TMI-2 ACCIDENT SCENARIO UPDATE[a]

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ABSTRACT

Estimates of the end-state core configuration have been developed from recent inspection of the lower regions of the TMI-2 core, core support assembly, and lower plenum regions. The inspection data have provided a basis for estimating the extent of damage to the core and core support structures and have confirmed that the migration pathway of the molten core material to the lower plenum occurred in the east quadrant of the reactor vessel. This paper integrates the core inspection data with other TMI-2 data and supporting analysis to update the best-estimate core damage progression scenario.

INTRODUCTION

The TMI-2 Accident Evaluation Program[1] is being conducted by the Department of Energy (DOE) primarily to (a) develop an improved understanding of the physical mechanisms that controlled core damage progression during the accident and (b) utilize this improved understanding towards resolving severe accident and source term issues for light water reactors. Reactor defueling work completed over the past two years has confirmed that damage to the TMI core was extensive, with significant core material melting and relocating to the lower plenum region of the reactor vessel. As they become available, the defueling data are being integrated with the instrumentation data recorded during the accident and with independent severe fuel damage experimental data to develop a best-estimate scenario of the TMI-2 core damage progression.

The previous scenario work[2] was based on very limited knowledge of the damage in the lower half of the core, or confirmatory information relative to the core failure mechanism and the core-to-lower plenum migration pathways.

Recent inspections of the lower core, core support assembly (CSA), and lower plenum region[3,4] are consistent with the initial core relocation

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mechanisms discussed in the previous accident scenario work. The inspection data also provide additional information to improve understanding of the potential core failure mechanisms and the interaction of the molten core materials with the core support structures and the lower reactor vessel head. This paper integrates the inspection data into the core damage progression scenario during the first 4 h of the accident. Details of the accident prior to 100 min will not be included, since coolant flow during this period prevented core heatup. References 5 and 6 provide a synopsis of the loss-of-coolant period of the accident between 0 and 100 min.

The accident progression after 100 min is divided into the following three time periods:

1. 100 to 174 min--initial core heatup and degradation period.

2. 174 to 224 min--pump transient, initial emergency core cooling system (ECCS) injection, and continued degraded core heatup,

3. 224 to 230 min--core failure and relocation of molten core material into the lower plenum region.

Figure 1 shows the measured reactor system pressure and provides a timeline perspective of the accident during the first 4 h. Important mechanisms controlling the core damage progression during each of these time periods are discussed with emphasis on the impact of the recent core inspection data.

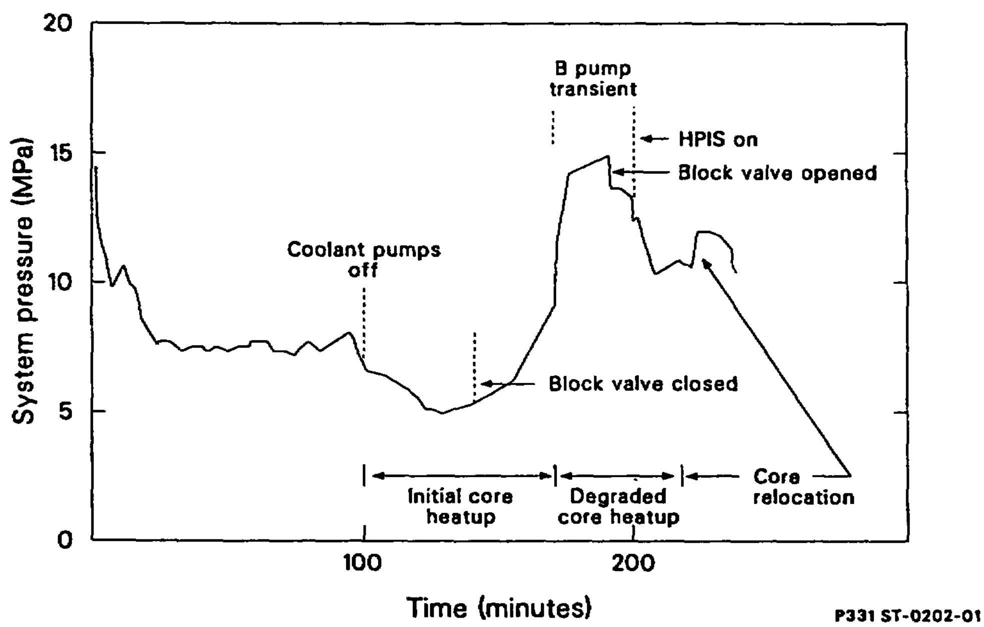

Figure 1. Measured reactor system pressure during the first 4 h hours of the TMI-2 accident, showing the major core damage progression time periods discussed in the paper.

INITIAL CORE HEATUP AND DEGRADATION (100 TO 174 MIN)

The important data sources relative to the initial core heatup and degradation include the following:

1. Hot leg superheat measured at 110 to 113 min indicates that core uncovery occurred before this time; the response of the ex-core source range monitor also suggests core uncovery as early as 110 min.

2. Measured increases in containment radiation levels starting at approximately 140 min indicates that a significant number of fuel rod failures (clad bursting) had occurred by this time.

3. Rapidly increasing primary system pressure after 150 min indicates that (a) a significant amount of hydrogen was present by this time and was degrading heat transfer to the steam generators, and/or (b) relocation of molten core material to the lower core regions was increasing the steam generation rate.

4. Anomalous self-powered neutron detector (SPND) behavior starting at 150 min suggests that rapid core oxidation was occurring by this time.

5. In-core instrument alarm data suggest no abnormal core behavior at core elevations lower than approximately 30 in.

Core heatup predictions[7] during this period are useful in interpreting the above data. Figure 2 presents the calculated mid-core temperature

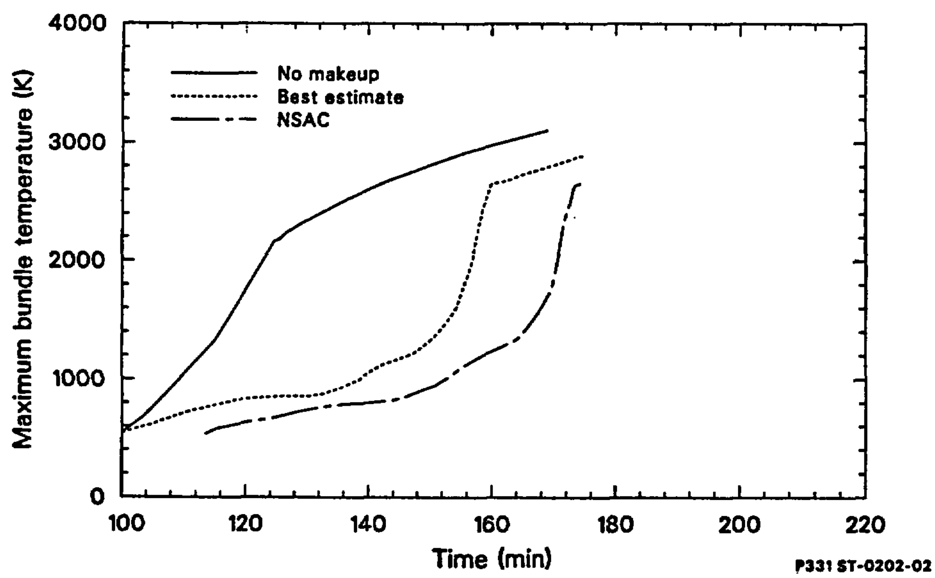

Figure 2. SCDAP predicted mid-core temperatures during initial core heatup period (100-174 min) for assumed lower and upper bounds and best-estimate cases of core liquid level.

responses for assumed bounding and best-estimate cases of core liquid level. The lower-bound core heatup case assumes the core liquid levels from early NSAC analyses.[8] The upper-bound core heatup case assumes no coolant addition to the reactor vessel after 100 min. The best-estimate case uses the NSAC-predicted core liquid levels shifted in time by about 10 min, resulting in earlier core uncovery and calculated core temperatures more consistent with the above data sources.

The best-estimate core heatup calculations suggest that by 150 min the predicted core temperatures have increased sufficiently to result in rapid cladding oxidation and melting. The molten zircaloy cladding dissolves some fuel, and the U-Zr mixture flows downward and solidifies in the lower, cooler regions of the core near the coolant interface. The relocated core material fills the coolant channels surrounding the fuel rods and forms a crust, as shown in Figure 3. From 150 to 174 min, the core temperatures are predicted to increase further from oxidation and decay heat. By 174 min (just prior to the pump transient), core temperatures near the core midplane may have exceeded 2400 K, sufficient to melt the U-Zr-O ternary material. The estimated extent of core material relocation at 174 min is shown in Figure 4; the relocated core material likely formed a region from 1 to 2 m in height extending radially outward as far as 1 to 1.5 m. The damage to the upper fuel assembly grid may have occurred by this time, caused by hot gas exiting the core during the initial core rapid oxidation; the damage to the grid structure was highly localized, as shown in Figure 5.

The end-state core configuration based on the core bore inspection data indicates that the bottom crust of relocated core materials is funnel shaped with the lowest point at about 0.5 m. Intact rods below 0.5 m suggest that the coolant level was maintained near this elevation. Coolant injection into the reactor vessel at 174 min suggests that the minimum coolant level likely occurred just prior to 174 min.

DEGRADED CORE HEATUP (174 TO 224 MIN)

The first significant coolant addition to the reactor vessel occurred at 174 min when the 2B coolant pump was turned on. The coolant delivery to the reactor vessel rapidly pressurized the reactor system (Figure 1). The resulting thermal/mechanical forces would fragment the highly oxidized fuel rod remnants in the upper core region, thus forming a rubble bed on top of the relocated core materials in the center region of the core. This configuration is shown in Figure 6.

Original estimates suggest that as much as 1000 ft^3 of water may have been injected into the reactor vessel. However, extensive core flow blockage would have limited the flow and cooling within the central regions of the degraded core.

Coolant addition at the time of the pump transient was substantiated by both the in-core thermocouple alarm data and the source range monitor

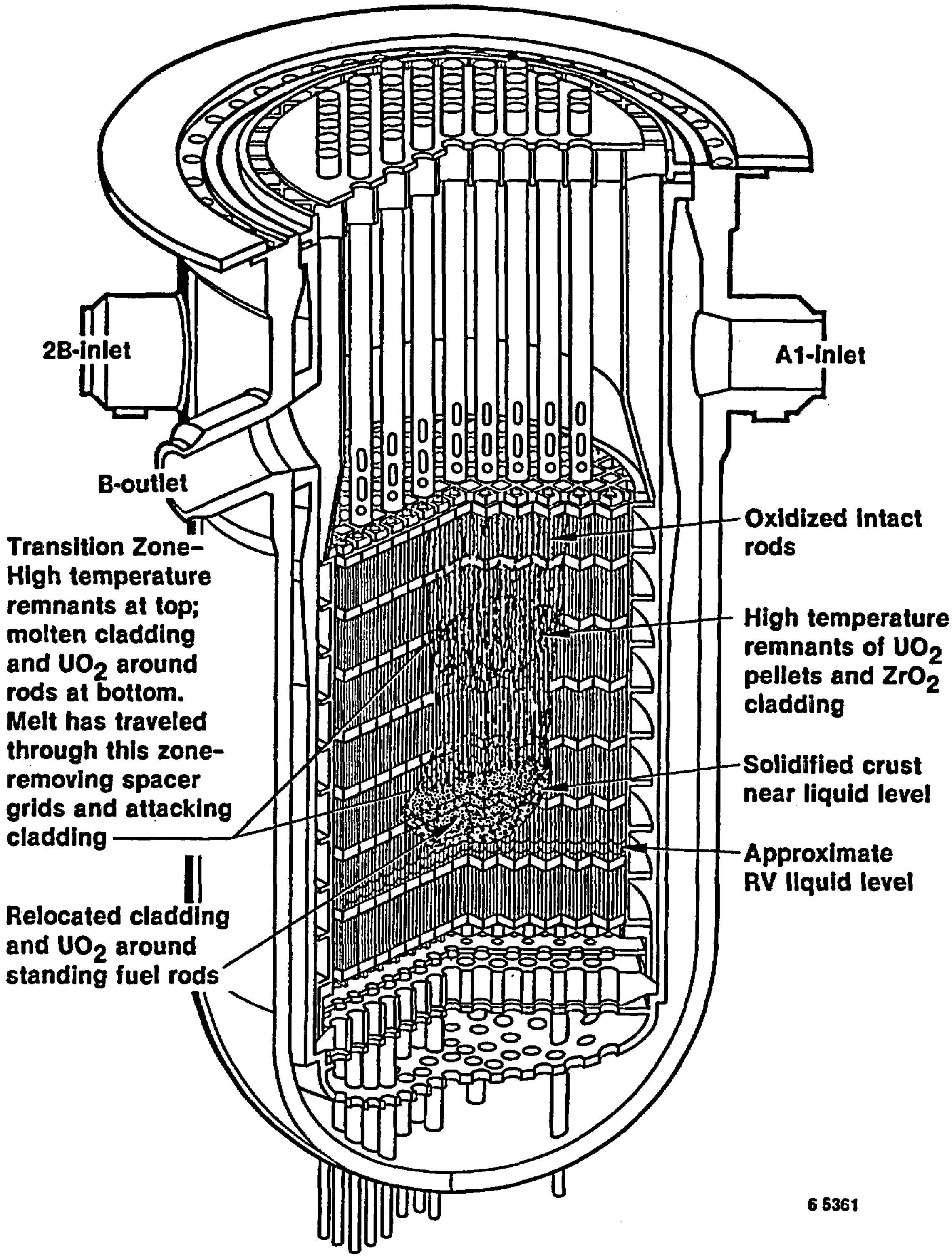

Figure 3. Estimated core configuration at 150 min showing the initial relocation of core materials.

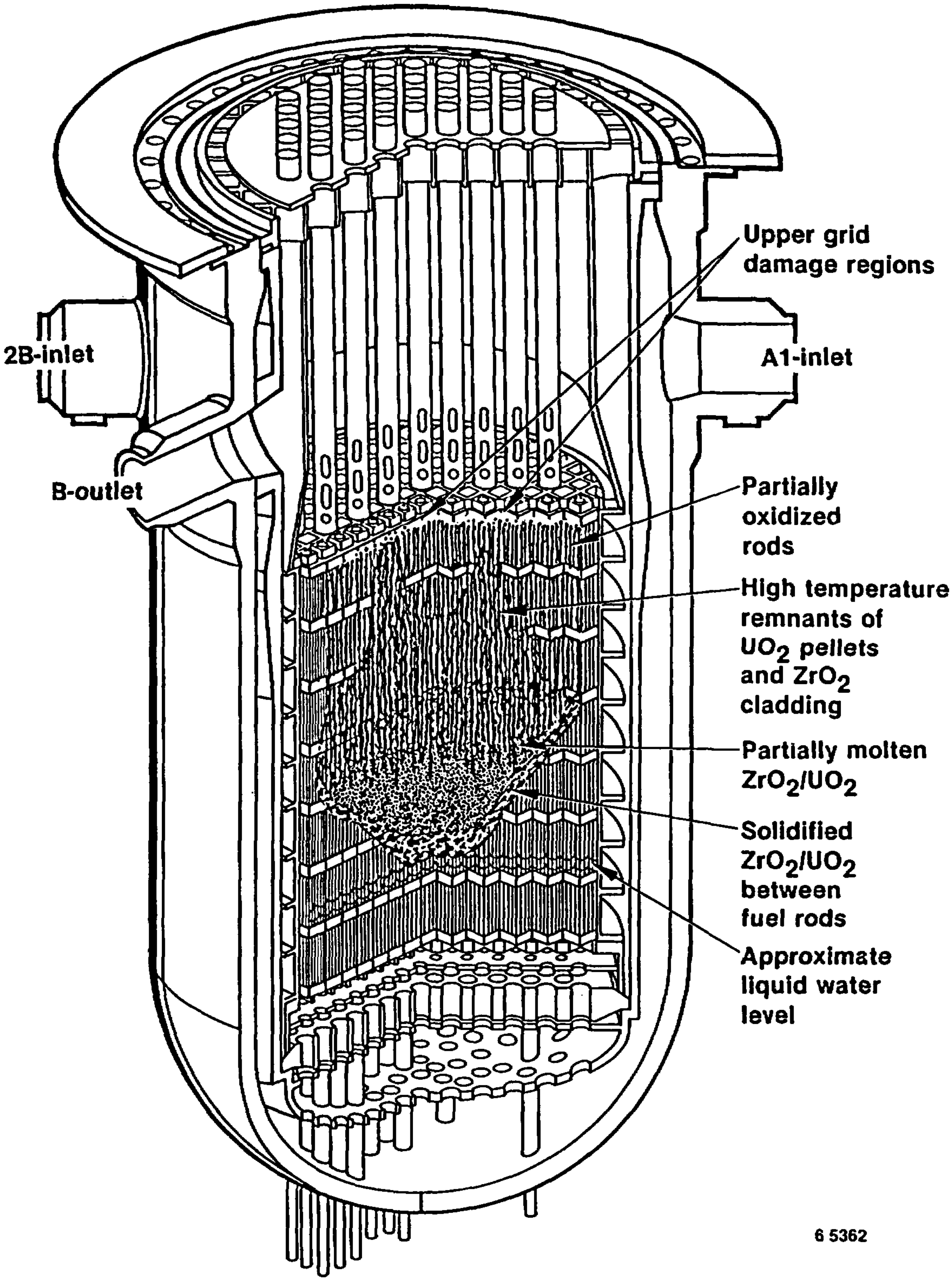

Figure 4. Estimated core configuration at 174 min, just prior to the pump transient, showing extensive core material relocation.

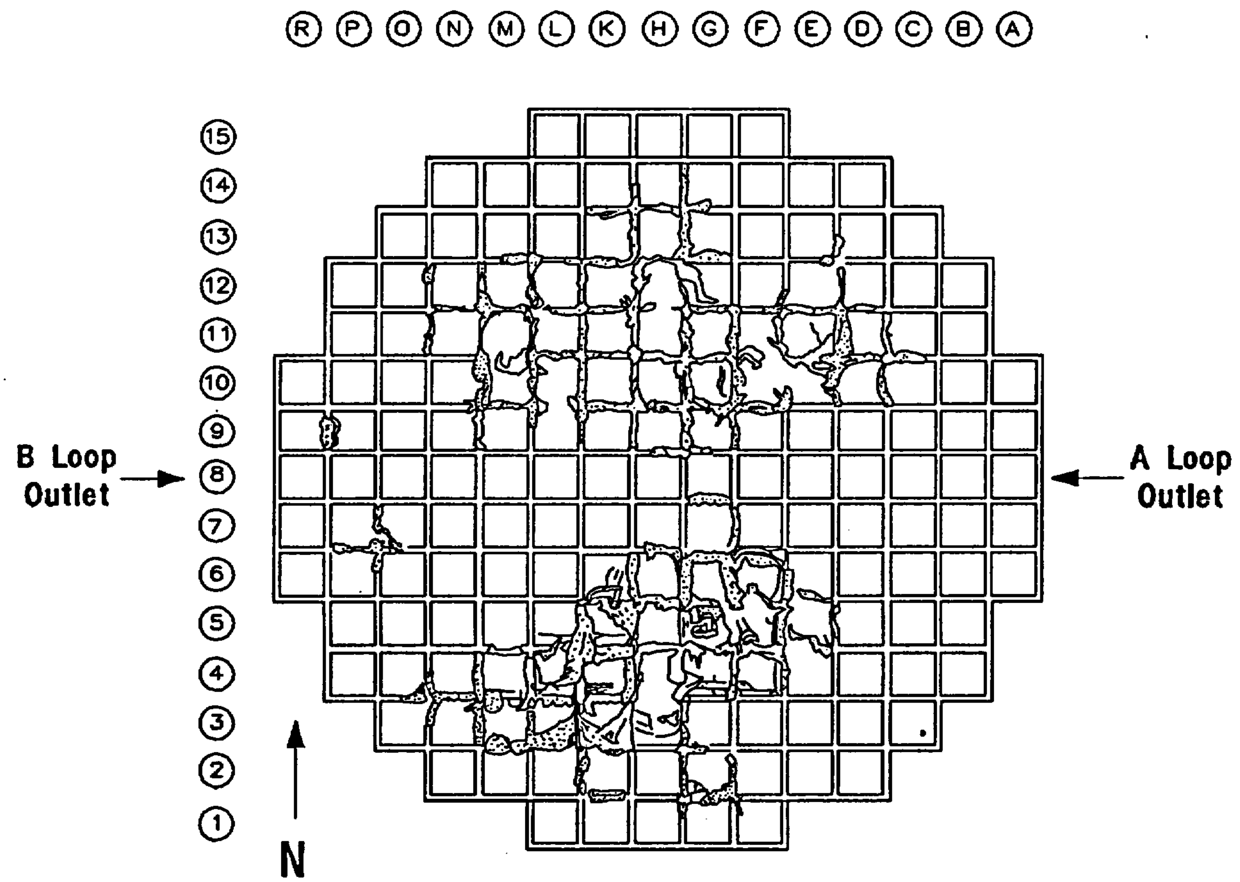

Figure 5. Damage zones to the lower surface of the upper fuel assembly grid structure.

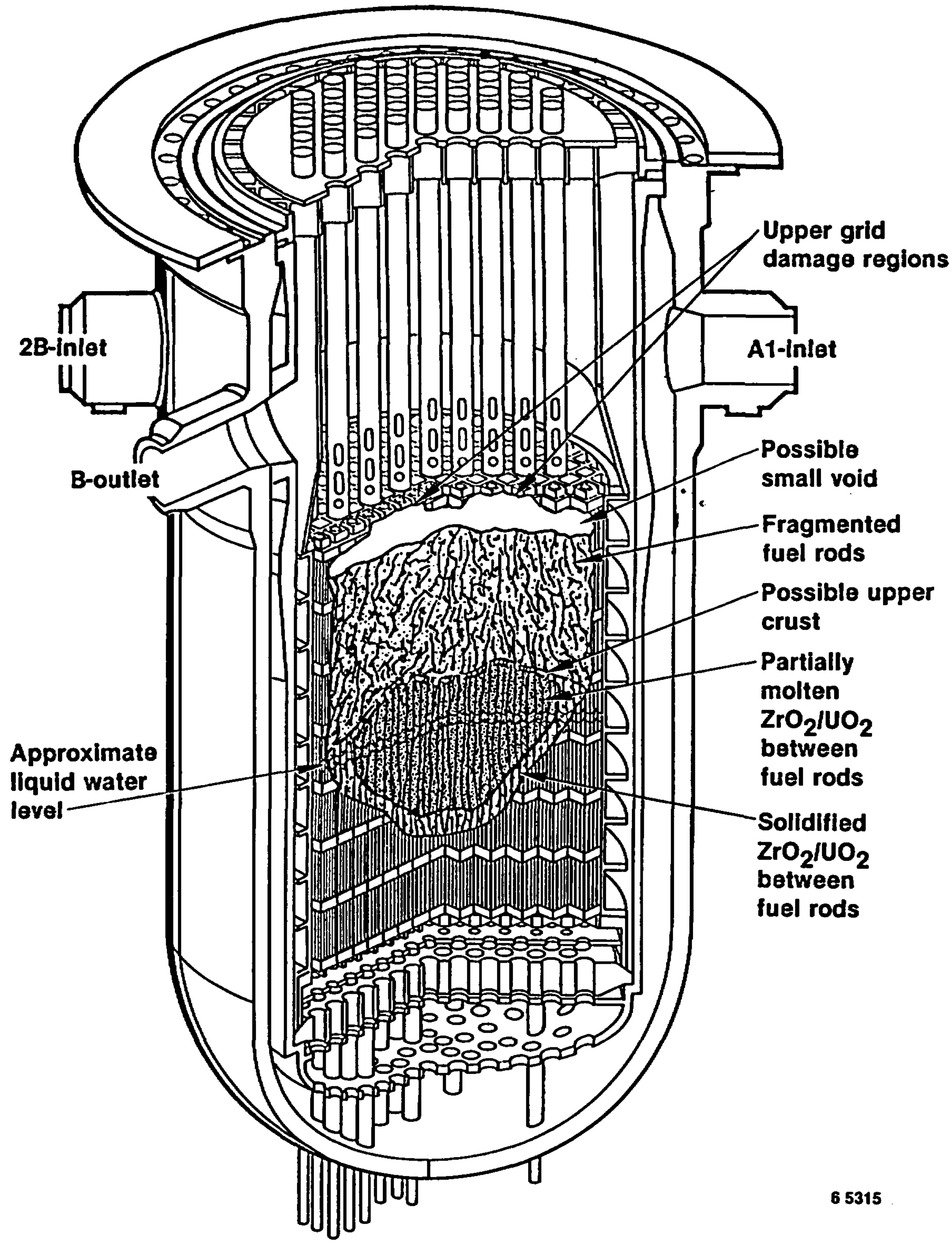

Figure 6. Estimated core configuration at 175 to 180 min showing the upper rods fragmented, forming a debris bed.

response. Those core thermocouples that were cooled as a result of the pump transient are shown in Figure 7. Note that only those thermocouples generally on the periphery of the degraded core were cooled. These data suggest that formation of the degraded core and lower core crust occurred prior to 174 min, as depicted in Figures 3 through 5. Subsequent alarm data show that all thermocouples cooled by the pump transient again alarmed off-scale (heated up) prior to emergency core coolant injection at 200 min, indicating concurrent reduction in the reactor vessel liquid level during the 174- to 200-min time period.

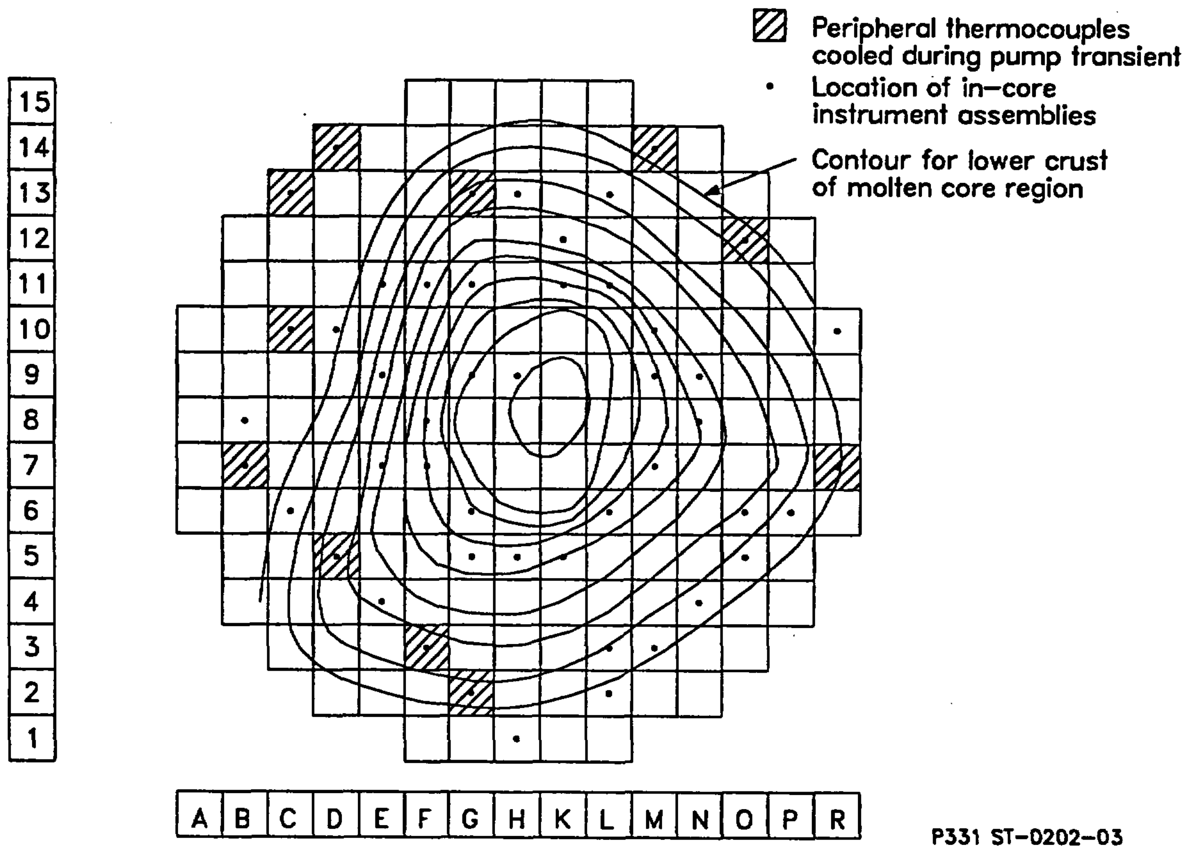

Figure 7. Overlay of the in-core thermocouple positions that were cooled by the pump transient and the end-state contour of the lower molten zone crust.

At 200 min, the high-pressure injection system was turned on. The coolant injection is somewhat uncertain; however, the best estimate of the injection rate and the water injected by the pump transient, if directed entirely into the reactor vessel, would have resulted in a covered core sometime between 200 and 220 min. Cooling of the upper debris bed may have been a long-term process, with water gradually penetrating the interior of the debris bed from the core periphery. The resultant steam and hydrogen would rapidly flow from the core into the upper plenum and may have also contributed to the observed damage to the underside of the upper fuel assembly grid. The debris bed cooling process may have mixed the debris bed and resulted in some molten ceramic material from the top of the molten core zone being mixed into the upper debris bed. Examination of the upper core debris particles indicate some molten material on selected particles.

The source range monitor response is also consistent with coolant addition and subsequent boiloff, although the relative effects of coolant level and core reconfiguration tend to confound estimates of the liquid levels. Neutronic analyses are currently underway to study the relative effect of core configuration versus liquid level.

Calculations[9] to estimate the thermal response of the degraded TMI-2 core configuration generally represented in Figures 4 and 5 indicate that the central core regions will continue to heat up independently of any cooling at the surface of the degraded core region, as shown in Figure 8.

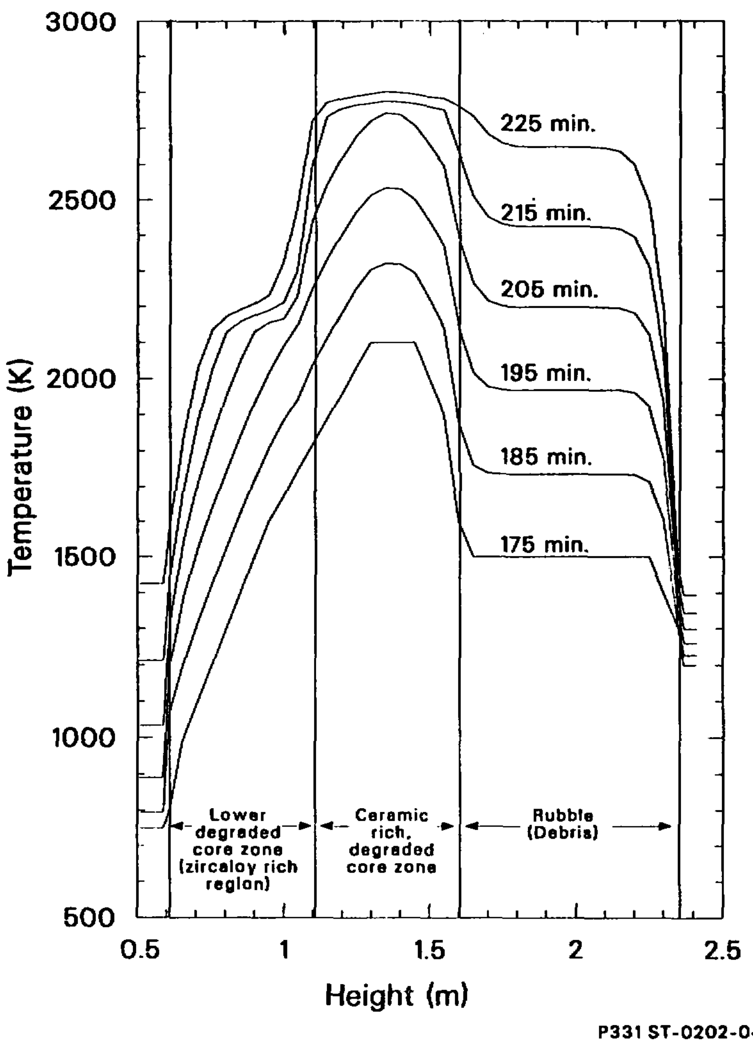

Figure 8. Estimated degraded core thermal response from 175 to 225 min.

Notice that during the 174- to 224-min time period the center regions of the degraded core material are predicted to reach temperatures above 2500 K.

Thus, the estimated core configuration just prior to the core failure and migration of core material to the lower plenum at 224 min is shown in Figure 9. The central regions of the degraded core are predicted to be molten. Cooling of the lower crust was maintained by water in the reactor vessel. However, the configuration and cooling of the upper crusts are much less understood due to (a) uncertainty in the growth rate of the molten zone, which is predominantly in the upward direction due to the convective heat transfer, and (b) uncertainty in the coolability of the upper debris bed.

CORE FAILURE AND RELOCATION (224 TO 240 MIN)

At approximately 224 min, a global change in the core condition occurred as indicated by the in-core SPND and thermocouple alarm data, the measured reactor system pressure and temperatures, and the source range monitors. The source range monitors, which directly measure changes in core configuration, increased significantly in less than 1 min and then decayed normally, suggesting that the major relocation occurred in less than 1 min. The measured cold leg temperatures also increased rapidly (less than 10 s). The in-core SPNDs located in the bottom 30 in. of the core alarmed off-scale for the first time during the accident. For many of the in-core instrument assemblies (particularly near the core center), off-scale alarms were recorded at all SPND axial elevations.

The core bore inspection data summarized in the previous paper provides information for estimating the location of core failure and the flow path of molten material to the lower plenum. The end-state core configuration cross sections as described in the previous paper suggest that failure of the core support crusts likely occurred, at least initially, in the southeast quadrant of the core. Figure 10 shows the core cross sections through the Row 6 fuel assemblies. At the core periphery in fuel assemblies O, P and R, the upper crust of the molten core zone is below the projected bottom crust (based on the core bore contour data). This apparent discrepancy was also observed in the core cross section through the P row of fuel assemblies and can be explained by localized failure of the core crusts in these regions.

The core bore inspection data also showed that significant molten material in the core support assembly regions was limited to only the east quadrant of the reactor vessel, consistent with the inferred core failure locations shown in Figure 10.

Another key observation consistent with localized core failure in the east/southeast quadrant is the relative timing of the SPND alarms. At 224 min, close examination of the in-core instrument alarm data shows that those SPNDs in the east quadrant alarmed first, followed by SPNDs located near the core center.

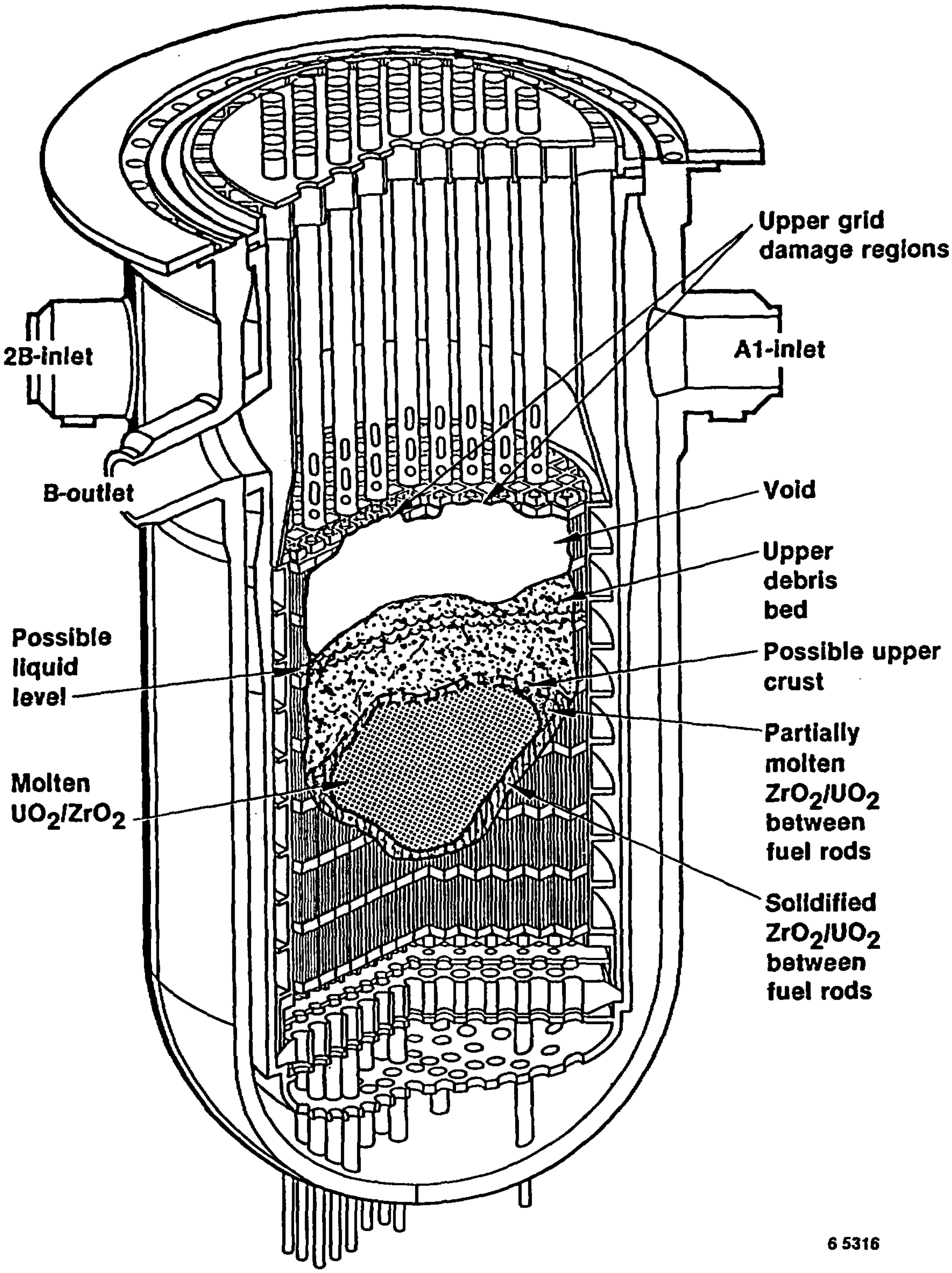

Figure 9. Estimated core configuration just before core failure and relocation at 224 min.

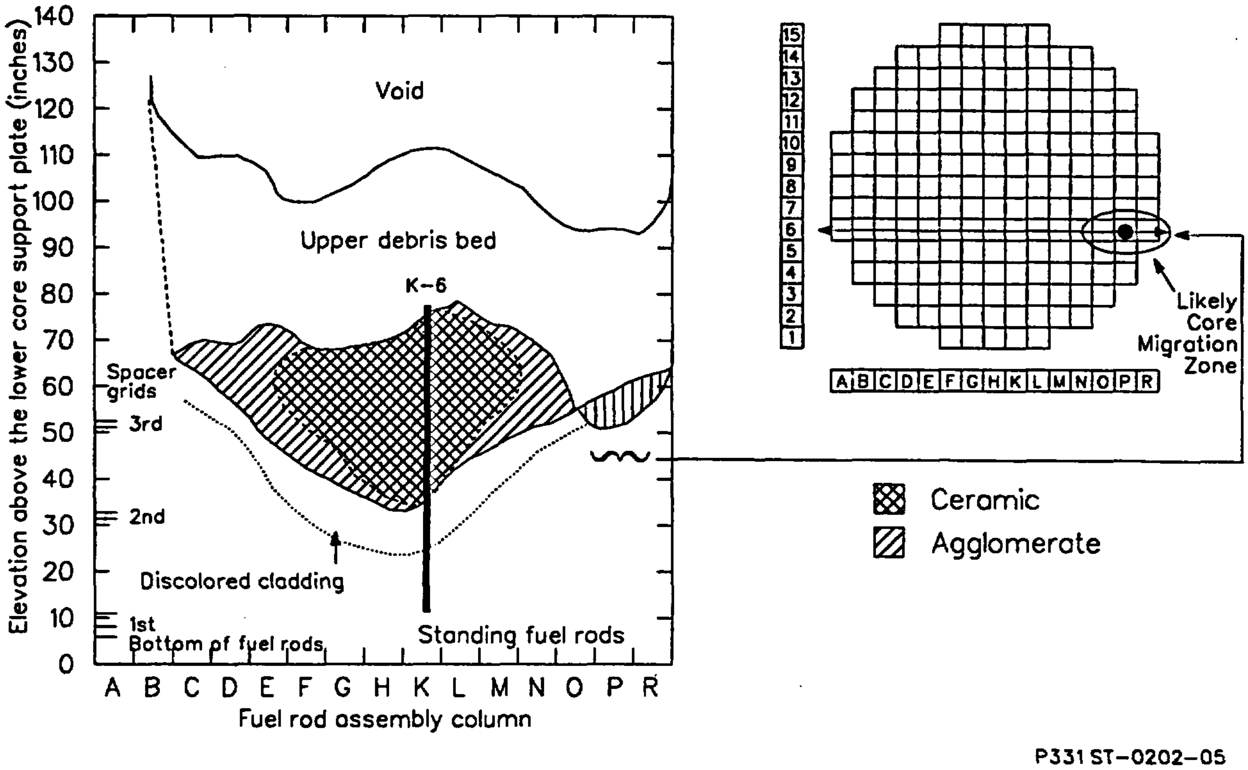

Figure 10. End-state core cross section (through the Row 6 fuel assemblies) showing inconsistency in the upper and lower surfaces of the molten core zone (failure location) near the core periphery in the east quadrant.

Thus, at 224 min, failure of the supporting core crusts occurred, followed by a rapid fuel migration into the lower plenum region as depicted in Figure 11. Several core failure mechanisms have been hypothesized. These include (a) melting of the upper crust as the degraded core materials continue to heatup, (b) mechanical stress on the crust due to pressure differences between the molten interior and exterior of the degraded core region, and (c) possible interactions between the degraded core materials and the core former wall at the core periphery. Further core characterization and supporting analysis work will be required to converge on a best-estimate core failure mechanism. This work will be essential to complete our understanding of the extent of damage to the CSA and lower vessel head and instrument tube penetrations.

SUMMARY AND CONCLUSIONS

The TMI-2 Accident Evaluation Program is providing a more complete understanding of the core damage progression through characterization of the degraded reactor core and supporting analysis to interpret the data. Important conclusions from this work include:

1. The accident scenario provides a generally consistent interpretation of the TMI-2 end-state characterization data and on-line measurements.

2. The core failure location appears to be at the periphery of the molten zone, near the top. More examination of the core failure region and supporting analysis work will be required to more clearly identify the most likely core failure mechanism.

3. The bottom core crust was stable as a result of water in the reactor vessel.

More work will be necessary to characterize and evaluate the damage to the lower core and CSA migration pathways and the damage to the lower vessel head and instrument tube penetrations. Improvements to the accident scenario will be made as the core is defueled and examinations completed on the core, CSA, and lower plenum debris samples.

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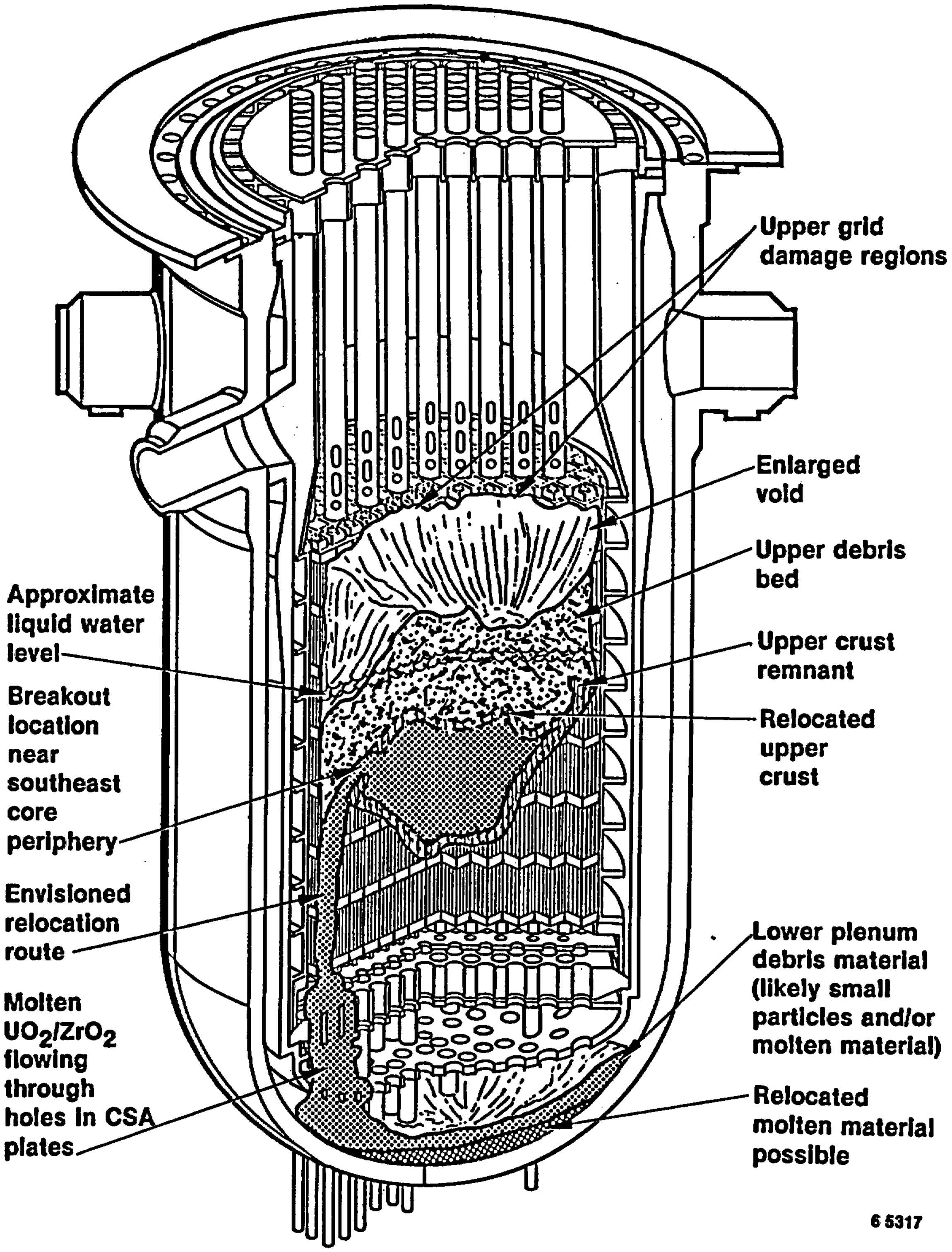

Figure 11. Estimated core configuration at time of core failure (224 min) showing the failure location and migration path to the lower plenum.

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