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MELCOR Analysis of the TMI-2 Accident*

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ABSTRACT:

This paper describes the analysis of the TMI-2 standard problem that was performed with MELCOR. The MELCOR computer code is being developed by Sandia National Laboratories for the Nuclear Regulatory Commission for the purpose of analyzing severe accidents in nuclear power plants. The primary role of MELCOR is to provide realistic predictions of severe accident phenomena and the radiological source term.

The analysis of the TMI-2 standard problem allowed for comparison of the model predictions in MELCOR to plant data and to the results of more mechanistic analyses. This exercise was, therefore, valuable for verifying and assessing the models in the code. The major trends in the TMI-2 accident are reasonably well predicted with MELCOR, even with its simplified modeling. Comparison of the calculated and measured results is presented and, based on this comparison, conclusions can be drawn concerning the applicability of MELCOR to severe accident analysis.

DISCLAIMER

1.0 INTRODUCTION

The MELCOR computer code [1] developed by Sandia National Laboratories for the Nuclear Regulatory Commission is a second-generation plant risk assessment tool and the successor to the Source Term Code Package. MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants. The spectrum of severe accident phenomena is treated in MELCOR in a unified framework covering reactor coolant system and containment thermal-hydraulic response, core heatup, degradation and relocation, and fission product release and transport. The results of these calculations are to be used as an integral part of probabilistic risk assessment studies. Current use of MELCOR includes estimation of severe accident source terms, including sensitivity and uncertainty studies, for a variety of applications.

The first four phases of the TMI-2 standard problem [2] have been analyzed with MELCOR version 1.8.0 on a VAX 8700 computer system. The purposes of these analyses were twofold. First, while MELCOR has been used extensively to analyze BWR plants, it had not been used to analyze commercial PWR plants. Therefore, one goal of the analysis was to identify any PWR specific features that were needed within MELCOR.

Second, the analysis of the standard problem allowed the predictions of models in MELCOR to be compared to plant data, and to the results of more mechanistic analyses. This exercise was, therefore, valuable for verifying and assessing the models in the code. As will be shown, the major trends in the TMI-2 accident are reasonably well predicted with MELCOR, even with its simplified modeling.

This paper describes the analysis of the TMI-2 standard problem that was performed with MELCOR. A comparison of the calculated results and measured or inferred data is presented and, based on this comparison, conclusions are drawn concerning the applicability of MELCOR to severe accident analysis.

2.0 THE TMI-2 STANDARD PROBLEM

The TMI-2 accident is partitioned into four distinct phases for the purpose of the standard problem analysis. The sequence of events and related phenomena are described in detail in the latest accident scenario [3]. Phase 1

covers the period from accident initiation (0 minutes) to shutdown of the last RCS coolant pump (100 minutes). Phase 2 (100 to 174 minutes) begins with a core boildown, leading to core uncovery, heatup and early degradation. Phase 3 (174 to 200 minutes) was initiated by an RCS pump transient which injected coolant into the core, followed by continued heating of core debris already in an uncoolable geometry. Phase 4 (200-300 minutes) is initiated by restoration of full HPI flow, leading to a recovering of the core. Perhaps most significantly in phase 4, a relocation of molten core debris from the core region to the lower plenum occurred at ~224-226 minutes. Through this redistribution of core debris, a coolable configuration was reached and the accident progression was terminated.

3.0 MELCOR NODALIZATION AND MODELING

The MELCOR model of the TMI-2 reactor system was developed from a RELAP5/SCDAP input deck of the system that is included as part of the standard problem package [2]. The Initial Condition and Boundary Condition (ICBC) database [2] was also used to set the initial conditions for the input decks. Relatively few nodes are employed in the MELCOR model to balance the desire to maximize running speed with the complexity required to provide realistic simulation of the TMI-2 accident progression.

In the analysis performed, the first phase of the accident was simulated independently of the following three phases. This approach is used for two reasons: one is to have both the first and second phases conform with the initial conditions imposed by the standard problem guidelines, and the second is to prevent errors in the phase 1 calculation from propagating into phase 2. Because there is currently no method within MELCOR for starting calculations with damaged cores or restarting calculations with altered database values, such as liquid inventory, the phase 3 and 4 calculations were run directly from the end of the phase 2 calculation. As a consequence, two different MELCOR input decks are used, one for the first phase and one for the subsequent phases, 2 through 4. The only major differences between the two input decks are the initial conditions imposed for phases 1 and 2, and the use of the MELCOR radionuclide package in the second and subsequent phases. The use of the radionuclide package is required in order to model the transport of fission products when released from the fuel as the core degrades.

The reactor core is modeled with three radial rings at 14 axial levels for a total of 42 core cells. The upper 12 axial levels are modeled as fueled, with the lower two levels representing the core support structures and lower head

volume. The reactor vessel and internal structures are modeled with 26 heat structures. The reactor containment is simply modeled by one control volume.

Figure 1 shows the MELCOR nodalization of the reactor coolant system (RCS) and secondary side loops. The RCS is modeled as 11 control volumes, connected through 15 flow paths, and containing 18 heat structures. The two actual pumps on each RCS loop are lumped together so that each loop has one equivalent pump model. It should be noted that MELCOR does not contain an explicit pump model; pumps were simulated using a homologous model built with MELCOR control functions, including two-phase degradation of pump performance. The pressurizer is represented with a single control volume that in turn connects to the containment volume through the Pilot Operated Relief Valve (PORV) drain line. The pressurizer heater bundle is modeled by directly depositing power into the pressurizer liquid. The PORV is operated through MELCOR control functions to open at the design set pressure and latch open, thus initiating the accident sequence.
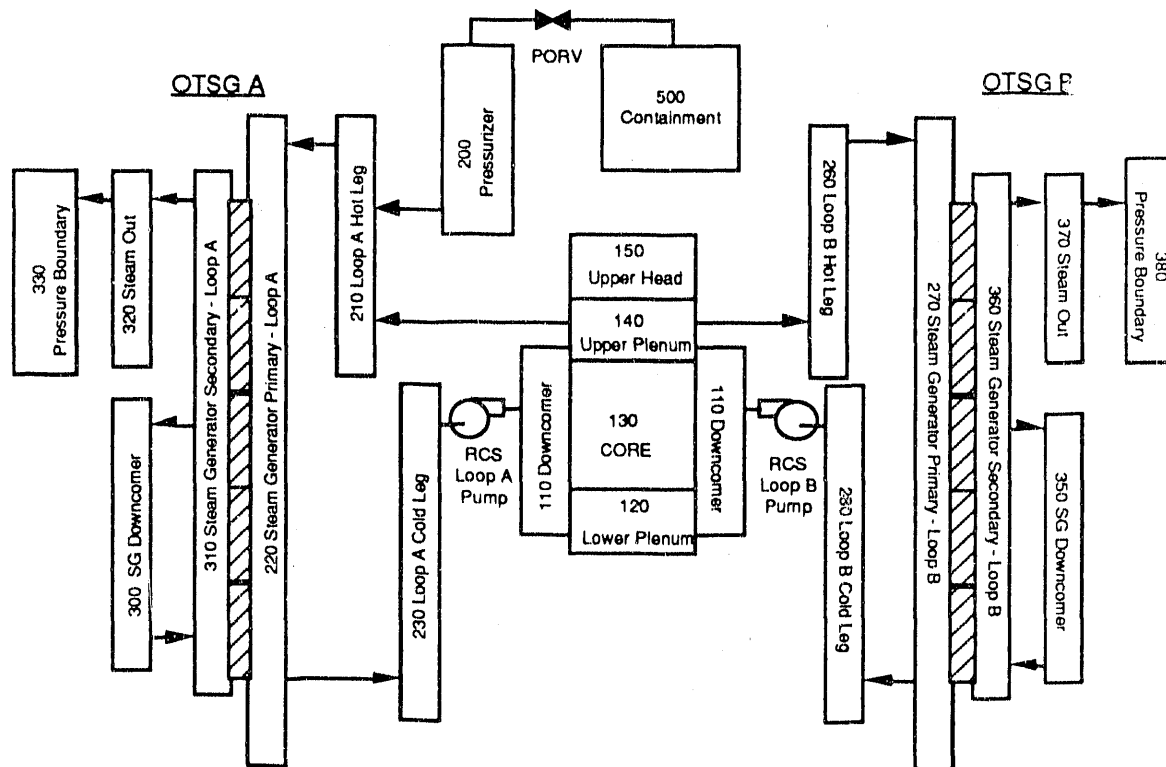

Figure 1.
MELCOR Nodalization of the TMI-2 Reactor Coolant System.

Each Once Through Steam Generator (OTSG) is modeled using five heat structures that represent the tube bundle as divided into five axial sections. These heat structures communicate energy between the RCS primary and secondary side control volumes. The use of axial segmentation provides a means of representing axial temperature gradients in the OTSG, a phenomenon which is important to correctly model primary to secondary heat transfer under severe accident conditions. Both secondary side heat transfer loops are modeled with four control volumes, connected through four flow paths and containing six heat structures. The unique nature of the OTSG and the complex thermal-hydraulic behavior during the accident transients made the OTSG simulation especially challenging.

The RCS letdown and High Pressure Injection (HPI), along with OTSG Auxiliary Feedwater flow rates, were modeled as hydrodynamic material sources and sinks in the lower plenum volume and secondary side steam generator volume, respectively, and are simply input as tabular functions. All of the tabular input for these quantities were taken as the suggested values from the ICBC. No attempt was made to assess the adequacy of these values with the MELCOR predicted response, i.e., the calculated liquid levels of the receiving volumes.

The above nodalization was used in calculations of all four phases of the accident. The initial conditions for phase 1 were obtained by setting the reactor power, the pump speed, and the secondary side flow rate to their nominal operating values [2] and running a null transient to produce an equilibrium solution. The results of this null transient were compared to the nominal steady-state operating conditions. Slight adjustments were made until the steady-state operating conditions were satisfactorily predicted; the RCS pressures and temperatures were calculated to within a few percent of nominal operating values. This steady-state condition then served as the initial condition for phase 1.

For phase 2, the initial conditions were obtained from the standard problem package [2]. The best-estimate value for the RCS inventory at 100 minutes was used as input for the code. Phases 3 and 4 were simulated by continuing calculations from the end of phases 2 and 3, respectively. The current debris models in MELCOR employ simple spherical particle heat transfer correlations and do not take debris packing and consolidation effects into account. Therefore, in an attempt to more correctly model the debris bed heating and consolidation, the effective convective heat transfer was reduced

at the time of the phase 3 calculation restart through the use of MELCOR sensitivity coefficients.

The loop 2B pump transient that marks the initiation of phase 3 was simulated with a mass source to the downcomer volume and a corresponding mass sink in the loop B cold leg. Using a mass source/sink rather than the pump model allowed for direct control over the amount of mass injected. The pump transient was modeled as transferring the equivalent mass of 28 m^3 of liquid, over a 15 second period [2].

The key event of phase 4 is the relocation of debris into the lower plenum. There is currently no model in MELCOR to allow the radial migration of debris, so simulation of the debris relocation was made through resetting of the core support flags at 224 minutes in the calculation. The net effect of this flag being reset was to convert the remaining core to particulate debris and to allow the debris to relocate to the lower plenum.

4.0 RESULTS

4.1 Phase 1 Results

Phase 1 of the accident can be considered a small break LOCA; is it basically a simple thermal-hydraulic transient. During this phase, prediction of primary system pressure is the key quantity of interest. A consideration of the system characteristics shows that the primary system pressure is a function of mass inventory and heat transfer to the secondary side. Both of these parameters are not easily determined for the accident due to the uncertainty in the letdown and HPI flowrates on the primary side, coupled with auxiliary water flowrates to provide cooling on the secondary side.

It should be noted that MELCOR was not designed to model this type of thermal-hydraulic transient in great detail because the early phase of severe accidents are not considered to have a major quantitative impact on the magnitude of the source term. Since the intended role of MELCOR is as a support calculation tool for PRAs that can cover integrated severe accident sequences, an approximate treatment of this initial phase is considered satisfactory. A detailed, accurate representation of the thermal-hydraulics during the initiating event and first minutes of the accident is not intended in this analysis.

Calculating the RCS mass inventory is crucial to a correct result for phase 1 since it directly affects the system pressure and sets the initial liquid inventory for phase 2 (if calculation of that phase were to be continued directly). The RCS inventory is primarily dependent on the mass loss through the PORV, as modified by HPI and letdown flows. The PORV mass flow rate in turn depends on primary system pressure and the loss coefficient used for choked flow in the PORV. The approach used was to benchmark the MELCOR PORV model against experimental data to verify that correct performance would be represented in the phase 1 calculation.

The discharge coefficients of 0.787 for steam and two-phase flow and 0.60 for liquid flow are suggested as best values for the standard problem simulation [4]. Benchmark calculations were made with MELCOR and show that MELCOR predicts steam and liquid flows to be within 8 and 6 percent, respectively, of the EPRI test results for the Dresser model 31533VX-30 PORV [5]. Although these EPRI tests were for transient operation of the PORV, as compared to steady-state calculations, the MELCOR results were found to compare favorably with the test results for PORV discharge flowrates.

Not surprisingly, calculations of the full TMI-2 system model show reasonable agreement in instantaneous PORV flow rates, which in turn leads to an integrated mass loss through the PORV sufficiently accurate to model the accident sequence. At the end of phase 1, the integrated PORV loss was computed to be 126000 kg as compared to the result of 105000 kg given in reference [4]. The difference can be accounted for by the fact that the calculations in reference [4] employ the homogeneous equilibrium model (HEM) for critical flow, whereas MELCOR uses the Moody model. In general, the Moody model predicts higher flowrates than HEM, except near saturated liquid enthalpy. While the discharge coefficient used in MELCOR could easily be adjusted to produce better results, it was determined that the current model was adequate for this simulation considering that the stated accuracy of reference [4] was ±20% total inventory over the accident.

The calculated primary system pressure is compared with the TMI-2 plant data in Figure 2. For the early transient phase, the MELCOR calculations predict the system pressure reasonably well. Later in the transient some divergence of the results is seen. The underlying cause has been determined to be the OTSG model used. The complexity of tube bundle heat transfer with differing heat transfer regimes cannot be easily modeled. In MELCOR, the control volumes are assumed to be well mixed so that each control volume has only one liquid temperature and one vapor temperature. If large temperature gradients should exist in the volume atmosphere or liquid, then

the code can only resolve these if a finer control volume nodalization is used. Also, the heat transfer model for heat structures is relatively simple and does not include complex flow regimes that occur in each OTSG during the accident. For example, the heat structures cannot model water directly impinging on them, as the Auxiliary Feed Water (AFW) does in these heat exchangers. The resulting model simplification causes the primary-to-secondary heat transfer to be overpredicted, thus leading to the underprediction of pressure.
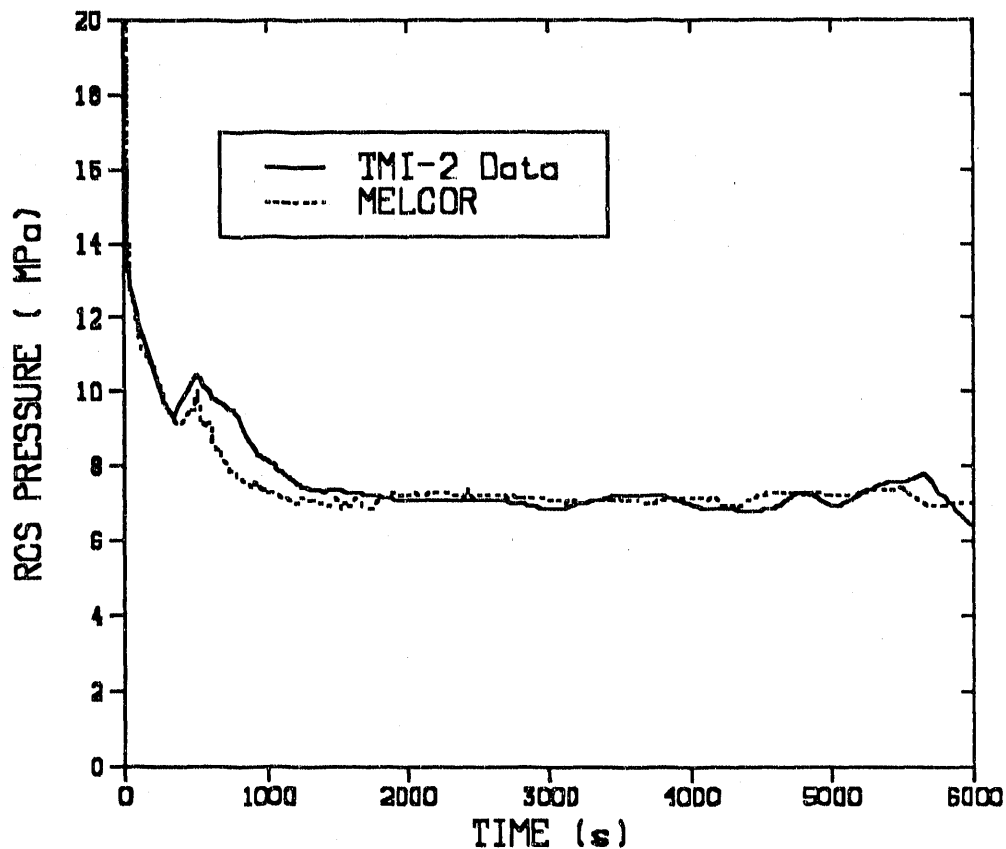

Figure 2.
MELCOR Prediction of the Reactor Coolant System
Pressure Response During Phase 1.

In spite of these simplifications, the pressure response was predicted reasonably well. The trends are well represented and better quantitative

agreement could be obtained by modifying heat transfer model parameters and using a finer nodalization.

There were some unresolved difficulties in using MELCOR for phase 1 calculations. The thermal-hydraulics associated with the two competing circulating flows of loops A and B, coupled with increasing void in the RCS primary system, caused the calculation to be numerically inefficient. Due to the relatively simple modeling of two-phase degradation, the RCS pump model provided less physically realistic results as the RCS voided. Nevertheless, calculation of the first phase was successfully completed for the goal of determining the accuracy of predicting the coolant inventory at the start of phase 2.

In summary, the MELCOR predictions for phase 1 are in reasonable agreement with the data. The RCS inventory loss was well predicted for phase 1 and the key trends in the pressure response are predicted. Excellent quantitative agreement is not achieved due to the simplistic treatment of the primary-to-secondary heat transfer. However, for severe accident simulations for risk assessment studies, the current modeling is considered to be satisfactory.

4.2   Phase 2 Results

Phase 2 of the standard problem covers the period from core uncovery to initial core degradation. During this phase, one is interested in predicting the core liquid inventory, core heating, hydrogen production, and the cladding melting and relocation. While the data for this phase is less quantitative than in phase 1, there is sufficient information to perform an assessment of the core degradation modeling.

The results for phase 2 show reasonable agreement with the available data. Table I lists the timing of key events during this phase. The predicted timing of most events was found to be relatively good. However, the fuel rod rupture time is predicted early which is most likely due to the simplified treatment of this model. The hydrogen production is calculated to occur over a prolonged period. This is due in part to an intentional reduction in the oxidation rate modeled in the calculation, accomplished through MELCOR sensitivity coefficients. It was found through sensitivity studies that using reduced oxidation rates lead to smoother hydrogen production which leads to improved thermal-hydraulic prediction and calculational performance.

Key Event	Standard Problem Best Estimate [2]	MELCOR Calculation
Hot Leg Superheat Detected	6300 s	6100 s
Initial Hydrogen Production	7800 s	7600 s
Cladding Failure (1200 K)	7900 s	7700 s
PORV Block Valve Closed	8340 s	8340 s*
Initial Melt Relocation	(?)	8800 s
Rapid Oxidation Begins	9000 s	8600 s
Hydrogen Production Ends	9200 s	10440 s

* Set to ICBC Value

TABLE I.
Timing of Key Events During Phase 2.

As in phase 1, the prediction of primary system pressure is found to be very sensitive to the primary-to-secondary side heat transfer. The primary system pressure is plotted with the TMI-2 plant data in Figure 3 and is found to be in good agreement with the data. In phase 2, the production of hydrogen in the core leads to a significant degradation of the primary-to-secondary heat transfer. This is because the noncondensible hydrogen gas "blankets" or "blocks" the tube side of the OTSG and prevents flow through the steam generator. Furthermore, the production of hydrogen leads to higher primary system pressure through the partial pressure contribution of the noncondensible gas. The good agreement here indicates that the timing of hydrogen production and the effect of hydrogen production on heat transfer are being predicted well. Sensitivity studies confirm this conclusion.

Calculations that predict a later hydrogen production will in turn predict pressurizer draining that will greatly lessen the predicted phase 2 core damage. Late in phase 2, the primary system pressure is underpredicted.
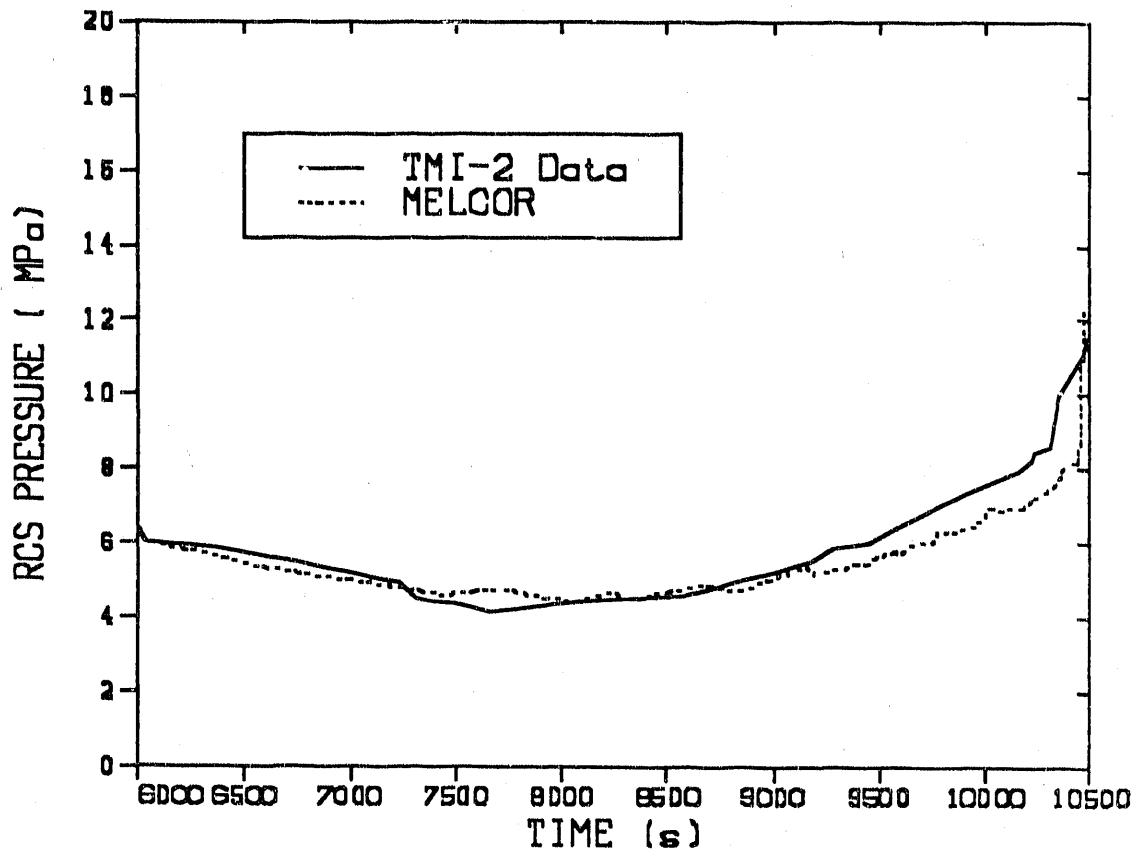

Figure 3.
MELCOR Prediction of the Reactor Coolant System
Pressure Response During Phase 2.

There appear to be two reasons that can at least partially account for this. First, due to both the hydrogen partial pressure contribution and steam generator blocking , the rate and total amount of hydrogen production is crucial to system pressure prediction. Secondly, it appears that at the end of phase 2, other phenomena may have been occurring that are not adequately documented, and therefore no adequately modeled, such as localized core debris slumping or dripping that led to rapid steam generation. There is a

large pressure increase observed that is at least partially accounted for by the operation of the 2B main coolant pump. This can be seen at the latest times plotted in Figure 3. Since this defines the end of phase 2 and start of phase 3, it is unclear how to interpret data at the end of phase 2.

The fuel assembly models predict dryout, subsequent heating, cladding oxidation, cladding rupture, and melting and relocation in the upper portions of the core by the end of phase 2. The lower levels in the core exhibit varying degrees of heating and oxidation. The calculation shows that the core gradually uncovers with the liquid level reaching a lower limit of approximately 1.3 m above the bottom of the core, exposing the upper 2.4 m of the core to steam. The core liquid level (swollen) as a function of time is shown with the downcomer liquid level in Figure 4.
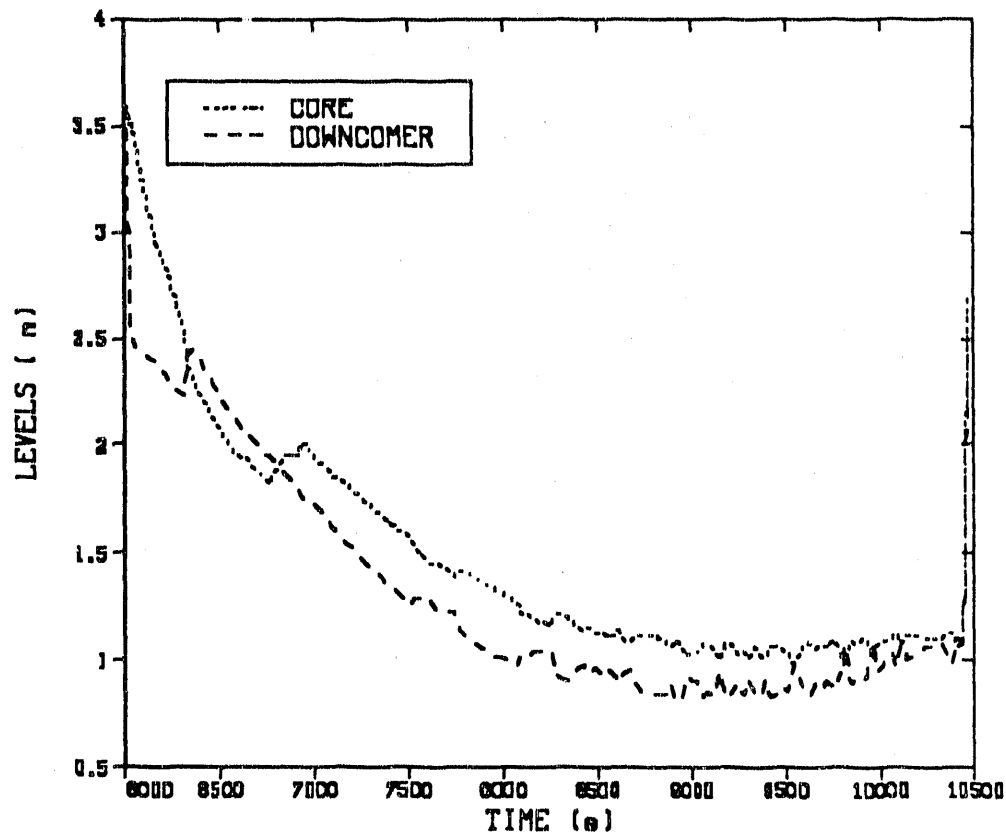

Figure 4.
MELCOR Prediction of the Liquid Levels; Core and Downcomer Volumes
During Phase 2. Heights are Relative to the Bottom of Active Fuel.

The initial fuel rupture was calculated to occur at 7700 seconds after the beginning of the accident. The plant data indicate that this event occurred at about 8200-8400 seconds, and the computed best-estimate value is 7900 seconds [2]. MELCOR predicts rupture early. However, if the rupture temperature criterion were 100 K higher, the calculated rupture time would be approximately 300 seconds later. If one considers the uncertainty in the rupture model, then the results are in reasonable agreement with the data. Again, this indicates that the core heating is being adequately modeled with MELCOR.

Figure 5 shows the time history of hydrogen production, which begins around 7600 seconds and rapidly increases around 9000 seconds. At this point, "blanketing" of the heat exchangers should be fully established. The total calculated hydrogen production is 225 kg, which is in good agreement with the standard problem package value (~200 kg [2]).

MELCOR predicts core relocation (i.e., candling and particulate debris formation) to begin around 8800 seconds. There is a MELCOR core model that simulates the hold-up of molten Zircaloy behind the ZrO_2 shell. The effective release temperature of the oxide shell is 2500 K by default and relocation cannot, therefore, begin until this temperature is exceeded. Figure 6 shows the time history of fuel temperatures at five axial levels for the inner radial ring, indicating the axial temperature variation in the core. The maximum core temperatures at the end of phase 2 are about 2900 K. Table II shows the average component temperatures and surrounding fluid temperatures through the core at the end of phase 2. Axial levels are numbered 3 through 14 from the bottom of the active core upwards. Radial rings are numbered 1 to 3 from inner to outer. Approximately 35% of the core has been degraded and 25% of the total core Zircaloy has been oxidized at this point in time. Obviously, the upper regions of the core are predicted to be heavily oxidized. The degraded state of the core is represented schematically in Figure 7. There is significant radial deviation in damage state. This is due, at least in part, to the radiation model employed. Within the current MELCOR core model only global radiation view factors are used for each core cell and structure, whether intact or debris. To represent core structure and debris radiation heat transfer in a reasonable manner requires a compromise value for the overall cell view factor. This modeling limitation also accounts for some of the high local temperatures predicted for the inner radial ring, as exhibited in Table II.
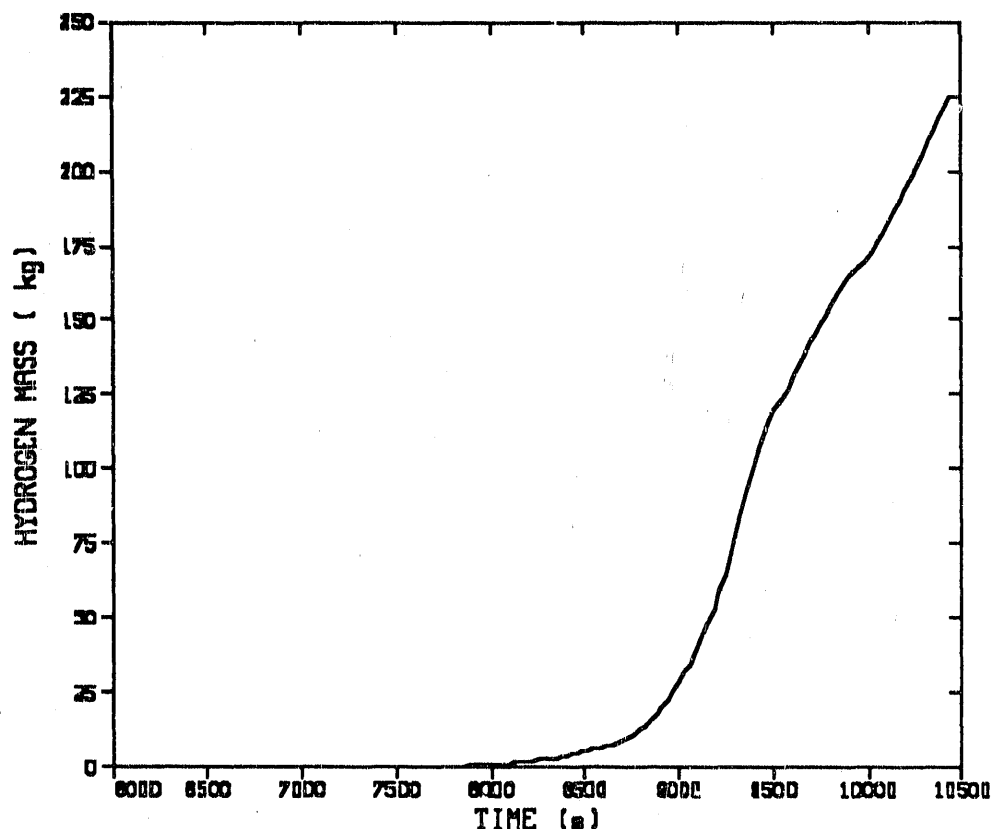
Figure 5.
MELCOR Prediction of Integral Hydrogen Production During Phase 2.

The only significant problem encountered in the phase 2 analysis was calculating the correct response or the pressurizer after the PORV block valve is closed. It was found that a delicate balance exists between the RCS pressure and pressurizer level. If the RCS pressure falls too low, then the pressurizer can empty and effectively terminate the accident progression in phase 2. In the initial MELCOR calculations for this phase, the pressurizer level was treated as a boundary condition beyond 9000 seconds and was not allowed to empty. In subsequent calculations, when the core hydrogen production model was operating in the proper time frame, this boundary condition was eliminated and the code calculation predicted that the pressurizer indeed did not drain. Figure 8 shows the calculated pressurizer level as compared to the plant data. The MELCOR calculations do indicate good agreement; the pressurizer does not drain, but is held back by a positive pressure difference

from the primary system. This is due in large part to the rate of hydrogen production, as alluded to in earlier discussion. An improved model for the blocking effect of hydrogen in the OTSGs will likely reduce the heat transfer and lead to a higher primary system pressure prediction and, therefore, further reduce the minor pressurizer draining that is still indicated late in the phase 2 calculation.
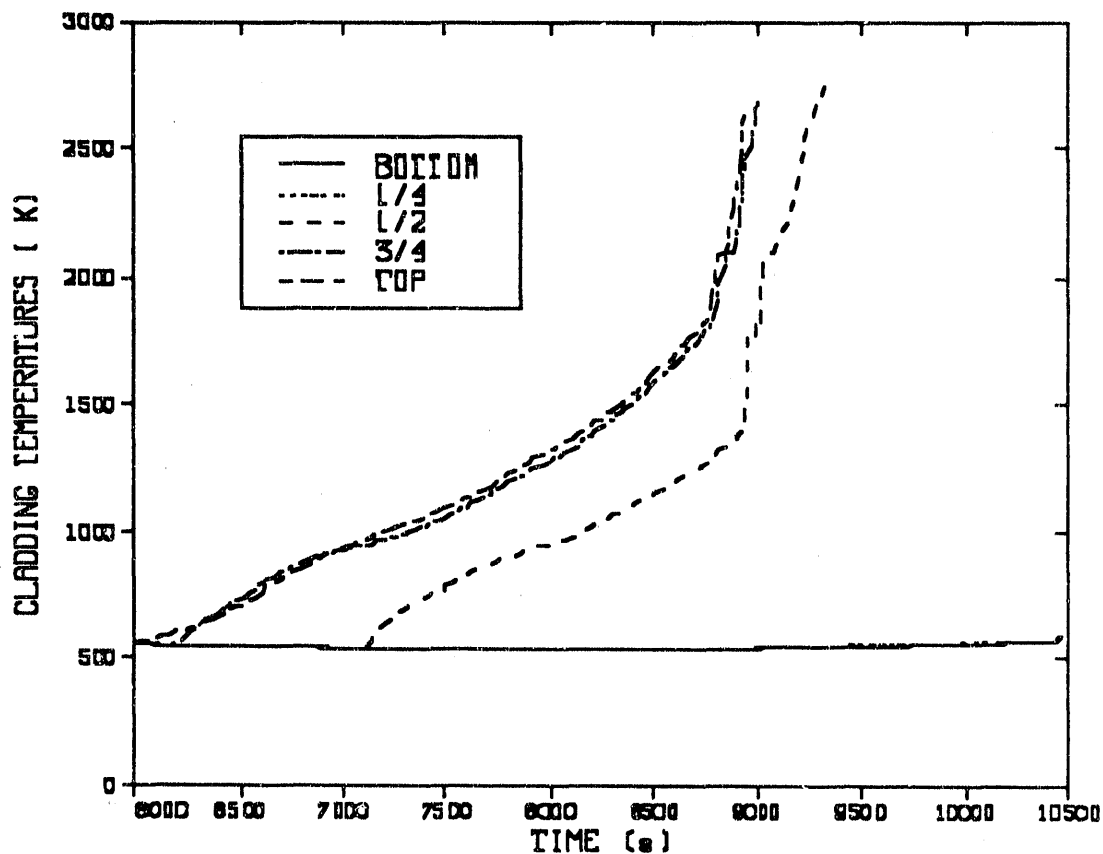

Figure 6.
MELCOR Prediction of Inner Radial Ring Cladding Temperatures at
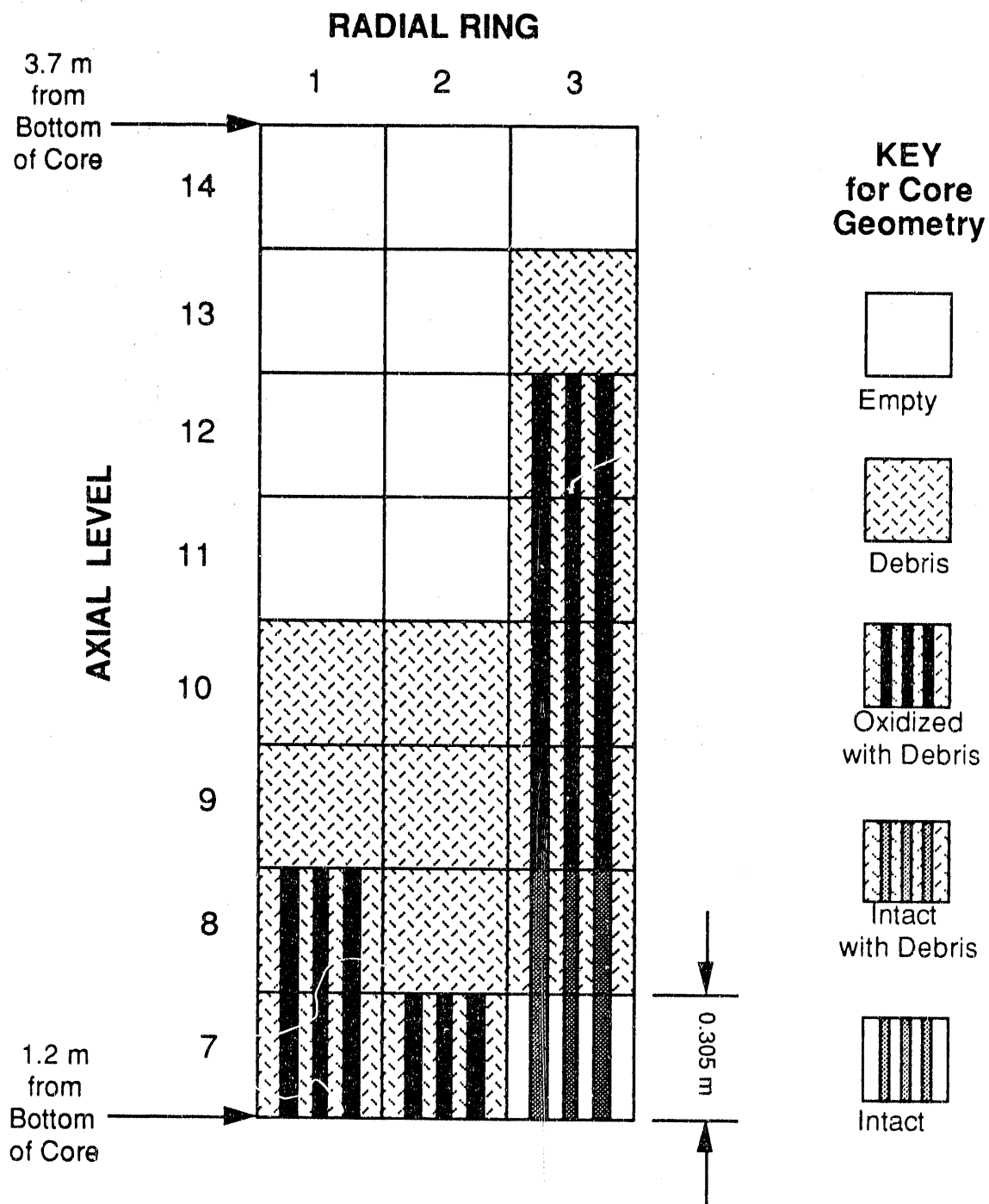Various Axial Levels During Phase 2.

Figure 7.
Schematic Representation of the Degraded Core State at the End of Phase 2
as Predicted by MELCOR.

Figure 8.
MELCOR Prediction of Pressurizer Level Response During Phase 2.

In summary, the MELCOR simulation of phase 2 is quite good. The timing of key events appears to be acceptable considering the uncertainty in the phenomena. Hydrogen production and the state of the core at the end of phase 2 are in reasonable agreement with the estimates found in the standard problem package. This agreement shows that core degradation modeling in MELCOR is applicable to severe accident analysis.

Axial Level	Radial Ring		
	1	2	3
14	NA	NA	NA
	2846.10	2679.79	2486.37
13	NA	NA	2685.89
	2846.10	2679.79	2486.37
12	NA	NA	2516.19
	2846.10	2679.79	2470.97
11	NA	NA	2100.95
	2846.10	2679.79	2056.70
10	2845.73	2679.44	1954.34
	2846.10	2679.79	1821.35
9	2956.53	2764.22	1416.62
	2956.90	2764.66	1269.80
8	2568.58	2596.02	1014.32
	2567.18	2597.58	878.46
7	1191.66	1167.15	583.48
	1305.02	1194.35	567.12
6	576.46	575.25	573.61
	568.95	568.95	568.95
5	574.39	573.88	573.24
	568.95	568.95	568.95
4	573.64	573.20	572.65
	568.95	568.95	568.95
3	572.84	572.50	572.04
	568.95	568.95	568.95

TABLE II.
Average Core Cell Temperatures at the End of Phase 2 (10440 s).
Top number is average component temperature.
Bottom number is channel fluid temperature.

4.3 Phase 3 and 4 Results

During phase 3 there are several computationally challenging events taking place; the loop 2B pump transient, core debris heatup and consolidation, and recovery of liquid level over the top of active fuel. In terms of the ability to calculate the basic thermal-hydraulics associated with the pump transient and recovering of the core, MELCOR performed well in that there were no great computational problems experienced. The difficulties in the simulation of phase 3 and 4 were due to the simplified debris heat transfer models that exist in the current MELCOR code.

Figure 9 shows the predicted RCS pressure during phases 3 and 4. It is clear that the calculation is not following the trends shown in the data. There are at least two reasons for this behavior: (1) the hydrogen blocking model is insufficient, as discussed in the phase 2 results, and (2) the simplified debris heat transfer models are inadequate. All hydrogen production ends at the loop 2B pump transient. This is because there are no reflood phenomena related hydrogen production models in MELCOR, such as a core-shattering, rapid-oxidation model. The pump transient initiates a high steaming rate that serves to cool the existing debris and core structures below rapid oxidation temperatures. This cooling effect precludes any subsequent hydrogen production in phases 3 and 4 which, in turn, accounts for some underprediction in RCS pressure due to the missing hydrogen partial pressure contribution.

The MELCOR debris models are lumped-parameter heat transfer calculations employing a single temperature for all debris at any particular axial level in the core model. The convective correlations are for single spheres in an infinite medium, not packed beds. A simple boiling model that is employed globally in the core is applied to the debris without any consideration of bed dryout. Therefore, a stratified structure with steep temperature gradients, such as existed at TMI-2, is difficult to represent with this model. Since MELCOR can only resolve stratification to the level of core nodalization with simple lumped parameter models, it is not surprising that the code does a poor job representing the thermal response of debris during this phase. Table III presents the core thermal state in phase 4, just prior to debris relocation. It is clear that the core debris and remaining structures are all near liquid saturation temperature; the debris has cooled. The core geometry at the end of phase 3 and into phase 4 is essentially the same as at the end of phase 2 because the debris and core structures are cooled during the pump

transient and subsequent core reflood and thus do not exhibit any continued melt progression.
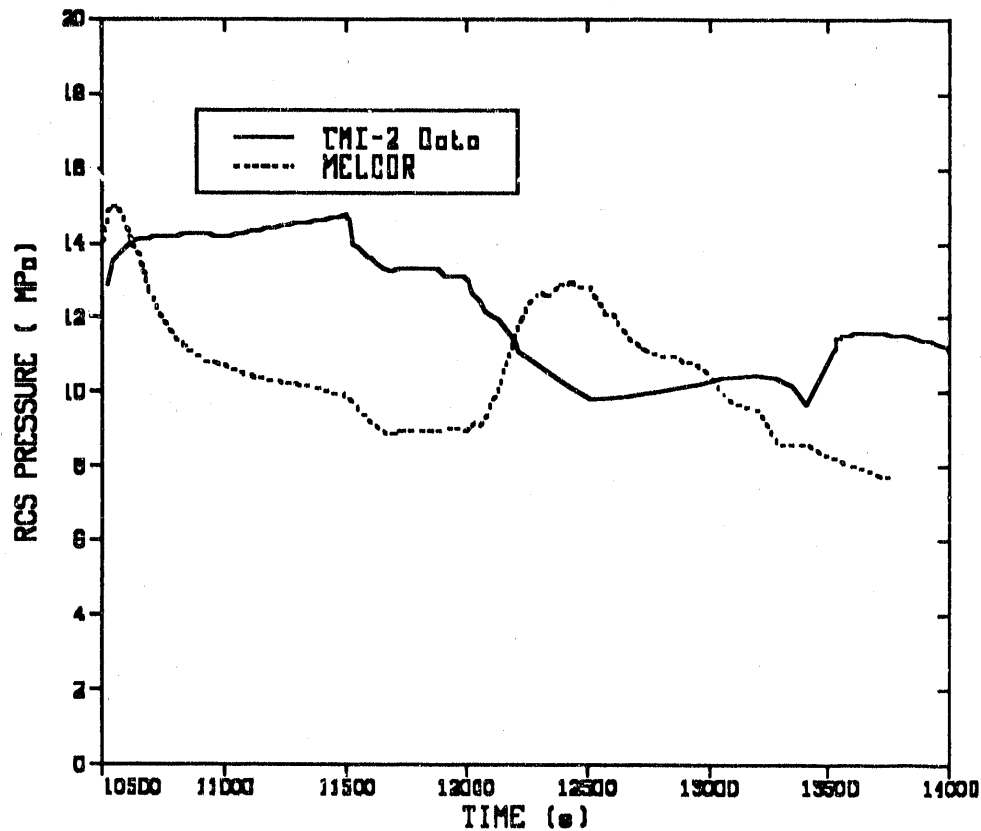

Figure 9.
MELCOR Prediction of Level Response in the Reactor Coolant System
During Phases 3 and 4.

Figure 10 shows the core, downcomer and upper plenum liquid levels for phases 3 and 4. The initial surge in core level from the pump transient is apparent at 10500 seconds, but drops off due to boiling. The core liquid level again increases in the 12000-12500 second time frame with a corresponding pressurization that can be seen in Figure 9. After 12500 seconds, the core is completely covered with liquid.

	Radial Ring		
Axial Level	1	2	3
14	NA	NA	NA
	544.31	544.31	544.31
13	NA	NA	548.43
	544.31	544.31	544.31
12	NA	NA	549.89
	544.31	544.31	544.31
11	NA	NA	550.87
	544.31	544.31	544.31
10	553.41	551.49	551.61
	544.31	544.31	544.31
9	554.14	553.06	548.43
	544.31	544.31	544.31
8	551.37	547.76	551.92
	544.31	544.31	544.31
7	547.44	548.60	551.80
	544.31	544.31	544.31
6	554.43	552.95	551.49
	544.31	544.31	544.31
5	553.39	552.05	550.74
	544.31	544.31	544.31
4	551.77	550.67	549.58
	544.31	544.31	544.31
3	550.13	549.29	548.43
	544.31	544.31	544.31

TABLE III.
Average Core Cell Temperatures Just Prior to Debris Relocation (13440 s).
Top number is average component temperature.
Bottom number is channel fluid temperature.

Although the calculation was continued through the debris relocation portion of phase 4, an inspection of Table III reveals that there is no molten debris to relocate to the lower plenum volume, as in the accident. The MELCOR phase 4 calculation therefore "predicts" relocation of hot solid core debris to the lower plenum. The calculation was terminated at 230 minutes because the MELCOR calculation predicts the debris to have all solidified in a coolable geometry.
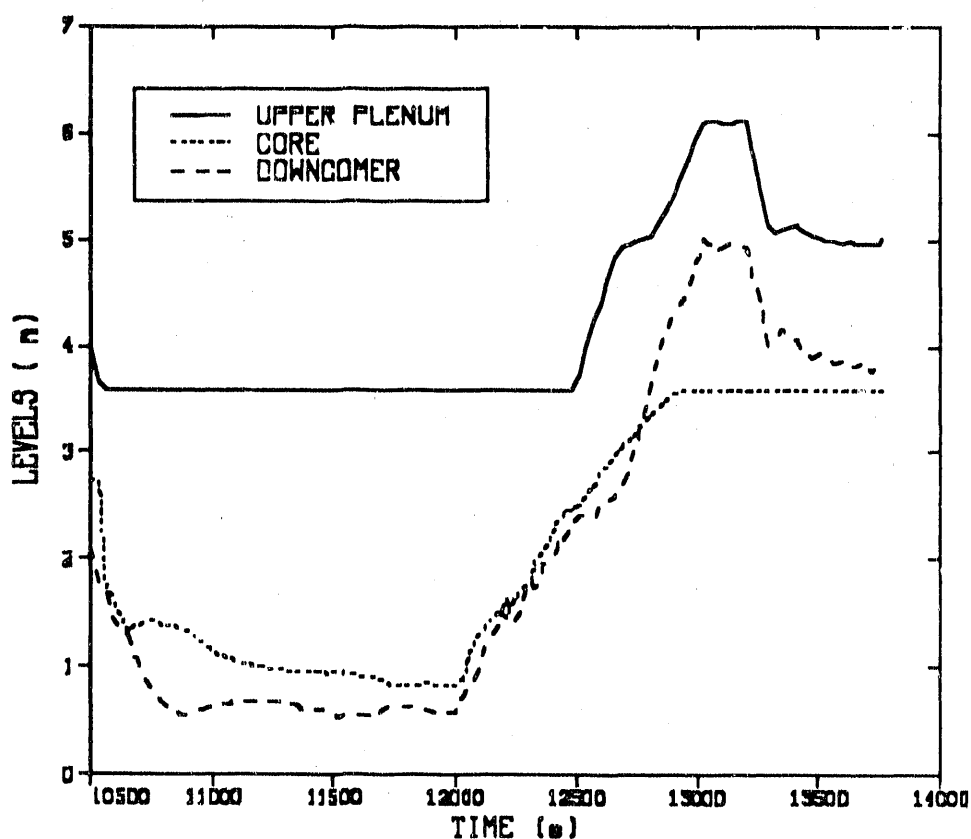

Figure 10.
MELCOR Prediction of Level Response in the RCS During Phases 3 and 4.

5.0 CONCLUSIONS

The MELCOR 1.8.0 computer program has been shown to be capable of modeling the TMI-2 standard problem for the first four phases of the standard problem exercise, for the first 230 minutes of the accident. Although improvements are still needed for various models in MELCOR, the calculations are capable of simulating the course of events in the TMI-2 accident, with the exception of core debris models that can adequately model the complex thermal behavior and radial relocation.

In phase 1, the MELCOR predictions are in reasonable agreement with the data. The key trends in the pressure response and the inventory loss are well predicted. Excellent quantitative agreement is not achieved in pressure prediction due to the simplistic treatment of the primary-to-secondary heat transfer.

In phase 2, the MELCOR analysis is quite good. While the timing of some events is slightly incorrect, the general trends are very good. Hydrogen production and the state of the core at the end of phase 2 are in reasonable agreement with the estimates found in the standard problem package. From these results, it can be concluded that the core degradation modeling in MELCOR is applicable to severe accident analysis.

The phase 3 and 4 calculations demonstrate that MELCOR is capable of handling recovered core sequences, even if in a limited manner; more sophisticated core debris and relocation models are required to correctly represent the true events that took place in the TMI-2 accident.

One particular outcome of this analysis is demonstration of the ability of MELCOR to analyze severe accidents in PWR plants. With future code development efforts, guided in part by this work, the ability of MELCOR to simulate, with confidence, the full range of LWR accidents will be greatly improved.

One observation that can be made is that the ability to use a computer code such as MELCOR for prediction of severe accident progression is best early in the accident and becomes progressively less certain later in the accident. This is due both to the accumulation of uncertainty in calculation, and through the addition of severe accident phenomena with their associated uncertainty to the calculation. The TMI-2 analyses provide a good demonstration of this principle. The Phase 1 results were predicted fairly easily, although there is

some uncertainty as to what the RCS inventory would be as a function of time. The phase 2 calculation demonstrates the ability to generate divergent results, due to the addition of highly non-linear processes such as core oxidation and counter-current limited flow in the pressurizer drain line. Without the known "correct answer" of plant data from the accident, it would be easy to generate different consequences ranging from minimal to a highly damaged core.

It should be clear from these analyses that the ability to simulate an accident sequence will be highly dependent on the code user. The user must select the appropriate nodalization and provide the appropriate models for phenomena that are important for the accident sequence to be simulated. It is obvious that the models for appropriate accident phenomena must exist. It is unclear how to best represent the effects of possible operator interactions, such as imposing them as timed events or as keying off of system variables, such as pressure. Finally, it is clear from these analyses that great difficulty exists in capturing bifurcation points in the calculation, such as the possibility of pressurizer draining that existed in phase 2. When the "correct answer" is not known *a priori*, there is little chance of following all the correct branches.

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