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Transient Behavior of Corium Layers in the Lower Head with External Reactor Vessel Cooling under Severe Accident

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1. Introduction

Once the extensive molten core relocates in the lower head during a severe accident, there is a complex phenomenon associated with the heat transfer from the molten pool to the surroundings. Thermal analysis of the molten pool behavior in the lower head is conducted using lumped parameter computer codes such as MAAP5, which is the main approach for utilities [1] as well as MELCOR, which is preferred by authorities [2]. Very detailed analysis using CFD codes at the level of the turbulent eddy scale is also applicable in the academic fields [3]. Due to the complexity and uncertainty surrounding the behavior of the molten pool, a wide range of results was reported. Consequently, efforts were made to reduce the gap between computational codes, specifically MAAP and MELCOR [4].

This paper describes the transient behavior of a molten pool with a three-layer model using MAAP5.06 (hereafter, referred to as MAAP5) for the extra scenario, and provides the interface data for the CFD analysis of the molten pool behavior and for finite element analysis of vessel failure, following the co-work for the Korean MAAP-MELCOR Crosswalk [4]. The conditions for the calculation will be discussed in the next section. The last section discusses the evolution of the temperature of the corium layers, the thickness of the crust, and the amount of heat transferred through the vessel wall. The amount of fission product release is also influenced by temperature and the residence time of the corium in the lower head as time progresses. The study on the fission product release will be presented in additional papers.

2. Calculation Conditions for MAAP5

2.1. Accident sequence

The initiating event is the loss of offsite power with the failure of emergency diesel generators and alternative AC diesel generators, typically mentioned as extended loss of AC power (ELAP) like the Fukushima accident. Later, AC power is restored, and the pump for external reactor vessel cooling (ERVC) is available only. Therefore, core damage is inevitable, but the reactor vessel is expected to not fail. The safety depressurization valves atop the pressurizer are manually stuck open prior to the DC battery depletion.

2.2. MAAP5 models for corium in the lower head

The MAAP5 code provides two user options for the molten pool configuration in the lower head: the conventional two-layer model and the three-layer model, which has a heavy metal layer. The user should select the model before running the code. The recommended option from the developer is a two-layer model. A three-layer model is implemented in MAAP after version 5.01, 2011. Conceptually, un-oxidized Zr presented in the molten pool in the lower head can react with UO2 to produce metallic U, and then the heavy metal layer will separate from the molten pool, which is mixed with U, Zr, steel, and oxygen. A separate heavy metal layer is assumed to be immiscible with the molten oxidic pool.

MAAP5 requires three pre-conditions to calculate the formation of a heavy metal layer: the whole core must be dumped into the lower plenum; the bulk average temperature of the corium must be higher than the eutectic temperature of the pseudo-binary Zr-UO2 system (2,673 K); and the reactor vessel must not fail. If these pre-conditions are met, MAAP5 calculates the formation of a heavy metal based on a simplified quaternary phase diagram of U-Zr-Steel-O.

Part of the core decay heat would be generated inside the heavy metal layer, so the natural convection heat transfer inside the heavy metal layer is also solved. Under the given thermo-physical properties of the heavy metal layer, Rayleigh number based ACOPO correlation is applied here for upward, downward, and sideward directions to get the heat transfer coefficient.

As observed in the TMI-2 accident, the preservation of the vessel was a significant factor for the accident management. The ERVC strategy is being applied here to investigate the performance of heat removal. The insulator channel along the outer surface of the lower head is modeled as a one-dimensional nodal network, which includes inlet holes and steam venting outlets. To account for the heat transfer along the azimuthal angle at the outer surface of the reactor vessel, Yang's correlation [5] is chosen for both nucleate boiling and critical heat flux in a plain vessel with enhanced thermal insulation.

Lastly, at this stage, we are neglecting the presence of lower head penetrations.

3. Calculation Results

3.1. Transient response of the molten pool

Figures 1 and 2 show the mass and bulk average temperature of each layer with respect to time. To simplify things, the initial relocation time is reset to zero. Only a small amount of particulate bed is generated due to the limited mass of water present in the lower plenum, and it rapidly re-melts. The particulate bed has a maximum thickness of about 23 cm. The mass of the upper and lower crust increases up to 12 tons and 17 tons, respectively. Continuing relocation from the core region to the lower plenum leads to a final mass of corium in a lower head of up to 210 tons, with the majority being comprised of an oxidic pool (140 tons) and light metal (40 tons). The MAAP5 prediction indicates that the whole core will dump into the lower plenum 8,420 seconds after the initial relocation, and the formation of the heavy metal layer will occur at that time. The mass of the heavy metal layer and its bulk average temperature are 21 tons and 2,600 K, respectively. Since the liquidus and solidus temperature of heavy metal is estimated around 1,900 K and 1,700 K, the heavy metal layer seems to be pure liquid rather than a 2-phase mixture. The initial relocation results in the corium layer being around 1.1 m in thickness, primarily consisting of the oxidic pool. This is followed by the development of a 20 cm-thick metal layer on top of the oxidic pool. The formation of a heavy metal layer resulted in a layer that is 60 cm thick on the lower crust.

3.2. Transient response of lower crust and vessel wall

Figure 3 illustrates the development of the lower crust, which is in contact with the inner surface of the lower head. Note that the times given in the legend box represent the flight time from the initial relocation of the molten core. The lower crust, initially created at a lower angular region, starts to re-melt over time. However, after the formation of the heavy metal layer at around 8,420 seconds, the crust distribution shows a reversed trend (refer to t=9k sec in the figure) due to significant heat transfer from the heavy metal layer to the lower crust, it subsequently causes the re-melting of the existing lower crust beneath the heavy metal layer (the top level of the heavy metal layer occurring at 9k sec is 45°). Figure 4 represents the thickness of the lower head wall. The first erosion of the lower head wall is predicted to occur at the location 65°, where approximately 2/3 of the oxidic pool is. Maximum erosion occurs at 75° to 85°, the locations where the 30 cm-thick light metal layer is in contact. In the heavy metal layer, wall erosion shows a local maximum at 40°

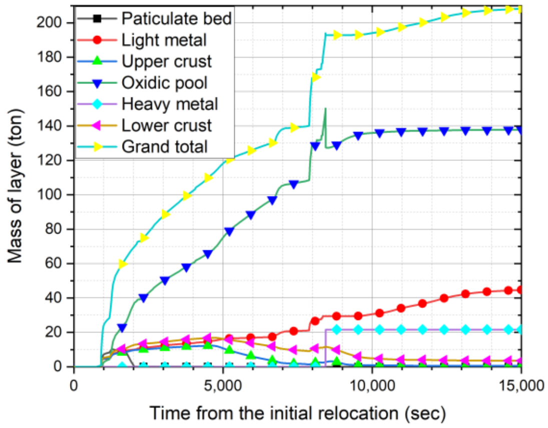

Fig. 1. Mass of each layer

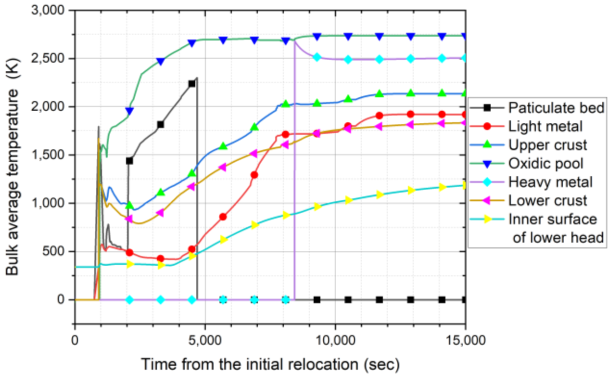

Fig. 2. Bulk average temperature of each layer

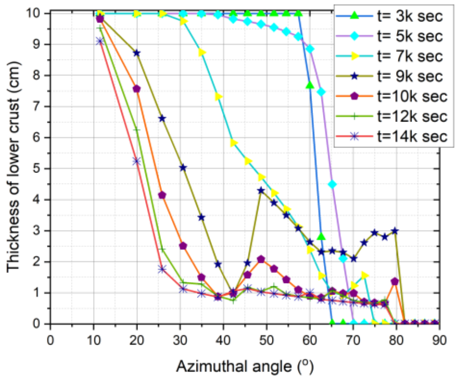

Fig. 3. Thickness of lower crust along the lower head

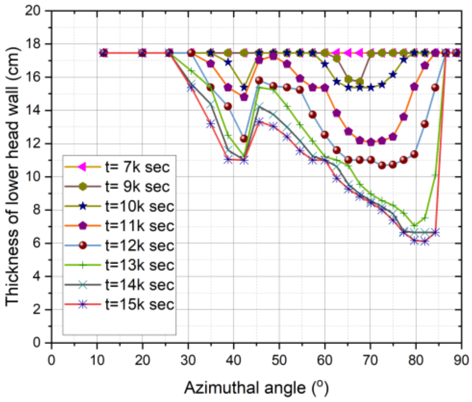

Fig. 4. Thickness of vessel lower head along the lower head

locations where the top level of the heavy metal layer is present. The analysis indicates that the lower head is eroded to two-thirds of its original thickness (remaining at 6 cm) in the light metal layer region.

3.3. Heat flows from the corium to external water

Figure 5 illustrates the heat flux that is extracted from the outer surface of the lower head and transferred to the water within the insulator channel. Before the formation of the heavy metal layer, the peak location of heat flux is associated with the position of the metal layer, which is placed on top of the oxidic pool. Later, the formation of a heavy metal layer changes the profile of heat flux, particularly at the top of the heavy metal layer (at the angle of 45°). Eventually, the highest heat flux of ~600 kW/m^2 is predicted at an angle of 80°, that corresponds to the top of the light metal layer. Regarding the critical heat flux given by [5] > 1.3 MW/m^2, the heat removal via ERVC is confirmed.

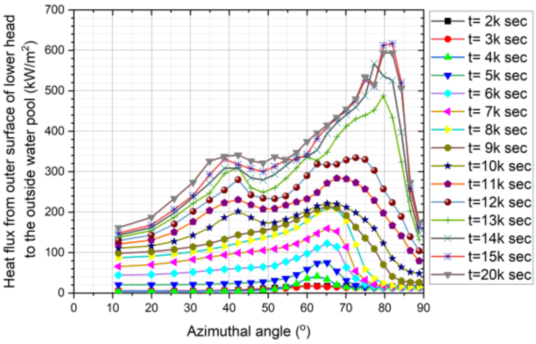

Fig. 5. Heat flux removed at the outer surface of lower head along the lower head

4. Summary

The MAAP5 code is used to account for transient heat transfer analysis for the corium in the lower plenum, considering ERVC operation and the formation of a heavy metal layer. With the realistic inputs for the SBO scenario, the top of the corium in the lower head reaches a height of 2.2 m. The predicted mass of heavy metal formed in the lower plenum is 21 tons, which is 1/10 of the total mass of the corium. The minimum thickness of the vessel lower head of 6 cm remains at an angle of 80°. The ex-vessel heat flux to critical heat flux ratio is approximately 0.5. Therefore, the vessel's lower head is capable of preservation during ERVC operation. The next step will involve further study with the presence of penetrations.

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