International Conference on Probabilistic Safety Assessment
Methodology and Applications
November 26-30, 1995, Seoul, Korea

MAAP4.0 BENCHMARKING WITH THE TMI-2 EXPERIENCE

Chan Young Paik, Robert E. Henry, Michael A. McCartney

Fauske & Associates, Inc.
16W070 West 83rd Street
Burr Ridge, IL 60521, USA

ABSTRACT

The Modular Accident Analysis Program (MAAP) is a computer code that simulates the response of nuclear power plants to postulated accident scenarios. The new version of this code, MAAP4, offered by the Electric Power Research Institute (EPRI) and developed by Fauske and Associates, Inc. (FAI), is intended for accident management evaluations and severe accident analyses for existing and Advanced Light Water Reactors (ALWRs). MAAP4 has the capability of modeling core heatup, subsequent melting and relocation, and lower head debris interaction in greater detail. This paper describes MAAP4 simulation of the Three Mile Island Unit 2 (TMI-2) accident. Comparisons of the MAAP4 model with TMI-2 data show that the MAAP4 code calculations are in general agreement with the overall plant response during the accident through the first 5 hours, which includes uncovering of the core, core damage, reflooding of the damaged core, and drainage of a significant fraction of the core, as a melt, into the lower plenum. MAAP4 calculates the formation of a molten pool within the core region, subsequent failure of the side crust, draining of molten material into the lower plenum, and overheating of the RPV wall followed by cooling of the wall and debris. This TMI-2 benchmark demonstrates the capability of MAAP4 used as an accident management tool, to simulate severe accident and operator actions.

1. INTRODUCTION

The Three Mile Island Unit 2 (TMI-2) accident caused the most serious core damage in the history of the U.S. nuclear industry. As such the accident offers a unique source of data for understanding core degradation phenomena and for benchmarking severe accident analysis computer codes.

1.1 Definition of Accident Phases

The early phases of the accident (0 to 174 minutes) were simulated by MAAP 2.0 [1] and by MAAP 3.0B [2]. A simulation of the first 224 minutes of the TMI-2 accident before relocation of the core material into the lower plenum was carried out using MAAP-DOE and MAAP 3.0B [3]. The comparison was good up to the time of severe core degradation, and afterwards did not compare well. With the new core and lower plenum models in MAAP4, the benchmark was successfully extended to include the relocation of molten core material to the lower plenum, the thermal transient response of the reactor pressure vessel (RPV) wall and the subsequent cooling of the core debris in the vessel. This paper describes the MAAP4 comparison with the TMI-2 data including the containment response during the first five hours of the accident.

The TMI accident can be considered in five distinct phases of accident progression, and these are:

<u>Phase 1</u>: From 0 to 100 minutes. This phase represents the part of the accident where some or all of the main coolant pumps were operating.

<u>Phase 2</u>: From 100 to 174 minutes. In this phase, all coolant pumps were shut down and resulted in the boiloff of water in the reactor pressure vessel (RPV) and progressive uncovering of the core, causing major core damage.

<u>Phase 3</u>: From 174 to 224 minutes. This phase represents the first core recovery event resulting in significant quenching of the degraded core when the 2B main coolant pump was activated at 174 minutes. During this phase, MAAP4 code predicted continued core heatup and damage, even when the core is covered as a result of high pressure injection (HPI) after 200 minutes.

<u>Phase 4</u>: From 224 to 235 minutes. During this phase, molten core material relocated into the RPV lower head as a result of melting through the side crust of the molten pool and the steel core former wall.

<u>Phase 5</u>: From 235 to 300 minutes. Debris in the lower plenum caused the RPV wall temperature to increase to about 2012°F and the carbon steel wall subsequently experienced rapid cooling.

In this paper, the MAAP4 PWR code Version 4.0.2 was used to simulate all five phases of the TMI-2 accident progression.

1.2 Description of MAAP4

The MAAP4 code is an integrated severe accident analysis code which contains thermal hydraulic and fission product models to simulate plant response for all phases of a severe accident progression. In addition to treating all the important phenomena, MAAP4 also models all important safety systems, such as emergency core cooling, containment sprays, residual heat removal, etc. MAAP4 provides the technical basis for assessing the integral system response to the implementation of operator actions taken to recover from an accident. MAAP4 contains substantial mechanistic model improvements over its predecessor, MAAP 3.0B. There are five major areas of improvement in MAAP4 over MAAP 3.0B: 1) core heatup and melt progression, 2) lower plenum debris behavior, 3) reactor vessel failure mechanism, 4) generalized containment model, and 5) ALWR specific models including improvements in the pressurizer model. With these new improvements, MAAP4 now has the capability to model in-vessel recovery when reflooding the reactor core and considers the potential for quenching core debris both within the original core boundaries and in the pressure vessel lower head. A brief summary of the model improvements made in the core heatup model and lower plenum debris behavior follows. Descriptions of the vessel failure mechanism, generalized containment model, and ALWR specific models are available in references [4], [5], and [6].

Core heatup and melt progression are important because a primary goal of accident management is the prevention of core damage, or at least its arrest within the core boundary. In MAAP4, the reactor core is divided into a number of axial rows and radial rings (r- and z-nodalization). Each core node contains materials such as fuel, cladding, control rod materials, fuel can, and control blades. MAAP4 also models material interactions that may form eutectic mixtures such as U-Zr-O or B-Zr-SS-C-O. Since these eutectic mixtures and individual components have different melting temperatures, MAAP4 tracks each eutectic mixture and component temperature and relocates them separately. Because of a low melting temperature, control rod materials will relocate first, followed by metallic cladding material and U-Zr-O eutectics. The downward relocation of molten material is calculated according to a consideration of external film flow and internal pipe flow models. When the downward relocation is impeded due to a blocked node below, sideward relocation is allowed. After the substantial core degradation, a molten pool with a surrounding crust boundary may form within the original core boundary. The MAAP4 molten pool model includes: 1) the heat and mass transfer within the molten pool due to natural circulation induced by internal heat generation, 2) the peripheral crust formation and subsequent breach, and 3) in-core gas flow diversion due to the presence of a crust boundary. There are two mechanisms for core material relocation into the lower plenum from the original core boundary in MAAP4, and these are: 1) downward relocation through the failure of the bottom core plate, and 2) sideward relocation due to a side crust rupture as was observed in the TMI-2 accident.

Significant model advancements have been made in lower plenum debris behavior in MAAP4. The debris bed in the lower head is segregated into a particulate bed on top of a metal layer and an oxidic pool with surrounding crust boundary. Two other options (user input) for the debris bed configuration are: 1) a homogeneous mixture without a separate metal layer and a particulate bed, and 2) a particulate bed and an oxidic pool with surrounding crusts without the metal layer. A particulate bed can be formed as a result of the entrainment process when a molten debris jet descends into the water-filled lower plenum. Quenching, oxidation, and fission product releases are all modeled as the molten jet breaks up in the water pool. Crusts can be formed at three surfaces in the oxidic debris pool, i.e., the top surface, the reactor pressure vessel wall surface, and internal structure surfaces. Quenching due to water ingression at the top of the surface is modeled separately from the energy transfer within the crust. One area where limited experimental data is available is the quenching of over-heated debris in-vessel prior to vessel breach. Quenching of debris in-vessel is significant because the operator can potentially cool the core debris in the lower head by injection or by providing external RPV cooling, and thereby preventing vessel failure. MAAP4 includes models for in-vessel cooling and external RPV cooling to evaluate whether a safe, stable state can evolve following water addition into the reactor vessel and/or the containment.

In the TMI-2 accident, molten core material drained into the lower plenum and caused the RPV wall to reach peak temperatures of about 1100°C (2012°F) over an area about 1 m in diameter. After reaching this temperature, the wall apparently exhibited rapid cooling. A mechanism which can explain this rapid cooling is a limited amount of material creep in the RPV wall, resulting in a gap between the wall and the core debris material. This is the case if the debris does not adhere to the RPV wall. Experimental evidence with both molten aluminum oxide and molten steel [7] shows that molten material poured through water does not adhere well to a steel wall. This development of contact resistance may be due to the vaporization of water in surface cavities. Specifically, formation of a significant contact resistance was observed in the EPRI-sponsored experiments on the response of lower head penetrations when submerged in a high temperature melt. Thus, relative movement between the RPV wall and the debris bed crust would be expected when the RPV wall experiences material creep. As the gap between the RPV wall and the debris crust grows, water can ingress between the debris and the RPV wall to cool the wall and terminate the material creep.

2. BOUNDARY CONDITIONS

Two input files, a parameter file and an input file, were required to simulate the TMI-2 accident with MAAP4. The parameter file specifies the TMI-2 plant geometry, system performance, controls, and initial conditions. The input file defines the operator actions and the boundary conditions during the TMI-2 accident progression. Plant parameters that have the most important effect on the accident simulation are those controlling the water inventory and distribution in the primary system.

When simulating the TMI-2 accident, plant data for the secondary system serves as boundary conditions. Specifically, the data for the secondary side of the steam generators includes water levels and pressures for both the A and B Once Through Steam Generators (OTSGs). With the pressure information, the approximate settings for the atmospheric discharge of steam can be determined. Two types of water level measurements (operating and startup) were provided for each steam generator. The former is intended for nominal conditions at power and is temperature compensated while the latter is not. Therefore, where possible, the operating level information is used.

Operator actions are specified in the input deck. In particular, operation of the high pressure injection (HPI) and the reactor coolant pumps (RCPs) at the appropriate times are necessary to simulate the accident. For the period between 100 and 174 minutes, the HPI flow rate was not recorded and a large uncertainty exists. However, mass balance calculations have been made to estimate the total amount of water injected by HPI during this period [8]. A flow rate of 4 kg/s was recommended for use in the TMI-2 standard problem exercise, and was used in this MAAP4 simulation. The main coolant pump for the B loop operated for a short period at 174 minutes, and the A loop coolant pump was also operated for a short period at 248 minutes. Other important MAAP4 operator actions included the operation of the pressurizer power operated relief valve (PORV) and the main steam isolation valves (MSIVs).

The basic parameter file and input deck were adapted from those created by Malinovic [3]. Malinovic's parameter file containment parameters were changed from Oconee's to TMI's values. In addition, the steam generator water levels in A and B loops, used as boundary conditions, were changed based on the actual operating range measurements. A detailed discussion of the preparation of the parameter file and the uncertainties in plant parameters and boundary conditions that affect the TMI-2 simulation were previously discussed by Malinovic [3] and Sharon [2].

3. DISCUSSION OF THE RESULTS

The results of the base case and a sensitivity study of the RPV lower head response when debris drains into the lower plenum is presented here. The sensitivity study analyzed several key model parameters such as the initial contact resistance formed (gap size) between the wall and the debris crust, the entrainment coefficient for debris draining into the lower plenum, and the multiplier for the gap heat transfer coefficient. These parameters are a part of the fundamental mechanisms in MAAP4 which prevent the vessel from failing, therefore a sensitivity study of the influence of the initial contact resistance and the gap heat transfer are of crucial interest for accident management evaluations. The MAAP4 results were compared with the TMI-2 data as reported on the reactimeter or strip chart recorders. An instrument module was written to process the MAAP thermal-hydraulic data into the equivalent TMI-2 instrument signals. As an example, the TMI-2 instrument records a collapsed level between the instrument taps and therefore must be corrected when the "boiled-up" level exceeds this height when representing water level information. Furthermore, the instrument reference legs are sensitive to changes in the containment temperature. Thus, the module includes the influence of void, temperature compensation (or lack thereof) for the reference leg state and the calibration conditions.

3.1 Base Case Results

The boundary conditions imposed on the calculation are the water levels in the A loop and B loop steam generators, as shown in Figures 1 and 2. TMI-2 water level measurement locations were taken from NSAC [9]. Note the operating level does not "see" below 8 ft in the steam generators and provides data in terms of percent of full scale. When the water level is below the bottom operating level instrument tap, the start-up measurement was used to assess the approximate water level for the boundary condition. These water levels are imposed boundary conditions for the Reactor Coolant System (RCS).

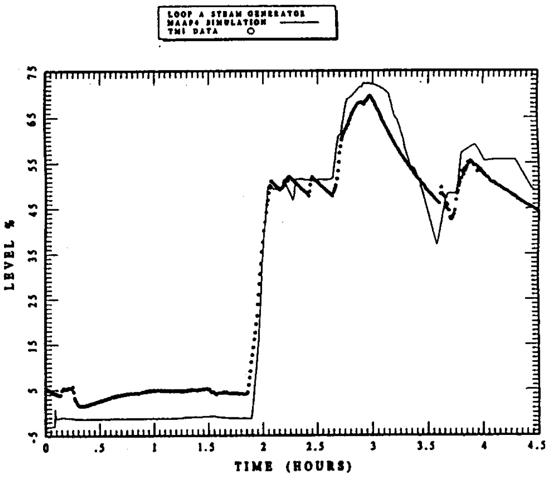

Figure 1. Water level on the secondary side of the A loop steam generator.

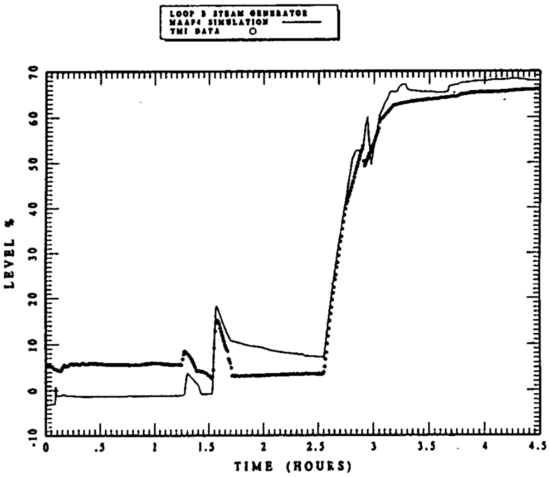

Figure 2. Water level on the secondary side of the B loop steam generator.

Figure 3 illustrates the calculated and measured RCS pressure response. As shown, the MAAP4 calculation provides a good representation of the pressure history during the time at which the core was uncovered (~ 112 minutes) through the time of the 2B reactor coolant pump start at 174 minutes. There are some differences in the primary system pressure after 174 minutes. After the 2B reactor coolant pump starts, MAAP4 over-predicts the primary system pressure, which is partially due to under-predicting the heat transfer to the B loop steam generator. After the HPI injection at 200 minutes, the predicted primary system pressure starts to deviate from the data. This difference in the primary system pressure may be due to the representation of the condensing potential in either the downcomer following HPI injection or in the coupling between the cold leg and the pressurizer through the open pressurizer spray line. The valve controlling the pressurizer spray was cycled at different times during the accident following the pump start at 174 minutes. However, the spray line is off the discharge side of the 1A reactor coolant pump, and since the pump was not operating at this time and the cold leg was voided, this provides a higher resistance but a parallel path with the surge line coupling the pressurizer and the RCS. This comparatively high resistance path connects the 1A cold leg to the pressurizer gas space, and is not currently modeled in the MAAP4 code or in previous versions of MAAP.

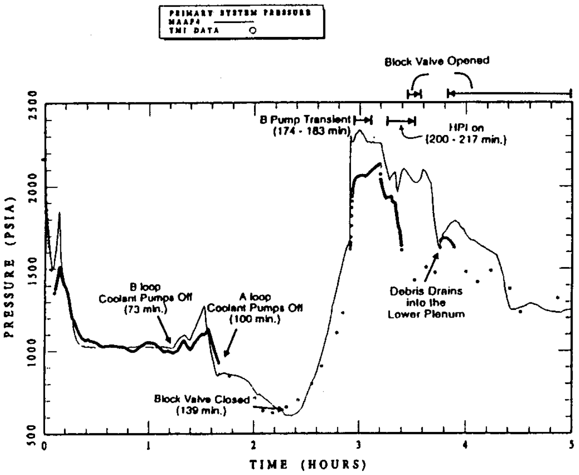

Figure 3. Calculated and measured primary system pressure during the first five hours of the accident.

When the molten corium drained into the lower plenum at 224 minutes, the primary system pressure increased due to steaming from the quenching process. MAAP predicts an initial pressure increase of about 100 psi compared to 200 psi for the data. However, MAAP4 predicts about 200 psi of total pressure increase for a little longer period than the data. This pressure increase depends on the amount of jet breakup, which in turn depends on the entrainment coefficient in MAAP4, as corium drains into the lower plenum water. The base case used a value of 0.05 for the entrainment coefficient. When a value of 0.09 is used for the entrainment coefficient, the calculated pressure increase is about 50 psi more than that of the base case.

Figure 4 shows that the pressurizer water level calculation with the TMI-2 reactimeter data are in good agreement for the most of the transient. When the B loop steam generator water level sharply increased at about 1.52 hours, MAAP4 calculated a decrease of the pressurizer water level which was recovered to the top of the pressurizer at about 1.67 hours. The core was uncovered at about 1.82 hours reducing the steaming rate from the core and the A loop steam generator water level increased sharply at about 1.85 hours resulting in increased steam condensation. As soon as hydrogen was generated, the steam condensation in both the A and B loop steam generator tubes were reduced such that the pressurizer water level remained steady until the B loop pump started at 174 minutes. The predicted water level and the data both increased sharply at 174 minutes as more water came into the core inducing rapid steaming. After the HPI flow was initiated at about 200 minutes, the pressurizer drains sharply both in the prediction and the data. The overall agreement between the pressurizer level response and the reactimeter data is substantially better than those calculated for the MAAP 3B and MAAP-DOE codes. This shows that the new pressurizer model, which was principally developed for the substantially different AP600 designs, provides an improved representation of the TMI-2 pressurizer behavior.

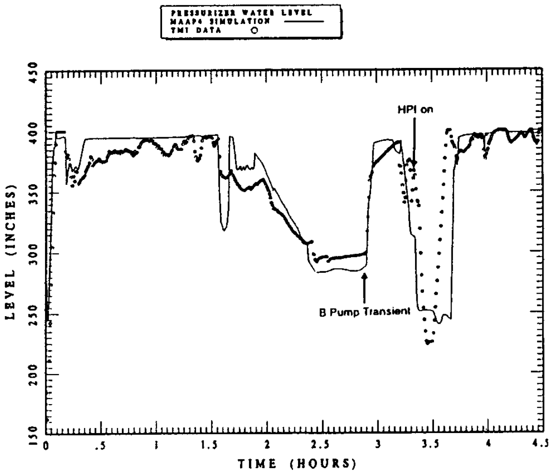

Figure 4. Comparison of the calculated and measured pressurizer water level.

The respective pressures in the secondary side of the A and B loop steam generators are shown in Figures 5 and 6. There is general agreement with the data. However, the A steam generator experiences pressurization in the MAAP4 calculation at 174 minutes which was not observed in the accident data. Figure 6 indicates that in the MAAP4 evaluation, the B loop steam generator does not depressurize as much at ~ 100 minutes as recorded by the measurements. Also, the MAAP calculation does not predict the strong pressurization of the B loop steam generator at 174 minutes when the reactor coolant pump was started. Even though there are some uncertainties in the steam generator water levels and the fraction of the opening in steam dump valves, the general character of the secondary side behavior is adequately represented by the MAAP4 calculation.

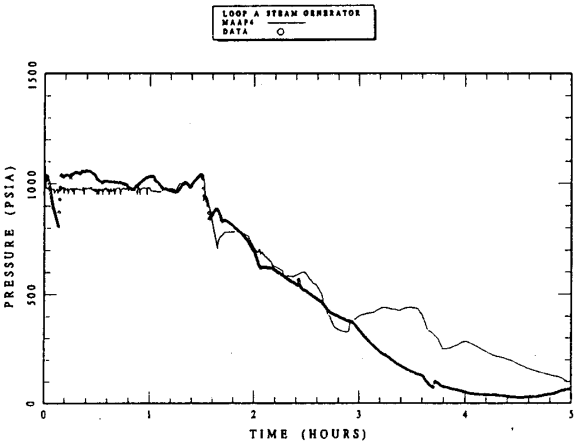

Figure 5. Comparison of the calculated and measured secondary side pressure in the A loop steam generator.

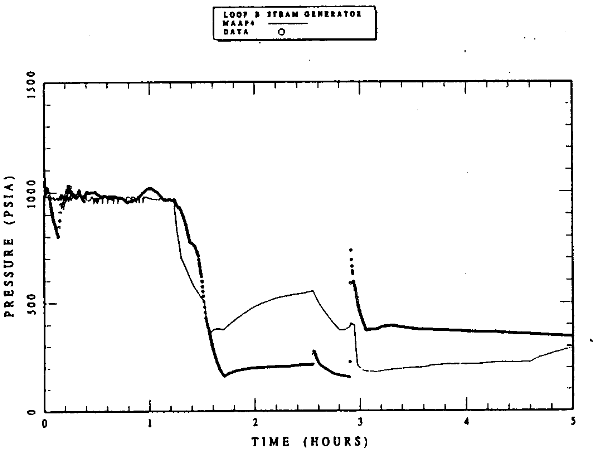

Figure 6. Comparison of the calculated and measured secondary side pressure in the B loop steam generator.

Figure 7 illustrates the extent of hydrogen produced for this calculation. As shown, about 750 lbs. are produced prior to the B loop pump start with the total being about 1010 lbs. It is generally considered that about 1000 to 1150 lbs. of hydrogen was produced in the TMI-2 accident. However, the only indications of the interval during which hydrogen was produced was at 150 minutes, when sufficient hydrogen was accumulated in the A steam generator to prevent condensation, and at 10 hours into the accident when a burn was observed in the containment atmosphere. Therefore, the calculated quantity of 1010 lbs. is consistent with the available TMI-2 data.

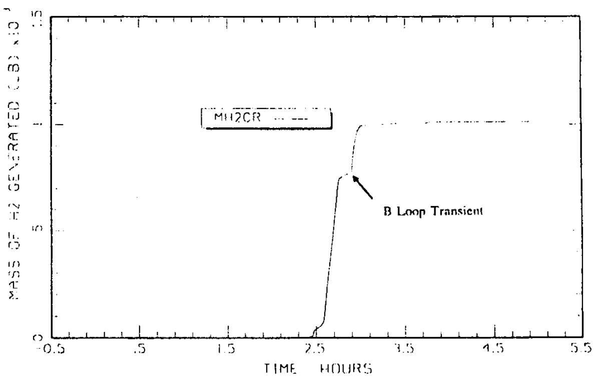

Figure 7. Calculated hydrogen generation history.

MAAP4 models include the formation of a molten pool within the original core boundaries as a result of melting and downward core relocation, along with the energy added to the core material as the decay power and chemical oxidation reactions. Before the 2B pump transient at 174 minutes, MAAP4 predicted a substantial amount of molten material, more than 20,000 lbs., in the core. At the time of the relocation of the core material to the lower plenum at 224 minutes, the total molten material in the core was about 52,000 lbs. In this TMI-2 simulation, the molten pool side crust rupture was manually initiated at 224 minutes in the input file. The MAAP4 predicted core map, including the molten pool and surrounding crust at 220 minutes, is shown in Figure 8. The lowest bottom crust of the molten pool is at row #7 and the side crust at row #8 is the location of the failure four minutes later. The calculated crucible core mass above the top crust at 220 minutes is about 22% of the original core mass.

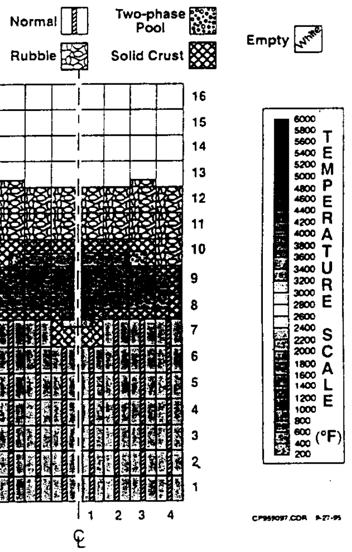

Figure 8. Schematic description of the predicted core conditions at 3.67 hours.

MAAP4 calculates about 43,000 lbs. of core debris drains into the lower head, which is reasonable when compared to about 42,000 lbs. observed in TMI-2. Similar to the data, MAAP4 predicted that most of core debris in the lower head was oxidic. Specifically, MAAP represented this as a U-Zr-O eutectic with sufficient oxygen to essentially oxidize the metals to UO_2 and ZrO_2. When the molten mass flows out of the original core region, it drained into the lower plenum with some of the molten material entrained and particulated into the water pool, with the remainder forming a continuous layer on the RPV lower head. MAAP4 has new models for the thermal response of the lower head in-core instrument penetrations. In the simulation, the instrument penetrations were melted and the molten fuel transported into the tube to the calibration chamber which was at containment pressure. The molten fuel quickly solidified within the tube and plugged (resealing) the potential flow path for the molten material out of the RPV.

Since the debris entered a water filled lower plenum, the accumulation of a continuous layer also created a contact resistance, i.e., a thin gap between the core debris and the RPV wall [7]. Initially this gap is insufficient to allow the cooling of the debris and the RPV wall overheated. Figure 9 illustrates the wall overheating once core debris accumulates in the lower plenum and as shown, the temperature increase is substantial (approaching 1100°C/2000°F). At this combination of high wall temperature and internal pressure, the RPV wall expanded due to material creep which increased the gap between the debris and the RPV wall. This resulted in sufficient growth of the gap such that water can ingress between the debris and the RPV wall to cool the exposed region. Once the carbon steel wall was sufficiently cooled, the material creep terminated. Note that the water ingression provides an important cooling path for the core material such that, while the debris may still be overheated in the pool, the debris does not have a mechanism for continued thermal attack of the vessel wall. This history of temperature increase to ~ 1100°C with a subsequent relatively rapid cooling is consistent with the observations from the TMI-2 vessel investigation project (VIP) [10].

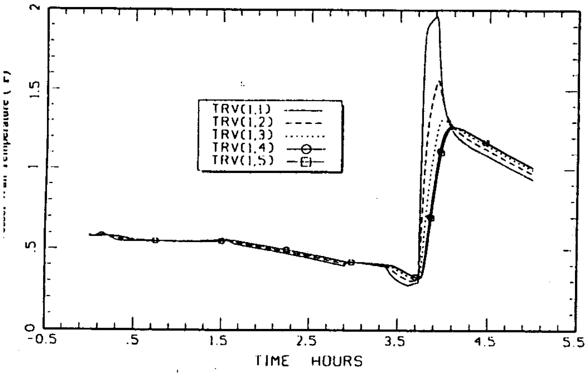

Figure 9. Calculated temperature of the bottom node of the reactor vessel wall.

The TMI-2 accident also provided containment data that can be used to benchmark the MAAP4 generalized containment model for accident conditions in which the containment heat removal function is available (safety grade fan coolers) and containment response to operator actions as a result of opening and closing of the block valve for the pressurizer PORV. The MAAP4 generalized containment model provided a good representation of the containment pressure and temperature trend during the first five hours of the TMI-2 accident described in reference [4].

3.2 Sensitivity Study

MAAP4 has been developed to provide a tool for accident management evaluations. Perhaps the three most important aspects demonstrated by the TMI-2 accident were: 1) that core damage could occur in a matter of a few tens of minutes if the core was uncovered, 2) that reflooding of a badly damaged core did not result in any catastrophic consequences with respect to the reactor coolant system but was insufficient to cool the core debris within the original core boundaries, and 3) that the drainage of molten core debris into the lower plenum could overheat the reactor vessel wall but did not result in wall failure. As discussed previously, the MAAP4 code represents all of these attributes from the accident with the last observation perhaps being the most crucial from an accident management evaluation standpoint. The model in MAAP which determines that the vessel wall can become overheated and not fail is the material creep model coupled with the formation of a contact resistance and gap heat transfer when the molten material drains into the water filled lower plenum. The key parameters of these models are user specified entrainment coefficient, which determines how much of molten jet could be entrained into the water pool and become a part of the particulate bed, an initial contact resistance between the debris crust and the vessel wall, and a multiplier for the gap heat transfer rate. It is then appropriate to examine the sensitivity of these parameters which are important to accident management results with respect to the entrainment coefficient, the initial contact resistance, and the multiplier for the gap heat transfer rate.

A sequence of runs were performed varying only the entrainment coefficient, or the initial contact resistance, or the multiplier for the gap heat transfer to address the sensitivity of these parameters which have an impact only after molten debris is calculated to drain into the lower plenum. The debris jet particulation is represented as the erosion of a cylindrical jet using the Ricou-Spalding correlation [11] for entrainment.

For this sensitivity study, the entrainment coefficient was varied from 0.01 to 0.09. The entrainment coefficient affects how much of the molten jet would remain as a continuous jet and become a part of the continuous debris bed which can subsequently heat the reactor vessel wall. It also affects the quantity of steam generation due to quenching of the debris particulation. The influence of the entrainment coefficient on the reactor vessel wall temperature is shown in Figure 10, i.e., the temperature of the entrainment coefficient of 0.09 was lower than the other two cases. The total primary system pressure increase due to debris quenching and steaming was about 100, 200, and 250 psi for the entrainment coefficients of 0.01, 0.05, and 0.09, respectively.

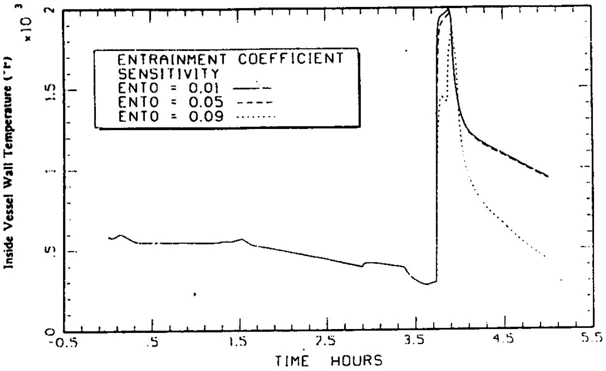

Figure 10. Calculated temperature of the inner vessel wall as a function of entrainment coefficient.

In MAAP4, the heat flux from the debris to the gap was calculated with the Monde model [12], which correlated experimental data on the rate of cooling due to boiling in narrow gaps. Here, FHTGAP is a model parameter which can be used to vary the effectiveness of the heat transfer with 1.0 resulting in the Monde value. For this sensitivity study, the initial gap resistance was varied from 10 microns to 60 microns with the smaller value precluding any initial water cooling and the larger value enabling some water cooling but also substantially increasing the resistance to heat transfer from the debris to the wall when the debris first drains into the lower plenum. Of course, when the major mode of energy transfer is radiation, the influence of the contact resistance is substantially lessened. For all of these cases, the wall eventually became sufficiently hot that material creep was initiated and the gap increased until it was sufficiently large to enable water ingression which cooled both the reactor vessel wall and the outer surface of the debris crust. Figure 11 illustrates the thermal transient for the inner layer of the reactor vessel wall as a function of the initial contact resistance. As shown, the smaller gap results in a somewhat higher temperature with the larger gaps resulting in progressively lower peak temperatures. Most of this is due to the fact that the smaller gap deposits more energy in the wall before significant straining actually begins. However, substantial variations in the contact resistance do not change the ultimate disposition of materials within the lower plenum, i.e., in all cases the reactor vessel wall is cooled and the core debris, while remaining hot within the central region of the continuous layer of debris, is cooled on all of its surfaces such that it does not induce further thermal attack of the RCS wall pressure boundary.

For the sensitivity study of FHTGAP, the parameter which multiplies the heat flux from the debris to the gap was varied from 0.25 to 1.0. The difference in the peak temperature of the inner vessel wall between the result of FHTGAP 0.25 and FHTGAP 1.0 was about 100°F which was smaller than the differences observed in the gap size sensitivity results.

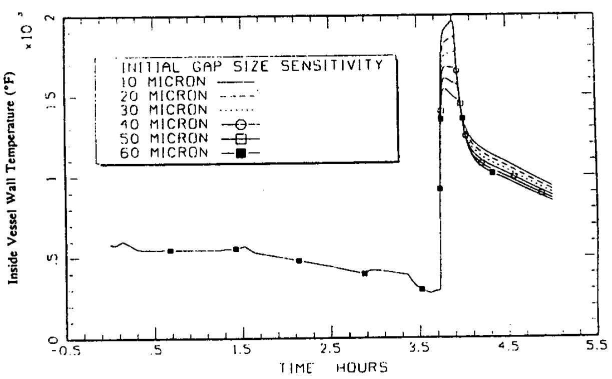

Figure 11. Calculated temperature of the inner vessel wall as a function of initial gap size.

In summary, substantial variations in the contact resistance and uncertainty in using Monde's correlation can be postulated and this has some relatively minor influence on the thermal transient within the reactor vessel wall. However, from an accident management evaluation standpoint, the ultimate disposition of the core material and the integrity of the RPV wall are not altered when these key model parameters were varied.

4. CONCLUSIONS

Comparisons of the MAAP 4 model predictions with the TMI-2 data show that the MAAP4 code calculations are in good agreement with the overall plant response during the accident. This includes the reactor coolant system, the steam generators, and containment. MAAP4 provided an accurate characterization of the system response for the general trend of the primary system pressure, the hydrogen production, and the behavior of pressurizer water level, for the TMI-2 accident transient up to 5 hours when the reactor pressure vessel became essentially full of water. Furthermore, MAAP4 calculated the formation of a molten pool within the core region, the subsequent melt- through of the side crust, the draining of molten material into the lower plenum, resulting in overheating of the RPV wall followed by cooling of the wall and the debris. As a result, MAAP4 provided a reasonable simulation of the TMI-2 system response in terms of the behavior before the core was uncovered, the response of the primary system while the core degraded, the response of the RCS when the core was reflooded at 174 minutes as well as the lower head response after 224 minutes. Sensitivity studies with respect to the principal model characterizing the lower head response show that, while uncertainties can somewhat modify the thermal transient in the lower head, the fundamental conclusions for accident management are largely unaffected by these uncertainties. Thus, the severe accident modeling advanced by the new MAAP4 models gave a reasonably good characterization of the TMI-2 system response for the five major accident management intervals initially discussed in the introduction of this paper.

REFERENCES

[1] Kenton, M.A., et al., 1986, "Simulation of the TMI-2 Accident Using the MAAP Modular Accident Analysis Program, Version 2.0", EPRI NP-4292.

[2] Sharon, A., et al., 1989, "Simulation of the First 174 Minutes of the TMI-2 Accident Using MAAP 3.0B", EPRI NP-6202.

[3] Malinovic, B., et al., 1990, "Simulation of Phases 3 and 4 of the TMI-2 Accident Using MAAP-DOE and MAAP 3.0B Task 3.9", DOE/ID-10259.

[4] MAAP4 User's Manual, Vols. 1 ,2, and 3, EPRI, 1994.

[5] Paik, C.Y., et al., "MAAP4 Models and Its Application To Westinghouse AP600 Plant", Proceedings of the Second International Conference on Nuclear Engineering (ICONE-2), San Francisco, California, March 1993.

[6] Plys, M.G., et al., "MAAP4 Model and Validation Status", Proceedings of the Second International Conference on Nuclear Engineering (ICONE-2), San Francisco, California, March 1993.

[7] Henry, R.E., Hammersley, R.J., Klopp, G.T., and Merilo, M., 1994, "Experiments on the Lower Plenum Response During a Severe Accident", Proc. of the 4th Intl. Topical Meeting on Nuclear Thermal-Hydraulics, Operations and Safety, Taipei, Taiwan, Vol., pp. 27-C-1 through 27-C-6.

[8] Anderson, J.L., "Recommended HPI Rates for the TMI-2 Analysis Exercise (0-300 minutes)," EG&G Idaho, Inc., September 1987.

[9] NSAC, 1980, "Analysis of Three Mile Island - Unit 2 Accident", Nuclear Safety Analysis Center Report, NSAC 80-1.

[10] Wolf, J.R. and Rempe, J.L., 1993, "TMI-2 Vessel Inspection Project Integration Report", Idaho National Engineering Laboratory Report TMI V(93)EG10. Prepared as part of the OECD-NEA-TMI-2 Vessel Inspection Project for the Division of Systems Research, Office of Nuclear Regulatory Research.

[11] Ricou, F.B. and Spalding, D.B., "Measurements of Entrainment by Axisymmetrical Turbulent Jets," Journal of Fluid Mechanics, Vol. 11, pp. 21-32, 1961.

[12] Monde, M., et al., "Critical Heat Flux During Natural Convective Boiling in Vertical Rectangular Channels in Saturated Liquid", ASME Journal of Heat Transfer, Vol. 104, pp. 300-303, May 1982.