MAAP-MELCOR Crosswalk Phase 1 Study

David L. Luxat and Joshua T. Hanophy
ERIN Engineering and Research, Inc.
158 W. Gay St., Suite 400, West Chester PA, 19380
dlluxat@erineng.com; jthanophy@erineng.com
Donald A. Kalanich and Randall O. Gauntt
Sandia National Laboratory
Operated for the U.S. Department of Energy
1515 Eubank SE, Albuquerque, NM 87123
dakalin@sandia.gov; rogauntt@sandia.gov
Richard M. Wachowiak
Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, CA 94304
rwachowiak@epri.com

ABSTRACT
The Modular Accident Analysis Program, Version 5 (MAAP5) and Methods of Estimation of Leakages and Consequences of Releases (MELCOR) are used integral plant response analysis computer codes. Both programs have been developed over the past 30 years for the purpose of simulating a range of beyond design basis accidents. They are supported by extensive benchmarking against numerous separate effect experiments that reflect, to varying degrees, conditions expected to arise in light water reactor accidents. Such separate effect tests, however, do not completely represent the novel physics that can arise through the interaction of multiple phenomena and physical processes at a reactor scale. Furthermore, aside from the Three Mile Island, Unit 2 (TMI-2) core damage event, there is limited information available to evaluate reactor scale behavior. Both MAAP5 and MELCOR have developed models to capture reactor scale accident progression that, to a certain extent, extrapolate from separate effect experiments, with assessment against the TMI-2 event. Due to the limited information available to assess these extrapolated reactor scale models, differences in MAAP5 and MELCOR code predictions do exist, most notably in the simulation of in-vessel core melt progression. While these differences are not necessarily influential for key metrics evaluated in Probabilistic Risk Assessments (PRAs), they can have a more pronounced impact on studies assessing the efficacy of accident management measures. This paper reports the first phase of a MAAP-MELCOR crosswalk designed to identify the key core melt progression modeling differences [1]. The results of this study highlight the impact that assumptions about reactor scale, in-vessel core debris morphology have on a) the potential for high temperatures to develop above the reactor core and in the main steam lines, b) the magnitude and extent of the period for in-vessel hydrogen generation, and c) the rapidity with which a degraded core can be recovered. These examples play critical roles in the evolution of challenges to the RPV pressure boundary and containment, and are ultimately central to the evaluation of accident management effectiveness.

KEYWORDS
MAAP, MELCOR, core melt progression, severe accident modeling

1. INTRODUCTION

Fukushima Daiichi Unit 1 is believed to have experienced significant ex-vessel core debris relocation due to the long period without RPV water injection. There is, however, limited information available from during the period of likely most extensive core melting at Unit 1 with which the status of core debris inside the Fukushima Daiichi Unit 1 containment can be inferred.

Analytical methods, thus, provide the potential for a refined understanding of the ex-vessel status of the core debris. In particular, these types of analytical investigations can aid in development of insights into the a) timeframe over which the ex-vessel debris was quenched, b) degree of spreading of debris over the drywell floor, c) potential for melt attack of the drywell shell and d) extent of reactor pedestal, reactor pedestal sump, and drywell floor concrete erosion. Such insights can help inform the effort to decommission the damaged Fukushima Daiichi units.

As part of the Department of Energy: Office of Nuclear Energy (DOE-NE) initiative to investigate the Fukushima Daiichi event, MELTSPREAD and CORQUENCH were applied to assessing the status of ex-vessel core debris at Unit 1 [2]. MELCOR [3] and MAAP5 [4] simulations were used as part of this study [2] to provide necessary inputs to the MELTSPREAD and CORQUENCH analyses.

MAAP5 [5] and MELCOR [6] are integral plant response codes that are capable of calculating core debris discharge transients into containment following RPV lower head breach. The transients from the MAAP5 [4] and MELCOR [3] Unit 1 simulations were thus used as the basis for the enhanced ex-vessel analysis study [2]. At the outset of the enhanced ex-vessel analysis, it was observed that the MAAP5 and MELCOR debris discharge transients were in fact quite different. MAAP5 calculated a relatively hot and rapid discharge of debris from the RPV lower head (i.e., a large fraction of the debris was molten and entered into the reactor pedestal over a period of tens of seconds). The MELCOR-calculated debris discharge transient was by comparison relatively cold and prolonged (i.e., with a relatively large solid fraction entering the reactor pedestal over a period of about an hour).

These differences stimulated a follow-up study that has become known as the “MAAP-MELCOR crosswalk”, which reported on a first phase of results at the end of 2014 [1]. This study was initiated to develop insights into what causes these differences between the MAAP5 and MELCOR simulations. The DOE-NE and EPRI are jointly sponsoring this activity. This paper summarizes the first phase of this comparative study [1]. Since this effort is still evolving, it is anticipated that subsequent efforts will supplement the discussion provided in this paper, with the complete study documented in a future final report. The summary of the work provided in this paper should therefore be considered as a summary of ongoing efforts.

The discussion in this paper is intended to highlight how, in the development of different code models, the extrapolation of separate effect tests has resulted in divergences between MAAP5 and MELCOR simulations of reactor scale accident progression. An accident sequence similar to the Fukushima Daiichi Unit 1 event is used to provide simulation results to support this discussion. Both MAAP5 and MELCOR have been successfully applied to represent the overall thermal hydraulic response of the RPV and containment at all three affected Fukushima Daiichi units [2, 3]. This behavior is primarily influenced by overall mass and energy balance considerations. As noted above, during the MELTSPREAD and CORQUENCH analyses, it was realized, however, that the MAAP5 and MELCOR simulated core melt discharge transients from the RPV lower head are quite different.

Despite both codes being benchmarked against similar fuel melt experiments, these tests are not at reactor scale. Since separate effect tests cannot represent all the interactions between physical processes and phenomena that occur at reactor scale, it is not possible to *a priori* demonstrate that these tests fully represent the types of physical behavior that might emerge at reactor scale. Furthermore, attempts to capture aspects of reactor scale conditions in separate effect tests, in particular related to material interactions, cannot represent the *geometric* conditions that play a critical role in influencing the course of large-scale core melt progression. The areas in which MAAP5 and MELCOR are found to exhibit key differences represent a key area of epistemic uncertainty regarding in-vessel core melt progression that is only resolvable through careful analysis of currently and to be available reactor scale evidence.

The comparative study, thus, has broader implications in light of ongoing efforts to decommission the three Fukushima Daiichi units which experienced core meltdowns. This study identifies critical areas of differences between the two code models that can aid in the development of decommissioning plans as well as the focus the interpretation of decommissioning evidence on areas having the most benefit to enhancing the severe accident knowledge-base.

2. BENCHMARKING SCENARIO

The accident scenario developed for this MAAP5 and MELCOR comparative study is based on the Fukushima Daiichi Unit 1 accident scenario. This scenario has many of the same features as a typical unmitigated station blackout (SBO), with the following key exceptions.

While decay heat removal function is assumed to ultimately be lost in this scenario, an initial one-hour period of Isolation Condenser operation is credited. The assumed operation of the Isolation Condenser over this first hour is discussed in more detail in the Crosswalk study [1]. Furthermore, the RPV is assumed to depressurize prior to RPV lower head breach due to seizure fully open of a cycling Safety Relief Valve (SRV). This seizure is assumed to occur at 7 hours after the initiating event, with the suppression pool assumed to receive all discharge from the RPV through the open SRV. Thus, this scenario is distinct from many stylized SBO scenarios in which core debris breaches the RPV lower head with the RPV at high pressure. As a result, high pressure melt ejection (HPME) cannot occur in the type of scenario used in this comparative study and identified as a plausible representation of Fukushima Daiichi Unit 1 event progression [2, 3]. A detailed description of the detailed assumptions characterizing the event scenario simulated by MAAP5 and MELCOR is provided in the Crosswalk study [1].

3. COMPARISON RESULTS

3.1 Overall Accident Progression

The accident progression event timings calculated by MAAP5 and MELCOR are shown in Table II. There is reasonable agreement between the two codes in the simulation of event times, particularly prior to the onset of core damage. This is largely due to the fact that event times prior to core damage are primarily influenced by the overall energy balance in the system. The amount of decay heat generated determines, for example, how quickly water boils away or different structures, such as the RPV lower head wall, heat up.

It is important to note, however, that event timing deviations do arise following the onset of core degradation. While a key metric, the time of RPV lower head breach, is remarkably similar between the two simulations, there are notable differences in event timings related to the collapse of fuel assemblies within the core region. These differences, as will be discussed further below, ultimately reflect the distinct modeling differences between MAAP5 and MELCOR. Generally, MAAP5 simulations identify much more extensive damage across the radial extent of the core. By contrast, MELCOR simulations tend to find much less coupling between different regions along the radial extent of the core, identifying a primarily downward motion of debris toward the core plate.

As a consequence, MAAP5 simulations can in some cases calculate a challenge to the integrity of the reactor shroud due to contact with high temperature core debris. MELCOR simulations, on the other hand, do not find this type of challenge to the reactor shroud. The principally downward relocation of core debris onto the core plate calculated in this MELCOR simulation (and others), however, drives a thermal transient in the plate capable of ultimately causing a relatively early failure of parts of the plate below the central region of the core. By contrast, the MAAP5 simulation identifies a slower downward relocation of core debris into ultimate contact with the core plate, largely due to formation of debris crusts in the lower parts of the core that promote sideward motion of core debris toward (ultimately) the reactor shroud. As a result, the MAAP5 simulation finds a core plate failure occurring over 3 hours after the onset of core plate failure in the MELCOR simulation.

Table II. Summary of Key Event Timings

Accident Progression Event	MAAP5 Simulated Timing	MELCOR Simulated Timing
Core Water Level at TAF	3.20 h	2.70 h
Core Water Level at 2/3 Active Core Height	3.40 h	3.00 h

Table II. Summary of Key Event Timings

Accident Progression Event	MAAP5 Simulated Timing	MELCOR Simulated Timing
Core Water Level at 1/3 Active Core Height	3.66 h	3.30 h
Onset of In-Vessel Hydrogen Generation	3.70 h	3.60 h
Initial fuel assembly collapse in Ring 1	4.30 h	5.00 h
Initial fuel assembly collapse in Ring 2	4.29 h	8.40 h
Initial fuel assembly collapse in Ring 3	4.31 h	9.00 h
Initial fuel assembly collapse in Ring 4	4.45 h	no collapse
Initial fuel assembly collapse in Ring 5	5.88 h	no collapse
Initial core plate failure	8.82 h[1]	5.10 h
Shroud failure	8.46 h	event not predicted
Lower Plenum Dryout	8.54 h	10.36 h
Initial RPV Lower Head Breach	12.60 h	14.45 h

Despite these timing differences in finer scale features of core melt progression, the overall global event timing similarities emerge because of relatively similar bulk responses. A key example of this type of bulk response is the RPV pressure transient found by the two simulations, which is shown in Figure 1. This agreement should be expected given the overall similarity in how the two codes represent the transport of decay heat away from the fuel prior to the onset of core melting.

While not gross, deviations in the simulated RPV pressure transient can be seen in Figure 1 to arise just following the onset of core oxidation. In particular, the MAAP5 simulation illustrates a less pronounced SRV cycling frequency following the onset of core oxidation and melting. This reflects the decrease in steam generation as the RPV water level falls below the core. Complementing this in the MAAP5 simulation is a decrease in the heat rejection from the core debris that occurs once core debris begins to form in the MAAP5 simulation, altering the original core geometry. The MELCOR simulation, however, maintains a relatively high rate of SRV cycling even after core oxidation, with a brief period of cycling rate decrease around 4.5 hours corresponding to depletion of water in the core region. Beyond this time, however, progressive core damage ultimately leads to core plate failure in the MELCOR simulation, facilitating continual debris relocation into the lower plenum, and thereby sustaining steam generation.

[1] MAAP5 simulates a gross failure of the core plate. Debris remaining in the core region relocates into the lower plenum at this time.

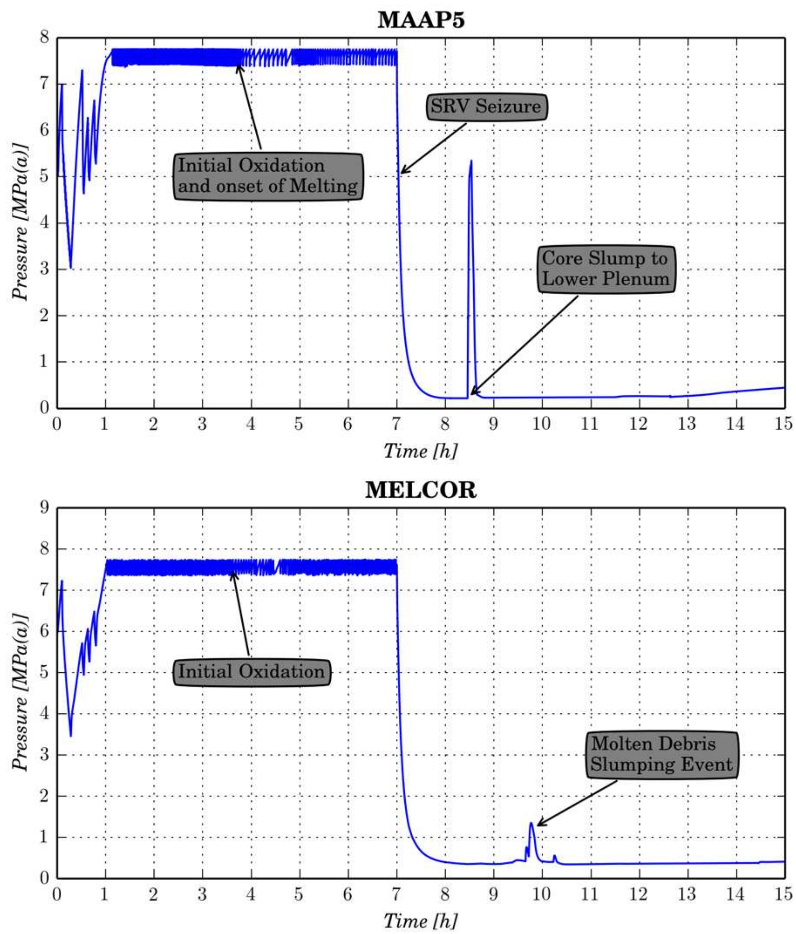

Figure 1. Comparison of RPV Pressure Transient Simulations

These differences in the rate of SRV cycling found between the two simulations are ultimately symptoms of a more dramatic difference in how the two codes represent transport of decay and chemical energy away from core materials once core degradation starts. Figure 2 shows a comparison of the MAAP5 and MELCOR simulated overall energy balances. As part of this comparison, the different pathways for decay and chemical heat rejection are shown. As can be seen in Figure 2, MAAP5 predicts a substantially different amount of heat rejection into RPV fluids (i.e., water, steam and hydrogen) once core oxidation and core melting begin. The MAAP5 calculation finds that rejection of decay and chemical heat to RPV fluids is quite limited, with much of this energy being rejected into core material stored energy (i.e., increasing the temperature of core materials and promoting further melting). By contrast, the MELCOR simulation finds that the bulk of decay and chemical energy continues to be rejected into RPV fluids. This key difference illustrated in Figure 2 ultimately stems from the distinct way in which the two codes represent the geometry of a degraded core, and consequently the surface area available for interaction with RPV fluids (i.e., the heat transfer surface area).

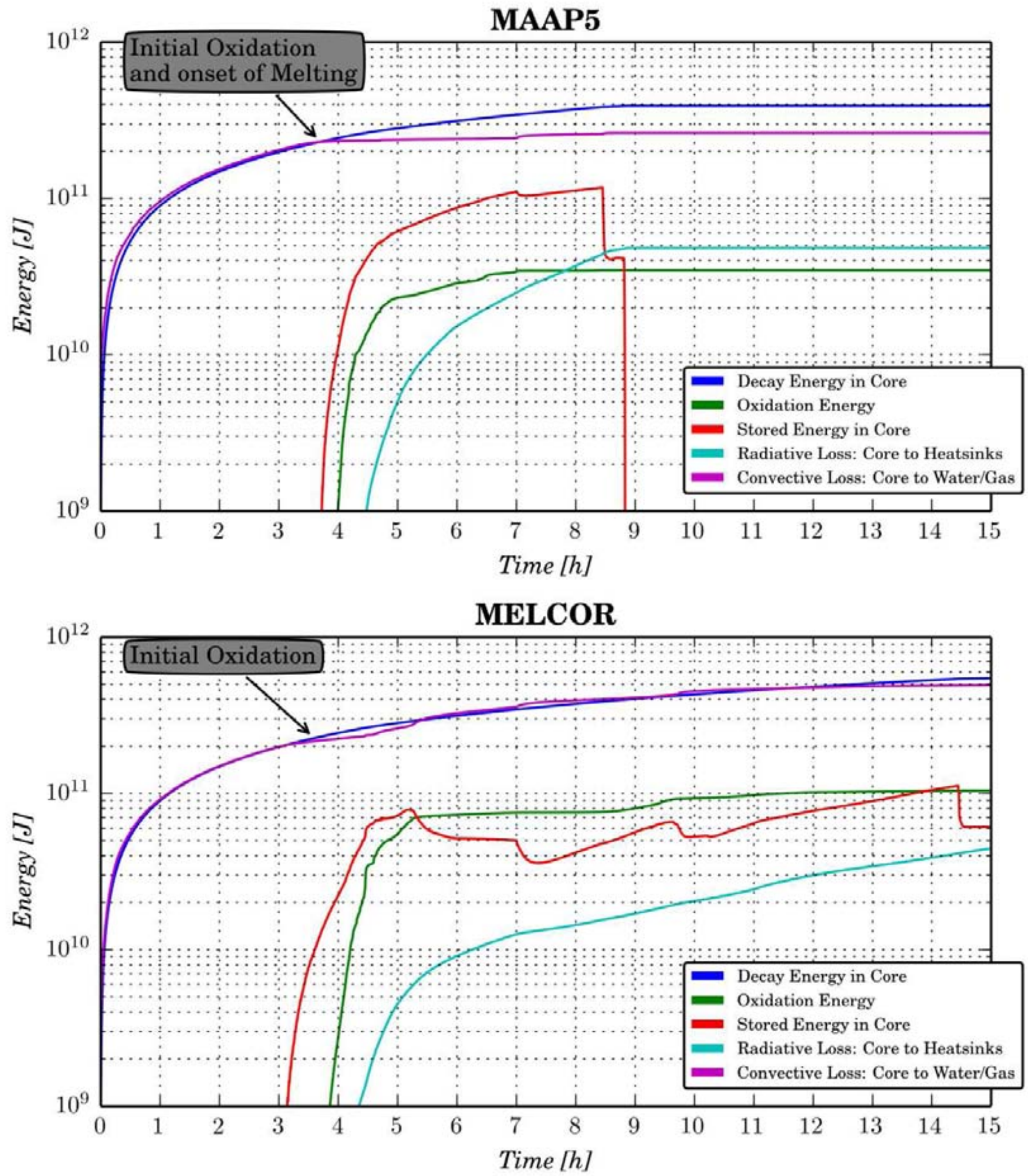

Figure 2. MAAP5 and MELCOR Simulation of Decay and Chemical Heat Transport from Core/Core Debris

3.2 Simulation of Core Degradation

Figure 2 illustrates fundamentally different MAAP5 and MELCOR calculations of heat transfer away from the core, with these differences emerging once core degradation begins. The discussion in this section focuses on identifying core degradation modeling differences between the two codes and showing how these differences ultimately contribute to the type of simulation differences seen in Figure 2.

MAAP5 allows molten debris to relocate into open volumes (i.e., voids) in particulate debris beds. This has the effect of reducing the porosity and effective heat transfer surface area in a particulate debris bed. MELCOR, however, idealizes particulate debris beds as consisting of fixed-diameter particulate spheres. As a result, molten debris that freezes when it relocates into a particulate debris bed is assumed to form into these fixed-diameter particulate spheres. This has the effect of increasing the total volume of the particulate debris bed without affecting the ratio of debris-to-void volume. By contrast, this ratio would tend to increase in the MAAP5 modeling of particulate debris beds. The MELCOR model, thus, maintains a particulate debris bed morphology in which voids continue to form fluid flow channels that support motion of fluid into and out of the debris bed. As a result, the heat transfer surface area in a particulate debris bed does not degrade in the same way as represented in the MAAP5 simulation[2].

Representation of particulate debris bed heat transfer surface area is, thus, a key difference between the two computer code models, influencing the extent of heat transfer away from core debris. For rod-like geometries, the two codes employ similar flow and heat transfer models. In both codes, the freezing of debris in open flow channels on solid core structure surfaces results in a reduction in the heat transfer surface area to volume ratio for fuel rods. Particulate debris bed geometries, however, are treated in significantly different manners. In MAAP5, particulate debris beds have lower heat transfer surface areas than the rod-like core geometry. The heat transfer surface area decreases as a greater amount of core debris volume fills in a particulate debris bed (i.e., there is less empty volume for gases to pass through and exchange energy with core debris particles). In MELCOR, particulate debris beds are represented in terms of particles with fixed diameter so that the heat transfer surface area tends to be enhanced relative to a rod-like geometry. MELCOR never completely blocks flow through the particulate core node—though it does decrease with decreasing porosity. MELCOR also models the effective heat transfer surface area as increasing with the total particulate volume[3].

Ultimately, this modeling difference results in MAAP5 and MELCOR simulating two distinct degraded core geometries. As noted above, MELCOR simulates a more extensive downward relocation of debris toward the core plate combined with a failure of the core plate at the first radial core region prior to significant melt formation. On the other hand, the accumulation of debris within particulate debris beds ultimately results in MAAP5 simulating the formation of blockages/crusts in the lower region of the core, above the core plate leading to a) build-up of debris above these crusts, with this suspended debris becoming molten, b) convective circulation within molten debris nodes transferring heat primarily to neighboring core nodes in the radial direction, and c) radial spreading of the core region molten pool. This is illustrated in Figure 3, which shows the active region fuel temperature distribution predicted by MAAP5. The MELCOR simulation indicates a much less extensive coupling of damage across the radial extent of the core. The heatup and degradation of fuel assemblies is relatively decoupled from radial ring-to-radial ring. This can be seen in Figure 4, which shows the active region fuel temperature distribution predicted by MELCOR.

In the long-term, the evolution to these initially different degraded core morphologies persists, resulting in fundamentally different modes of core debris slumping to the lower plenum. Figure 5 shows the fuel temperature distribution in the active fuel region calculated by the MAAP5 simulation to the end of the simulation (at 15 hours).

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2 This MELCOR modeling abstraction is intended to capture inhomogeneity around a core radial ring. In MAAP5 and MELCOR simulations, this inhomogeneity is not captured directly because the average fuel properties are represented in the nodalized core. The MELCOR modeling assumes that this inhomogeneity results in flow pathways through the core remaining open.

3 MELCOR assumes that the effective “connectedness” of a debris bed is unchanged with accumulation of particulate (i.e., decreasing porosity). This is intended to reflect the incoherent degradation of fuel assemblies around a radial ring. In this abstraction, there will always be open flow areas through a particulate debris bed. Increasing the volume of particulates thus serves to increase the effective heat transfer surface area.

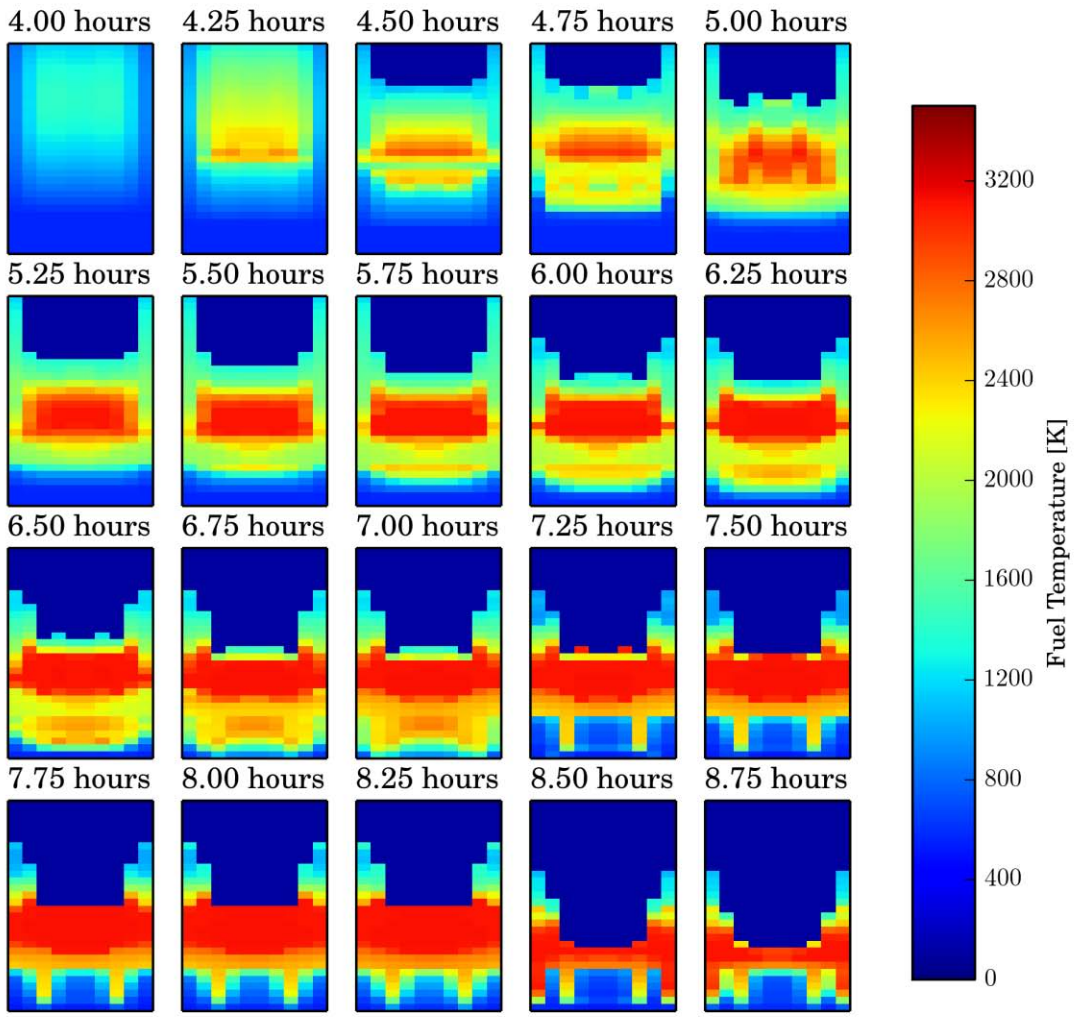

Figure 3. Distribution of Active Fuel Region Fuel Temperatures at different times in MAAP5 Simulation

The results shown in Figure 5 highlight the extent to which MAAP5 degraded core geometries ultimately behave in a relatively coherent way across the radial extent of the core. The formation of a radially-extended molten pool in the core region, which can be seen at the 6-hour mark in Figure 5, effectively subsumes most of the peripheral fuel assembly debris. With the eventual failure of the core plate, this radially-contiguous core debris bed relocates in a largely coherent manner into the lower plenum.

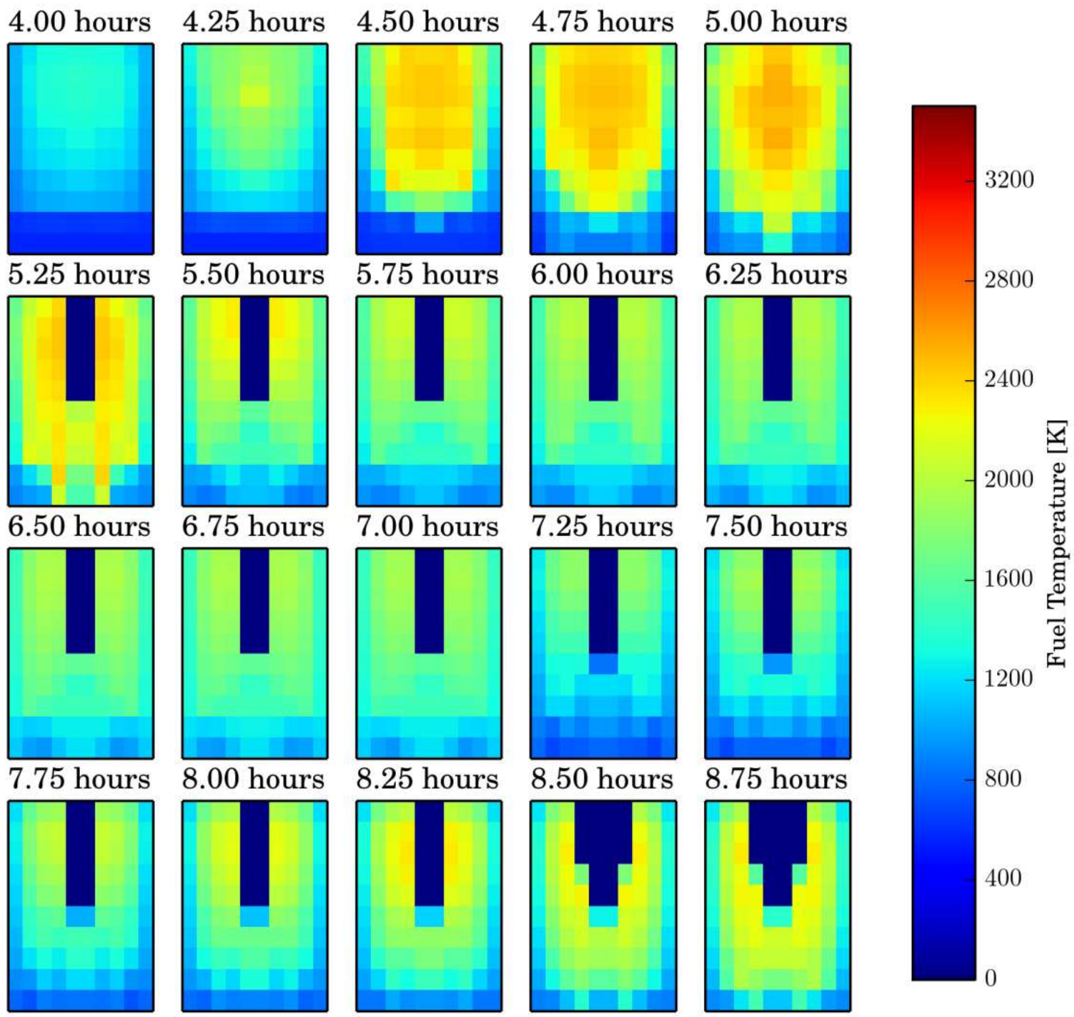

Figure 4. Distribution of Active Fuel Region Fuel Temperatures at different times in MELCOR Simulation

The comparable active region fuel temperature distribution calculated by MELCOR is shown in Figure 6. Unlike the much more radially extended core debris bed shown in Figure 5 for the MAAP5 simulation, the MELCOR simulation results presented in Figure 6 illustrate a radially more decoupled progression of core degradation. In effect, the fuel assemblies in different radial regions of the core are decoupled in the MELCOR simulation. This promotes a greater amount of core debris remaining in the peripheral parts of the core after the initial core plate failure around 5 hours. The slumping of core debris into the lower plenum is thus relatively incoherent in the MELCOR simulation, with each radial region slumping to the lower plenum somewhat independently of the other.

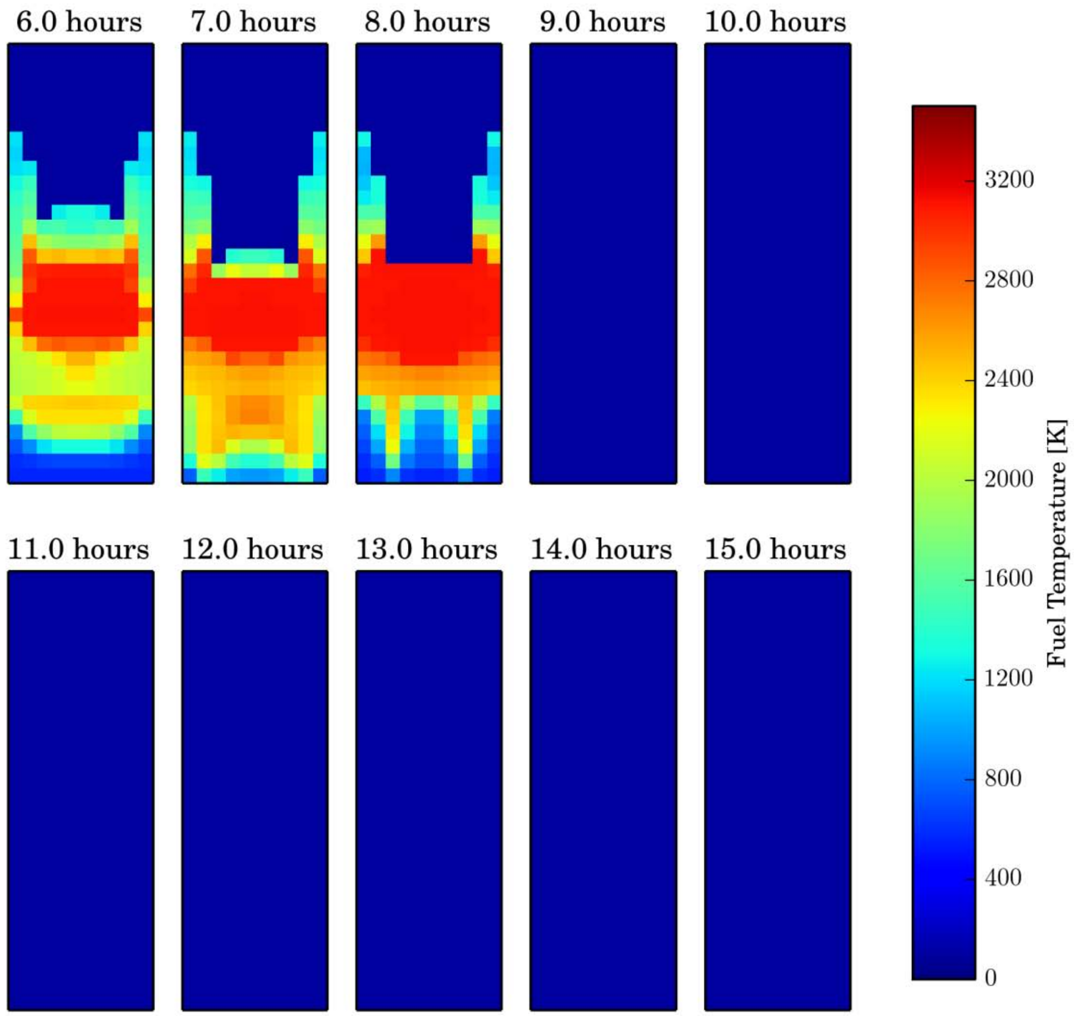

Figure 5. Distribution of Active Fuel Region Fuel Temperatures to End of MAAP5 Simulation

The representation of heat transfer from particulate debris to RPV fluids is the most significant difference between MAAP5 and MELCOR modeling abstractions. Both codes have been validated against numerous separate effect experiments related to core melt progression. MAAP5 code validation is summarized in Volume 3 of the MAAP5 computer code manual [7]. MELCOR code validation is summarized in [8].

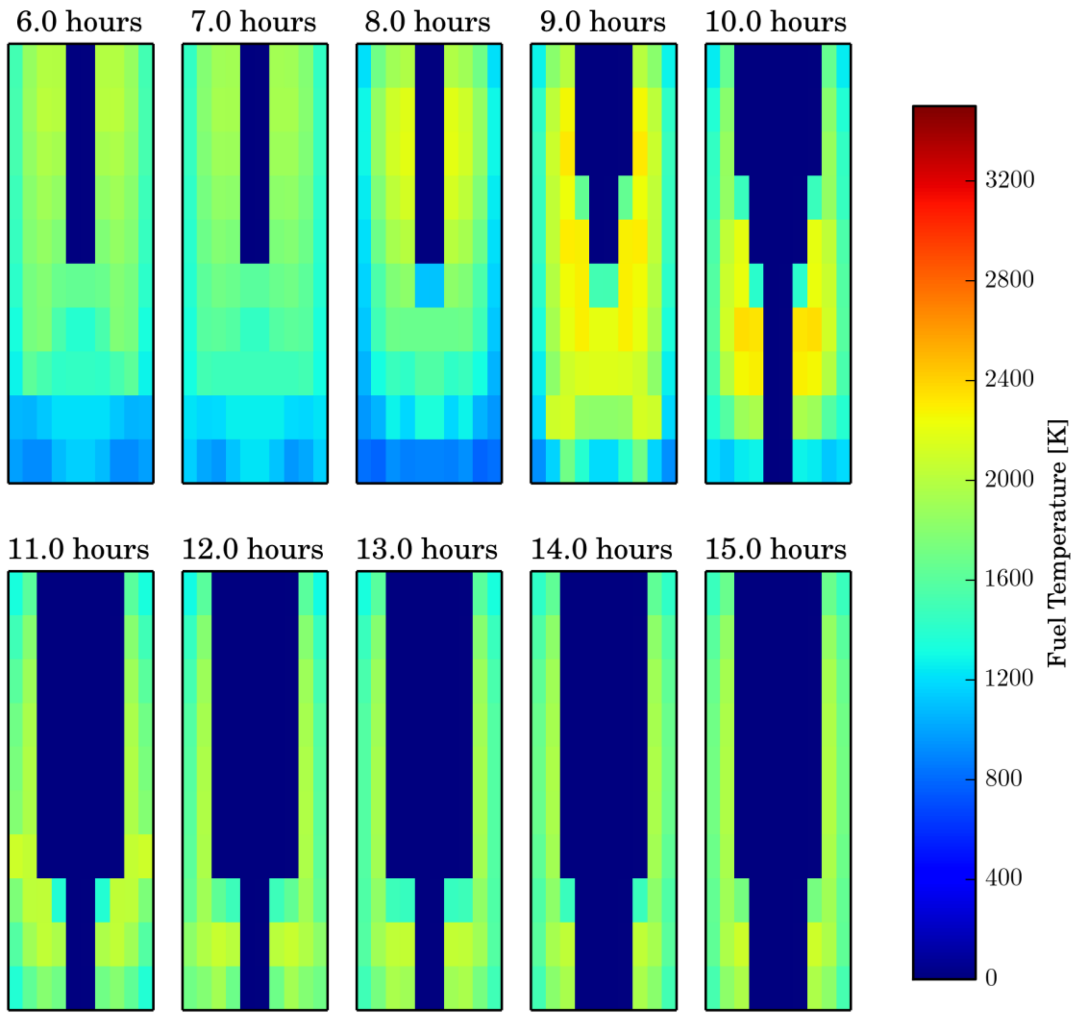

Figure 6. Distribution of Active Fuel Region Fuel Temperatures to End of MELCOR Simulation

3.3 Key Consequences of Different Core Degradation Modeling

3.3.1 RPV Above-Core Gas Temperatures

The different core debris geometries simulated by MAAP5 and MELCOR ultimately give rise to the distinct types of energy transport away from core debris illustrated in Figure 2. The much greater dissipation of decay and chemical energy into RPV fluids for the MELCOR simulation, as identified in Figure 2, has further consequences on overall accident progression.

In particular, the greater rejection of decay and chemical energy into RPV fluids found in the MELCOR simulation presents a means to transport this energy into the RPV steam dome and main steam lines (MSLs). This has a critical effect on the potential for a challenge to the RPV pressure boundary developing prior to RPV lower head breach. The occurrence of high temperature MSL creep, furthermore, has the potential to ultimately enhance any fission product release to the environment by establishing a direct flow pathway between the RPV and drywell.

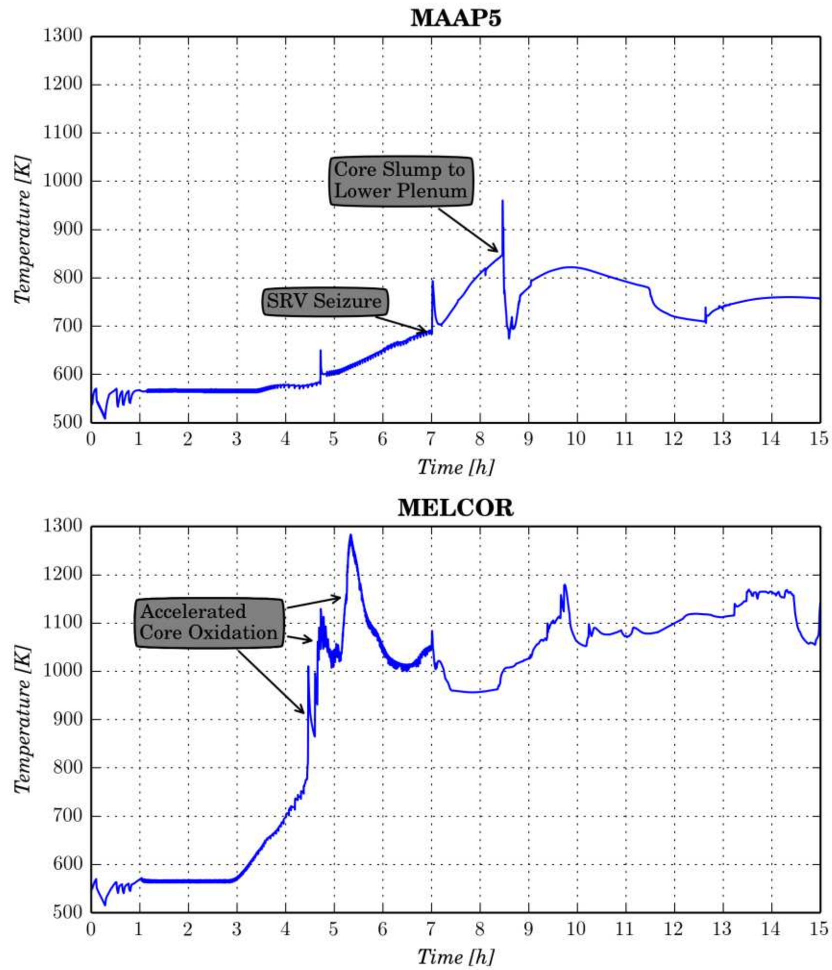

Figure 7. Comparison of RPV Steam Dome Temperature Transient Simulations

Figure 7 shows a comparison of the MAAP5 and MELCOR calculations of the RPV steam dome gas temperature transients. The MELCOR simulation exhibits a severe temperature transient in the RPV steam dome and MSLs, relative to the MAAP5 simulation. The potential for MSL creep rupture, prior to RPV lower head breach, thus exists in MELCOR simulations. It has been identified as a likely means of depressurizing the RPV prior to RPV lower head breach in SOARCA Peach Bottom uncertainty study [9]. By contrast, MAAP5 simulations do not identify the potential for MSL creep rupture in the simulation for this study. This result is generic across a range of MAAP5 simulations performed in different studies (see, for example, the simulations performed to investigate the Fukushima Daiichi event progression [3]).

3.3.2 In-Vessel Hydrogen Generation

These different representations of degraded core geometry have a further impact on the evolution of in-vessel flammable gas generation throughout the course of an accident. A degraded core geometry that remains relatively open to steam flow through it can support prolonged flammable gas generation. Furthermore, it can also be susceptible to more pronounced in-vessel flammable gas generation in a core reflood situation, particularly relative to a degraded core geometry that possesses much more limited open flow pathways to support steam incursion and interaction with hot metal debris surfaces.

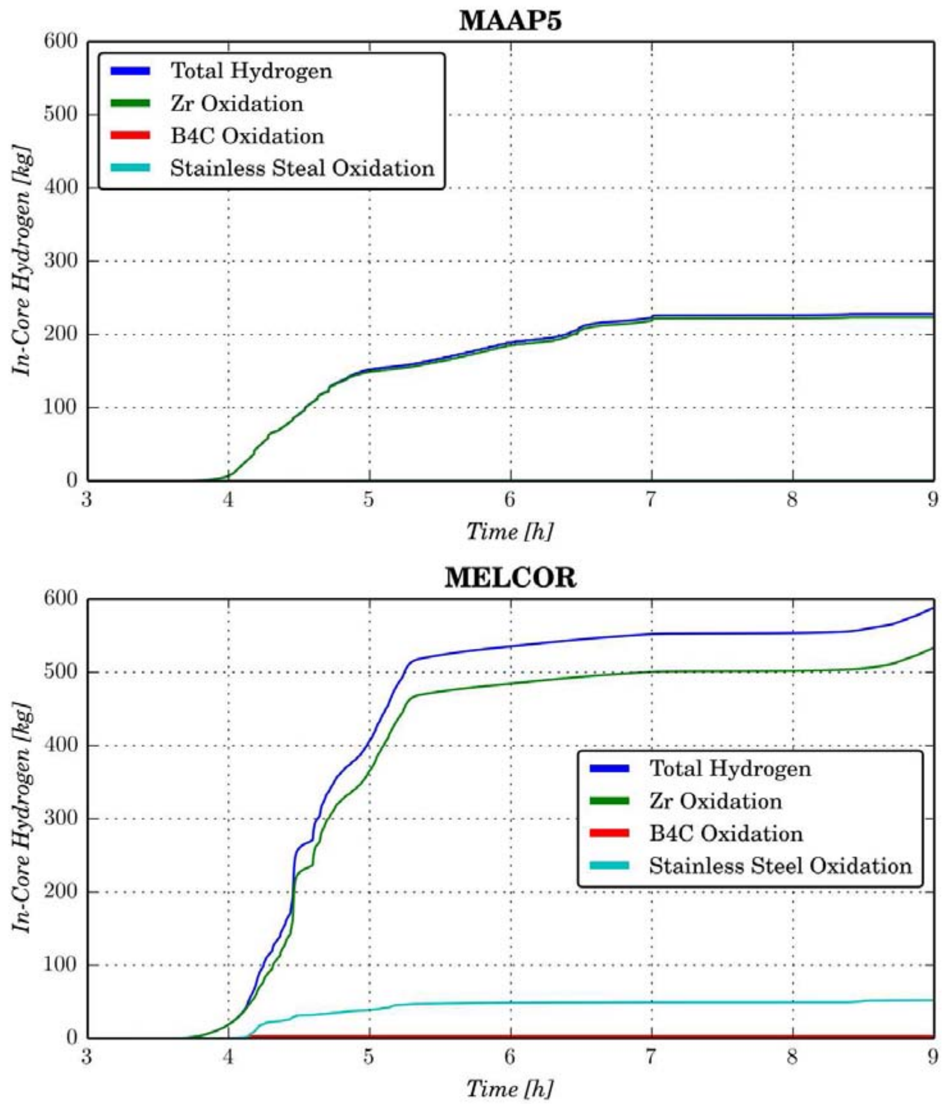

Figure 8. Comparison of In-Vessel Hydrogen Generation Transient

The distinct representations in MAAP5 and MELCOR degraded core geometries ultimately drive distinct in-vessel hydrogen generation transients. An example of the distinct in-vessel hydrogen generation transient that can arise across different MAAP5 and MELCOR simulations is shown in Figure 8, for the Fukushima Daiichi Unit 1 scenario considered in this study. These results indicate the potential for the type of degraded core geometry represented by MAAP5 to result in, by comparison to the MELCOR-simulated hydrogen generation transient in Figure 8, a) a lower amount of in-vessel hydrogen generation, and b) a shorter period over which this hydrogen generation occurs.

Core debris configurations that remain more open (i.e., like those in MELCOR simulations) will allow for more extensive hydrogen generation over a longer period of time should RPV water injection be recovered. By contrast, the type of core debris configuration represented in MAAP5 simulations results in less exposed surface area. Steam generated upon RPV water injection recovery does not necessarily contribute to extensive oxidation of Zircaloy. Furthermore, should sufficient surface area be open and above 1200 K, the rapid generation of chemical energy will result in debris formation and relocation into debris beds that have limited open flow area. Thus, MAAP5 simulations exhibit inherent limitations on the amount and duration of in-vessel hydrogen.

4. DISCUSSION

In the MAAP5 simulation developed for this comparative study, the melting of core debris in the central region of the core results in a downward flow of molten debris. As it freezes on colder surfaces of the core at these lower elevations, debris begins to accumulate in the initially open flow channels. With sufficient melting of debris, these open areas in the lower region of the reactor core will become filled-in (i.e., blocked to continued upward flow). Axial flow of steam becomes consequently degraded.

Interaction between steam and hot Zircaloy is thus limited in the MAAP5 simulations due to formation of flow blockages. The MAAP5 simulations show that the open flow area in the reactor core decreases to below about 10%[4]. The formation of molten debris in the central region of the core results in progressive relocation of molten debris sideward. The blockage of the reactor core proceeds from the center to the periphery of the core; i.e., from the region with the highest powered fuel assemblies to the region with the lowest powered fuel assemblies. This occurs through spreading of molten debris as side crusts fail and enhanced sideward heat fluxes melt neighboring fuel assemblies/debris

By contrast, the amount of flow area that remains open in a flow channel does not decrease as significantly in the MELCOR simulation developed for this study. The MELCOR simulation results indicate that the fraction of open flow area remains above about 60% of the initial open flow area through a ring in the nodalized reactor core. Thus, the available area for steam and noncondensable gases to continue to flow upward through the reactor is dramatically different in the MELCOR simulation when compared with the MAAP5 simulation.

This has the consequence of promoting much more significant in-vessel hydrogen generation in the MELCOR simulation, relative to the MAAP5 simulation. About 400 kg of additional hydrogen are generated in the MELCOR simulation, as can be seen in Figure 8. Importantly, MELCOR simulates continued hydrogen generation from the peripheral fuel assemblies, beyond the time at which MAAP predicts steam flow through these fuel assemblies has become blocked.

Thus, the different manner in which degraded core morphologies can develop blockages in the two code simulations can drive a fundamentally different prediction of core oxidation. The generation of hydrogen is consistent and comparable between the two codes prior to appreciable disruption of the initial core geometry.

In the MELCOR simulation, the candling of debris can result in accumulation of debris into initially open flow channels. Following the collapse of fuel assemblies, however, MELCOR represents the resulting debris bed geometry as a largely particulate debris bed. This debris bed is assumed to have flow geometry similar to a bed of spherical particles having a diameter of 1 cm in the core regions at and above the lower core plate, and a diameter of 2 mm in the core regions below the lower core plate. The associated heat transfer surface area for this type of debris bed is proportional to the volume of particulate debris.

The particulate debris bed that forms in the MAAP5 simulation, however, is assumed to have flow and heat transfer surface areas that decrease with increasing particulate mass. That is, the accumulation of more debris in the particulate debris bed is assumed to occupy only open volume. As a result, the open volume of the particulate debris bed decreases with increasing amounts of debris. Furthermore, the available heat transfer surface area also decreases with the decrease in open flow area in the debris bed.

This key modeling difference between the two computer codes has the following effects. MELCOR simulations assume that the heat transfer surface area tends to increase with the volume of debris forming a particulate debris bed. A greater amount of gas thus flows through particulate debris, facilitating a much larger rejection of heat from the core debris to the gas in the RPV. This allows for continued interaction of steam with overheated core metals, which drives significant in-vessel hydrogen generation (in excess of

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4 At this open flow area fraction, the MAAP5 simulation assumes that a flow channel is “blocked” to continued upward flow.

800 kg of hydrogen). The degradation of heat transfer surface area in the MAAP5 simulation results in less gas flowing through the debris. A significant reduction in the amount of core heat rejected to gas in the RPV is simulated. As a result, significant impedance of continued hydrogen generation occurs in the MAAP5 simulation once core debris begins to form. These key differences in the treatment of flow through a degraded core are illustrated in Figure 9.

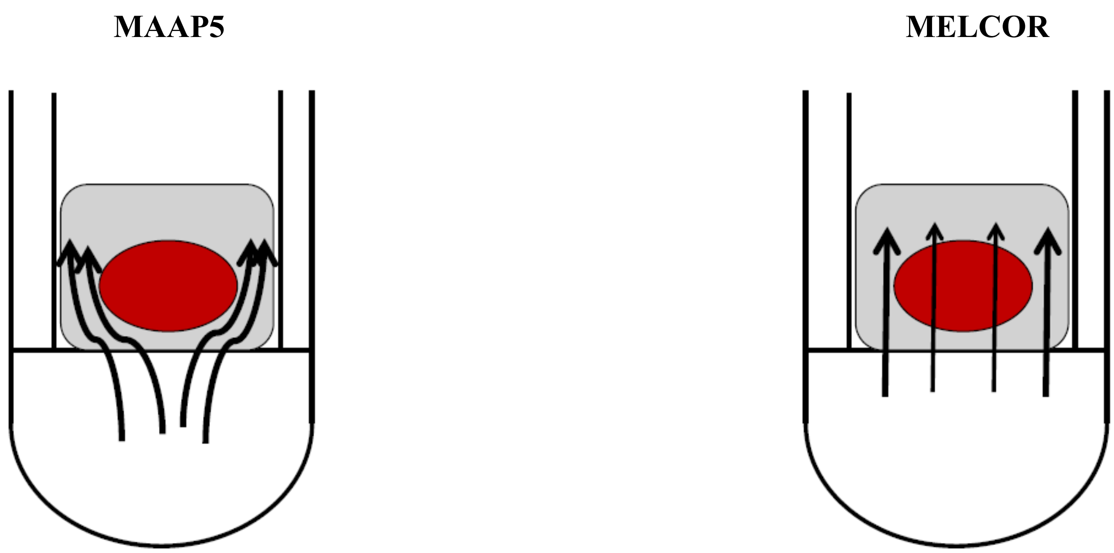

Figure 9. Illustration of Different Flow Geometries through a Degraded Reactor Core

5. CONCLUSIONS

The above discussion has highlighted the key modeling differences between the two codes. The key area in which the codes differ is the representation of degraded core morphologies. This has the following consequences on the progression of core damage within the core region.

<u>Downward relocation of particulate debris</u>: MELCOR represents far more extensive relocation of fuel particulate debris on to the core plate. This is based on a model which captures debris relocating into the core bypass to minimize the debris static head. MAAP5 tends to limit the downward relocation of particulate fuel debris because of the limited open volume in lower regions of fuel assemblies—this facilitates build-up of debris above the core plate into particulate beds having low porosities.

<u>Flow and heat transfer area through a particulate debris bed</u>: MELCOR represents a particulate debris bed in terms of fixed diameter particles—additional debris does not accumulate within open volume and thereby reduce the heat transfer surface area. MAAP5 assumes that a particulate debris bed can continue to accept debris into open regions, and thus will lose flow and heat transfer surface area as these pores are "filled up" beyond a critical value.

<u>Fraction of core forming molten debris</u>: As a result of these distinctly different ways of modeling degraded core geometries, MAAP5 simulates far more extensive melting of core debris than MELCOR.

The areas in which the two computer codes differ relate to how models have been extrapolated from available experimental tests, as well as the TMI-2 event. The differences between the two codes should not be interpreted in terms of level of correctness, since both codes represent the known physics in the same manner. They differ in areas of incomplete knowledge due to reactor scale information not being available. Thus, the differences between how the two codes represent core degradation, prior to core slumping, should be treated as a reflection of epistemic uncertainty.

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Larry Humphries, Sandia National Laboratory
Richard Lee, NRC/RES
Sung Jin Lee, Fauske & Associates, LLC
Allen Notafrancesco, NRC/RES
Chan Y. Paik, Fauske & Associates, LLC
Martin Plys, Fauske & Associates, LLC
Robert Sanders, AREVA
Rick Wachowiak, EPRI
Quan Zhou, Fauske & Associates, LLC

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