MAAP BWR and PWR Lower Plenum Model Improvements

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ABSTRACT

The Modular Accident Analysis Program (MAAP) was improved to provide additional detail in the PWR and BWR lower plenum debris bed behavior during severe accident scenarios involving core relocation. Previous versions of MAAP modeled a single particle bed and a single oxidic debris pool. To address the shortcomings of the MAAP model, it was improved to remove many simplifying assumptions. The features of the new model are discussed and results of the new model are presented for a simulation of the Fukushima Dai-ichi Unit 1 accident. The enhancements described in this paper will become new features of MAAP 5.04.

In the new model, the particle bed is nodalized into radial rings and the oxidic debris bed is axially nodalized into up to 100 layers. Each debris layer consists of a molten central region and crusts on the vessel wall and on CRD tubes. The material composition and energy in each central region and crust are tracked.

The new model allows the history of different material relocations to the lower plenum to be preserved and used for more accurate assessment of the vessel wall response. This includes the calculation of "hot spots" when newly relocated molten debris comes in direct contact with the vessel wall.

Another key improvement made in the lower plenum model is a more realistic treatment of the metal layer. Instead of artificially segregating metals as the corium relocates to lower plenum and depositing them in the metal layer, the intact corium jet is allowed to fill the debris bed layers without separating out metals. This improvement is particularly important in assessing the focusing effect of the thin stratified metal layer overlying the corium pool.

KEYWORDS
MAAP, severe accident, lower plenum, debris bed

1. INTRODUCTION

Lower plenum conditions for certain aspects of important severe accident scenarios could not be adequately simulated in the previous version (MAAP 5.02) of MAAP. These included conditions observed at Three Mile Island Unit 2 (TMI-2) [1] and expert inference regarding Fukushima Dai-ichi Units 1, 2 and 3 [2]. Also, results of recent experiments had brought attention to additional conditions requiring investigation [3]. In order to provide more accurate simulations of these severe accident conditions, the following enhancements are added to MAAP:

- Radial nodalization of Control Rod Drive (CRD) tubes and particle bed
- Axial nodalziation of CRD tubes
- Spreading of debris particles between CRD tubes
- Layering of material in lower plenum

2. DESCRIPTION OF THE ENHANCEMENTS

2.1. Radial Nodalization of CRD Tubes and Particle Bed

In MAAP 5.02, all CRD tubes are assumed to be located at the center of the lower plenum. Also, the individual core channel melt flows are lumped into a single molten jet and use a single, average fall height for the calculation of particulation in water. The thermal responses of CRD tubes will be more accurately represented by nodalizing the CRD tubes in radial groups. This way, each CRD tube group can behave differently and fail at different times. Similarly, by tracking individual channel core melt relocation, different fall heights and jet break-up can be represented.

A group of CRD tubes is modeled as shown in Figure 1, with nodalization corresponding to the radial core nodalization. Multiple water pools inside CRD tubes are also tracked. Multiple embedded crusts (crusts on CRD tubes) are tracked. When a group of CRD tubes fails by creep rupture, it will be determined whether the fuel assemblies supported by the CRD tubes collapse. If the fuel assemblies collapse, they fall on the core support plate. Failure of the core support plate is also considered. The particle bed is nodalized according to the radial core nodalization. Also, an additional node is considered without any CRD tubes for the corium jet delivery through the downcomer.

2.2. Axial Nodalization of CRD Tubes

Currently MAAP considers thermal attack of CRD tube from the debris. However, the current model considers only the control rod guide tube and CRD housing. It would be more realistic to model CRD tubes consisting of three regions with different heat capacities: the control rod guide tube, CRD housing, and stub tube. These different regions should be considered to improve the thermal phenomena affecting the melting and collapse of the CRD tubes.

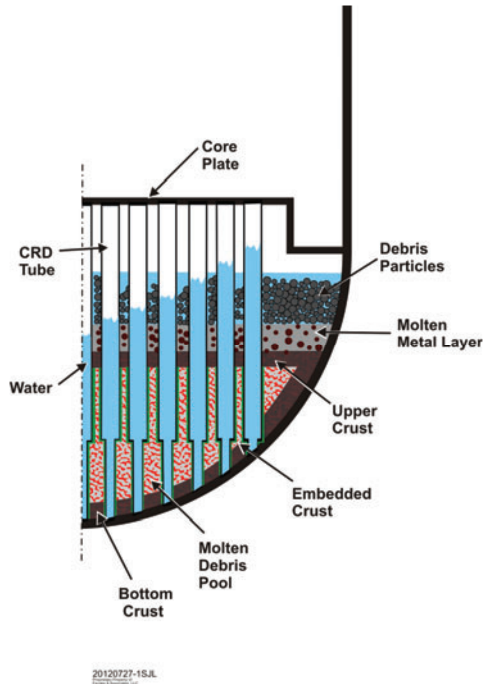

Figure 1. Radial nodalization of CRD tubes.

CRD tubes in each radial group are axially nodalized consistent with the continuous debris bed nodalization. Axial nodalization represents the non-uniform heat transfer areas and heat capacities at the CRD tube wall (shown in Figure 2). The heat capacity of the index tube inside the CRD tube is considered. Crust on individual CRD tube wall heat sinks submerged in the corium pool is also tracked.

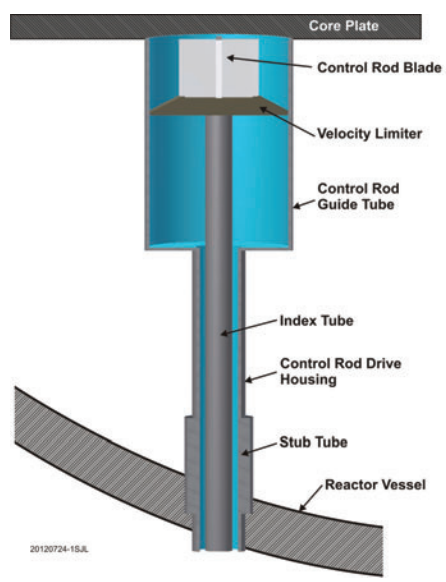

Figure 2. Three section representation of CRD tubes.

2.3. Spreading of Debris Particles Between CRD Tubes

MAAP 5.02 considers a single particle bed in the lower plenum. The corium jet breaks up as it falls through the water pool in the lower plenum and the quenched particles accumulate on top of the debris bed. When the corium jet is considered for an individual core channel in the new code, the particle bed also needs to be radially nodalized. The particle bed is radially nodalized in the same way as the core. A model is developed for dispersal of particles from one node to the adjacent nodes. The water velocity in the vicinity of the jet impingement zone is high enough to cause the particles to spread via a saltation mechanism.

2.4. Layering of Material

In MAAP 5.02, the lower plenum debris bed was represented as three homogeneous layers:

- The top debris layer was the particle bed. The particle bed is assumed to remain on top as additional material is added to the debris bed. This model did not account for the possibility that particles could be submerged in the oxide pool.

- The middle debris layer was the metal layer. All metal added to the debris bed was assumed to be molten and immediately added to this layer.

- The bottom debris layer was the oxide pool. The oxide pool was modeled as a combination of a top crust, multiple bottom crusts, single embedded crust (on the CRD tubes) and a central molten region. The CRD tubes were represented as a single set of tubes in the center of the RPV, with uniform axial shape. This model assumed that CRD tubes failed instantaneously when the temperature of the tube reached the melting temperature of steel.

This approach assumes uniform composition of material within each of the three layers, and does not account for variations in composition of material, or the variation of temperature within the central molten region of the oxide pool, that would be expected in real systems.

In MAAP 5.04, the lower plenum debris bed model is refined:

- The particle bed is nodalized into radial rings (consistent with core radial nodalization). This model accounts for the possibility that particles could be submerged in the molten corium.

- The new enhancement treats the debris bed as a mix of partially molten material including UO_2 and other oxides, and liquid metal, such as steel and zirconium. The liquid metal is less dense than the oxides, so it rises to the top, gradually forming a liquid metal layer which floats at the top of the debris bed (Figure 4).

- The new model represents the debris bed as layers of differing composition and temperature. Early-arrival corium may be submerged in water and rapidly quenched, converting the water to steam. As an accident progresses, the amount of liquid water decreases until all the water has been converted to steam. Late-arrival corium may contact little or no liquid water. Hence, corium entering the lower plenum forms layers of differing temperature and composition. Embedded crusts form on CRD tubes. The CRD tubes are represented as groups of tubes radially distributed in the RPV, with varying axial shape. This enhancement also introduces a model for failure of CRD tubes due to creep (Figure 3).

- The new model represents the global circulation flow pattern in the molten corium pool in the lower plenum, which allows material flow between layers. The corium pool consists of three regions: an upper well-mixed isothermal region, a stably stratified lower region and a wall boundary layer (see Figure 5). The cold, descending boundary layer along the spherical wall generates an upward vertical flow in an otherwise stably stratified lower pool region. The relatively cold upper boundary of the pool produces a turbulent and well-mixed, nearly-isothermal upper-pool layer. An important byproduct of the model is the prediction of the vertical temperature distribution in the core of the pool.

The total heat of the molten corium entering the lower plenum is the same in the homogenous model as the layered model. However, the layered model better accounts for local effects, including:

- Rapid cooling of early-arrival corium by submersion and quenching in liquid water (Figure 6).

- Potential hot spots where freshly relocated hot corium contacts the reactor pressure vessel (RPV) wall (Figure 6).

- Potential hot spots where liquid metal contacts the reactor pressure vessel (RPV) wall. Liquid metal may carry a significant amount of heat, and with limited surface area in contact with the RPV wall, leading to high heat flux (focusing effect) at the contact surface between liquid metal and the RPV wall. This focusing effect will lead to hot spots in the absence of water which cause weakening or failure of the RPV wall in the lower head.

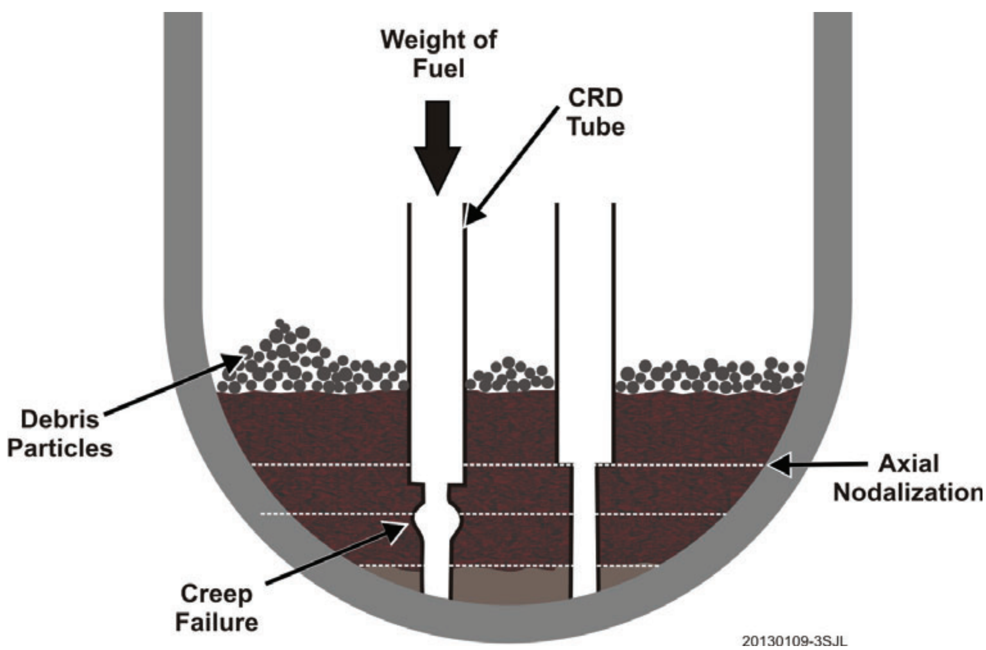

Figure 3. **CRD tube creep rupture.**

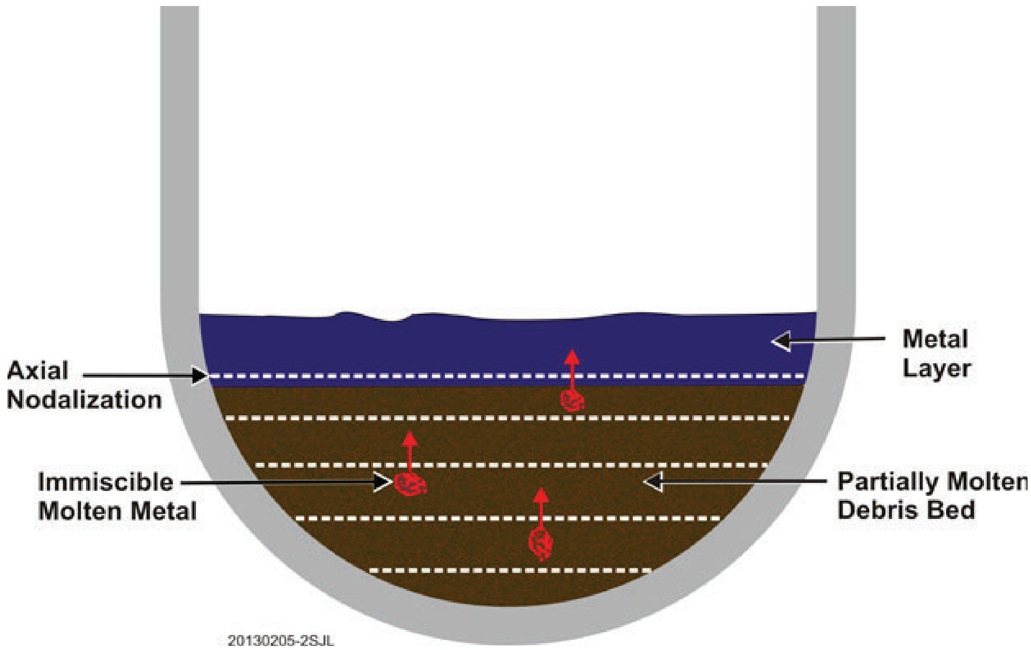

Figure 4. Formation of metal layer.

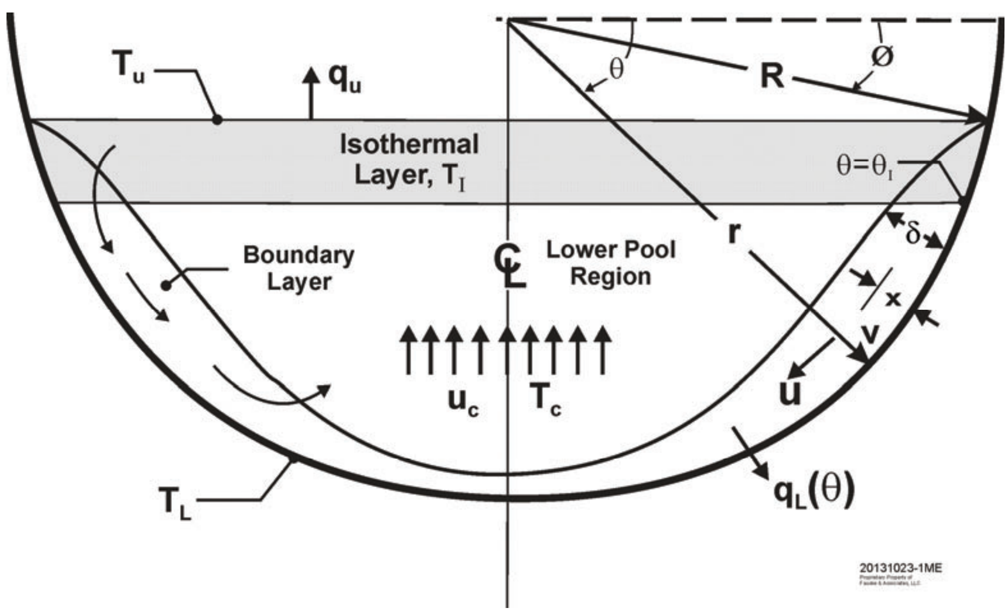

Figure 5. Corium pool convection model.

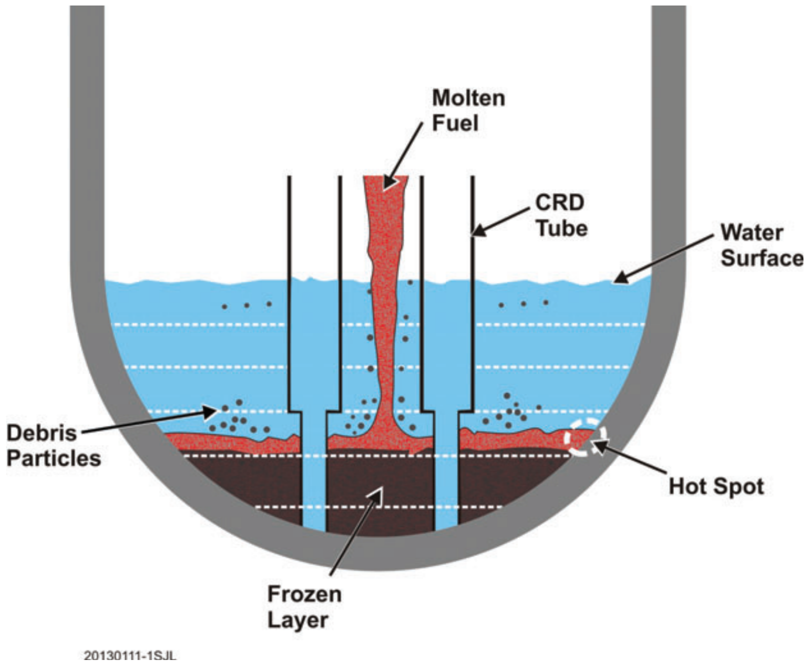

Figure 6. **Stratified layers in debris bed.**

3. RESULTS: FUKUSHIMA DAI-ICHI UNIT 1 SIMULATION

The layering model was tested by simulating the Fukushima Dai-ichi Unit 1 accident. Figure 7 shows the mass of core debris and water in the lower plenum. The first major relocation occurs at around 36,000 seconds. The water in the lower plenum boils off at around 46,000 seconds. The water in the CRD tubes boils off gradually over the next few thousand seconds. At around 62,000 seconds, the entire core is relocated to the lower plenum. At around 68,000 seconds, the reactor vessel fails due to instrument penetration weld failure at lower head node-10. The lower head is modeled using 25 axial nodes.

Figure 8 shows the corium jet flow rate from the core to the lower plenum in each radial channel. The sudden increases in the mass of the debris in the lower plenum correspond to corium jet deliveries. Figure 9 shows the top debris bed layer index. Normally the index increases monotonically as debris accumulates in the lower plenum up to the time of vessel failure. However, in this simulation, the index decreases from 19 to 17 at around 64,000 seconds when molten metal leaves the debris bed and joins the metal layer on the top of the debris bed.

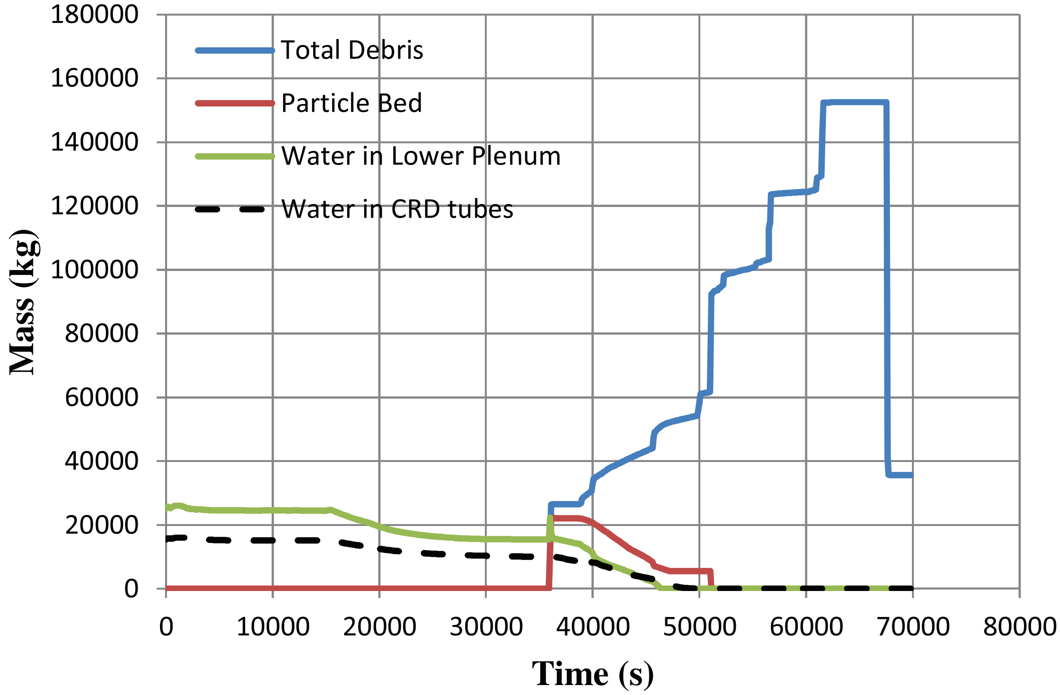

Figure 7. Mass of Core Debris and Water in Lower Plenum

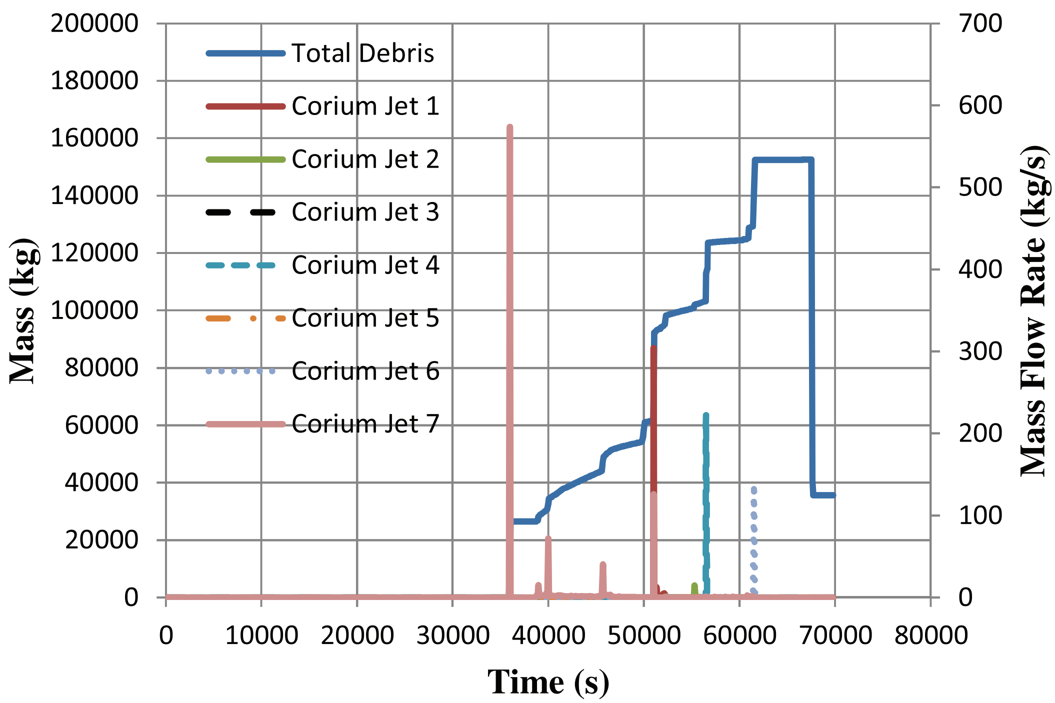

Figure 8. Corium Jet Flow Rates

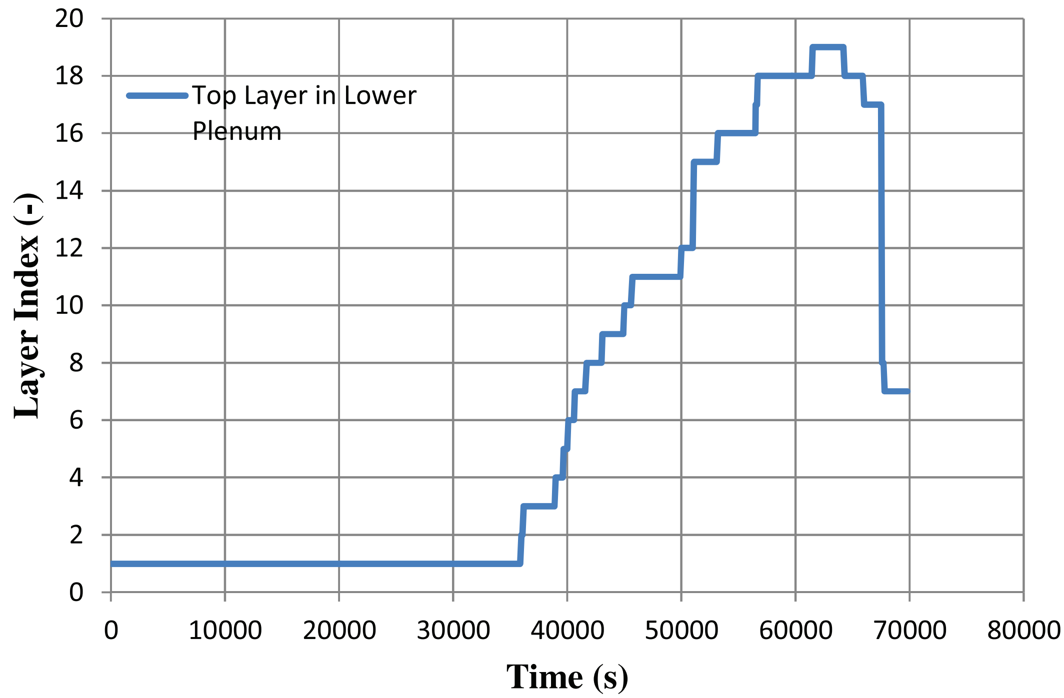

Figure 9. Index of Top Debris Bed Layer in Lower Plenum

Figure 10 shows the mass of particle bed and water in the lower plenum. About 22,000 kg of particle bed is formed during the first major relocation. Note that the corium relocation occurs due to a side core shroud melt-through. Subsequently the molten corium above the failure location drains out of the core. The corium jet melts through the bottom of the jet pump and the shroud water is added to the lower plenum. The water in the lower plenum boils off gradually and the subsequent corium jets do not break up into particulates. The molten corium that is delivered by subsequent corium relocation submerges the existing particle bed. The submerged particulates become part of the continuous bed and are removed from the particle bed.

Figure 11 shows the CRD tube collapse flags and the mass of water inside CRD tubes. The CRD tubes remain intact while there is water in the CRD tubes. After the water in the CRD tubes boils off, the debris bed starts to heat up and the CRD tubes begin to fail by creep rupture. CRD tubes in the center rings fail first. CRD tubes in the peripheral ring fail last. All CRD tubes fail within about 2000 seconds of the onset of CRD failure.

Figure 12 shows temperatures of the central region and crust in layer-10. Figure 13 shows the thicknesses of the crusts in layer-10. When the corium arrives in the lower plenum to fill layer-10, there is some water in the lower plenum and CRD tubes available to quench the corium. The crusts grow slowly on the vessel wall and on the CRD tubes, reaching the 10 cm maximum crust thickness in a few hundred seconds. The CRD tubes initially remain cold because they are cooled by the water they contain. The CRD tubes dry out at around 50,000 seconds. After the CRD tubes dry out, they quickly heat up and fail by creep rupture. The collapsed CRD tubes are added to the debris bed, lowering the layer temperature. Thus, the layer central region temperature decreases each time a group of CRD tubes collapses.

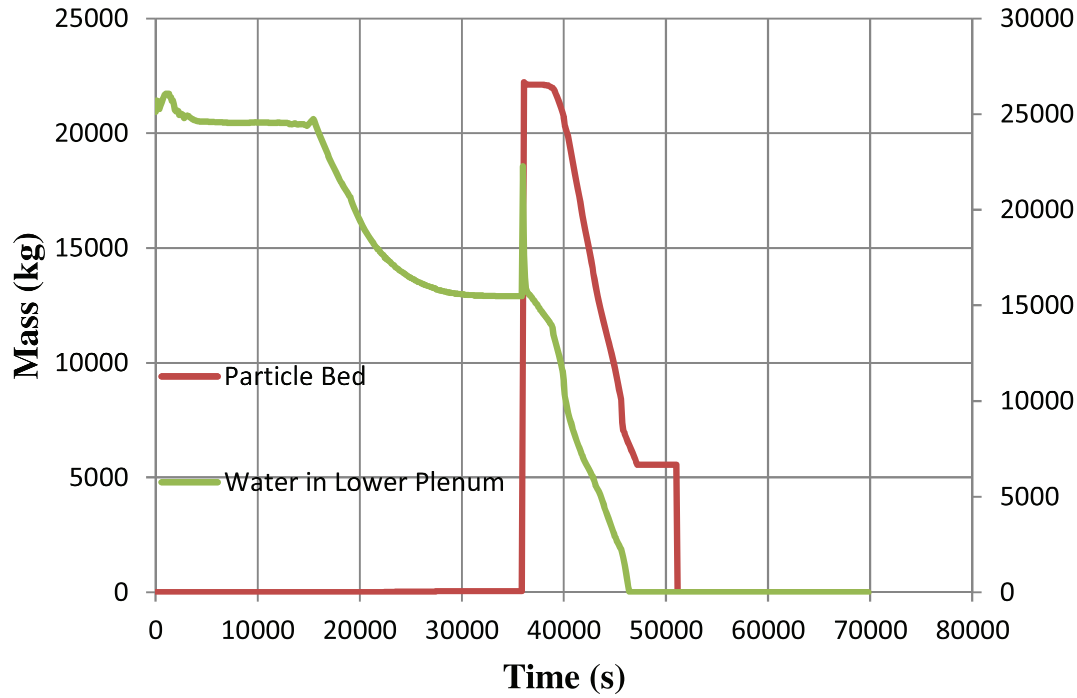

Figure 10. **Mass of Particle Bed and Water in Lower Plenum**

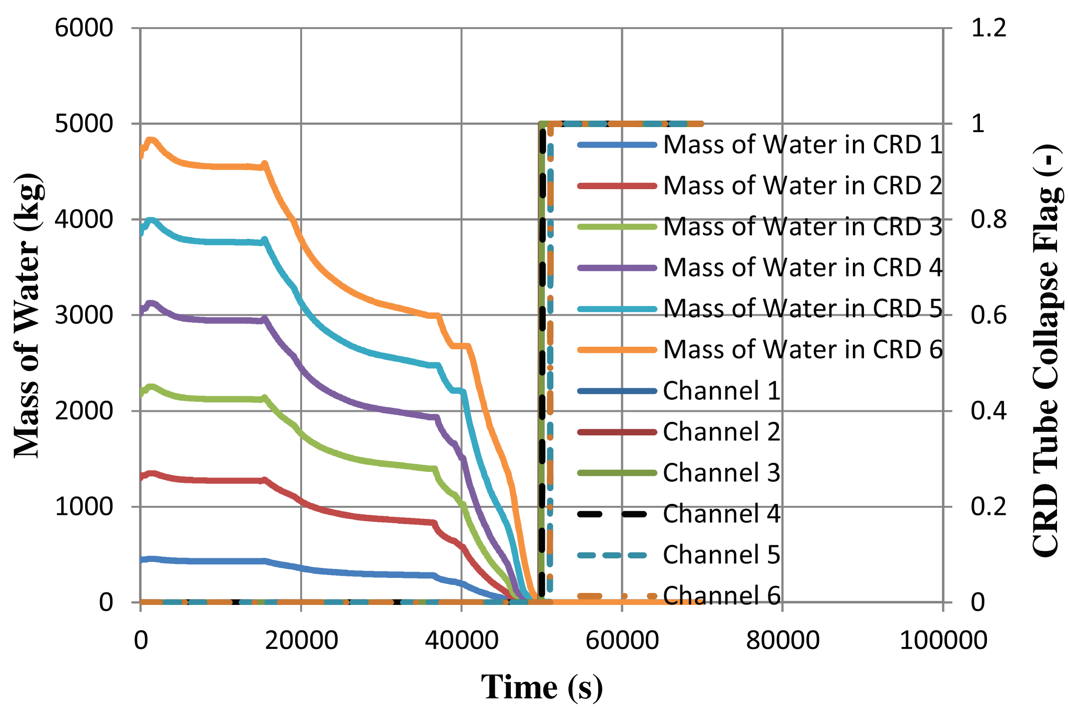

Figure 11. CRD Water Mass and Tube Collapse Flag

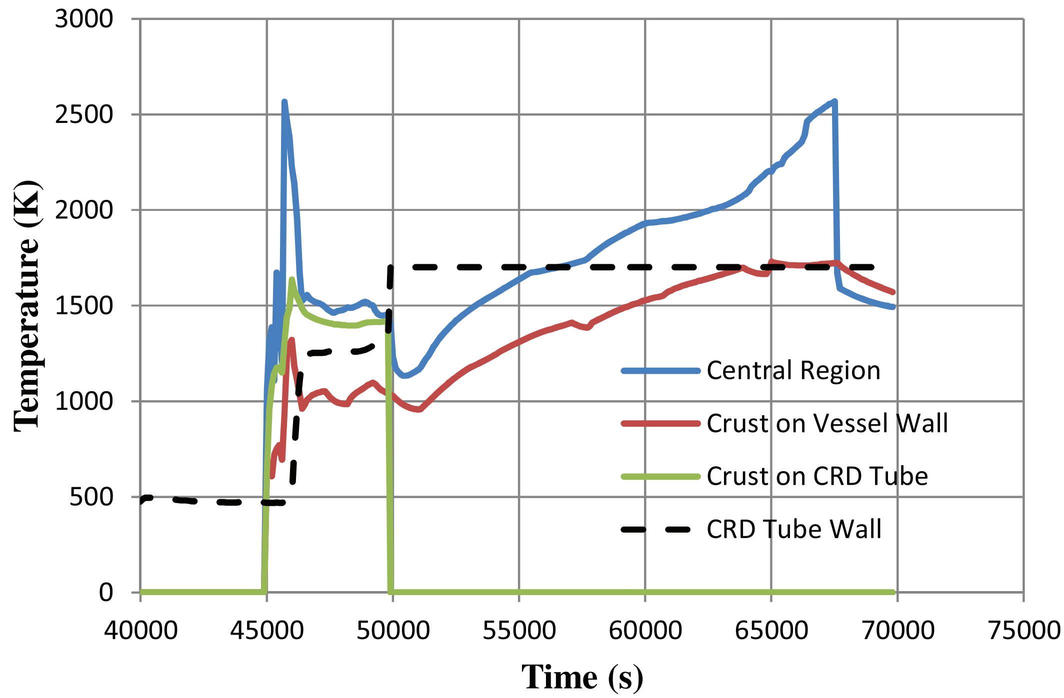

Figure 12. Temperatures in Layer 10

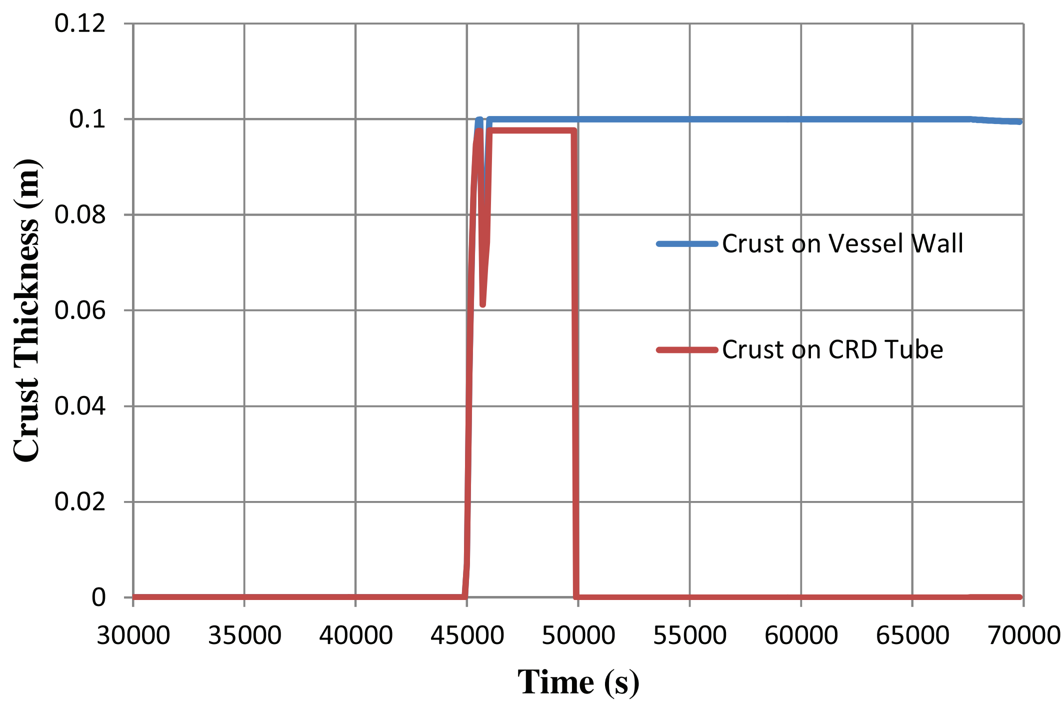

Figure 13. Crust Thicknesses in Layer 10

Figure 14 and Figure 15 show the central region and crust temperatures in each layer. The first layer central region temperature is not shown because the first layer is completely occupied by crust and there is no central region. Debris in layers up to layer-9 is quenched by the water in the lower plenum. Once the lower plenum dries out, the debris heats up gradually due to decay heat. Note that layer-18 disappears when the debris bed shrinks. This occurs because molten metal leaves the continuous debris bed to join the metal layer. Layer mixing promotes uniform temperature in contiguous layers once the layer temperature reaches the solidus temperature.

Figure 16 shows the mass of the metal layer. As the layer temperature exceeds the metal melting point, the molten metal in the layer rises to the next layer up and eventually joins the metal layer at the top of the debris bed. When the crust average temperature exceeds the metal melting point, the metal in the crust is added to the central region in the layer. The metal layer is continuously cooled by a small water injection (0.28 kg/s) in the core.

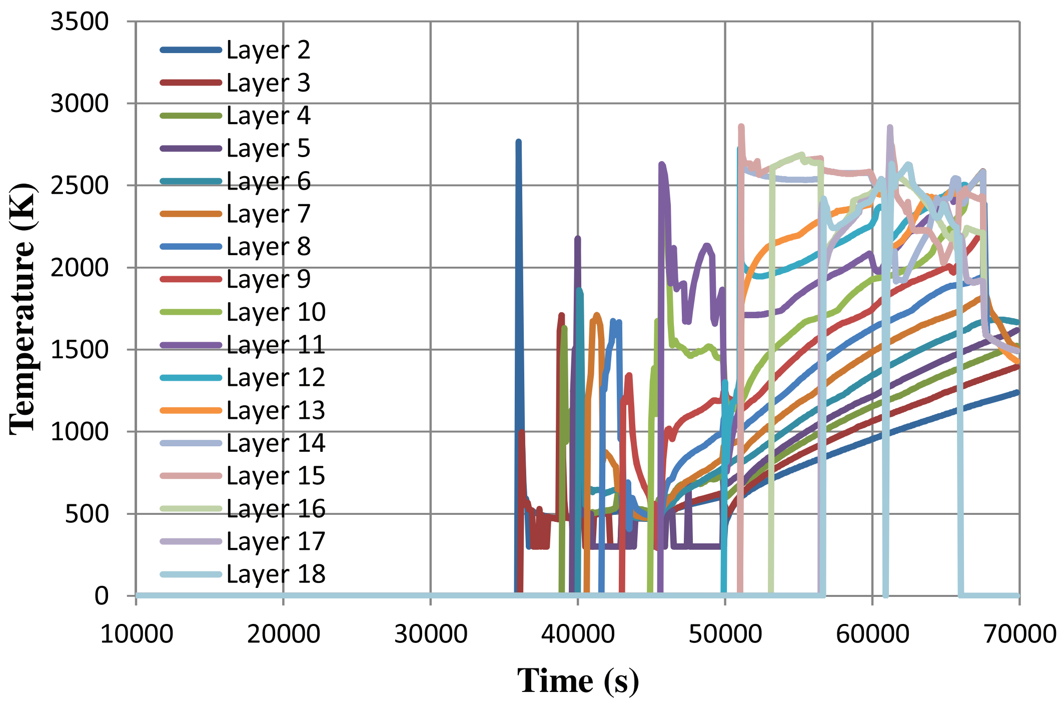

Figure 14. Temperature of Central Region ("Molten Pool") in Each Layer

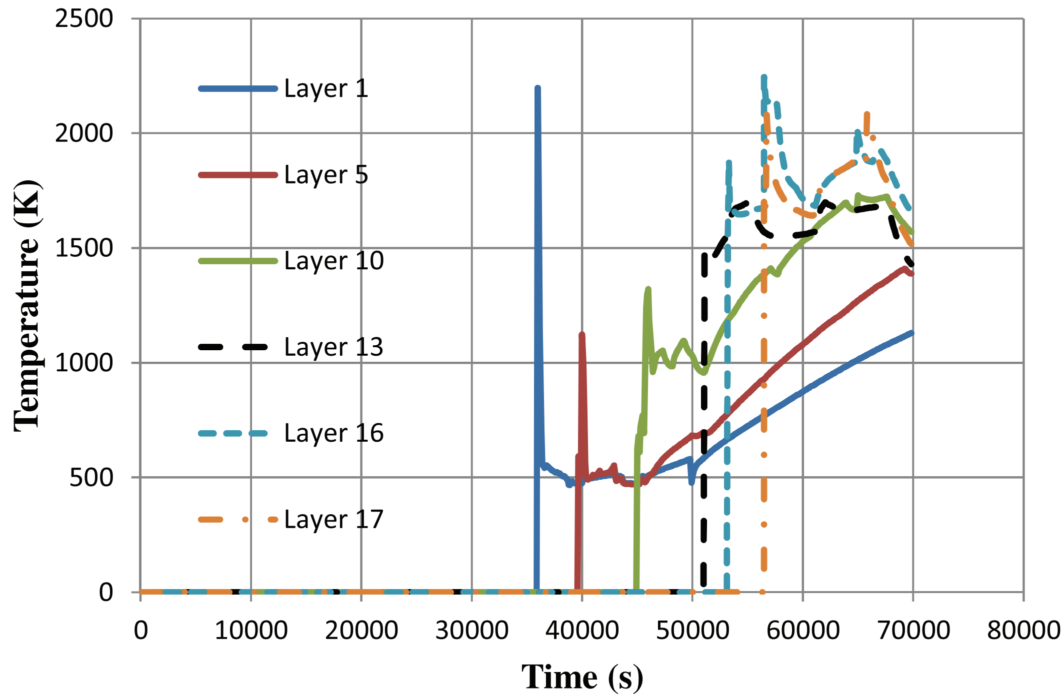

Figure 15. **Temperature of Crust on Vessel Wall in Each Layer**

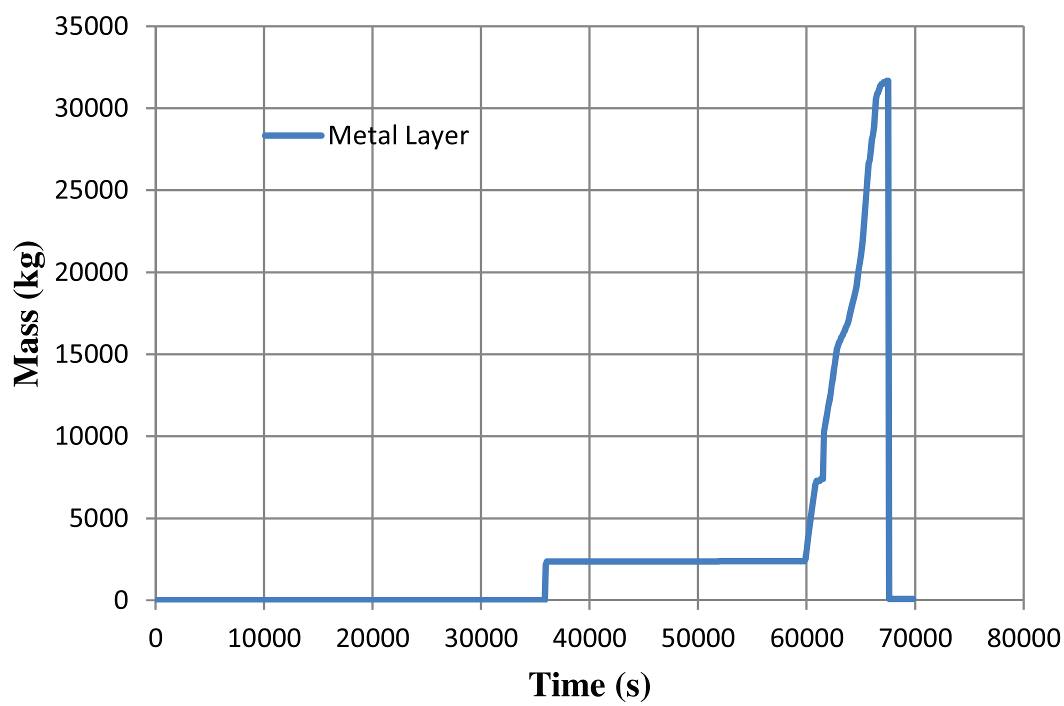

Figure 16. **Mass of Metal Layer**

4. CONCLUSIONS

In the new model, the particle bed in the lower plenum is nodalized into radial rings and the CRD tubes are nodalized into radial rings and axial nodes. The oxidic debris bed is axially nodalized corresponding to the vessel lower head axial nodalization. The layering model results of the Fukushima Dai-ichi Unit 1 accident show that early relocated corium is quenched whereas the late relocated corium remains molten. It also shows delayed formation of the metal layer as the quenched debris re-melts and the metal mass in the debris rises to join the metal layer on the top of the debris bed. The single pool model cannot capture these details.

The lower plenum model was validated against the LIVE experiments [5]. The lower plenum model can be improved further in following areas:

- Extend the corium pool convection model (Figure 5) to mechanistically model the local flow, heat transfer and entrainment rates in the boundary layer. Currently, they are constructed based on the well known heat flux distribution correlation for a semicircular heat generating pool reported by Jahn and Reineke [4].

- Radially nodalize the crusts and track the temperature and mass composition in each radial node in the crust. Currently, the lower crust is nodalized only in axial direction along the vessel wall. Such a model can be used for more accurate evaluation of the thermal response of the reactor pressure vessel penetrations submerged in molten core debris.

- Determine the appropriate corium pool boundary temperature based on the local mass composition in the curst. Currently, the code user decides whether to impose the solidus or liquidus temperature at the corium pool boundary.

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