FORMULATION AND USE OF UNCERTAINTY AND SENSITIVITY ANALYSES

Uncertainty Working Group of the MAAP User's Group

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1.0 INTRODUCTION

Where core damage events (severe accidents) have occurred, they have been the result of inadequate core cooling. If core damage does occur, recovery from the accident condition requires that the core debris is cooled, which necessitates that water is added to cover and submerge the debris. Moreover, the choice of which actions to take and the response of the reactor system and containment have inherent uncertainties. These include:

- Is the core damaged, and if so how severe is the damage?
- If it is damaged, how coolable is the core debris configuration?
- Has hydrogen been released to the containment, and if so, how much?
- Is containment integrity in question?
- If an action is taken, could the response realistically jeopardize containment integrity?
- Do all of the instruments indicate a consistent picture of the core, the Reactor Coolant System (RCS) and containment status?

Fundamentally, there are two types of uncertainties to be addressed in severe accident analyses;

- uncertainty in the physical phenomena, and
- uncertainty in the interpretation of the instrument signals, i.e. the accident state.

Only the first is discussed here and an example is given on how a phenomena should be examined.

The MAAP User's Group (MUG) has formed an Uncertainty Working Group to study the influence of phenomenological uncertainties on severe accident evaluations. Of principal interest are the magnitude of uncertainties in various phenomena and the different predictions by different computer codes. Through this process the MUG is evaluating all of the major physical processes related to accident management.

2.0 UNCERTAINTIES TO BE EVALUATED

2.1 Uncertainty in the Physical Phenomena

For these evaluations, we define three types of phenomena and therefore three types of uncertainties

- dominant phenomena which determine the major events in the accident progression,
- significant phenomena which contribute to the accident progression and may cause major changes in the accident state, and
- minor phenomena which have a limited influence on the accident.

Uncertainties in these phenomena lead to characterization of dominant, significant and minor uncertainties. A preliminary assessment of severe accident phenomena is given in Table 1. Note that uncertainties related to fission product release and deposition are not included. This is not because these processes have small uncertainties. Quite the opposite. Rather it is because severe accidents have such a substantial release from the fuel matrix that the uncertainties which matter are thermal-hydraulic in nature.

Table 1
Preliminary Assessment Characterization of Severe Accident Physical Phenomena

Phenomena	Dominant	Significant	Minor
1. Clad oxidation.		√	
2. Core melt relocation.		√	
3. Molten pool in core.		√	
4. Crust formation and failure.		√	
5. RCS failure modes.	√		
6. In-vessel steam explosion.			√
7. In-vessel steam generation.			√
8. In-vessel debris formation.			√
9. RPV failure modes.		√	
10. In-vessel cooling mechanism(s).	√		
11. RPV external cooling.	√		
12. Ex-vessel steam explosion.			√
13. Direct containment heating.		√	
14. Mark I liner attack.		√	
15. Ex-vessel debris cooling.	√		
16. Steam inerting of the containment.	√		
17. Hydrogen burning in containment.		√	

A phenomenon (or mechanism) which can prevent RPV failure is clearly a dominant phenomenon since this would also prevent the release of core debris to the containment. In contrast, consider the uncertainties associated with reflooding of a damaged core and the quenching rate that could result. If the debris develops large cracks and water penetrates into the core, the debris could be cooled in place. If these cracks do not develop, molten debris may drain into the lower plenum, as occurred in the TMI-2 accident.

Uncertainties associated with core debris cooling, while significant, would not determine if reactor vessel failure would occur. Therefore, these uncertainties are *dominated*, by the physical processes characterizing cooling of the RPV lower head. *In other words, if the in-vessel cooling mechanism is sufficiently well understood, decisions can be made independent of the uncertainties related to covering and cooling of a damaged core.*

Fortunately dominant phenomena are the easiest to identify since they directly affect the key events of (1) uncovering of the reactor core, (2) major core damage (loss of geometry), (3) reactor pressure vessel failure and (4) containment failure. Obviously these are related to protecting the fission product barriers and stopping the accident progression. Hence, attention can be focused on those sub-processes which make up the dominant phenomena to examine the level of importance of each and determine whether sufficient justification exists for each sub-process.

3.0 HOW CAN UNCERTAINTY IN THE PHYSICAL PHENOMENA BE ADDRESSED?

Table 2 describes a six step process to produce a structured evaluation of severe accident uncertainties and document the results. This is a process that can be conveniently updated as new results become available.

Table 2 Approach to Uncertainty Evaluations	
1.	List and characterize the uncertainties in individual phenomena.
2.	Document how each uncertainty can be studied using MAAP4 (or any other codes) that are available.
3.	Determine the code(s) and version(s) to be used.
4.	Construct a matrix for all code runs.
5.	Determine if any of the dominant uncertainties would change the occurrence of key events.
6.	Document the results.

Next, we use this process to examine the in-vessel cooling dominant phenomenon.

4.0 EXAMPLE OF UNCERTAINTY EVALUATION: IN-VESSEL COOLING

4.1 Task 1: Characterize the Individual Phenomena

The phenomena in Table 1 are characterized in terms of major observations from experimental and analytical studies published in the open literature. Specifically, these should be interpreted in terms of MAAP-like models to assess how each can be represented in accident analysis integral codes. Table 3 lists some of the major experiments and relevant experience. In this characterization, the ranges of the observed behavior must be evaluated and documented in terms of how the important aspects of a given phenomenon have been observed to vary.

Table 3 **Characterize the Individual Phenomena**
Experimental data and analyses that can be used to characterize the uncertainty in individual phenomena. • CORA tests. • FAI/ULPU external RPV cooling tests. • LOFT FP-2 test. • TMI-2 Vessel Investigation Project (VIP). • COPO tests. • SNL/ANL/FAI DCH experiments. • ALPHA tests. • HDR tests. • NUPEC tests. • MACE tests. • EPRI/FAI tests. • FARO tests.

These individual assessments are characterized in a form that each can be easily updated. Experiments which narrow the uncertainty bands associated with individual phenomena are of particular importance.

During the TMI-2 accident, molten core material drained into the RPV lower plenum at about 227 mins. [1]. Until then, the core material had remained within the original core boundaries, and furthermore, had been submerged in water for more than 30 mins. Densification of the core material due to slumping resulted in a reduced cooling potential for the core, i.e., it cannot be cooled even when it was submerged. This is an important observation, i.e., *molten core material can relocate and potentially attack the RCS pressure boundary even when completely submerged in water*.

Following this relocation of 20 tonnes of core material, the RPV lower plenum wall was heated to temperatures (~ 1100°C) where the structural integrity would be in question. Immediately thereafter the wall exhibited a cooling trend that was in the range of 10°C to 100°C/min. This cooling mechanism is of major significance for severe accident decision making.

Two mechanisms have been proposed for the TMI-2 in-vessel cooling [2,3]. Current experimental information does not enable one to decide which, if either, of these mechanisms represents the TMI-2 behavior and both certainly depict behavior which is consistent with the overall observations. It is also possible that both mechanisms apply to some extent. Certainly both mechanisms can be generally characterized as requiring relatively small flow paths between the core debris and the reactor vessel wall and flow paths eventually within the core debris itself. However, the limited wall creep (RPV wall) mechanism [2] can result in much larger flow paths for the coolant if needed. Presently there is substantial evidence that molten core debris would not adhere to the reactor vessel wall if the material drained through water in the lower plenum. This has been observed in the TMI-2 VIP, EPRI sponsored experiments [4] and in the FARO tests [5]. With this consistent observation from several different experiments and experience, it is appropriate to assume that the core material would not adhere to the wall. Therefore, a coolant flowpath exists, and the next issue is to determine whether it is of sufficient magnitude to cool the RPV wall.

In the TMI-2 accident, the evaluated wall temperatures indicate that the initial gap formed did not provide sufficient cooling to prevent the wall from overheating. This is also the conclusion from the EPRI sponsored experiments [4], which indicate that the initial gap size formed is small, perhaps of the order of 100 microns. However, we should examine whether the ultimate cooling of the lower head is sensitive to this value. Does success of the in-vessel cooling depend on the initial gap size?

One of the mechanisms [2] considers that the gap could increase as a result of material creep in the RPV wall should temperatures reach values approaching 1100°C. MAAP analyses [6] show that material creep can occur on a timescale which is short compared to the time to failure. Furthermore, since the lower plenum wall experiences no substantial neutron flux, the wall will remain ductile. There is no question that the wall would strain considerably before failing and the existence of material creep of the carbon steel wall can be taken as an engineering certainty.

Once element that can influence the possibility of creep is whether the accident sequence results in external cooling of the reactor vessel lower plenum. If this is the case, the cooler RPV outer wall temperatures mean that the extent of material creep is minimized, or perhaps eliminated. Hence, the uncertainties associated with in-vessel cooling are not independent of other phenomena, such as the existence of external RPV cooling.

The first element to be considered is the influence of the RCS pressure. Typical sequences considered include those at essentially full RCS pressure as well as those which could be fully depressurized. For this latter case, the only stress in the wall is due to the weight of the core debris. Furthermore, some PWR high pressure sequences could result in creep failure of the RCS boundary, for example one of the hot leg walls. To address uncertainties with respect to

RCS pressure, MAAP4 results were used to consider a substantial range in pressure by varying the accident sequence. (Here is one use of sensitivity analyses since a convenient way to obtain a high pressure sequence is to “rule out” hot leg creep rupture. This is a convenient sequence definition, but it is essential that the results be considered in the proper content, i.e. to understand the influence of RCS pressure on in-vessel cooling.)

Monde et al., [7] measured the critical heat flux in a narrow gap with heating on a single side. A correlation was recommended and is one of the approaches used in the analyses. In addition, FAI performed fundamental experiments for quenching in narrow annular gaps [8]. The measured average quenching rates are close to the Monde correlations, i.e. using values of 1.0 and 0.5 times the calculated values from the Monde correlation bound the measured average quenching rates.

Lastly, long term in-vessel cooling must consider that the reactor system water may contain dissolved minerals. If cooling requires substantial vaporization, these minerals could be distilled within the cooling paths thereby making the debris less coolable. Does this potential for decreasing of coolant flow affect the two different proposed mechanisms in the same manner? Is this potential uncertainty influenced by other dominant phenomena? These are uncertainties related to long term behavior of in-vessel cooling.

4.2 Quantification of the In-Vessel Cooling Uncertainties

Next, we will assess the importance of the above sub-phenomena associated with in-vessel cooling.

Table 4 lists the MAAP4 model parameters varied and the extent of these variations. After the sub-phenomena have been evaluated we will investigate the interaction between in-vessel cooling and external RPV cooling. For this example, we consider a Westinghouse 4 loop PWR with a Zion-like containment with external cooling “ruled out”. ECCS is recovered at the time that core debris is calculated to drain into the lower plenum. Furthermore, we will restrict the discussion to a station blackout sequence with hot leg creep rupture suppressed. This makes the analysis a sensitivity evaluation but highlights the important behavior.

Table 4
Parameters to be Varied and the Magnitude of the Variation for Sub-Phenomena Evaluations

Sub-Phenomena	Parameter Varied	NSSS Type	Magnitude of the Variation
Initial gap formed between the RPV wall and core debris.	XGAPLH	B/P	10^{-4} m (U)[1] 10^{-5} m (S)[2] 10^{-6} m (S)
Efficiency of cooling in narrow gaps.	FHTGAP	B/P	1.0 (U) 0.5 (U) 0.2 (S) 0 (S)

Table 4
Parameters to be Varied and the Magnitude of the Variation for Sub-Phenomena Evaluations

Sub-Phenomena	Parameter Varied	NSSS Type	Magnitude of the Variation
Rate of strain for the RPV wall.	ECREPF	B/P	2.0 (U) 0.2 (U) 0.02 (U) 0 (S)
Influence of water ingression.	FQUEN	B/P	1.0 (S) 0.36(U) 0.036 (U) 0 (S)

[1] Uncertainty evaluations.

[2] To clearly demonstrate the influence of certain phenomena, these phenomena are sometimes "ruled out" or varied outside the uncertainty range.

4.2.1 Uncertainties in the Size of the Initial Gap

Figure 1 shows the primary system pressure, the inside RPV wall temperature for the lowest node in the vessel, the size of the gap between the core debris and the RPV wall and the average core debris temperature in the lower plenum. As shown, there is no discernable influence on the primary system pressure or the average core temperature in the lower plenum. As illustrated by the crust/RV gap thickness in node 1, an initial value of 100 microns is sufficient for the initial cooling but it eventually increases to about 270 μm. With injection, the RCS is depressurized to approximately 5 MPa. At this pressure, a gap of 10 μm is not sufficient to prevent the wall from overheating, but as a result of the overheating, the gap grows large enough to result in efficient cooling of the reactor vessel and the vessel does not fail. The final gap size depends on the rate at which the wall temperature increases and the rate of wall strain. In all cases, the wall strain is small compared to that which would be necessary to fail the RPV. Note that the core material temperature remains high but a safe stable state exists where in the core material does not thermally attack the reactor vessel wall. Analyses with an initial gap of μm show the same response.

4.2.2 Uncertainties in Gap Cooling

The cooling efficiency within the narrow gap can be bounded by a value of FHTGAP=1.0 (the Monde CHF correlation), and a value of FHTGAP=0.5, i.e. one half of the value calculated from the Monde correlation. This represents realistic uncertainty bounds for heat removal within the gap. Water ingression was "ruled out" (FQUEN=0.0) to focus attention on the gap cooling model, thus these are sensitivity analyses. To illustrate the large tolerance with respect to gap cooling, we included another sensitivity analysis for the heat removal

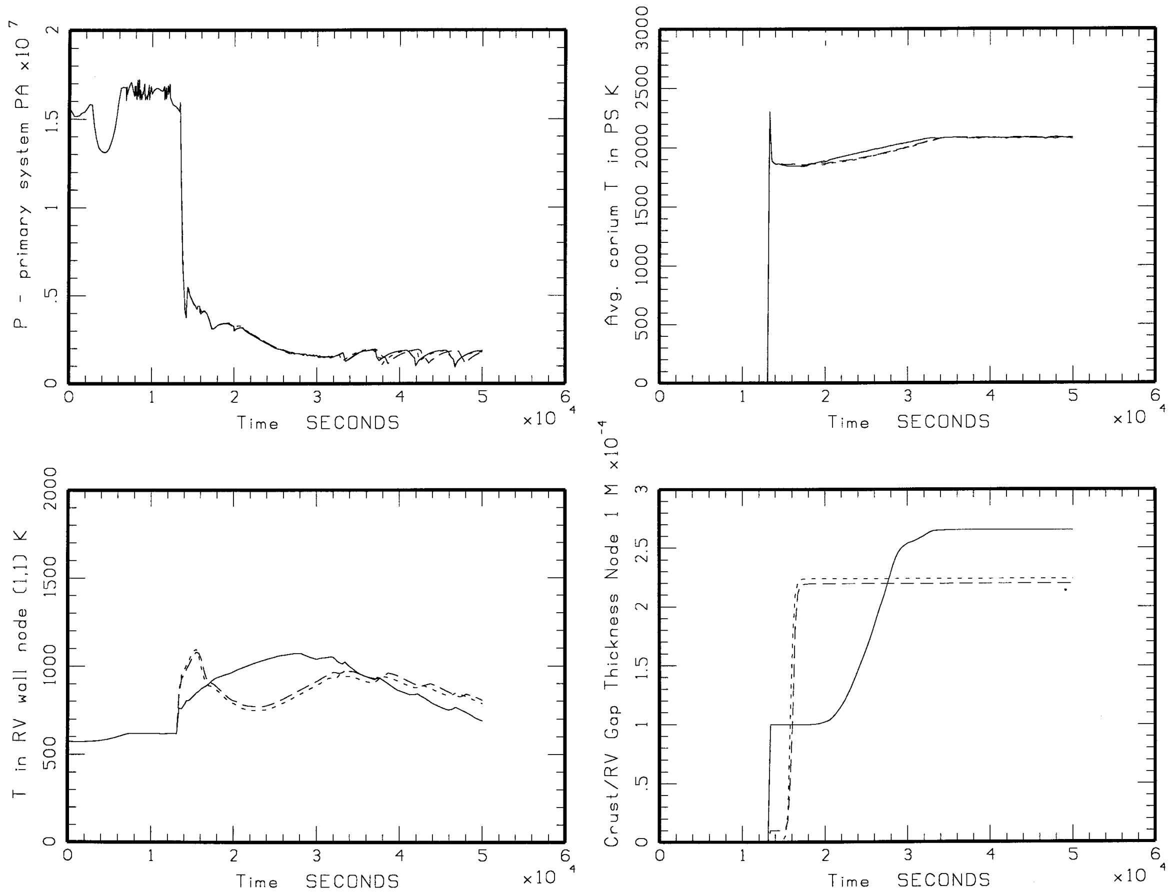

Figure 1,
Comparison of integral calculations for sequence designator IVC/W/Z//XGAPLH/TMLB No HL Creep variations in the initial gap size (XGAPLH) with the variations designed by 100 microns (———), 10 microns (— — —), and 1 micron (-------) with the efficiency of the gap heat transfer (FHTGAP) equal to 0.5 and FQUEN equal to 0.

efficiency, i.e., FHTGAP=0.2. These results demonstrated the robustness of the limited strain model in that a degradation of the heat removal process merely means a somewhat larger gap is formed.

The calculated primary system pressure history is virtually identical to that considered for the analyses with variations in the initial gap size and the expected behavior was observed, i.e. a larger gap is formed when the energy transfer in the gap is degraded. The RPV integrity was preserved in all cases.

4.2.3 Uncertainties in Water Ingression

For large accumulations of core debris in the lower plenum, the debris is too thick to remove the decay heat by thermal conduction. A slab of core material that is 15 cm thick, and cooled by water on both sides, would approach the melting at the center. Therefore, complete quenching requires water ingression into the core material. As discussed in the Summaries of

Severe Accident Phenomena [9], one mechanism considered for in-vessel cooling is the shrinkage of core debris away from the RPV lower plenum wall and internal structures as the debris cools. Water ingression into the shrinkage region could provide long term heat removal. Shrinkage could result in cracks in the debris crusts that would also enable water to ingress and promote the long term cooling process.

Significant cracks in core debris have been observed in experiments with simulant materials [10]. However, these experiments also demonstrate that a substantial part of the shrinkage potential is realized within the frozen material as internal voids which are not interconnected.

Considering the uncertainties, it is also important that the experiments used sufficient quantities of molten material such that it is not completely particulated as was the case in the initial FARO test [5]. Furthermore, it is also important that such experiments include lower plenum structures to correctly represent the water ingression potential around structural supports, as well as the strength of the core material. Since the only information currently available is the TMI-2 accident, the uncertainties must be considered as large.

At one end of the spectrum, the water ingression is given by the Grimsvotn experience [11] such that the heat removal rate is characterized by FQUEN=0.036. Here the experience is large scale and with oxidic materials, but the observation is only after 14 days and the result in interpreted as an average quenching rate. It is possible that the upper regions of the lava could have quenched at a faster rate. On the other end of the uncertainty band, the ingression could be sufficiently strong that it would approach the behavior observed in simulate fluid tests [10] and in the MACE test [12] as summarized by [13].

Figure 2 shows that uncertainties in the water ingression rate have no significant influence on the RCS pressure behavior. However, the reactor vessel wall clearly is influenced by the ability to remove heat through water ingression. The gap dimension does not increase but, as expected, the core material temperature in the lower plenum is also strongly influenced by the extent of water ingression. For the lower bound value, we see the core debris temperature increases to a value of approximately 1300°K.

Contrast this with the sensitivity analyses presented in Figure 3 in which all other variables remain the same except the gap cooling efficiency is set equal to 0. Specifically, the RCS pressure is identical to that in Figure 2 until approximately 27,500 seconds when the vessel fails for FQUEN=0.036. Thus, successful cooling of the vessel demonstrated for FQUEN=0.36 (the upper end of the uncertainty band) in Figure 3 is due to water ingression. When the value of FQUEN is reduced to (0.036), the combination of no RPV failure in Figure 2 and RPV failure in Figure 3 shows that water ingression into the gap is a substantial part of the cooling process.

4.2.4 <u>Uncertainties in Material Creep</u>

To represent the uncertainties related to the strain rate, it is recommended that the rate of material strain, with respect to the Larson-Miller approach, be reduced by a factor of 10 and increased by a factor of 10.

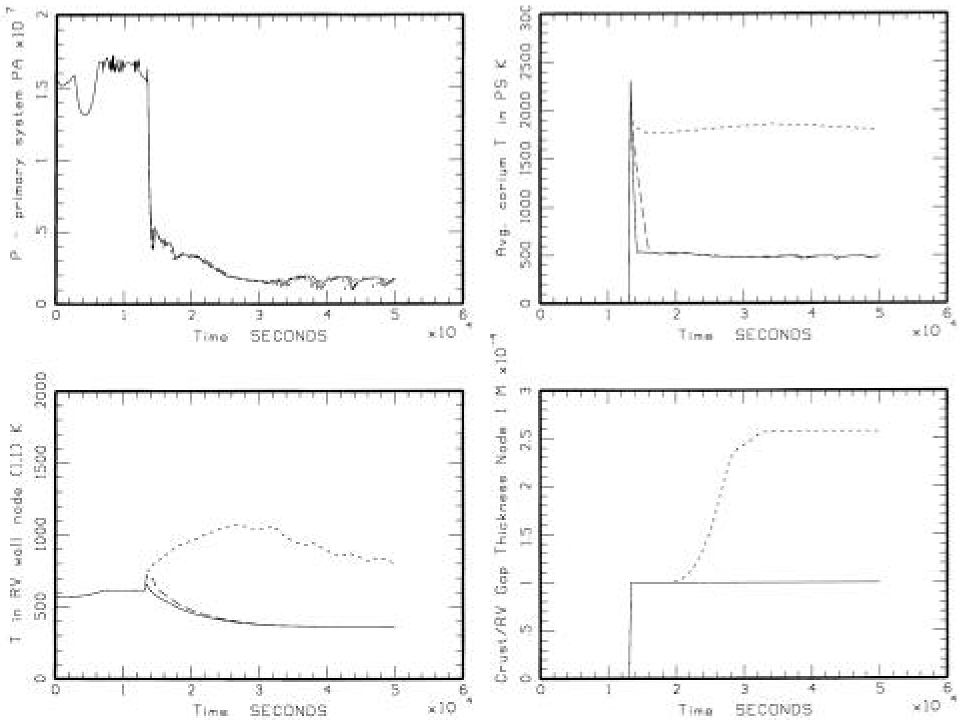

Figure 2,
Sequence designator IVC/W/Z//FQUEN/TMLB No HL Creep with variations in FQUEN 1.0 (———), 0.36 (—‑——), and 0.036 (-------) with XGAPLH equal to 100 microns and FHTGAP = 0.5.

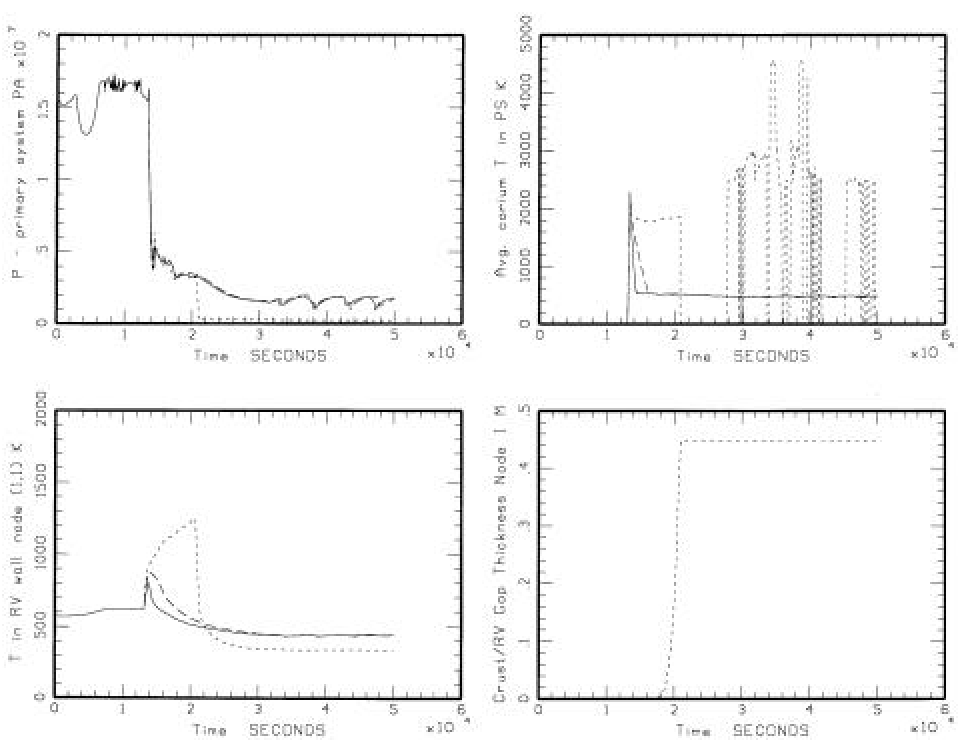

Figure 3,
Sequence designator IVC/W/Z//FQUEN/TMLB No HL Creep with variations in FQUEN of 1.0 (———), 0.36 (———), and 0.036 (-------) with XGAPLH equal to 100 microns and FHTGAP = 0.0.

When the lower plenum wall is overheated, the calculated pressure is approximately 5 MPa and with an initial gap size of 100 microns and a gap heat transfer characterized by FHTGAP=1.0, the initial gap size is sufficient to cool the RPV wall. To focus attention on the strain rate, water ingression was "ruled out" by setting FQUEN equal to 0. (This creates a sensitivity analysis but this is useful to isolate the influence of the material strain rate.) In all cases, only a small gap was formed and the RPV did not fail.

4.2.5 Uncertainties Due to Dissolved Materials

For PWRs, the dissolved material within the coolant (principally boric acid) could be concentrated in the lower plenum as a result of the accident sequence and precipitated (distilled) within the core debris as a result of the vaporization. This could begin to limit the coolability of the debris if the size of the coolant paths are limited. Such boron precipitation and obstruction of coolant paths were observed even for intact fuel rods for conditions like a design basis LOCA [14]. Separate effects calculations show that long term cooling of debris which uses very small coolant paths could be in jeopardy since a coolable configuration (cooling by vaporization) could eventually become non-coolable if the coolant flowpaths are reduced by precipitated boric acid.

The most important uncertainty is whether complete vaporization of the coolant is required for cooling of the debris, which is determined by the size of the coolant path. Certainty if the coolant could establish circulation through the debris and remove the decay heat without vaporization (single phase liquid circulation), there would be no precipitation within the debris. On the other hand, if complete vaporization of the coolant is required, there would be substantial precipitation of the dissolved material.

There is a substantially different response of the two in-vessel cooling mechanisms to the possibility of material deposits in the system. Specifically, those considerations associated with shrinkage of the core debris during its cooling process typically result in limited size coolant paths which likely require substantial vaporization for long term cooling. If this is the case, dissolved materials would be precipitated in these coolant paths thereby limiting the coolability and causing the core debris temperatures to increase. As the temperatures increase, the attractive features associated with shrinkage of core material reverse and tend to reduce the debris coolability.

The limited strain mechanism principally cools the reactor vessel wall. If this mechanism results in limited creep for the reactor vessel wall and vaporization of water in this narrow coolant passage with the associated precipitation of dissolved materials, the limited cooling would cause the vessel wall to ingress. Since the potential growth of the reactor vessel wall before failure is large compared to the size of a sufficient cooling path, it is well within the capabilities of this mechanism to establish a cooling path of sufficient magnitude.

4.2.6 Interaction Between Dominant Phenomena

When considering in-vessel cooling, the limited wall strain model results in cooling of the core material as a result of overheating of the wall and limited material creep. However, if the reactor vessel wall was submerged in water accumulated in the containment as a result of the accident sequence, the external cooling of the RPV wall could provide sufficient cooling that the reactor vessel wall would not overheat sufficient to enable limited strain to occur. In this case, the in-vessel cooling mechanism would not experience this "feedback" that could result in long term cooling.

The potential for external cooling of the RPV was activated (IEXVSL=0) as opposed to being deactivated (IEXVSL=1) in the previous analyses. For these assessments, we have used the lower bound of the uncertainty range for the gap size (100 μm), the lower bound of the water ingression rate into debris (FQUEN=0.036) and the results are presented for a series of gap cooling efficiencies, including both the upper and lower bounds, as well as a value of FHTGAP=0.2 (sensitivity analysis). Figure 4 shows an interesting interaction between in-vessel and external RPV cooling. For this high pressure scenario, the initial gap size of 1000 microns does not increase regardless of the gap cooling efficiency. The energy transferred to the RPV wall is removed as a result of external cooling and the vessel wall does not overheat sufficiently to strain. Hence, while there are substantial differences in the details of how the energy is extracted from the core material, the interaction between these two dominant phenomena results in the same ultimate condition for the debris, i.e. the internal energy generation within the debris is removed as a combination of heat removal from the debris crust (either through a sufficient gap heat transfer or through the RPV wall) and the remainder of the energy is transferred upward to the overlying water pool.

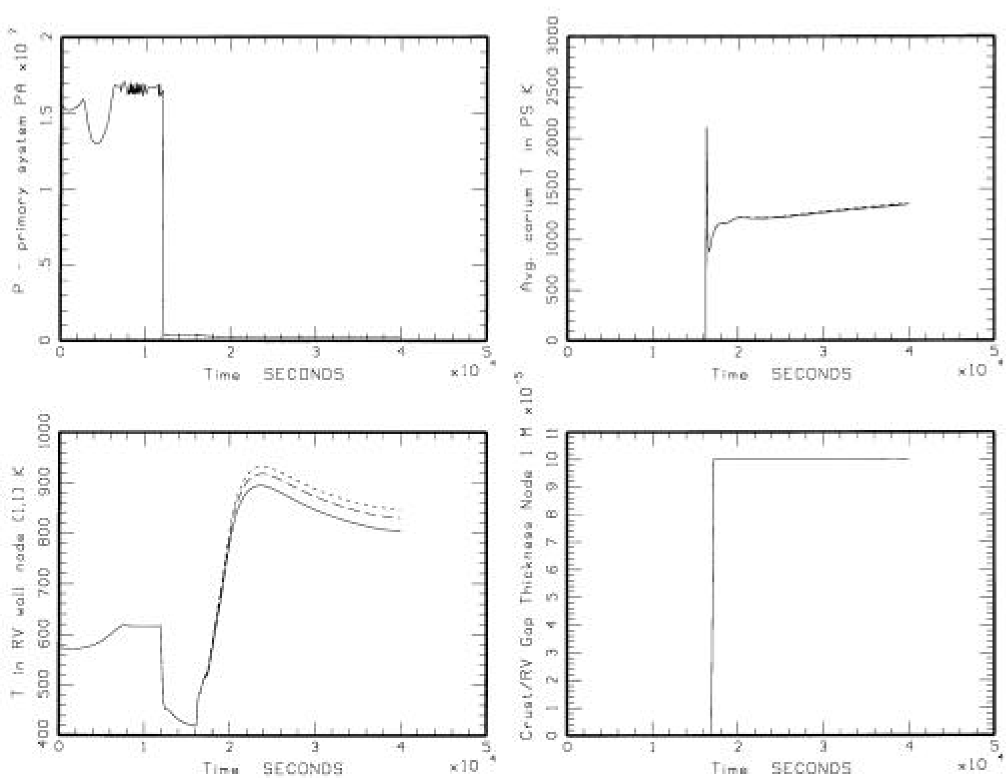

Figure 4,
Sequence designator IVC-REC/W/Z//XGAPLH/TMLB HL Creep with external cooling (IEXVSL=0) and with an initial gap size of 1000 microns with the efficiency of gas heat transfer (FHTGAP) equal to 1.0 (———), 0.5 (– – –), and 0.2 (-------) and water ingression (FQUEN) equal to the lower bound uncertainty value of 0.036

5.0 CONCLUSIONS

The proposed method for assessing uncertainties in physical phenomena provides a structured means of determining which phenomena are of (a) dominant, (b) significant, and (c) minor importance in severe accident decision making. Furthermore, it provides a convenient means of assessing the uncertainties in the list of major physical phenomena and their influential subprocesses. With this structured evaluation of the available literature, quantified uncertainty bands can be developed for the subphenomena. Perhaps of greatest importance, the process structures a means of evaluating the influence of uncertainties through integral code analyses such that the feedback, where appropriate, between physical processes is evaluated.

When this process is applied to the phenomenon of in-vessel cooling with its list of subphenomena, it is clear that the in-vessel cooling is one of the dominant physical processes in accident management decision making. Furthermore, it is also apparent that the issue associated with the cooling of the reactor vessel wall through limited material creep is of crucial importance in the overall modeling of the system response.

This structured process also provides a means of assessing differences between integral computer codes. Specifically, they must represent the same set of physical processes, particularly the dominant physical processes, before the codes can be compared in a meaningful way. Lastly, this process identifies those physical processes, as well as the subphenomena, which are fruitful areas for further research if the meaningful uncertainty bands are to be narrowed.

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