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A DIRECT COMPARISON OF MELCOR 1.8.3 AND MAAP4 RESULTS FOR SEVERAL PWR & BWR ACCIDENT SEQUENCES

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ABSTRACT

This paper presents a comparison of calculations of severe accident progression for several postulated accident sequences for representative PWR and BWR nuclear power plants performed with the MELCOR 1.8.3 and the MAAP4 computer codes. The PWR system examined in this study is a 1100 MWe system similar in design to a Westinghouse 3-loop plant with a large dry containment; the BWR is a 1100 MWe system similar in design to General Electric BWR/4 with a Mark I containment. A total of nine accident sequences were studied with both codes. Results of these calculations are compared to (a) identify major differences in the timing of key events in the calculated accident progression or other important aspects of severe accident behavior, and (b) to identify specific sources of the observed differences.

I. INTRODUCTION

The MELCOR[1] and MAAP[2] computer codes are used by many organizations world-wide to calculate the response of commercial nuclear power plants to postulated accidents that involve substantial damage to reactor fuel (i.e., severe accidents). Although both codes are designed to address the same general problem (i.e., the transient response of nuclear reactor systems to severe accidents), the modeling approach used to represent some important phenomena and the level of detail with which certain models are developed differ substantially between the two codes. As a result, differences in calculated results are often observed.

However, differences in results of MAAP and MELCOR calculations are also frequently observed due to factors unrelated to the inherent differences in their modeling approaches. For example, seemingly slight differences in the way a large complex system such as a nuclear reactor vessel, supporting coolant piping, steam generators, and containment structures are represented via *user input* to either code can cause major differences in calculated results. To further complicate matters, the format and nomenclature used to present results to the code user differs between the two codes for some parameters. As a result, it can be difficult to determine whether the two codes calculate different values for the same parameter because, in fact, the "same" parameter can represent slightly different quantities within each code.

With these challenges in mind, a systematic effort was made to compare results of calculations performed with both computer codes for five severe accident sequences in a representative BWR/4 - Mark I containment system and four accident sequence in a representative 3-loop (Westinghouse) PWR with a large dry containment. The calculations were performed with the MAAP4 (version 4.0.2) and MELCOR 1.8.3 computer codes. This paper summarizes the findings of this comparison effort.

II. SUMMARY OF WORK PERFORMED

MAAP4 and MELCOR 1.8.3 calculations were performed for the accident sequences shown in Table 1. The scope of the current comparison was limited to calculated results related to severe accident behavior. Particular emphasis was placed on early thermal hydraulic behavior (specifically, factors governing the depletion of the primary coolant system inventory), in-vessel and ex-vessel core melt progression, and resulting containment response. Calculated results regarding fission product release from fuel, deposition in various reactor/containment systems and ultimate release to the environment were not examined.

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Table 1. Accident Sequences Examined with MELCOR 1.8.3 and MAAP4

PWR:	BWR:
• Station blackout with an induced reactor coolant pump seal LOCA (TMLB); • Large break LOCA with failure of emergency coolant injection and containment sprays in the recirculation mode (AHF); • Large break LOCA with failure of emergency coolant injection and containment sprays (ADC) • Small break LOCA with failure of emergency coolant injection and containment sprays in the recirculation mode (S_2HF);	• Station blackout in which steam-driven coolant injection systems operate until battery (dc) power is exhausted (TB); • Transient with failure of decay heat removal, high-pressure injection and automatic depressurization (TQUX); • Transient with failure of decay heat removal, high- and low-pressure injection (TQUV); • Transient with failure of containment heat removal (TW); • Large break LOCA with failure of all coolant injection (AE).

III. COMPARISON OF PWR CALCULATIONS

Results of the MAAP4/MELCOR comparison for the four PWR accident sequences are described below. For brevity, a detailed discussion of the comparison is provided for one representative sequence, station blackout. However, this discussion is preceded by a summary of major findings of the comparisons for all four sequences.

A. Summary of Comparisons for All Sequences

A summary of the calculated timing of key events for each of the four PWR accident sequences is given in Table 2. This information is presented both in terms of the calculated time between major events as well as differences in the cumulative time to an event from the start of the accident.

The following general observations can be made from this information and from a review of the individual calculations by means of plotted variables.

1. With the exception of the large-break LOCA sequences (AHF & ADC), the early hydrodynamic response of the system (i.e., the time required for the primary coolant inventory to be depleted to the point that the top of active fuel is uncovered) is shown to be in good agreement between the two codes. This suggests that the factors influencing the overall mass and energy balances of the primary coolant system prior to the onset of core damage are calculated in a similar manner by the two codes. This was confirmed by a closer examination of plots for several calculated parameters.

The larger differences in the time to core uncovery shown in Table 2 for the two large-break LOCA sequences appear to be the result of at least two significant differences in the way in which emergency coolant injection flow into the primary coolant system was modeled. These differences are controlled primarily by user input, and do not appear to be the result of code models.

2. The time required for vessel breach to occur after large quantities of debris relocate into the lower head (i.e., after lower core support structure failure) is calculated to be much shorter in MELCOR than in MAAP. This result arises from significant differences between the two codes' models for debris heat transfer within the reactor vessel lower head, and for structural failure of the lower head. In MELCOR 1.8.3, vessel failure is calculated based on a relatively simple thermal penetration model; i.e., failure is assumed to occur when the temperature of a penetration (if modeled) or the inner surface of the lower head reaches a user-specified temperature. In MAAP4, vessel failure is calculated based on a cumulative damage (i.e., Larson-Miller creep rupture) failure model. As described below (Section B), a similar model has recently been installed in MELCOR, which, if activated, produces a time to vessel breach much closer to the MAAP result.

Table 2. Summary of Calculated Timing of Major Accident Events - PWR Sequences

Accident Sequence	All times in seconds ⇒		Time to Core Uncovery	Time to Failure of Lower Core Support Structure	Time to Vessel Breach	Time to Containment Failure
TMLB	Time between events	MAAP	8,501.	5,396.	3,396.	83,923.
		MELCOR	7,726.	4,956.	64.	126,238.
	Cumulative time from start	MAAP	8,501.		17,225.	101,148.
		MELCOR	7,726.		12,746.	138,984.
AHF	Time between events	MAAP	4,221.	3,846.	10,259.	58,651.
		MELCOR	3,211.	9,168.	67.	136,809.
	Cumulative time from start	MAAP	4,221.		18,326.	76,977.
		MELCOR	3,211.		12,446.	149,255.
ADC	Time between events	MAAP	1,699.	3,114.	8,801.	102,441.
		MELCOR	128.	3,359.	54.	203,094.
	Cumulative time from start	MAAP	1,699.		13,614.	116,055.
		MELCOR	128.		3,541.	206,635.
S_2HF	Time between events	MAAP	13,378.	10,747.	11,860.	47,620.
		MELCOR	14,416.	22,901.	60.	143,875.
	Cumulative time from start	MAAP	13,378.		35,985.	83,605.
		MELCOR	14,416.		37,377.	181,252.

An additional contributor to the observed differences in the calculated time to lower head failure is the way in which heat transfer between core debris and residual coolant in the reactor vessel lower head is modeled. The MAAP4 model operates on a conceptual picture of core relocation (from above the lower core support structure into the lower head) that is based on a contiguous pour (or jet) of molten material through a pool of water. Jet breakup and material fragmentation provide significant cooling of debris. MELCOR 1.8.3 provides an optional model for transient heat transfer (i.e., during relocation into the lower head), however, this model was not active in the present calculations. The default (operating) model only accounts for debris heat transfer after material has settled onto the inner surface of the lower head and formed a stable debris bed. The net result of this difference is a significantly lower average debris temperature in the MAAP4 calculations than in the MELCOR 1.8.3 calculations when lower head dryout occurs; this causes a delay in lower head failure in the MAAP4 calculations because the debris must first increase in temperature before it can challenge the lower head structure.

3. Finally, a large difference in the time at which containment over-pressure failure occurs is indicated for all of the sequences in Table 2. This is due primarily to differences in models in the two codes for heat transfer between core debris that emerges from the reactor vessel and water in the reactor cavity. Specifically, each of the MAAP4 calculations predict the formation of a quenched debris bed immediately after vessel breach; this result occurs independent of whether water exists in the cavity prior to vessel breach (as in sequences S_2HF or AHF) or arrives coincident with debris ejection (as in TMLB). Subsequent increases in containment pressure are governed primarily by ensuing steam generation in the cavity. In contrast, the MELCOR calculation does not predict a quenched debris bed after vessel breach for any of the sequences. The rate at which containment pressure increases after vessel breach in the MELCOR calculation is governed primarily by gas generation resulting from corium-concrete interactions.

B. Specific Results for Sequence TMLB

The following provides more detailed information on calculated results for one representative sequence, station blackout (TMLB).

1. Early Thermal Hydraulic Response

MAAP4 and MELCOR calculate a very similar thermal hydraulic response of the primary coolant system prior to vessel breach. In particular, the primary coolant pressure history and coolant inventory depletion characteristics are in very good agreement. As shown in Figure 1, both codes predict a sharp, but temporary, decrease in primary system pressure at 2700 seconds when the reactor coolant pump (RCP) seal LOCA occurs.

System pressure subsequently increases to the pressurizer relief valve setpoint and remains at that level until vessel failure occurs. The only significant discrepancy in the calculated pressure response is the *time* at which the rapid depressurization accompanying vessel breach occurs. The reasons for this difference were discussed in the summary section above.

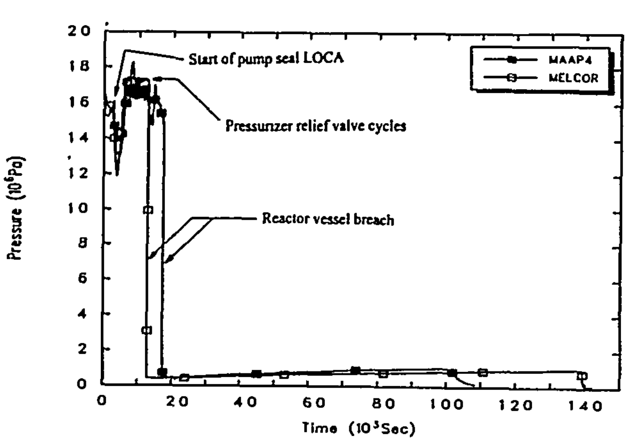

Figure 1. Reactor Vessel Pressure (PWR - TMLB)

The rate at which the primary coolant system inventory is depleted is also in good agreement between the two codes. This results in reasonably close agreement in the time at which the reactor vessel water level decreases to the top of the active fuel, and the onset of core damage. Some discrepancies in the *details* of the primary system inventory depletion characteristics are observed, however. For example, substantial differences are observed in the calculated flow rates of coolant through the two leak paths from the primary system, i.e., the RCP seal LOCA and the pressurizer relief valve. MELCOR calculates more coolant mass discharged through the RCP seal LOCA than MAAP4; however, this difference is balanced by MELCOR calculating a smaller loss of coolant through the pressurizer relief valves than MAAP4. Given the good agreement in important boundary conditions for these calculated parameters (e.g., the two codes calculate a very similar pressurizer water level), the most likely explanation for these differences is that they are caused by differences in the way the two codes calculate fluid (donor) conditions at a break (or relief valve) location. MAAP4 first compares the specified elevation of the opening in the primary system to the swelled-up water level in the portion of the system containing the opening. This establishes the local fluid void fraction. It then applies a correlation (curve-fit) for the Henry-Fauske critical flow model to calculate mass loss. MELCOR also calculates local fluid void fraction by comparing the elevation of the opening in the primary system to the swelled level in the local control volume. MELCOR then applies analytic fits to the Moody critical flow tables to calculate mass loss.

The difference in critical flow models between the two codes is <u>not</u> likely to be responsible for the observed difference in coolant flow rates through the ruptured RCP seal or the relief valve. Rather, the different ways in which the elevation of the openings in the primary system are defined and the calculations of swelled coolant level are calculated produces different estimates of local fluid conditions.

2. In-vessel Core Damage Behavior

Many similarities are also observed in the initial stages of in-vessel core melt progression. Initial fuel heat-up rates are similar and subsequent core melting and material relocation produces a similar level of cladding (Zircaloy) oxidation *prior to large-scale debris relocation into the lower head.* After lower core support structure failure, however, a relatively large difference in the cumulative mass of hydrogen generated is observed in the two calculations. This difference is created when rapid metal oxidation occurs in the MELCOR calculation as debris relocates into residual water in the lower head following failure of the lower core support structure. This increment is not observed in the MAAP4 calculation. The extent of clad oxidation calculated by each code can be inferred from the cumulative mass of hydrogen generated in-vessel as shown in Figure 2.

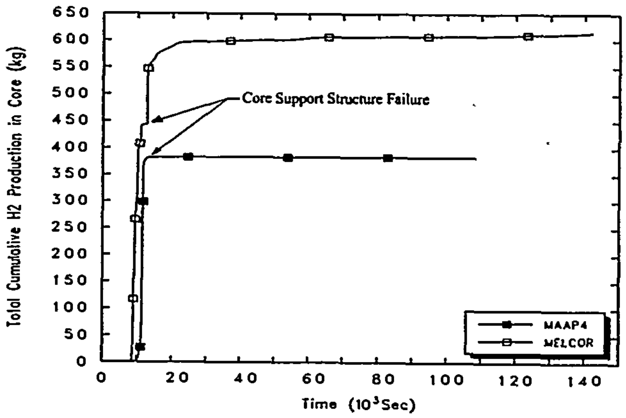

Figure 2. Total Hydrogen Generation (PWR - TMLB)

The modeling options used in the MAAP4 calculation related to debris formation and transport into the lower plenum are not known and, therefore, we can only speculate on the specific cause of the observed difference in in-vessel oxidation. However, there are several fundamental differences between MAAP4 and MELCOR related to late-phase material relocation which would produce such an effect. In particular, the MAAP4 models are based on a conceptual picture of late-phase material relocation that emphasizes the formation of a molten pool above the lower core support structure (similar to the one which formed in the TMI-2 accident). This molten material subsequently relocates in the form of a "jet" of molten material into the lower head. The process of debris bed formation within the lower head involves the breakup of this molten jet, and the relocation of collapsing solid materials into several separated layers of particulate debris, molten metallic components and partially-frozen ceramic debris. The resulting material geometry limits the extent to which unoxidized metallic components are exposed to steam generated as a result of debris relocation and cooling in the lower head, thereby limiting hydrogen generation. In contrast, the geometric picture represented by MELCOR can be thought of as a relatively open lattice of particulate and conglomerate debris within which unoxidized metals may exist. When the core water level decreases to very low elevations in the core, the rate of metal oxidation is limited mostly by the rate at which either (downward-directed) radiation heat transfer from the core or the relocation of hot debris into the water pool in the lower head generates sufficient steam to oxidize exposed metals. Thus, when lower support structure failure occurs, the large amount of steam produced can result in a brief, but significant, increase in oxidation.

Failure of the reactor vessel lower head occurs shortly following failure of lower core support structures in the MELCOR calculation; in contrast, MAAP4 does not predict vessel breach to occur until approximately one hour after lower support structure failure. There are two reasons for this substantial difference in time. First, the differences in the way the two codes model late-phase material relocation (described above) result in significantly different debris temperatures within the lower head. The MAAP4 model represents the formation of a debris crust against the inner wall of the lower head, which partially insulates this structure from the molten ceramic material. The particulate debris bed that forms above the molten pool is at least partially quenched by residual water. While MELCOR also calculates debris cooling at upper elevations of the debris bed, it does not explicitly represent the formation of an insulating crust on the surface of the lower head. As a result, debris temperatures at the bottom of the reactor vessel lower head are higher in the MELCOR calculation than in the MAAP4 calculation.

Second, the models used to calculate when structural failure of the lower head occurs are different in the two codes. In MELCOR 1.8.3, lower head failure is calculated based on a thermal penetration model; i.e., failure is assumed to occur when the temperature of a penetration (if modeled) or the inner surface of the lower head reaches a user-specified temperature, typically 1273K. In MAAP4, vessel failure is calculated based on a creep rupture (i.e., Larson-Miller) failure model. The combination of higher calculated debris temperatures at the inner surface of the lower head and the different lower head failure model in MELCOR resulted in the shorter time to vessel breach.

A Larson-Miller creep rupture model has recently been implemented in MELCOR, although it was not active in the present calculations. A sensitivity calculation for the TMLB accident sequence performed with this new model resulted in a delay in the time to lower head failure of nearly 3000 seconds, bringing the MELCOR result within approximately 400 seconds of the MAAP prediction. That is, much closer agreement between the two codes can be achieved when similar modeling approaches are used.

3. Ex-vessel Debris Behavior

Among the more important differences in the two calculations is the containment pressure history. With the exception of the time at which the prompt rise in containment pressure accompanying vessel breach occurs, the very early containment pressure response (described later) is quite similar in the two codes. However, the long-term response is quite different. MAAP predicts over-pressure failure to occur 28 hours after the start of the accident; MELCOR predicts failure to occur nearly 10 hours later. The cause of this large difference in timing can be traced to fundamental differences in models for heat transfer between debris that emerges from the reactor vessel following lower head failure and water in the reactor cavity. This difference is observed in the calculations for three of the four PWR accident sequences (sequence ADC being the only exception.)

In both TMLB calculations, the cavity is dry when debris first emerges from the reactor vessel. Therefore, the initial mass of debris that arrives on the cavity floor is very hot (i.e., approximately 2600K in MELCOR and 2100K in MAAP4). However, nearly 100,000 kg of water enters the cavity very soon after vessel breach. This water is discharged from the accumulators as the primary coolant system depressurizes following vessel failure. The coincident release of debris and water complicates a direct comparison of models related to debris/water heat transfer between the two codes because different heat transfer models are exercised when debris falls into water versus water falling onto an existing debris bed.

Nevertheless, the following observation can be made. The MELCOR model for the TMLB accident sequence did not contain any specific input for the FDI Package[a]. Therefore, heat transfer between debris discharged from the reactor vessel and water in the containment is governed exclusively by models that focus on boiling heat transfer at the surface of a *stable debris bed* [b]; a "quenched" debris bed can only be attained if the coolant can penetrate the surface of the debris bed (a process that is subject to debris bed flooding limitations -- i.e., the Lipinski correlation). As shown in Figure 3, sufficient debris cooling to prevent aggressive corium-concrete interactions (CCI) to begin promptly after vessel breach did not occur in the MELCOR calculation. In contrast, the MAAP4 calculation allows debris fragmentation and cooling to occur (at least for the debris mass that is ejected after some water is discharged to the cavity). The result is significant debris cooling and a delay in the onset of CCI until the water on the cavity floor is completely evaporated.

4. Containment Pressure Response

Differences in the thermal state of core debris released to the containment in the two calculations allows different processes to control the calculated containment pressure response. In the MAAP4 calculation, increases in containment pressure immediately following vessel breach (shown in Figure 4) are totally governed by steam generation in the cavity and the lower compartment (i.e., cooling of two quenched debris beds). Over this time period, containment pressure is calculated to increase at a rate of approximately 40 kPa/hr. Containment pressure response over the same time period in the MELCOR calculation is governed only partially by the evaporation of water in the cavity and containment; a significant portion of the debris' internal energy and decay heat are consumed in corium-concrete interactions in the cavity. Therefore, containment pressure increases at a lower rate of 25 kPa/hr in the MELCOR calculation. When the cavity water is eventually boiled away (at approximately 40,000 seconds in the MAAP4 calculation and 55,000 seconds in the MELCOR calculation), the containment pressurization rate decreases in both calculations. A second decrease in the rate of containment pressurization is observed in the MAAP4 calculation (at approximately 73,000 seconds) when water in the lower compartment is boiled dry; this effect is not observed in the MELCOR calculation.

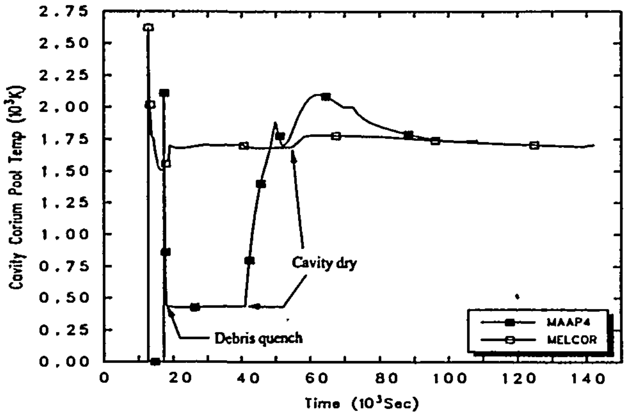

Figure 3. Debris Temperature in Cavity (PWR - TMLB)

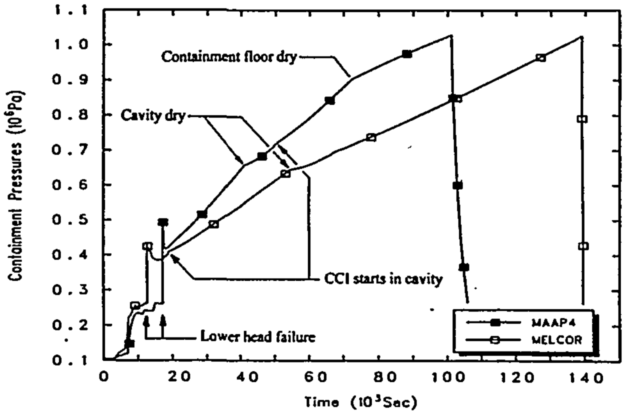

Figure 4. Containment Pressure (PWR - TMLB)

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[a] FDI is the portion of MELCOR that calculates debris-coolant heat transfer <u>during</u> relocation from the reactor vessel lower head to the containment/cavity floor.

[b] These models operate in the CAV (cavity) Package.

IV. COMPARISON OF BWR CALCULATIONS

A comparison of the calculated timing of key events for each of the five BWR accident sequences is given in Table 3; as with the PWR results, this information is presented both in terms of the calculated time between major events as well as differences in the cumulative time to an event from the start of the accident. Details of the BWR calculations are not presented here because the major findings are very similar to those identified from the PWR calculations. However, several of the observations are worth noting, particularly as they reinforce the conclusions one would draw from the PWR results.

1. The early hydrodynamic response of the reactor pressure vessel (i.e., the time required for the coolant inventory to be depleted to the point that the top of active fuel is uncovered) is shown to be in good agreement between the two codes. This suggests that the factors influencing the overall mass and energy balances of the reactor pressure vessel prior to the onset of core damage are calculated in a similar manner by the two codes. This was confirmed by a closer examination of plots for several calculated parameters.

2. The time required for vessel breach to occur after large quantities of debris relocate into the lower head (i.e., after core support plate failure) is calculated to be much shorter in MELCOR than in MAAP. This is due to the significant differences in the models for debris heat transfer within the lower head and for reactor vessel lower head failure described above.

3. In contrast to the calculations of PWR accident sequences, the general characteristics of ex-vessel behavior of core debris are calculated to be in reasonably good agreement between the two codes. That is, the calculated temperature histories of debris within the reactor pedestal are similar. This results from the minimal coolant mass that can accumulate in the drywell pedestal area to provide debris cooling; core concrete interactions are calculated to begin very soon after vessel breach by both codes. However, significant differences are observed in the calculated temperature of the drywell atmosphere after the onset of CCI; the MELCOR 1.8.3 results being significantly higher than the MAAP4 results.

V. CONCLUSIONS

Calculations were performed for a wide spectrum of severe accident sequences in representative PWR and BWR plant configurations using the MAAP4 and MELCOR 1.8.3 computer codes. The primary objectives of the current evaluation were to identify major differences in calculated results from the two codes and, when possible, identify the cause(s) of these differences. The process of identifying differences in the calculated results as well as identifying their causes was based primarily on direct comparisons of code output (in the form of plot variables).

Several differences were observed in the calculations. In many cases, the cause of these differences can be traced to known differences in the mathematical models used by each code to simulate complex physical phenomena or other aspects of severe accident behavior. However, in some cases differences in calculated results are caused by subtle differences in the specification (via code input) of plant system characteristics.

Several of the differences in calculated results involved relatively isolated aspects of severe accident progression or were observed only in particular types of accident sequence simulations. Examples include differences in the calculated distribution of coolant within the primary system during the blowdown period of large break LOCAs (explained by code hydrodynamic modeling differences) and differences in the total mass of coolant injected to the primary system from accumulators (unique to the PWR ADC and AHF accident simulation).

Two significant differences in the calculated results for all of the accident sequences are observed which can be attributed directly to code modeling differences. These are:

- The time required for reactor vessel failure to occur after a substantial mass of core debris relocates into the lower head is greater in MAAP4 than in MELCOR 1.8.3, and
- The time at which containment pressure is calculated to exceed the failure criterion differs between the two codes in virtually all the accident sequences. In general, containment failure occurs earlier in the MAAP4 calculations of the PWR accident sequences than in the corresponding MELCOR calculations; the reverse is observed for the BWR simulations.

The cause of the first difference (i.e., time to vessel breach) is the same for the PWR and BWR calculations. Namely, the two codes use different models for debris heat transfer within the lower head, and for the structural response and failure of the reactor vessel lower head. Sensitivity calculations performed with the developmental version of MELCOR (post-1.8.3) in which a new creep rupture (lower head structural failure) model is invoked suggest a significantly closer prediction of time to reactor vessel breach results when similar structural response models are used.

Table 3. Summary of Calculated Timing of Major Accident Events - BWR Sequences

Accident Sequence	All times in seconds ⇒		Time to Core Uncovery	Time to Support Plate Failure	Time to Vessel Breach	Time to Containment Failure
TB	Time between events	MAAP	36,501.	10,089.	7,144.	52.
		MELCOR	30,641.	8,107.	32.	3,328.
	Cumulative time from start	MAAP	36,501.		53,734.	53,786.
		MELCOR	30,641.		38,780.	42,108.
TQUX	Time between events	MAAP	1,897.	5,118.	3,269.	23,498.
		MELCOR	1,902.	5,201.	34.	17,220.
	Cumulative time from start	MAAP	1,897.		10,284.	33,782.
		MELCOR	1,902.		7,137.	24,357.
TQUV	Time between events	MAAP	1,171.	3,837.	8,013.	22,773.
		MELCOR	1,647.	3,269.	56.	19,571.
	Cumulative time from start	MAAP	1,145.		13,021.	35,794.
		MELCOR	1,647.		4,972.	24,543.
TW	Time between events	MAAP	*	14,975.	10,377.	*
		MELCOR	*	11,268.	36.	*
	Cumulative time from start	MAAP	119,516.		144,868.	109,153.
		MELCOR	115,309.		126,613.	108,357.
AE	Time between events	MAAP	35.	2,861.	10,123.	28,041.
		MELCOR	29.	1,458.	57.	21,724.
	Cumulative time from start	MAAP	35.		13,019.	41,060.
		MELCOR	29.		1,544.	23,268.

* Containment failure precedes onset of core damage.

The major source of differences in the calculated time to containment failure between MAAP and MELCOR in all of the calculations can be traced to differences in debris-coolant heat transfer after late-phase (large-scale) material relocation. However, these differences manifest themselves at different times in the PWR versus BWR calculations. In the case of the BWR calculations, the differences appear during the period of in-vessel melt progression. In particular, significantly lower temperatures of debris within the lower head are observed in the MAAP calculations than in the corresponding MELCOR calculations due to more efficient cooling. This difference has a significant impact on the time at which reactor vessel breach is predicted by the two codes, and on the mass of water that remains in the lower head at the time vessel breach occurs. These differences affect containment response by changing the timing and relative amounts of steam and non-condensable gas generation during the early and late periods of accident progression.

In the PWR calculations, MAAP4 predicts the formation of a quenched debris bed immediately after vessel breach in every sequence. This result occurs independent of whether water exists in the cavity prior to vessel breach (as in sequences S_2HF or AHF) or arrives coincident with debris ejection (as in TMLB). Subsequent increases in containment pressure are governed primarily by ensuing steam generation in the cavity. In contrast, the MELCOR calculation does not predict a quenched debris bed after vessel breach for any of the sequences. The rate at which containment pressure increases after vessel breach in the MELCOR calculation is governed to a lessor extent by steam generation in the cavity as a significant portion of energy transferred from core debris is involved in corium-concrete interactions.

ACKNOWLEDGMENTS

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