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TITLE: INTEGRATED TRAC/MELPROG ANALYSES OF A PWR STATION BLACKOUT

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INTEGRATED TRAC/MELPROG ANALYSES OF A PWR STATION BLACKOUT*

by

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ABSTRACT

The first complete, coupled, and largely mechanistic analysis of the entire reactor-coolant system during a station blackout (TMLB′) core-meltdown accident has been made with MELPROG/TRAC. The calculation was initiated at the start of the transient and ended with a late recovery of cooling. Additional cooling provided by water from the primary system delayed events relative to a standalone MELPROG calculation. Natural circulation within the vessel was established and primary-relief-valve action did little to disturb this flow. In addition, it was calculated directly that the hot leg reached a failure temperature long before vessel failure. Beyond relocation of the core, we have calculated the boiloff of the water in the lower head and have estimated the time of vessel failure to be at about 14700 s into the transient. For "nominal" corium-water heat transfer, the boiloff process (steam-production rate) is slow enough that the relief valves prevent pressurization beyond 17.5 MPa. Parametric cases with increased corium-water heat transfer resulted in steaming rates beyond the capability of the relief valves, leading to pressures in excess of 19.2 MPa. Natural convection flow around the loop, if started by removing the water in the loop seal, was blocked by a relatively less-dense hydrogen/steam mixture that flowed to the top of the steam generator. Emergency core-cooling system activation late in the transient (after core slump) resulted in rapid cooling of the periphery of the debris region but slower cooling in the interior regions because of poor water penetration. While these results should be considered preliminary, they demonstrate the advanced capabilities of MELPROG/TRAC.

INTRODUCTION AND SUMMARY

The results of the first complete, coupled, and mechanistic analysis of a reactor-meltdown sequence with MELPROG PWR/MOD1 were reported in Ref. 1. The sequence analyzed was a station blackout (TMLB′) for the Surry plant. This standalone MELPROG calculation

* *Work performed under the auspices of the US Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, Division of Accident Evaluation.*

was initiated when the primary coolant saturated and was run to vessel failure. The initial conditions were estimated based upon a TRAC-PF1 (Ref. 2) calculation for a similar plant.[3] The boundary conditions specified were zero flow at the vessel inlet and a constant pressure. the power-operated relief valve (PORV) set point (16.3 MPa). at the vessel outlet. These simplified boundary conditions do not account for possibly important reactor-coolant system (RCS) effects upon the transient. In addition to running MELPROG as a standalone vessel, it now can be run as a MELVSL (equivalent to a VESSEL) component within a TRAC-PF1(MOD2) calculation. In this configuration, the calculation can include all of the primary-system influences on the behavior within the vessel. Reference 4 provides a description of the numerical techniques used to implicitly couple MELPROG and TRAC.

The purpose of this paper is to present results of the first linked MELPROG-PWR/MOD1-TRAC-PF1(MOD2) calculation of a station-blackout transient for the Surry plant. The results will be compared to those obtained in Ref. 1. which will be considered a base case. The MELPROG model of the reactor vessel was the same for the two calculations. The primary and secondary systems were modeled in the usual manner with one-dimensional TRAC components. The linked calculation was run from the loss-of-feedwater initiator through disruption and relocation of the core. It was found that the event sequence given in Ref. 1 was not qualitatively changed, but that all of the important events were delayed. The major reason for the delay was the additional cooling provided by water from the primary system that was not included in Ref. 1. In addition, it was calculated directly that the hot leg reached a failure temperature long before vessel failure. It was also found that a stable natural circulation within the vessel was established and that primary-relief-valve action did little to disturb this flow, thus corroborating the results obtained in Ref. 1.

Beyond relocation of the core, we have calculated the boiloff of the water in the lower head and have estimated the time of vessel failure to be at about 14700 s into the transient. For "nominal" corium-water heat transfer, the boiloff process (steam-production rate) is slow enough that the relief valves prevent pressurization beyond 17.5 MPa. Since this is the first calculation, we felt that it was important to test some of the models and assumptions. Therefore, during the boiloff and vessel lower-head heatup phase some cases were run in which the heat transfer from the corium to water was changed to determine the effect on pressurization.

Increased heat transfer resulted in steaming rates beyond the capability of the relief valves leading to pressures in excess of 19.2 MPa. Pressurization in the core region also cleared the primary-system loop seal. Natural convection flow around the loop started but was blocked by a hydrogen/steam mixture that flowed to the top of the steam generator (SG).

As a final parametric case, the emergency core-cooling (ECC) system was activated late in the transient (after core slump) to test the numerics and to see its effect upon the course of the accident. It was found that the outer periphery of the debris region was cooled rapidly but that interior regions cooled slowly because of poor water penetration. The results obtained by this new calculational tool should be considered preliminary but they do demonstrate its capabilities. In what follows, the primary and secondary system model will be described. The accident sequence will then be presented and compared to the standalone calculation. Some of the details of the calculation and parametric cases will then be described. Finally.

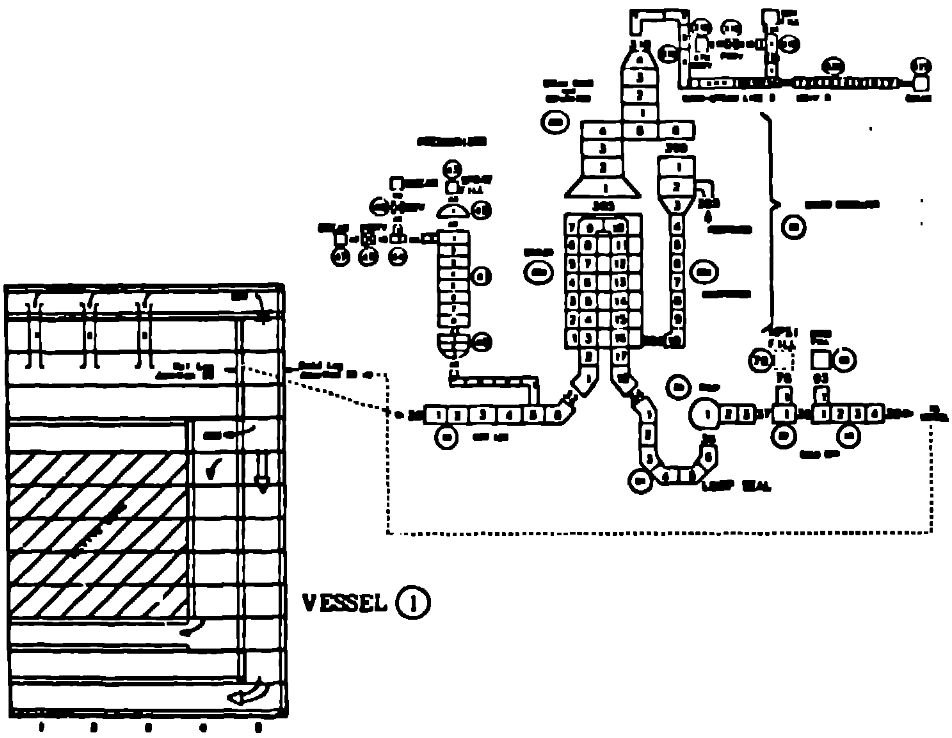

Fig. 1.
TRAC/MELPROG model for Surry.

some conclusions will be drawn about the importance of including the entire primary in the calculational model.

DESCRIPTION OF MODEL

Surry is a three-loop Westinghouse PWR with a power of 2440 MWt. For this application, the three loops were combined into a single-loop representation of the primary and part of the secondary cooling systems as shown in Fig. 1. Included in the model are the SGs, main coolant pumps (MCPs), loop seals, surge line, pressurizer, and primary and secondary relief valves. All thermal-hydraulic (flow) elements, except the vessel, were modeled in one dimension. For this transient, which involves a loss of all feedwater, a simplified secondary-system model is all that is required. The MELPROG vessel model, which is two dimensional and is described in detail in Ref. 1, is also shown in Fig. 1. MELPROG(MOD1) has a simplified fuel-rod model that depends upon temperature alone for predicting the onset of fuel material relocation. In Ref. 1 two failure temperatures were considered, 2200 and 2500 K. Here we have used the higher temperature because it leads to more realistic timing for gross fuel motion and causes a more severe test of the numerics.

STEADY-STATE CALCULATION

With the model given in Fig. 1, a steady-state calculation was run. The most important plant parameters are given in Table I, where they are compared to design values from the Surry Final Safety Analysis Report (FSAR) (Ref. 5)

TABLE I

COMPARISON OF MELPROG/TRAC AND FSAR STEADY-STATE PLANT PARAMETERS

	MELPROG/TRAC	FSAR
Vessel inlet coolant temperature	560.1 K	557.0 K
Vessel outlet coolant temperature	596.2 K	591.9 K
Coolent temperature increase	36.2 K	34.8 K
Primary coolant mass flow	12500.0 kg/s	12750.0 kg/s
Secondary-side water mass	136600.0 kg	127000.0 kg
Secondary steam flow	1304.0 kg/s	1328.0 kg/s
Secondary steam temperature	544.0 K	542.0 K

These parameters can and will be improved in the next run of this calculation. They were judged to be sufficiently close for the purposes of the first linked MELPROG/TRAC calculation.

TRANSIENT RESULTS AND DISCUSSION

The initiator of a station blackout or TMLB' transient is a loss of offsite power. This, in turn, results in main coolant and main feedwater (MFW) pump coastdown, turbine trip, reactor scram, main-steam isolation valve closing, and a signal to begin auxiliary feedwater (AFW). This transient additionally assumes that there is no AFW or emergency power with which to operate ECC. We have assumed that MFW flow decreases linearly to zero in 15 s. After MFW coastdown, the boiloff of secondary side water begins. The secondary-side pressure increases to the relief valve set point (7.25 MPa) where it remains throughout the transient. A natural-circulation flow of approximately 600 kg/s is established in the primary loop after the MCP has coasted down. Energy removal by the SG is sufficient to maintain the temperature of the primary coolant until approximately 3000 s into the transient. The coolant temperature and pressure in the hot leg are given in Figs. 2 and 3. By 3000 s, the SG energy-removal capability has been degraded and the temperature and pressure begin to increase.

At 4394 s, the primary-system pressure has reached the PORV set point and the PORV opens. At 4510 s, the SG is steam filled, decreasing its energy-removal capability, and the primary-coolant temperature increases rapidly. The accompanying expansion raises the water level in the pressurizer and at 5550 s it is full. The pressurizer water level is given in Fig. 4. The primary coolant is saturated at the top of the core at 6430 s and begins to boil. Temperatures in the primary system at the onset of boiling are uniform (a 6-K gradient axially in the core) because of flow and mixing that are induced by natural-circulation flow around the primary loops. The sequence of events of the MELPROG/TRAC calculation is given in Table II, where it is compared to those from the base-case calculation.[1] It can be seen that the estimated time at which boiling begins in the base case is very close to that calculated by MELPROG/TRAC. All of the other times are delayed, however. The delays can readily be explained by the amount of water, and hence cooling, that is available in the vessel. Figure 5 gives the two-phase water level in the core region for the two calculations. Both calculations show a rapid drop in level

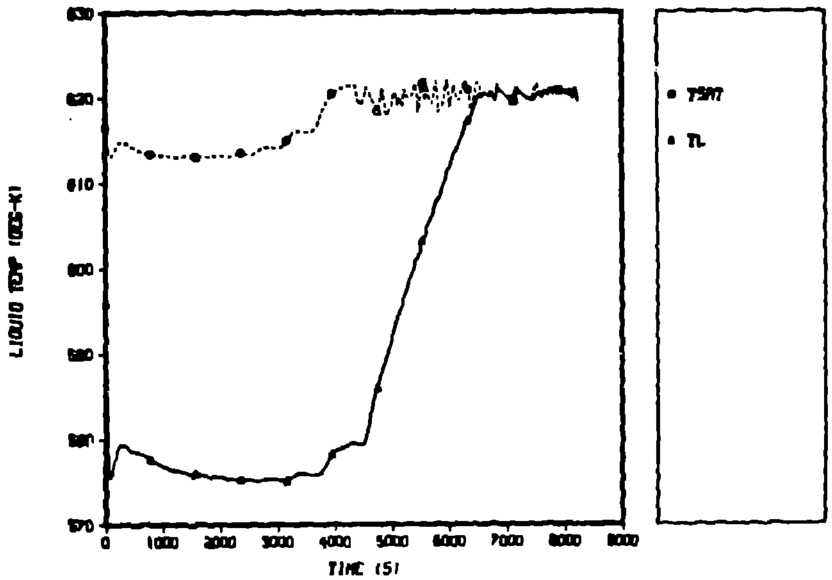

Fig. 2.
Hot-leg coolant temperature.

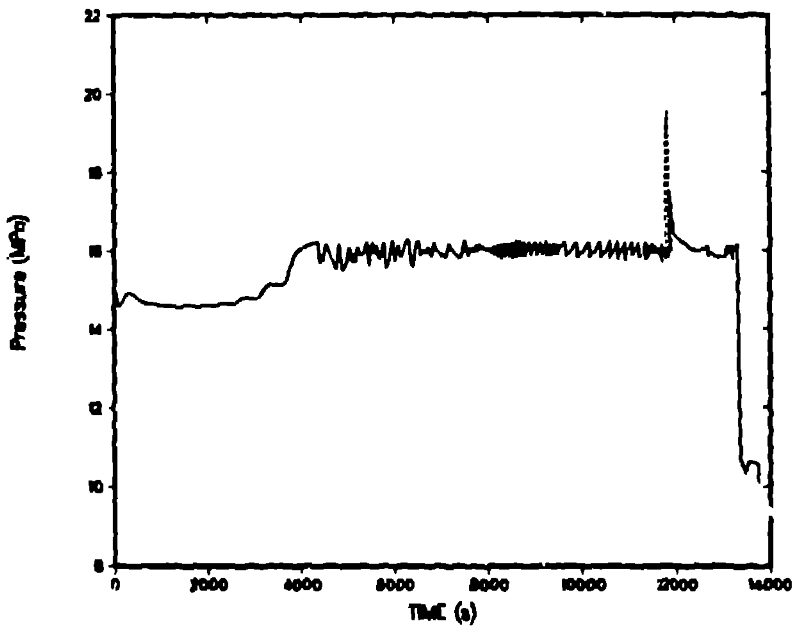

Fig. 3.
Hot-leg pressure.

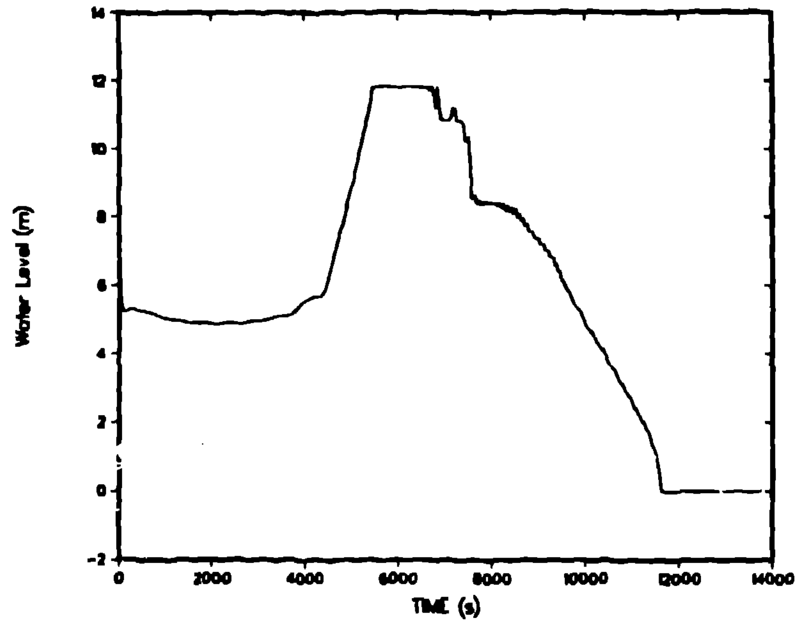

Fig. 4.
Pressurizer water level.

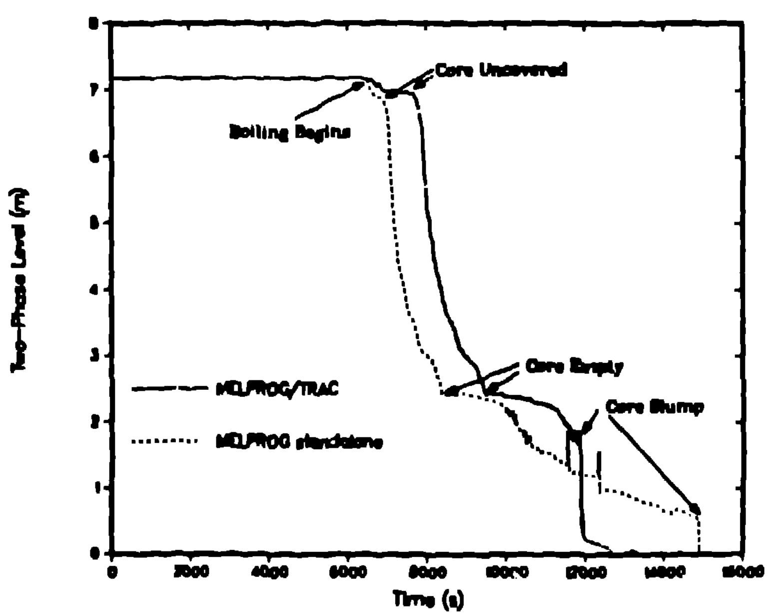

Fig. 5.
Comparison of two-phase water level.

TABLE II

COMPARISON OF BASE CASE (STANDALONE) AND TRAC/MELPROG EVENT SEQUENCES FOR SURRY TMLB′

Base Case	TRAC/MELPROG	Event
	0	Station blackout, begin TRAC/MELPROG
6500	6430	Incipient boiling, begin MELPROG base case
7070	7750	Core "uncovered"
8350	9450	Core empty
9280	10400	Hydrogen generation begins at top of core
		Cladding temperature>1273K
9970	11310	Control rods begin to fail
		Steam temperature >1700K
		Fuel rods begin to fail:
10181		Cladding molten and temperature>2200K
	11635	Cladding molten and temperature>2500K
10387	11638	Upper core plate melts in ring 1
10700	11870	Hot-leg failure
		Pipe-wall temperature>1000K
	11874	Debris regions released, start parametric cases
	13100	Empty loop seal
	13340	Start ECC and open PORV
11345		"Thin" metal in upper plenum begins to melt
11824		Core baffle begins to melt
14877		Debris region crust fails, core slumps
15928	14700*	Lower head fails, end MELPROG base case

*Estimated from debris condition at 11880 s.

after boiling begins. The level is maintained because of an equilibrium that is established between vapor formation in the core and draining of water into the core. In the base case, the only source of water is from the vessel and the core is "uncovered" at 7070 s. Once uncovered, there is no more draining into the core and the level drops as the water in the core is boiled away. A similar plateau is obtained in the MELPROG/TRAC calculation; however, water coming into the vessel from the primary system maintains this level for a longer time. Within approximately 200 s of uncovery, the maximum cladding temperature exceeds the saturation temperature and increases at a rate of 0.3 K/s. The cladding temperature at the top of the core in the central ring for the two calculations is given in Fig. 6.

Figures 7–9 graphically show the state of the vessel during this phase of the accident. The top number in each cell represents the temperature (K) of the fluid with the largest volume fraction, while the bottom number represents the surface temperature of the structure or fuel

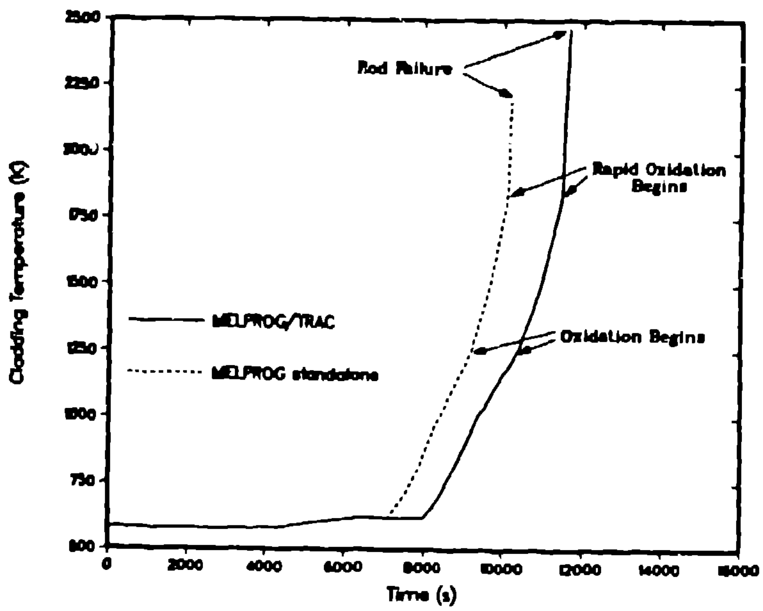

Fig. 6.
Comparison of maximum cladding temperature.

pins (in cells that contain both fuel pins and structure, the pin-surface temperature is shown). Dotted-line density is proportional to liquid water volume fraction, while the angle of the dotted line from the vertical is proportional to hydrogen partial pressure. The fuel-pin volume fraction is represented by the vertical solid lines, while inpenetrable (in the two-dimensional sense) walls are represented by closely spaced parallel lines. The velocity vectors show a four-point average of the axial and radial interface velocities for the fluid with the largest volume fraction in that cell. Additional imbedded flow paths that represent the control-rod drive covers and the upper-head spray nozzles are not shown for clarity. Figure 7 shows the state of the vessel when boiling has just begun at 6440 s. At this time in the transient, there is a flow of approximately 420 kg/s through the vessel. The temperature difference across the core is seen to be 6 K axially and uniform radially. The thin structure and rod-surface temperatures are within 1-3 K of the liquid temperature.

Figure 8 shows the vessel at 8360 s when the core is approximately 60% steam filled. By this time, a multidimensional circulation pattern has developed in the upper plenum that reaches down into the core. Steam exits the center of the core at 672 K, flows upward, is cooled in the upper plenum to 655 K, and re-enters the core at the outer radial edge. There it is heated and it flows back to the center of the core. The flow up the center of the upper plenum is larger than the flow out of the vessel and the steam exiting the vessel is 14 K cooler than the steam exiting the core. Figure 9 shows the vessel at 9555 s, about 105 s after the core has filled with steam. The circulation that developed earlier persists, but now extends one axial cell further downward into the core. An 83-K radial temperature gradient has developed across the top of the core as a result of heat transfer to cooler structures at

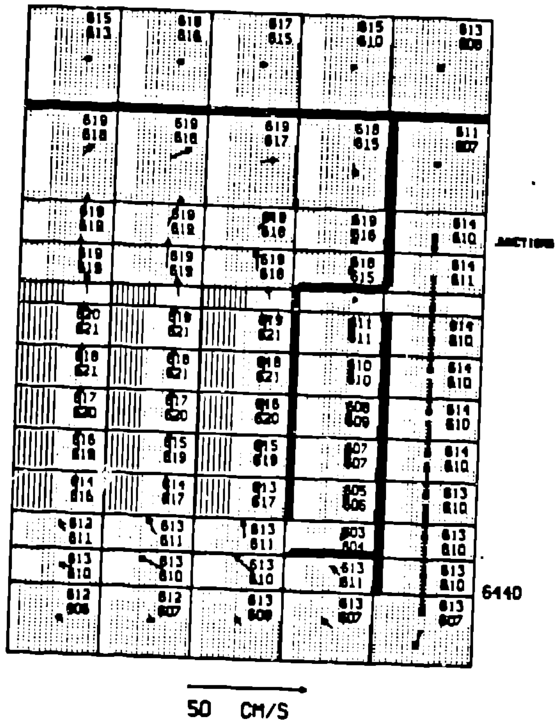

Fig. 7.
Vessel flows and temperatures at 6440 s.

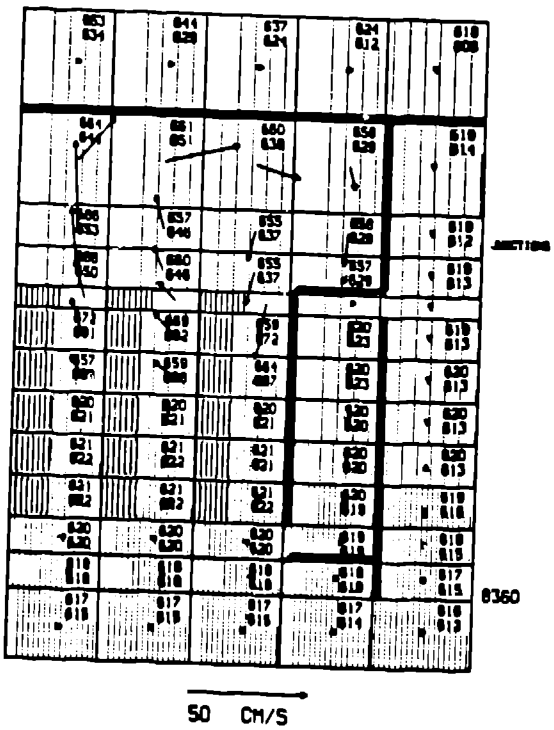

Fig. 8.
Vessel flows and temperatures at 8360 s.

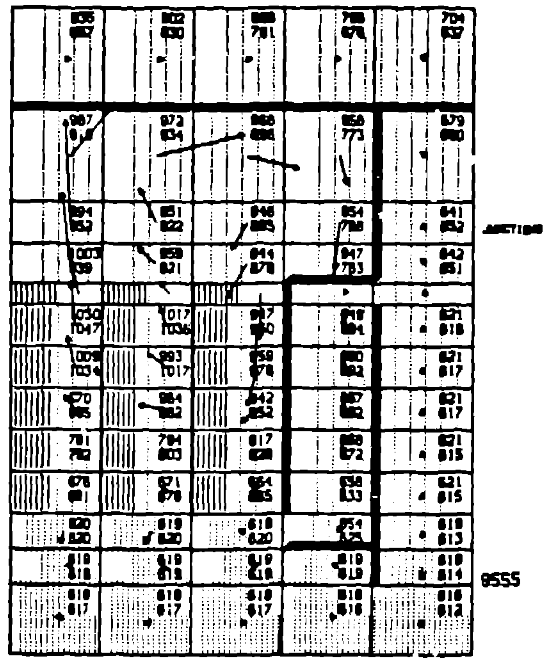

Fig. 9.
Vessel flows and temperatures at 9555 s.

the outer radial boundary. Note that the circulation has moved super-heated steam to the bottom of the core where it can contact the water below the core. The steam flowing from the vessel is 76 K cooler than that exiting the core and the flow rate remains low compared to the that in the upper plenum. A possibly important effect of the primary system is the disruption of in-vessel natural circulation when the PORV opens to maintain the system pressure. In our model the valve opens in 2 s when the pressure in the pressurizer goes above 16.3 MPa. Figures 10a-b show the effect of the valve action on the flows and temperatures in the vessel at a point in the transient 300 s before cladding oxidation begins (10130 s). At this time, the core has been empty for almost 800 s and the cladding is close to 1200 K at the top of the core in the center radial ring. The pressurizer still has approximately 3 m of water (see Fig. 4). This water is important in that it decreases the rate of depressurization when the PORV opens (flashing of this water tends to maintain the pressure). The pressure at the hot-leg connection drops 0.6 MPa in a period of approximately 20 s, at which point the PORV closes and the pressure once again increases. This pressure decrease results in increased steaming in the lower plenum which, in turn, cools the bottom of the core changing the flow there. The core-top and upper-plenum temperatures do not change significantly. This can be seen by comparing Figs. 10a and 10b. Because the temperatures at the top of the core and upper plenum drive the flow, the flow is not affected. This can be seen in the figures. When the PORV closes, the flow throughout the vessel, similar to that in Fig. 10a, is rapidly re-established.

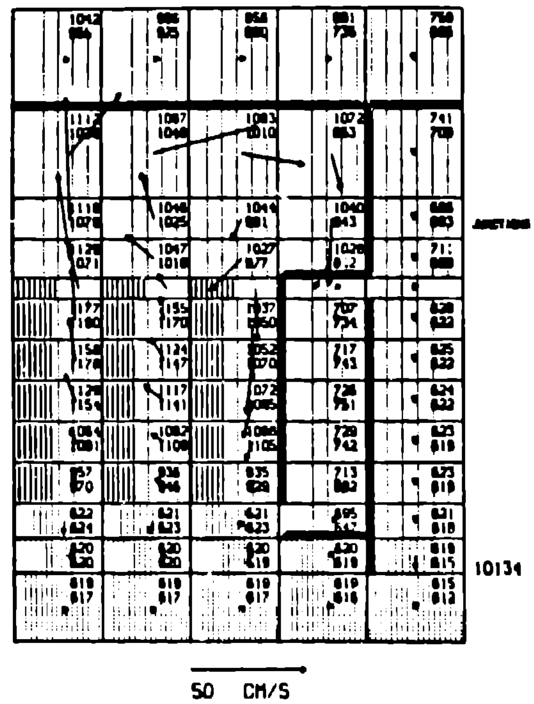

Fig. 10a.
Vessel flows and temperatures at 10134 s (PORV about to open).

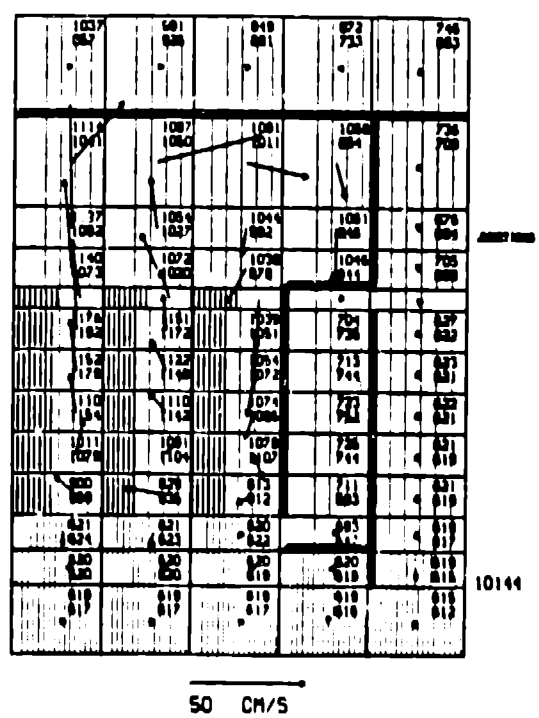

Fig. 10b.
Vessel flows and temperatures at 10144 s (maximum effect of open PORV).

At 10400 s, the rods in radial ring 1 at the top of the core (in level 8) are at 1273 K and begin to oxidize. Oxidation results in an increase in the rod-heating rate from 0.3 K/s to 0.8K/s (Fig. 6). The rapidly increasing fluid and structural temperatures in the core region will cause failure and the formation of debris regions. The first component to fail will be those portions of the control rods whose stainless steel cladding has reached the 1700-K melting point.

The liquefied control materials drain from the failed rods into the intact core and proceed downward until they have given up enough heat to cooler structures to cause them to freeze. The absorber material, whose freezing point is 1070 K, flows downward through the core. The minimum rod temperature in the core when absorber material begins to move is approximately 1200 K in node 4 at the bottom of the core. Therefore, the absorber material does not freeze until it contacts water in the lower plenum. Heat transfer from the absorber material to the water causes steaming in the lower plenum which, in turn, cools node 4 rods in all three rings. Continued heating results in the hottest rods reaching 1850 K at 11500 s, at which point a change in the ZrO_2 lattice structure causes an increase in the oxidation rate. The increased oxidation is manifested in a change in the rod-heating rate from 0.8 K/s to 2–5 K/s, which can be seen in the rod temperature plots (Fig. 6). With increased heating, the rods rapidly reach the cladding melting point (2180 K) and then the failure temperature (2500 K). In ring 1 at node 9 (the hottest location in the core), these events occur at 11560 s and 11635 s, respectively. Rod failure is indicated by the point at which the line ends in the rod temperature plots. Referring to Table II, it can be seen that the first fuel failure occurred 1400 s (24 min) later than in the base case. This delay, as mentioned before, was because of additional cooling that was provided by water from the RCS. A closer examination of the cold leg reveals that there is a steady, albeit low (1–5 kg/s), flow into the vessel even after the loops have drained. This low flow is a result of the fact that the vapor above the loop seal on the SG side remains approximately at the local saturation temperature (relatively dense), while the vapor on the vessel side becomes increasingly less dense. The level on the vessel side thus increases, allowing water to run into the cold leg and vessel. Over the next 100 s, all of the fuel rods in ring 1 but the lowest level in the core fail. Fuel material from the upper levels relocates downward to the bottom of the core where it freezes, blocks further downward motion, and forms a debris region. Some of the fuel material (corium) relocates out of the bottom of the core, contacts water, and induces steaming. The relocated ring-1 fuel heats the fuel in ring 2 at the core midplane, causing it to fail at 11772 s. Continued heating induces failures in ring 3 at the core midplane at 11803 s. The state of the vessel at 11859 s is given in Fig. 11. At this time, the two-phase water level is at the diffuser plate. The lower head has about 3700 kg of corium that has cooled to the local water saturation temperature. Ring-1 fuel has failed in all but level 4 (the bottom level of the core). Rings-2 and -3 fuel has failed in levels 6 and 7 and is disintegrating in level 5. This debris region in the core (indicated by the Xs in the figure) accounts for approximately 60 tonnes of corium at an average temperature of 2260 K

The fuel rods in levels 8 and 9 are oxidizing and heating rapidly and will reach the failure temperature within 30 s. The highest temperatures in the vessel are at these levels; the flow pattern is thus up the outer rings and down the center ring, as can be seen in the figure. The "thin" metal in the upper plenum is close to its melting temperature (1700 K). Interestingly,

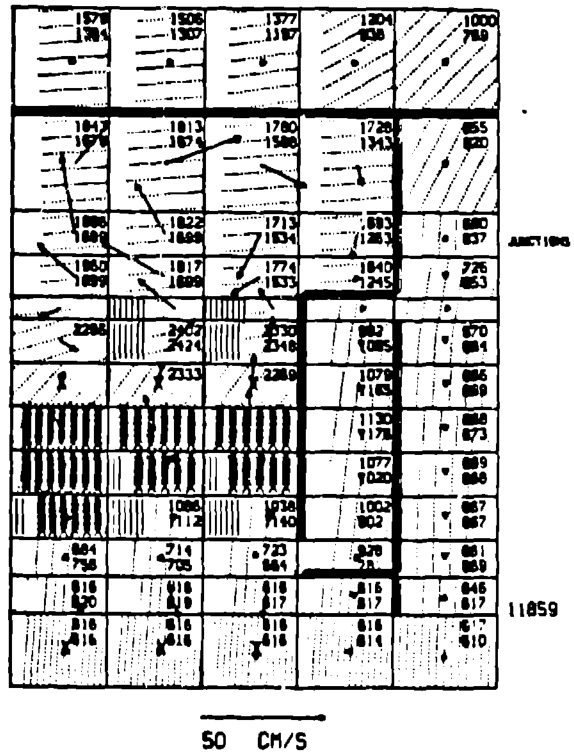

Fig. 11.
Vessel flows and temperatures at 11859 s.

the flow in the upper plenum remains in the normal (clockwise) direction. The upper plenum is 95% hydrogen because of the oxidation taking place at the top of the core. Referring to Table II, it can be seen that the hot-leg wall is estimated to fail at approximately 11870 s into the transient. The MELPROG/TRAC parametric cases were begun shortly after this time. Because the parametric cases represent a major deviation from "nominal" MELPROG-predicted results, it is worthwhile to review the RCS behavior up to this time. At the time the parametric cases were begun, the RCS had water only in the loop seal on the suction side of the MCP. This water effectively blocked vapor flow around the RCS. The water in the loop seal and the steam in the cold leg and SG were close to the local saturation temperature (620 K). Because of this relatively low vapor temperature, the components in this region of the RCS, in particular the vulnerable pump seals and SG tubes, also remained relatively cool. Figure 12 gives the tube-wall temperature at the inlet of the SG throughout the transient. The figure shows that the tubes remain below 630 K until, as a parametric case, the loop seal was emptied at 13100 s and flow around the RCS began. The vapor temperature in the hot leg on the path from the vessel to the PORV, on the other hand, is well above the saturation temperature. Figure 13 gives the vapor temperature in the hot leg at the vessel connection. Up to 8300 s, the temperature remains near saturation. After 8300 s, the boiloff that empties the core region maintains a steady flow of superheated vapor until approximately 9450 s. This steady flow decreases when the core is empty and an oscillatory temperature is seen until the pressurizer empties at 11740 s. The oscillatory behavior is a result of the PORV opening and closing. When the PORV opens hot steam flows out of the vessel and the temperature increases. When the PORV closes, water drains into the hot leg from the pressurizer and the temperature decreases, approaching the saturation temperature, as the water flashes cooling the hot-leg vapor. The effect of the vapor on the hot-leg wall temperature is shown in Fig. 14.

The figure shows a steady increase in the hot-leg wall temperature at the vessel connection and at 11870 s it is at 1000 K. The surge line wall remains relatively cool until the pressurizer is almost empty (compare Figs. 4 and 14): thereafter, it rapidly heats to 1400 K. The surge-line heats more rapidly because it is a thinner, smaller-diameter pipe. Initial indications are that a wall will fail rapidly if the temperature is above 1000 K (Ref. 6). If this is the case, then system depressurization by this means is likely by 11870 s into the transient. Note that this failure would occur before core slump and 2000 s before the estimated vessel failure time. Because primary-system depressurization represents a major break point and because debris-region heatup and crust failure were studied in detail in Ref. 1, it was decided to begin some parametric cases at this time in the calculation.

PARAMETRIC CASES

The parametric cases that were run represent either changes to key assumptions or parameters in the main calculation, or auxiliary calculations to look at some specific items of interest. The first thing that was done was to release the debris regions, allowing them to relocate to the lower head. Strictly, the crusts holding the debris regions in the core were still frozen and would have required approximately 1000 s to melt. On the other hand, considerably more material could have relocated to the lower head than was predicted by the existing simple crust-and-debris-region formation models. These models are currently being replaced by the more mechanistic CORE module, which allows fuel dissolution by the cladding and candling.

Release of the debris regions at 11874 s allows hot (2260 K) corium to contact saturated water in the lower plenum. In the first fraction of a second, direct contact between corium and water produces large quantities of steam that causes film boiling. The boiling rapidly reduces the level in the lower plenum, as can be seen in Fig. 4, and raises the system pressure as can be seen in Fig. 3. The PORV is unable to maintain the system pressure and the safety valve opens for 12 s, as most of the water in the lower plenum is boiled off in this time period. The water remaining in the vessel is boiled away over the next 14 min. The condition in the vessel during the boiloff is shown in Fig. 15. The figure shows that there is a small quantity of water in the lower head that is boiling. The flow of steam up through the debris region both cools materials and oxidizes zirconium. The flow is to the upper plenum with no recirculation, out of the vessel to the hot leg, and out the PORV, which remains fully open until approximately 12500 s, when almost all of the water has boiled away. With the vessel depleted of water, lower-head heating by conduction from the debris will lead to lower-head failure at 14700 s. The following parametric cases address the question of cooling provided by circulation around the primary loop or late actuation of the ECC system. Before proceeding with those cases, the effect of higher corium-water heat transfer is examined. "Nominal" heat transfer from corium to water in the lower plenum is determined by a fixed-diameter (0.1 m) corium sphere. The resulting system pressurization was discussed in the preceding paragraph. If the sphere diameter is reduced to 0.01 m, the increased surface area results in a steaming rate that cannot be accommodated by the safety valves and the system pressure increases to 19.2 MPa. This is shown by the dashed line in Fig. 3, which displays the pressure in the hot leg.

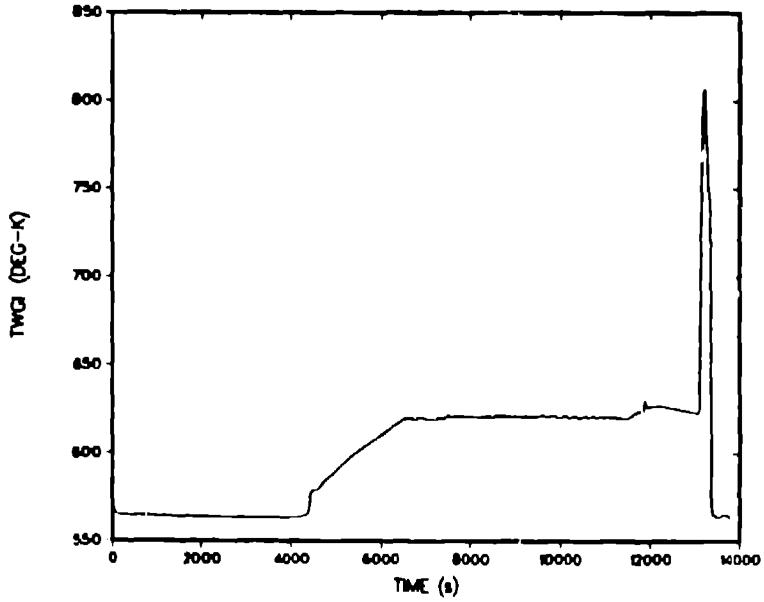

Fig. 12.
Tube temperature at inlet to steam generator.

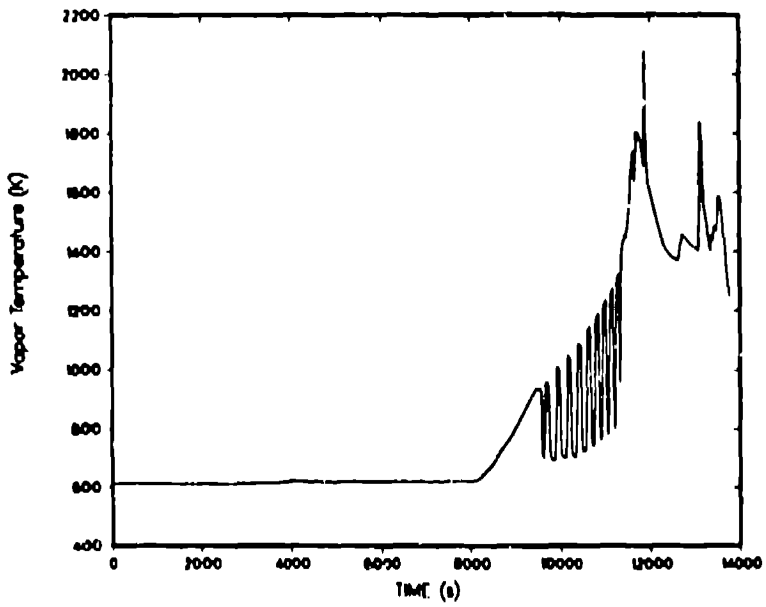

Fig. 13.
Vapor temperature in hot leg at vessel outlet

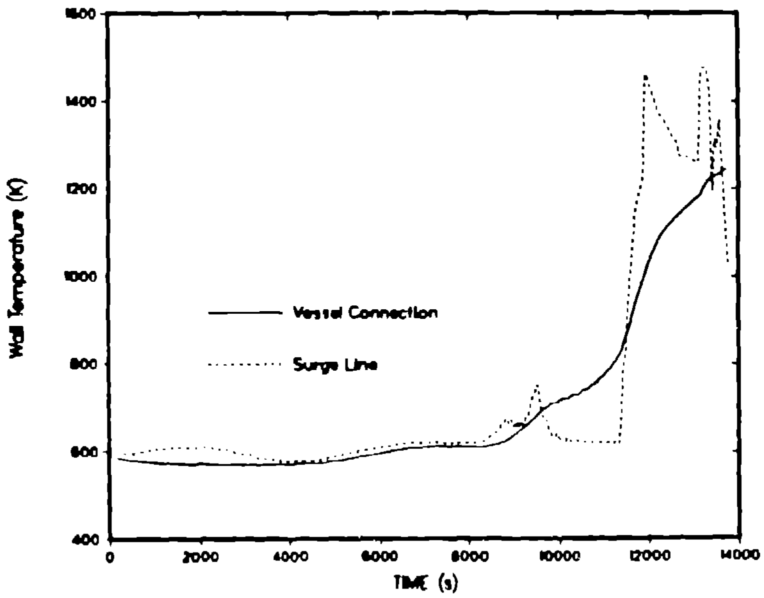

Fig. 14.
Wall temperature at vessel connection and in surge line.

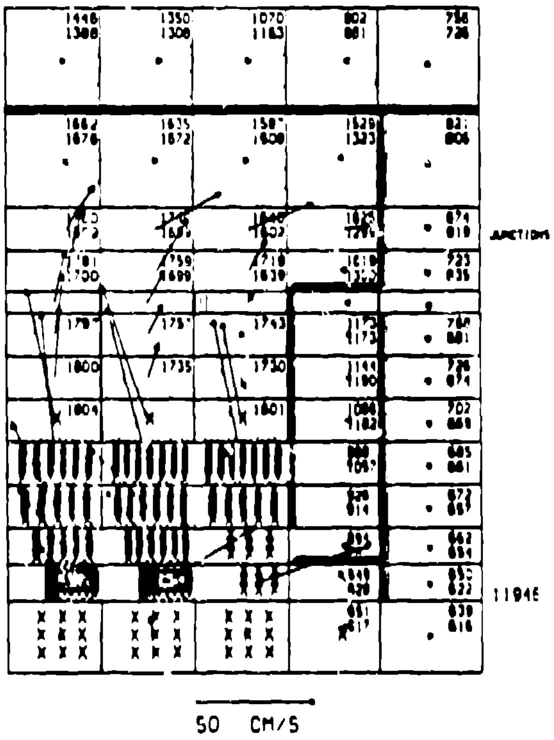

Fig. 15.
Vessel flows and temperatures at 11946 s

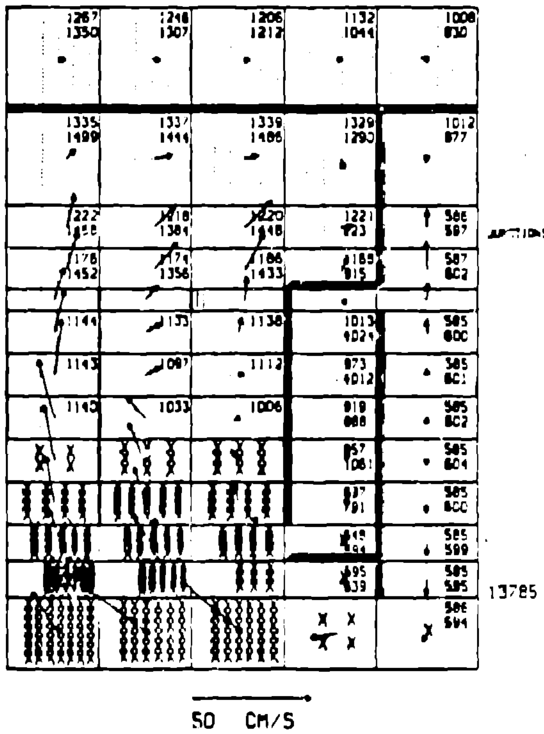

Fig. 16.
Vessel flows and temperatures at 13785 s.

This pressure level would certainly increase the likelihood of an RCS failure at core slump. The pressure increase in the core also induced a pressure drop across the loop seal that was high enough to move the water out of the loop seal, thus opening the possibility of flow around the primary loop. The effects of emptying the loop seal are examined next.

After the core debris had completely boiled the water in the lower plenum away, the water in the loop seal was removed to determine the effect of re-establishing natural circulation around the primary loop. The flow increased and a large amount of energy (1500 MJ) was removed from the gas, increasing the SG-tube temperature from 630 K to 800 K, as can be seen in Fig. 12. About 100 s after the loop seal had been cleared, the mixture of steam and hydrogen at the top of the SG tubes was low enough in density that the driving force for natural circulation ended, ending the flow around the loop. Thus, it appears that while the potential for removing a large amount of energy by means of natural circulation exists, flow around the loop will be blocked either by water in the loop seal or by a low-density mixture of steam and hydrogen at the top of the SG.

The final parametric case that was considered was to activate the ECC system and open the PORV at 13340 s into the transient. Flow through the PORV decreases the system pressure to about 10.0 MPa quickly. Boiling of ECC water as it contacts hot debris in the lower vessel head maintains the pressure at 10.0 MPa. At the end of the calculation at 13800 s, water from the ECC system is collecting at the bottom of the downcomer. Very little water has penetrated into the main debris region in the lower head. Instead, steam formation on contact with the hot debris flows up through the debris, as is shown in Fig. 16. The average debris temperature at the end of the calculation is approximately 1100 K, having been cooled an average of approximately 1.2 K/s from the time that the loop seal was cleared at 13100 s when the cooling process was begun. The upper-plenum structure is also cooling at approximately 1 K/s, but it remains hotter than the debris region, as can be seen in Fig. 16. The system is recovering, so the calculation was terminated at 13800 s.

CONCLUSIONS

The first complete, coupled, and largely mechanistic analysis of a TMLB' (station blackout) core-meltdown accident has been made with MELPROG/TRAC. The calculation was initiated at the start of the transient and ended with a late recovery of cooling. It was found that the event sequence given in Ref. 1 (a standalone MELPROG calculation) was not qualitatively changed, but all of the important events were delayed. The major reason for the delay was the additional cooling provided by water from the primary system that was not included in Ref. 1. In addition, it was calculated directly that the hot-leg nozzle reached a failure temperature long before vessel failure. It was also found that a stable natural circulation within the vessel was established and that primary-relief-valve action did little to disturb this flow, thus corroborating the results obtained in Ref. 1.

Beyond relocation of the core, we have calculated the boiloff of the water in the lower head and have estimated the time of vessel failure to be at about 14700 s into the transient. For "nominal" corium-water heat transfer, the boiloff process (steam-production rate) is slow enough that the relief valves prevent pressurization beyond 17.5 MPa. Since this is the first calculation, we felt that it was important to test some of the models and assumptions. Therefore, during the boiloff and vessel lower-head heatup phase, some cases were run in which the heat transfer from the corium to water was changed to determine the effect of pressurization and debris-region temperature. Increased heat transfer resulted in steaming rates beyond the capability of the relief valves, leading to pressures in excess of 19.2 MPa.

Natural convection flow around the loop, if started by removing the water in the loop seal, was blocked by a relatively less dense hydrogen/steam mixture that flowed to the top of the SG. As a final parametric case, the ECC system was activated late in the transient (after core slump) to test the numerics and to see its effect upon the course of the accident. It was found that the outer periphery of the debris region was cooled rapidly but that interior regions cooled slowly because of poor water penetration.

The results obtained by this new calculational tool should be considered preliminary, but they do demonstrate its capabilities and the importance of including the effects of the RCS. Most of the important phenomena occurring in the accident sequence were modeled in this calculation. The important exceptions are a treatment of cladding motion prior to major disruption of the fuel rods (as treated by the CORE module) and a treatment of the fission product release, transport, and deposition (as treated by the VICTORIA module that is being implemented). The calculation will be rerun with the CORE and VICTORIA modules implemented to determine the effects of the phenomena that they model.

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