BWR Lower Plenum Debris Characterization, Stabilization, and Ex-Vessel Transport

R. Wachowiak, T. Kindred,
Electric Power Research Institute (EPRI)
1300 West WT Harris Blvd
Charlotte, NC 28262
rwachowiak@epri.com, tkindred@epri.com

ABSTRACT

The three core damage events at Fukushima Daiichi were the first severe accidents to occur in a Boiling Water Reactor (BWR). The forensic reconstruction and evaluation of these events have found varying degrees of ex-vessel damage. The timing of core damage and attempts to recover and stabilize the degraded core were significantly different at each unit. The core damage events at Units 1, 2 and 3 provide unique perspectives on the response of core debris in the lower plenum and the characteristics of accident response strategies most likely to support stabilization of a large fraction of core debris inside the reactor vessel.

Fukushima Daiichi Unit 1 had the earliest progression to core damage with essentially complete ex-vessel debris relocation. Water injection was not provided until a few days after the initiating event. Unit 3 has substantial ex-vessel debris relocation, with substantial damage observed to below-vessel structures. Water injection to the Unit 3 reactor was provided but interrupted for periods of time. Unit 2 has a substantial mass of debris retained within its lower plenum. Reactor water injection, at times degraded, was provided continually.

To investigate the impact of these distinct accident progression mitigation characteristics, the MAAP5 computer code has been enhanced over the past few years with support from the Japanese Ministry of Economy, Transportation and Industry (METI). Refined modeling of lower plenum debris beds to capture axial distributions of molten debris, together with enhancements to the relocation of partially molten debris out of failures in the lower head wall, have been incorporated into MAAP5.

These MAAP5 refinements indicate the following. 1) The rate of relocation out of an initial vessel failure is governed by the initial supply of melt. Subsequent relocation is dominated by the debris melting rate. 2) Without water injection, continued debris melting causes a cascade of local failures in the lower head wall. Ultimately, gross creep failure of the lower head wall is likely to occur as observed at Unit 3. 3) Continuous water injection maintains debris in a more coolable particulate form. Interruption of water injection leads to melting throughout the lower plenum debris bed. This reduces water ingress into the debris bed, diminishing the potential to arrest lower head creep failure. This appears to be a key factor distinguishing Unit 2 from Unit 3.

KEYWORDS
Boiling Water Reactor (BWR)
Corium
Lower Plenum
Modular Accident Analysis Program (MAAP)

1. INTRODUCTION

The three core damage events at Fukushima Daiichi were the first severe accidents to occur in a Boiling Water Reactor (BWR). The forensic reconstruction and evaluation of these events have found varying degrees of ex-vessel damage. The timing of core damage and attempts to recover and stabilize the degraded core were significantly different at each unit. The core damage events at Units 1, 2 and 3 provide unique perspectives on the response of core debris in the lower plenum and the characteristics of accident response strategies most likely to support stabilization of a large fraction of core debris inside the reactor vessel.

The Modular Accident Analysis Program (MAAP) [1], developed by the Electric Power Research Institute (EPRI), is one of the most widely used severe accident simulation codes used by the nuclear industry. It was extensively benchmarked using the Three Mile Island 2 (TMI-2) accident from 1979. The configuration of TMI-2 is quite different than those of Fukushima and other BWRs. Most notably, there are numerous penetrations in the bottom of a BWR vessel and there are pipes (Control Rod Drive (CRD) Tubes) filled with water in the lower plenum. These features can have a significant influence on the behavior of core material in the lower plenum.

Following the investigation of the Fukushima Daiichi events, the MAAP5 computer code has been enhanced over the past few years with support from the Japanese Ministry of Economy, Transportation and Industry (METI). Refined modeling of lower plenum debris beds to capture axial distributions of molten debris, together with enhancements to the relocation of partially molten debris out of failures in the lower head wall, have been incorporated into MAAP5.

2. EVOLUTION OF THE MAAP LOWER PLENUM MODEL

In legacy MAAP versions (v5.02 and prior) the abstraction of the lower plenum was a fully developed molten corium pool. This was a simplifying assumption based on the observations at TMI-2. Following the investigations and expert discussions of the Fukushima Daiichi Units 1, 2, and 3 events, a new MAAP Lower plenum model was developed to remove many simplifying assumptions and more accurately model the phenomena occurring in the lower plenum. These changes took place over several versions of the MAAP code, from version 5.03 to the upcoming 5.05, as new information from the Fukushima Daiichi events became available. Figure 1 shows the evolution of the lower plenum model from legacy through version 5.04. MAAP 5.05 did not change the lower plenum model, rather insights into the failure and relocation mechanisms were investigated.

2.1. MAAP 5.02 Lower Plenum Concept

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

1. 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 metal layer or the oxide pool.
2. 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. This model did not account for mixing of molten metal with particles or the oxide pool.
3. 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 and a central molten region. Embedded crust formed on CRD tubes.

The CRD tubes in the vessel 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 and were added to the metal layer inside the vessel[1].

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.

[1] Failure of the CRD penetration is considered in a separate part of the code and is not covered here.

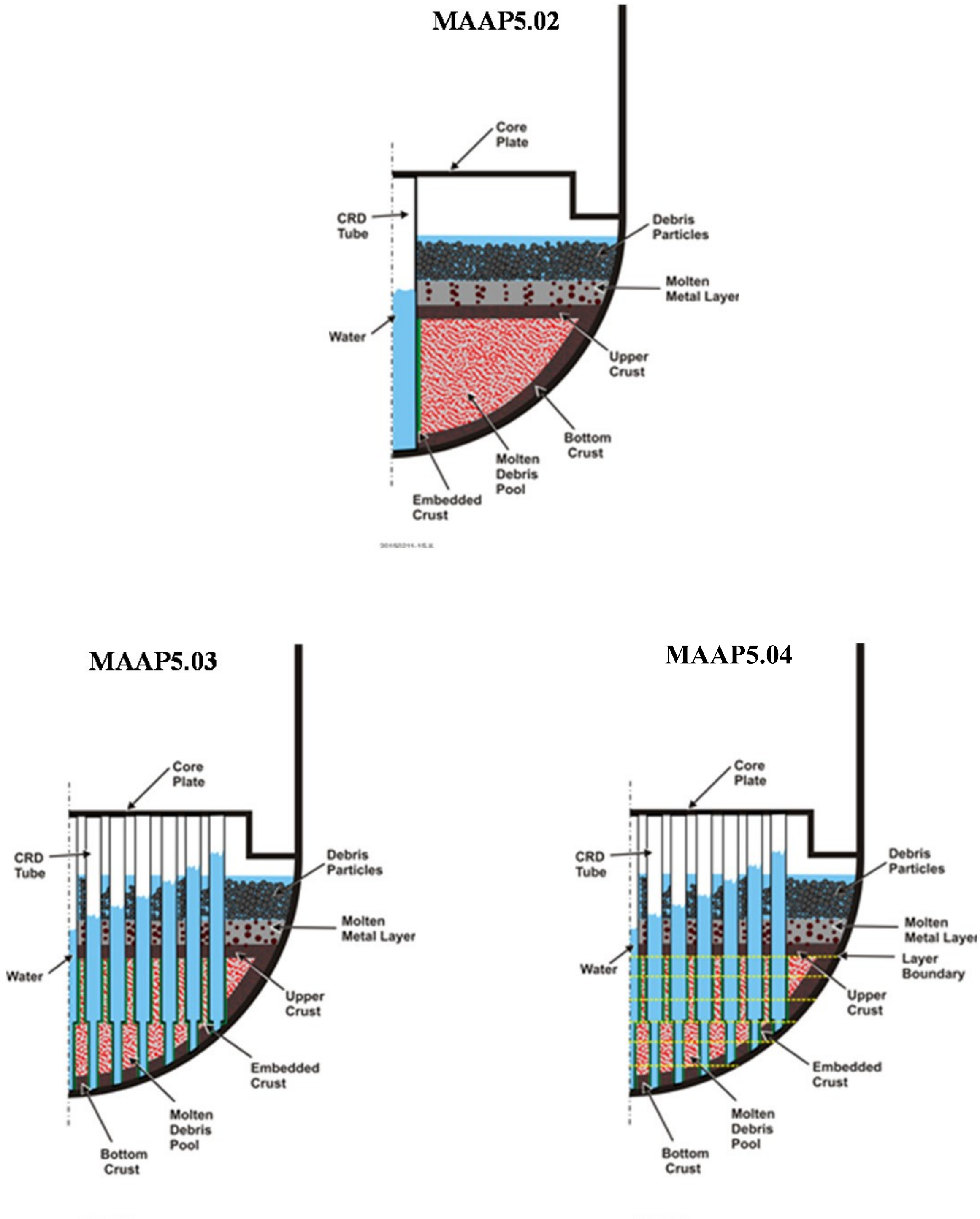

Figure 1 - Lower Plenum Model Evolution

This fully developed pool concept tends to lead to very high temperature debris at the time of vessel breach, very fast ablation of the vessel during the pour, and very fast relocation times that have historically been predicted in MAAP simulations.

2.2. MAAP 5.03 Lower Plenum Concept

In the MAAP 5.03 lower plenum model, like the MAAP 5.02 model, the debris bed consists of the particle bed, a metal layer, and an oxidic pool, arranged from highest elevation to lowest, respectively. The particle bed, however, is nodalized into radial rings consistent with the core radial nodalization. The mass and energy in each particle bed node are tracked. One metal layer is tracked. The oxidic pool in turn consists of the top crust, multiple bottom crusts, multiple embedded crusts, and the central molten region. One lower curst is defined for each vessel lower head (axial) node. The embedded crusts form on CRD tubes. Since the CRD tubes are axially and radially nodalized according to the vessel lower head axial nodalization and according to the core radial nodalization, there are corresponding multiple embedded crusts. Although the mass and energy are tracked in each crust, the material composition is assumed to be same in the crusts and in the molten oxidic pool.

In the MAAP 5.03 lower plenum model, the relocating corium jet breaks up into particulates in the water in lower plenum, if water exists. MAAP allows for the user to select which jet breakup model is used, including a particulate size selected by user input. All the particles are assumed to be of uniform size. The particulates are quenched by the water and combine with the particle bed, spreading over the radial channels in the vicinity. The intact jet is segregated between metals and oxides. The oxides form the oxidic pool and the metals are deposited into the metal layer. The oxidic corium freezes on the vessel and CRD tube wall and form the crusts. Figure 1 shows the lower plenum model in MAAP 5.03.

This concept is still very representative of a fully developed molten pool. As such, the melt temperatures and pour rates are similar to MAAP 5.02. One major difference is that the support for the core plate is more realistically modeled. Rather than one combined CRD tube in the model, multiple tubes are represented. This allows MAAP to better calculate when individual rings of the core plate would fail due to lack of support from below.

2.3. MAAP 5.04 Lower Plenum Concept

The MAAP 5.04 concept is a significant departure from previous versions. The fully developed pool model is removed and a layering model, with different compositions and temperatures, is used instead.

Early-arrival corium may be submerged in water and rapidly quenched based on heat transfer from the particle bed, converting the water to steam. As an accident progresses, the amount of liquid water decreases until all of the water has been converted to steam. Late-arrival corium may contact little or no liquid water. As the level of liquid water in the lower plenum decreases, corium entering the lower plenum forms layers of differing temperature and composition.

In this concept, the oxidic debris bed is axially nodalized according to the vessel lower head axial nodalization. The material composition and energy in each layer are tracked. The material composition in an individual crust is also tracked separately. For a group of contiguous molten layers (a molten pool), the average temperature and solid fraction of the molten pool are determined and used for convective heat transfer in each layer. For an isolated single molten layer, the layer temperature and solid fraction are used for convective heat transfer. Figure 1 shows the new lower plenum model. By layering the material arriving in the lower plenum, the history of different material relocations to the lower plenum can be preserved and used for more accurate assessment of the vessel wall response. For example, during the TMI accident the first material that reached the lower head contained both ceramic and metallic material, which formed basal crust structure that survived to protect the lower head. Also, the “hot spot” evaluation is possible when molten debris comes in direct contact with the vessel wall, either due to the absence of a protective layer or by disruption of the crust as shown in Figure 2. This 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. A binary phase diagram is included in the model to estimate the amount of solid and liquid in the melt. 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 3). All or part of the particle bed may be submerged in the metal layer or the oxide pool.

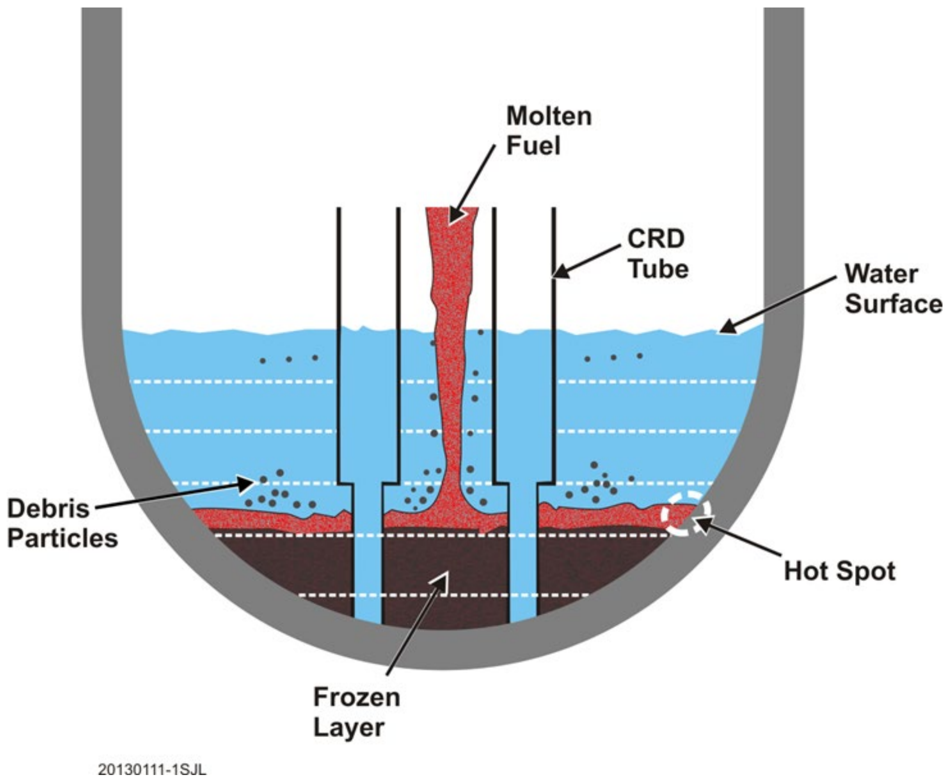

Figure 2 - Stratified Layers in Debris Bed

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.

In this model, the intact corium jet is allowed to submerge the existing particle bed. The submerged particles become part of the debris layer instead of having the particle bed artificially raised when new corium is added to the lower plenum.

Initially, the debris layers are cooled by water in the embedded CRD tubes and water above the corium pool. The water in the lower plenum and in CRD tubes boils off gradually due to decay heat from the core debris. After the water in the lower plenum and in CRD tubes has boiled off, the CRD tube walls heat up and fail by are assumed to fail by creep, as shown in Figure 4, using a Laron-Miller type of formulation using input parameters provided by the user. The failed CRD tube walls become part of the debris layers. The debris layers are repacked to fill the void left by failed CRD tubes. Fuel channels supported by failed CRD tubes may collapse and relocate to the lower plenum based on a calculation of the local strength of the core plate.

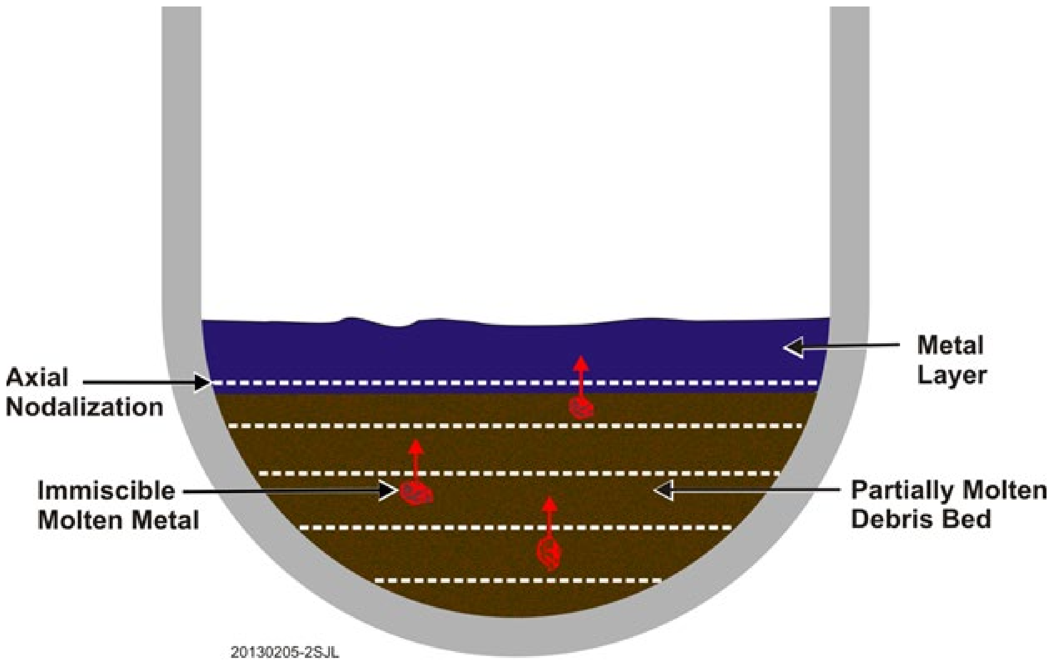

Figure 3 - Formation of Metal Layer

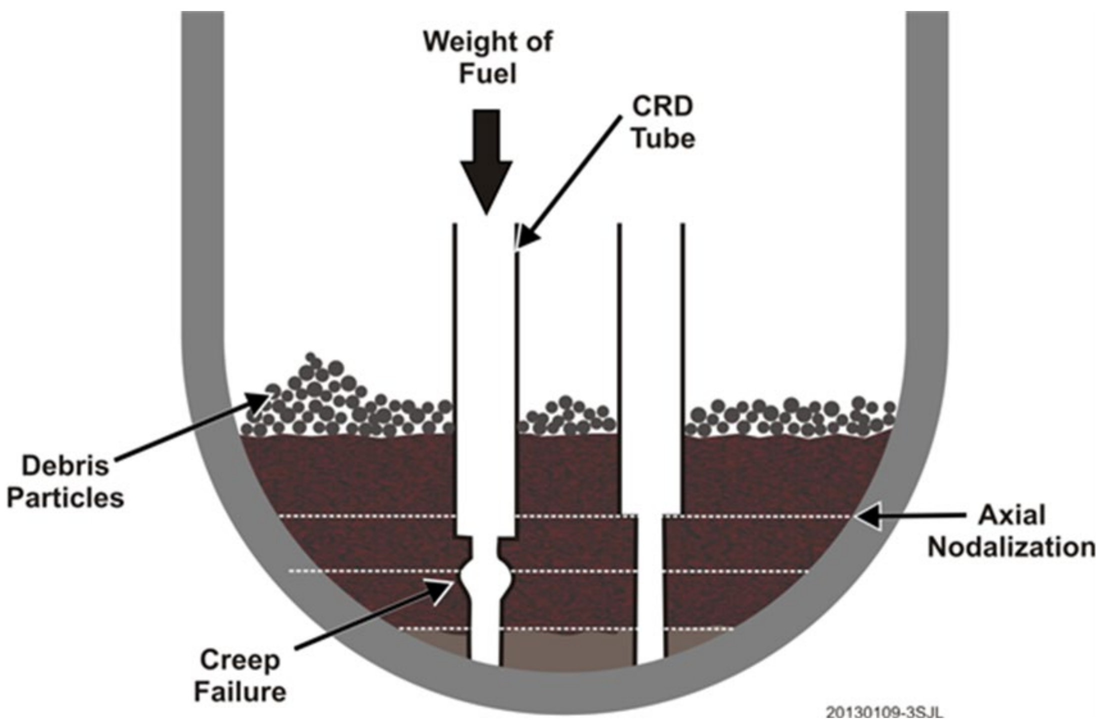

Figure 4 - CRD Tube Creep

The debris bed continues to heat up and begins to melt. A partially molten debris layer is divided into a solid crust on the vessel and CRD tube surfaces and a molten pool. When two or more adjacent layers become molten, the corium pool convection model is invoked. A global circulation develops in the corium pool surrounded by crusts. Mass and energy flow between layers are dictated by the circulation flow rate and the heat transfer rate to the crust on the pool boundary. This model is particularly important when vessel failure is either delayed or prevented by ex-vessel cooling and the debris is allowed to melt and develop a global circulation flow pattern.

The most important consequence for this model change is the characterization of the melt that leaves the vessel. Because the global molten pool is not assumed at the onset, the melt pour tends to be cooler and has a smaller impact on the containment. This will be discussed further in section 3 to tie this back to the observations at Fukushima.

3. EX-VESSEL RELOCATION ASSESSMENT

This paper outlines model enhancements that refine the MAAP5 calculation of debris relocation out of a breached RPV lower head and transport to the containment floor. The refined assessment of these processes is necessary to enable the realistic calculation of debris distribution at Fukushima Daiichi. Such realistic calculation of debris distribution between the RPV lower plenum and containment for partially mitigated accident scenarios has not typically been required for developing source terms for Level 2 PRAs. Thus, current MAAP5 models for this phase of core damage progression have typically been more approximate, typically biased toward maximizing the challenge to containment during the period after RPV lower head breach.

Modeling the progression of a severe accident after the breach of the lower head requires evaluation of how corium relocates out of the breached RPV lower head, interacts with structures underneath the vessel and ultimately spreads over and attacks the concrete containment floor.

TMI-2 provides a reactor-scale example of lower plenum debris response. However, this accident occurred under water. The debris in the lower plenum at TMI-2 remained cooled and did not pose a challenge to the lower head integrity. As a result, TMI-2 provides no information at reactor-scale relevant to assessing ex-vessel debris relocation modeling when injection of water is delayed. By contrast, the core damage events at 1F1, 1F2 and 1F3 provide 3 different BWR core damage events, each with varying degrees of core damage and conditions relevant to ex-vessel debris relocation modeling.

1F1 is an example of core damage progression without any mitigation. The relocation of debris into the containment is likely extensive. However, the degree of debris spreading through the containment is more limited than would be expected from a more bounding estimate of debris relocation from a breached lower head. Even though the relocation of debris from the lower plenum is significant for 1F1, the relocation of debris appears to be slower and at lower temperature than typically estimated by MAAP5 versions 5.04 and earlier.

1F2 is an example of a core damage event in which water injection could maintain significant fractions of core debris in the lower plenum. Muon tomography imaging suggests that as much as 80% of the core was retained in the lower plenum. Robotic investigations in the reactor pedestal indicate that relatively limited damage occurred due to a small amount of debris relocating from a failure at the periphery of the lower plenum. While lower head wall failure can occur, 1F2 suggests that significant amounts of debris can be retained in the lower plenum.

1F3 by contrast to 1F2 likely had significant amounts of debris relocating into containment. Robotic investigations taken by TEPCO illustrate the extensive damage to structures in the reactor pedestal.

Compared to 1F2, 1F3 had periods of water injection being interrupted. Thus, re-melting and relocation of debris ex-vessel likely occurred at 1F3. MAAP 5.04 modeling indicates lower plenum debris conditions at the time of vessel breach that could support the above observations. Figure 5 shows the results of a single 1F3 like simulation the solid fraction in each of the axial layers in the lower plenum. It shows substantial amounts of solid debris (80% or more) remaining in the lower plenum at the time of initial vessel breach in the simulation (at around 70 hrs). As a result, vessel breach does not necessarily lead to substantial amounts of debris relocation. Rather, initial vessel breach opens a hole in the lower head wall through which melting debris can subsequently relocate. This supports slower rates of debris relocation than previously found in MAAP5 simulations as well as a greater potential for lower plenum debris to be stabilized by water injection subsequent to initial vessel breach.

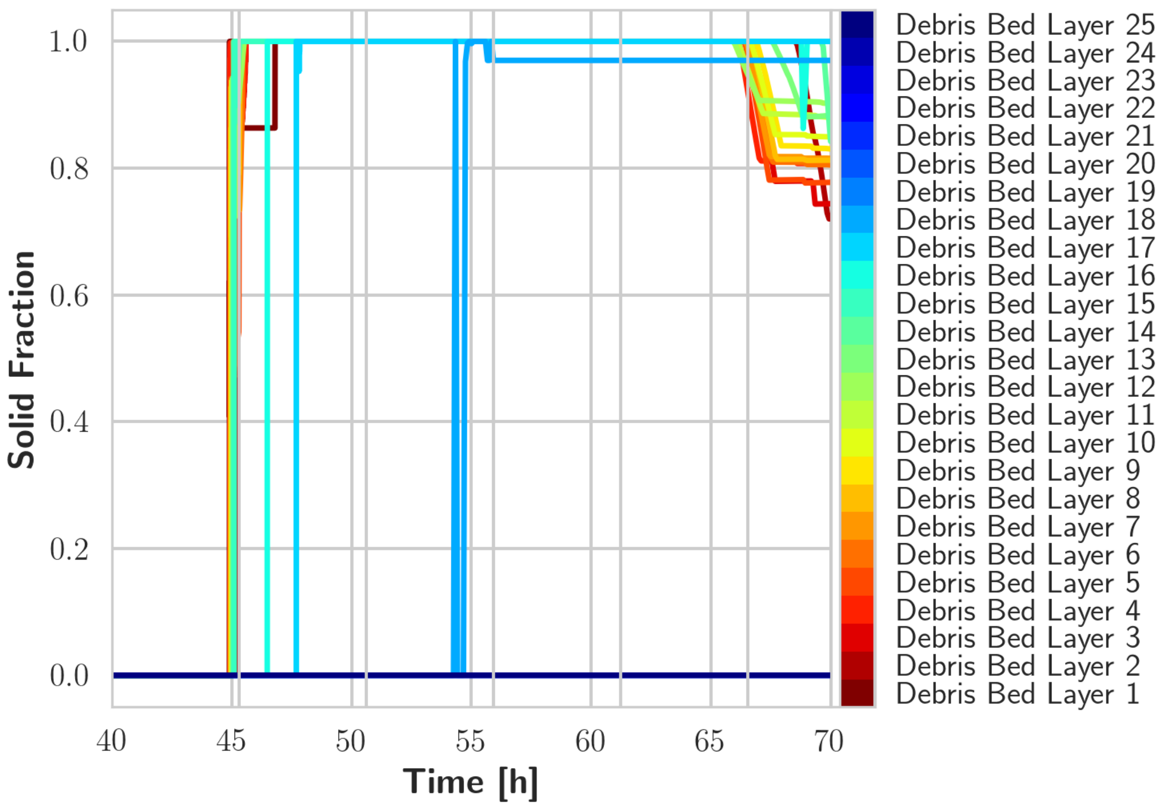

Figure 5 - 1F3 Like Lower Plenum Debris Bed Axial Solid Fraction

3.1. MAAP 5.05 Lower Plenum Concept

The modeling of ex-vessel debris relocation requires evaluation of the following distinct characteristics for debris motion out of a breach RPV lower head:

- Amount of relocatable debris
  How much debris above a lower head failure is liquid (or mobile) enough to flow out of the break?
- Incorporation of solid debris within the relocatable debris mass
  For debris beds with relatively large solid fractions, how do the solids move together with molten debris to the failure?
- Viscosity of relocatable debris

For debris beds with relatively large solid fractions, assuming liquid and solid material are mixed into a homogenous fluid, the viscosity of this fluid is relatively high. How does the fluid viscosity affect the rate of transport of lower plenum debris to the failure opening in the lower head wall?

- Flow pathway to lower head failure for relocatable debris
  Alternatively, under the assumption that liquid and solid debris motion is separated (i.e., there is a high slip velocity between the two constituents), the motion of the liquid through the solid matrix is likely to be significantly impeded. In this manner, even under the condition of a purely liquid motion, the effective viscosity of the molten debris could be quite high. How can the flow pathway be characterized under a condition of largely molten flow out of the breached lower head?
- Velocity of debris relocation within lower plenum
  Relocating debris can only move to the lower head wall failure opening at a rate determined by the fluid velocity. This is a combination of the extent to which fluid motion is resisted by either fluid viscosity or a flow medium (the solid debris matrix) that limits the free flow of viscous fluid. What is the velocity of flowing corium within the lower plenum?
- Area for relocation out of lower head failure
  The opening area in the lower head wall impacts how much mass can move out of the lower plenum at any one instant. The motion of hot debris past the lower head wall, however, generates ablative heat fluxes that tend to melt the carbon steel in contact with the debris stream. As a result, the relocation of debris through a lower head opening has the effect of increasing this opening area. Legacy models were formulated under conditions similar to high pressure melt ejection scenarios, which are quite distinct from the conditions of a low pressure vessel breach scenarios like at Fukushima Daiichi. How can the ablative heat fluxes be quantitatively characterized?
- Rate of relocation of debris to lower head failure location
  The combination of the above characteristics impacts the amount of debris that can relocate to and out of the failure opening in the lower head wall.

The following assumptions are made in formulating the modeling approach for enhancing ex-vessel debris relocation modeling in MAAP 5.05:

- Corium can be treated as a Newtonian fluid
- Variations in the debris thermo-physical state occur primarily along the axial direction in the lower plenum debris bed
- A single axial layer in the lower plenum debris bed is assumed to move to the lower head failure location at the same velocity
- Debris streams can be represented as two classes for model sensitivity evaluations
  1. A debris slurry in which the molten and solid debris is assumed to be a homogeneous mixture such that there is no slip between the moving solid and liquid (see Figure 3-4)
  2. A separated liquid stream (with some solid inclusions) moving through a static flow matrix formed by the remaining solid debris material
- Debris motion in the lower plenum does not result in sufficient convective heat fluxes to melt solid material in the lower plenum
- Debris layers that can relocate out of the vessel via the closest lower head node failure below the respective debris layer
- The light metal layer is assumed to only be relocatable once the continuous oxide debris bedhas relocated out of the vessel
- The particulate debris bed is assumed to not relocate until an extensive failure has occurred or it has melted into the continuous oxide bed.

Figure 6 illustrates the process used in this model.

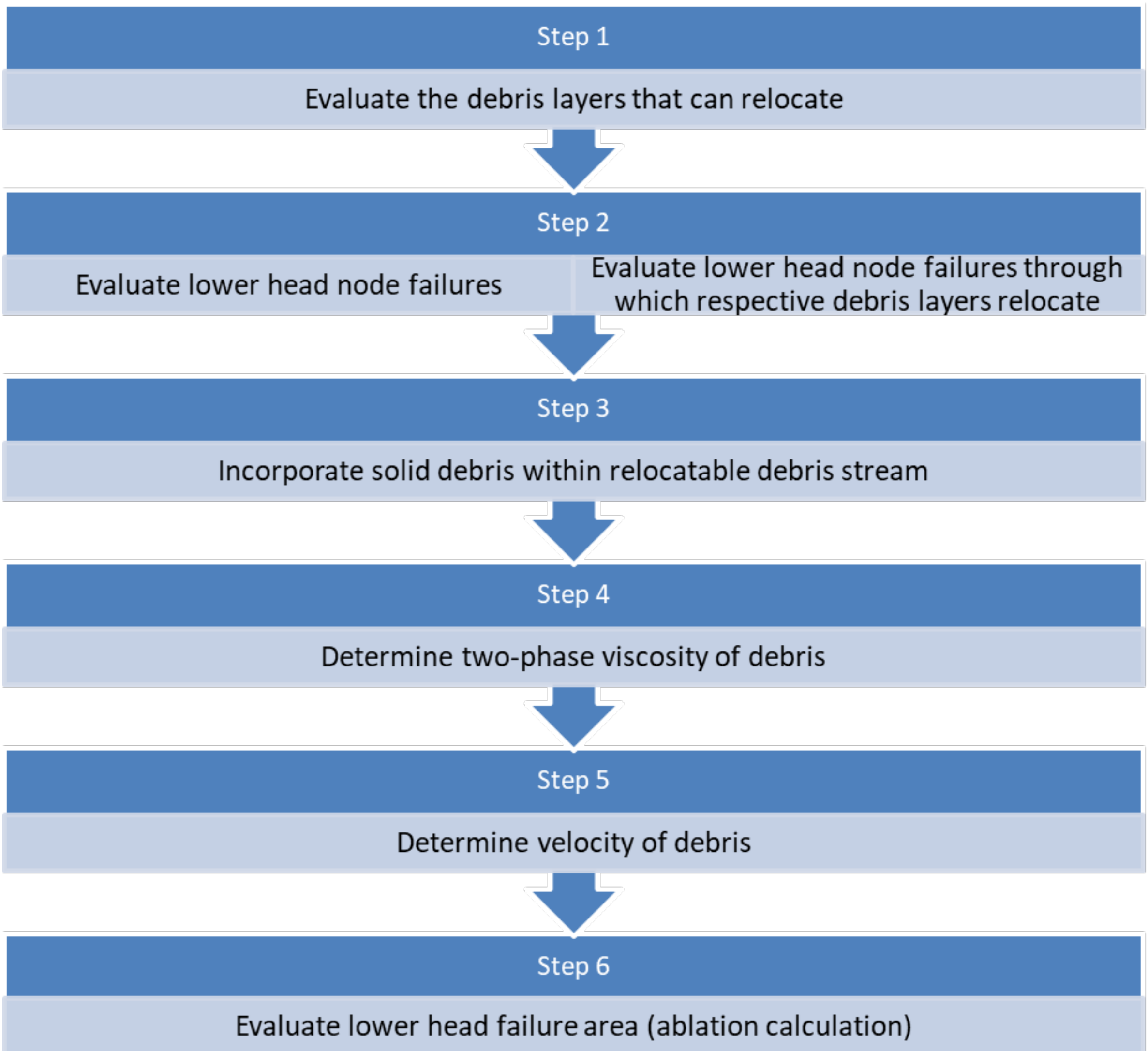

Figure 6 - Evaluation Steps for Ex-Vessel Debris Relocation Module

3.1.1. Evaluation of relocatable debris

The total mass of debris in an axial layer is the sum of solid (m_s) and liquid (m_l) material $m_{tot}=m_s+m_l$. The solid fraction of debris is defined as the ratio of solid debris mass to total debris mass.

The total mass of debris that is relocatable is defined in two different ways in this model.

1. Molten Relocation: The relocatable debris is primarily molten with some fraction of the solid debris entrained in the flowing molten mass.
2. Slurry Relocation: The relocatable debris is treated as a homogeneous mixture of the solid and liquid debris in a layer (i.e., a slurry) with a variable amount of solid debris assumed to be entrained in the slurry.

In both cases, the relocatable debris is evaluated in the following manner. The lowest debris layer that can relocate is determined by the lowest node in the lower head that has failed. The highest debris layer that can relocate is assumed to be at the top of the debris bed. The light metal layer can only relocate once the continuous oxide debris bed has relocated out of the vessel. And the particulate debris bed does not relocate unless an extensive failure has occurred or it has melted into the continuous oxide bed.

3.1.2. Evaluation of lower head failure nodes for relocation

As noted above, assumptions regarding lower head node failures that are "active" for different debris layers are made to simplify the overall process. A detailed flow calculation that accounts for motion of debris within the lower plenum is not implemented as part of this model. This added complexity is judged to not be critical to representing the overall effects in the containment. As a result, failed lower head nodes are mapped to debris layers as the active node through which debris in these respective layers can relocate. A relatively simplified logic adopted.

- A debris layer is assigned to the closest underlying failed lower head node for relocation.
- When a penetration failure is the governing mode of failure for the lower head node, the failure area has a circular cross-section
- When a creep failure of the lower head node becomes active, the failure area has a rectangular cross-section
- Following vessel failures in multiple layers an extensive failure is assumed to occur:
  - This failure is in the first lower head node
  - The area of the failure has a rectangular cross-section
  - All debris layers above this failure relocate out of this opening
  - The overlying metal layer relocates out of this lower head node failure
  - The particulate debris relocates out of this lower head node failure

3.1.3. Incorporation of solid debris within relocatable debris volume

The debris bed is assumed to be segmented in ways that would alter the overall solid fraction of debris available to relocate out of the lower plenum. It is assumed that a fraction of the exiting liquid debris stream consists of solid particulate. The total solid fraction in the debris stream relocating out of the vessel from a given layer is defined by a user parameter.

This parameterization has been chosen because it is a convenient way to express how much solid material is present in the actual debris stream. During testing of the model, different approaches to parameterizing the inclusion of solid material in the relocating debris stream were explored. Ultimately, this parameterization was chosen as the most natural means of capturing different degrees of solid inclusion in a relocating debris stream. The testing also provided a basis for a the fraction of solid moved value around 10% to 20%. Checks exist in the code such that there cannot be more solid mass included than actually is present.

Because many cases in MAAP 5.05 simulations typically have large amounts of solid fraction in a layer, it is desirable to incorporate solid debris into the relocating debris stream that is scaled based on how much liquid mass is available. Under situations with low amounts of liquid mass, small amounts of solid particulate should be available to leave to leave the vessel.

3.1.4. Viscosity of relocatable debris

Molten debris without any solid inclusions has a viscosity that is the mixture viscosity of the material components. This viscosity is calculated by MAAP. As solids are included in the lower plenum debris bed, the viscosity will be altered. This can be performed using different options already present for calculating viscosity in the MAAP5 code.

3.1.5. Velocity of debris relocation to lower head failure

As noted above, two different relocation modes are identified for evaluating debris flow to the lower head failure. These reflect uncertainties in characterizing the overall nature of debris flow to the failure location given uncertainty in state-of-knowledge regarding lower plenum debris bed dynamics as well as simplifications in the formulation of the lower plenum debris modeling in MAAP5.

The lower plenum continuous debris bed is characterized in a manner where it is assumed to homogeneous across the radial extent of each debris layer. Variation of the debris thermo-physical state is treated only in the axial direction in the MAAP5 extended lower plenum debris bed model. Given the large radial extent of the BWR lower plenum, there is likely appreciable variation in the thermo-physical state of the continuous debris bed along the radial extent of the lower plenum.

Different approaches to evaluating the motion of molten debris to the lower head failure location are provided. These different modeling options reflect overall uncertainty in charactering the nature of the lower plenum debris bed and the associated debris flow to the failure location. These modeling options are provided to facilitate evaluation of their impact on MAAP5 simulation results of relevance to overall plant response and ultimately parameters of interest in decision-making.

The following methods to calculate relocating molten debris velocity are provided:
- Bernoulli flow
- Flow of viscous fluid through a channel
- Flow of viscous fluid through a particulate

The relocation of a slurry is governed by the following:
- Density of corium
- Height of the debris bed
- Corium viscosity
- Effective length of debris passage through the lower head failure opening
- Radius of the failure opening in the lower head wall

The specific equations and user parameters are defined in the MAAP 5.05 User Manual.

3.1.6. Evaluation of lower head failure area

The interaction of a stream of relocating debris with the vessel wall can result in ablation of the wall. As a result, the failure area can grow with time during debris relocation out of the failure in the lower head wall. The temperature of the convective boundary layer in the debris has in the past been assumed to be the stainless steel melting point This assumption was based on work by Sandia National Laboratories related to high pressure melt ejection. For this scenario, the development of a stable boundary layer between the debris and the carbon steel wall is less likely. As a result, the temperature gradient driving convection within the debris can be assumed to be the difference between the bulk debris temperature and the carbon steel melting point. In contrast, for low pressure scenarios, the establishment of a boundary layer of solid debris (or crust) between the bulk debris and the carbon steel is more likely. The temperature difference driving convection could thus be limited by the crust/steel interface temperature. This is most likely to be the solidus temperature of the debris. This is subject to uncertainty, so the model incorporates an option to set this interface temperature to either the debris solidus or liquidus temperatures.

4. CONCLUSIONS

These MAAP5 refinements indicate the following. 1) The rate of relocation out of an initial vessel failure is governed by the initial supply of melt. Subsequent relocation is dominated by the debris melting rate. 2) Without water injection, continued debris melting causes a cascade of local failures in the lower head wall. Ultimately, gross creep failure of the lower head wall is likely to occur as observed at Unit 3. 3) Continuous water injection maintains debris in a more coolable particulate form. Interruption of water injection leads to melting throughout the lower plenum debris bed. This reduces water ingress into the debris bed, diminishing the potential to arrest lower head creep failure. This appears to be a key factor distinguishing Unit 2 from Unit 3..

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