by lots of small particles. As a result, more vigorous steam generation may affect the particle sedimentation significantly, which implies that the initial shape of a particle stream entering the pool may not be coherent jet any longer as assumed in the PDS-P [8] and DAVINCI [22, 23] experiments. Consequently, the effect of turbulent two-phase flow by melt jet breakup and fragmentation should be considered to estimate the final geometrical configuration of the debris bed.

2.2 Pressure Drop in Debris Bed

A pressure drop of two-phase flow in a porous debris bed is a key parameter to estimate the long-term debris bed coolability. A modified Ergun equation was adapted to two-phase flow in porous media by the inclusion of permeability, relative passability, and interfacial friction [10-13, 25, 26]. The Ergun constants were obtained, and the effective particle diameters such as area or length mean diameters of a particulate packed bed were investigated experimentally to predict the pressure drop in a debris bed. However, it is still needed to validate the model using poly-disperse and non-spherical particles, which are believed as the typical debris particles produced by the corium jet fragmentation, as shown in DEFOR [4-6], TROI [27] and FARO [28] experiments.

2.3 Debris Bed Heat Transfer

There are a few studies investigating the in-vessel debris bed (damaged reactor core) quenching characteristics by water re-flooding [29-31]. However, most researches were focusing on ex-vessel debris bed formation and long-term coolability, even though the debris bed cooling mechanism is identical regardless of the debris bed location. The main goal of the researches is to determine whether the bed is coolable at the given debris properties (e.g. porosity, particle size distribution etc.) and geometrical configuration of the bed. DHF (dryout heat flux) is defined as the maximum cross-sectional heat flux removed from a debris bed by coolant, and it is generally used a criteria for the long-term bed coolability [32-37]. That is, if a local heat flux exceeds DHF, the bed is non-coolable and thus remelted locally. The remelting of the debris bed is one of the recent topics drawing much attention of many researchers.

The existing empirical DHF models were developed based on the experiments using one-dimensional bed packed flooded by top, bottom, and lateral flooding.

However, recent experimental results using various geometrical configurations of the debris bed showed that DHF can be enhanced up to around 70% by facilitating multi-dimensional infiltration of water into the bed [12-14, 15, 33]. Therefore, the previous DHF models based on one-dimensional experiments have limitations to predict DHF for the multi-dimensional debris bed geometry. In this sense, DHF (W/m^2) may not useful for describing the debris coolability under multi-dimensional flooding conditions because it describes the heat flow through a surface or through a point. Instead, it is much more illustrative to compare the power density (W/m^3) or specific power (W/kg) [15].

3. KAERI Experimental Plan

The main objectives of our experiments are to develop the representative models of the multi-dimensional geometrical configuration of the debris bed and dryout criteria. From the assessment of recent researches, we confirmed three issues to be solved for further research:

i) The combined effects of 'self-leveling' and 'convective flow' by decay heat of the debris bed and melt jet breakup and fragmentation should be considered to estimate the final debris bed configuration.

ii) We need to validate the existing pressure drop models using prototypic debris particles having poly-disperse size distribution and non-spherical characteristics.

iii) A new dryout criterion is needed for the debris bed with multi-dimensional geometrical configuration.

Moreover, most researches assumed the saturated water pool. However, it was reported that the effect of water subcooling can affect development of natural convection and accordingly the formation of debris bed, substantially for the gradual melt release case [38-39]. Therefore, we have to consider the water subcooling effect.

In order to solve above the first issue, we are planning to perform a large-scale debris bed formation experiment using various heated mono-disperse simulant metallic and ceramic spheres particles. Also, a representative debris particle size distribution will be determined by analyzing previous experiments using prototypic corium melt, such as DEFOR [4-6], TROI [27] and FARO [28]. Then, we will perform additional experiments using heated poly-disperse simulant particles. Using the experiments results, a new model of the debris bed shape will be developed, and the model validation experiments will be performed using the several sets of corium particles produced in TROI experiments, which are believed as typical particles in a real severe accident. In addition, we need to construct a new facility similar to POMECO-FL [10, 11] and PICASSO [26]. We will perform the pressure drop and DHF experiments using various simulant particles having a representative size distribution, and TROI corium particles as well.

4. Conclusions

The assessment on the recent research on ex-vessel debris bed formation and coolability was conducted, and the KAERI experimental plan for the model development and validation was introduced. Further research is needed for the debris bed formation by considering the effects of 'self-leveling' and 'convective flow'. Also, several validation experiments of pressure drop and dryout criteria for the typical geometrical configuration of the debris bed are necessary to estimate the debris bed coolability.

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