8. DEBRIS RELOCATION SCENARIO

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8.1 Introduction

This section presents one possible scenario describing the relocation of debris to the lower head of the reactor vessel and is based on available plant instrumentation records and post-accident examination results. The scenario presented here is not the only potential debris relocation scenario, but is consistent with information obtained from plant data, VIP examinations, analysis efforts, and other TMI-2 programs.

This scenario addresses debris relocation events chronologically and assesses factors that may have contributed to the end-state condition of the lower head, the damage to the structures in the lower part of the reactor vessel, and the debris on the lower head. Included is the initial movement of molten material from the core, through the reactor vessel core support assembly to the lower internals, and finally onto the lower head. A general description of the accident scenario is presented in Section 2.

8.2 Initial Events

The initial event that affected the relocation scenario was the melting of control and fuel rods that occurred between 100 and 174 minutes when the upper half of the core was uncovered.[1] During this period, both fuel and control rod cladding melted and drained down through the uncovered core leaving intact fuel pellet stacks and rubble. The cladding material flowed down through the core to form a metallic crust 10 to 15 cm thick at the lower core region.[2] This lower bound was at the water level that was near the lowest grid spacer and about 20 cm from the bottom end of the fuel rods. This was the lowest water level during the entire accident and was about 2 m above the lower head.

At 174 minutes, the 2B coolant pump was activated for 19 minutes. However, significant flow through the core only lasted for about 15 seconds before the reactor coolant system repressurized. This repressurization was due to zircaloy oxidation and steam formation in the upper core debris bed caused by injection of relatively cool water by the 2B pump. Jets of steam from this event caused damage to the southern and northern portions of the upper fuel assembly grid and transported debris to the top of the upper plenum,[3,4] onto leadscrew surfaces,[5,6] and onto several other horizontal surfaces in the reactor vessel.[7] Examinations of the upper core debris indicated that the control rod materials (Ag-In-Cd) were concentrated in particles smaller than 1 mm and would thus be susceptible to transport as a hydrosol.

As discussed in Reference 6, the overall upper core debris region was composed of about 27,000 kg of material. Between 3 and 10% of this debris was less than 1 mm in diameter. Since particles less than 1 mm may be transportable as a hydrosol, quantities of loose debris from both control and fuel rods either settled directly in the lower part of reactor vessel during quiescent periods or were transported through the reactor coolant loop by the 2B pump transient and settled in areas such as the lower head where there was relatively low flow. Therefore, finding intergranular Ag-In-Cd in the surfaces of several nozzles and in the vessel cladding cracks should not be unexpected. Unfortunately, the amount of such material and the depth of the deposition layer on the lower head cannot be definitely determined.

8.3 Relocation to the Lower Head

Between 224 and 226 minutes, several almost simultaneous events indicated that a major change in core configuration occurred and that molten material relocated to the lower head in one continuous flow. The count rate of the neutron source-range monitor located on the outside of the reactor vessel increased sharply. Also, the simultaneous alarm of incore self-powered neutron detectors (SPNDs) at all levels on the same instrument stalk suggested that a common point of damage occurred. The molten material in the lower head heated the instrument nozzles sufficiently to produce thermoelectric currents in the SPNDs, which caused the instruments to alarm. Examination of the alarm data[8] indicated that the first alarms were for SPND stalks that were in instrument tubes on the east side of the lower vessel and then propagated to the center. Post-accident measurements of incore thermocouple loop resistance, as discussed in Reference 8, indicated that new thermocouple junctions were formed in the lower head as the leads were melted by high temperatures caused by the relocated fuel. The new junctions also resulted in alarms of several of the incore thermocouples. The alarms followed a sequence similar to the SPNDs. A primary system pressure pulse (2 MPa) also occurred during this time period. These data are indicative of the time when the relocation occurred and indicate that it initiated in the eastern part of the core and lower head.

8.3.1 Movement of Molten Material Through The Vessel

Post-accident examinations of the eastern half of the core region and lower vessel internals confirmed plant instrumentation data and showed that relocation of the fuel debris to the lower head occurred in the eastern half of the vessel. Overall, approximately 19 metric tonnes of material reached the lower head. As discussed in Section 5, the relocated material was primarily a $(U,Zr)O_2$ ceramic. Visual examinations of this part of the vessel during defueling indicated that the primary path through the vessel was through a hole melted in the R6 vertical core former wall and then downward through the horizontal baffle plates. Figure 8-1 shows a cross section of the reactor vessel internal structure. Fuel melt was found in the P-5 and R-6 assemblies near the bottom of the fuel assemblies, which indicated that some liquified fuel had drained into these assemblies and solidified during the relocation. However, as no flow path was found through these assemblies to the lower head, the principal relocation path was identified as being through the damaged core former at the R-6/P-5 core locations. Three holes in the core former wall were identified. Dimensions of the holes through the former wall ranged from 23 $\times$ 3 cm to 20 $\times$ 7 cm.[9,10] The damage to the core former wall was about 140 cm from the bottom of the core or a little below the midpoint of the reactor core. The damage location is indicated in Figure 8-2.

8.3.2 Movement of Molten Debris Through the Core Support Assembly

At the bottom of the vertical core former plates, the molten material melted back into the lower core support assembly (CSA). Visual observations indicate a massive hole and damage in the bottom on the vertical core former wall located at core grid locations R-6, R-7, P-4, and P-5.

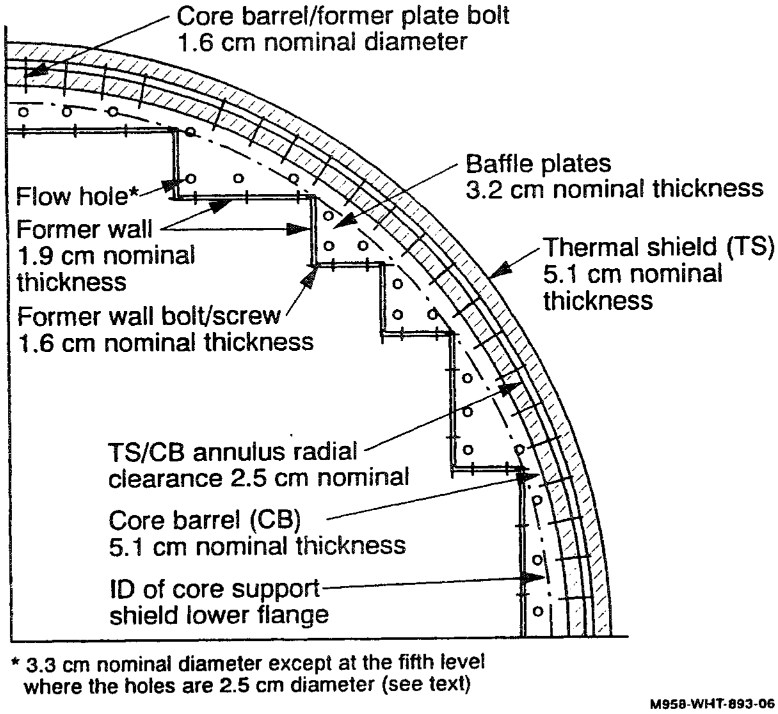

Figure 8-1. Reactor vessel internal structures.

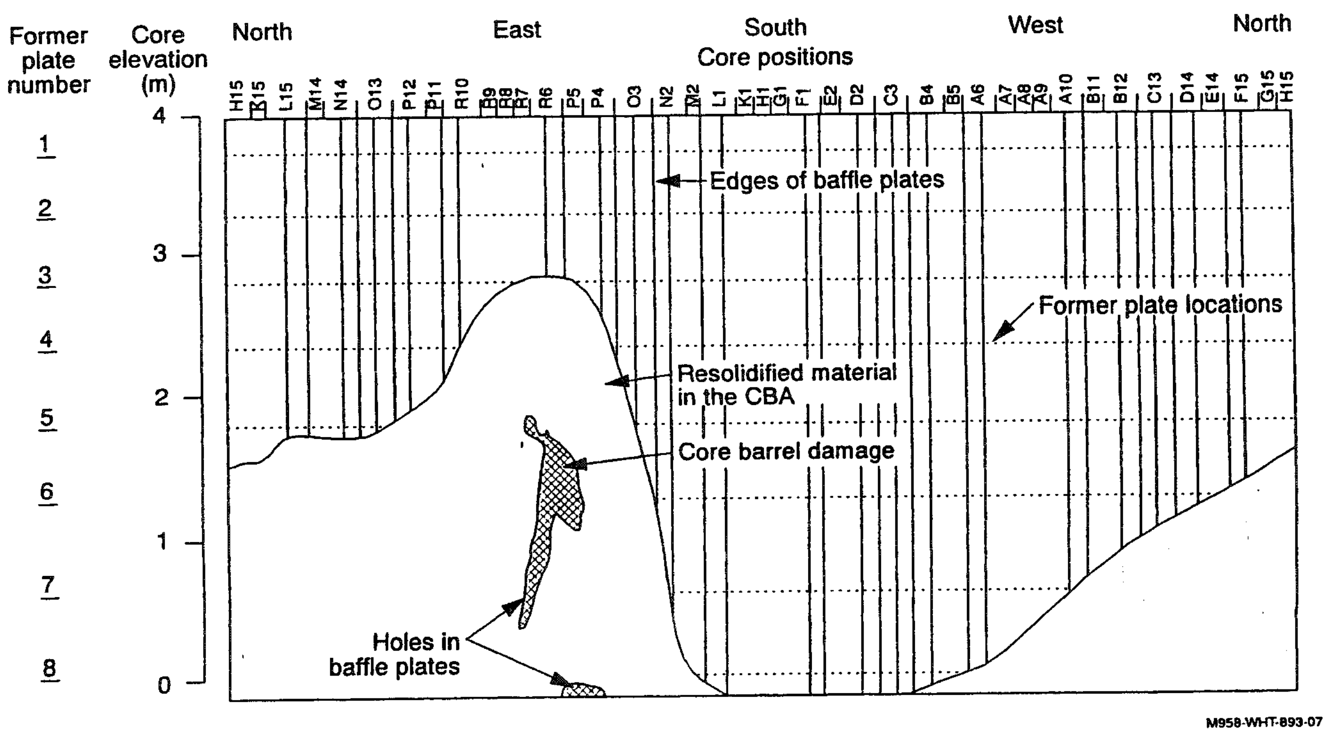

Figure 8-2. Fuel debris profile inside core former (laid flat).

It is very difficult to trace the exact path the molten material took as it moved through the CSA structures. The flow movement scenario presented here is based on evidence derived from the assumption that the presence of flow holes plugged with solidified material indicates that molten material flowed through these holes or adjacent holes during the relocation. It is likely that once a hole was plugged with solidified material, any subsequent material that flowed in that area was diverted by the plug and flowed downward through an adjacent hole.

The CSA geometry consists of a number of plates and forging and as shown in Figure 8-3. Once in the CSA, the majority of the molten material continued to flow down through the structures on the eastern periphery in the R-6/7 and P-4/5 area. However, visual examinations indicated that some of the molten material was found to have flowed around the perimeter of the CSA structures as it penetrated downward towards the lower head. Figure 8-4 shows the location of solidified material at several locations in the flow holes of the lower grid, the area between the lower grid and the flow distributor plate, and between the flow distributor plate and the grid forging. The presence of solidified material is assumed to indicate that molten material flowed through or adjacent to these locations.

8.3.3 Molten Debris Movement on the Elliptical Flow Distributor

Based on the locations of solidified material in the CSA as shown in Figure 8-4, it is postulated that the molten material flowed onto the elliptical flow distributor (EFD) from the same areas where plugged flow holes existed in the CSA. Figure 8-5 indicates the locations in the EFD where solidified material was observed in or above a flow hole.[11,12] As can be seen in the figure, these locations are in general agreement with the locations in Figure 8-4, where solidified material was observed in the CSA. As seen in Figures 8-4 and 8-5, many of the plugged flow holes line up quite well, which indicates that the flow moved vertically downward and covered much of the periphery of the CSA structure as it followed the flow hole alignment pattern onto the EFD. For example, the plugged holes near locations H-15, K-15, and L-15 shown in Figure 8-4 are near plugged locations H-15, K-15, and K-14 shown in Figure 8-5. Also, the plugged holes in location C-14 shown in Figure 8-4 are near the plugged holes in locations D-13 and D-14 shown in Figure 8-5.

The minimal amount of damage on the EFD suggests that the first material that reached the EFD, and subsequently the lower head, was probably relatively cool. The exact temperature depends on both the amount of heat given up by the molten flow before it reached the EFD and the exact composition of the molten flow. As the flow moved downward towards the EFD and eventually the lower head, heat was lost to the melting of core former structures and to water that filled the lower plenum region. If lower-temperature phases were present in the molten material, especially in the initial portion of the flow that would tend to incorporate melted structural material, it would be possible for this material to be mobile at temperatures below the solidus temperature of $(U,Zr)O_2$. Microstructural and microchemical examinations of portions of the loose debris that were removed from the lower head prior to the VIP[13,14] indicate that eutectic structures present in grain boundary phases could have had a solidus temperature that was considerably lower than that of the bulk $(U,Zr)O_2$ material. This low melting point compared to the bulk material suggests that the grain boundaries may have remained liquid after the grains themselves had solidified. This would have allowed portions of the molten relocation flow to remain mobile at temperatures below the bulk $(U,Zr)O_2$ solidus temperature.

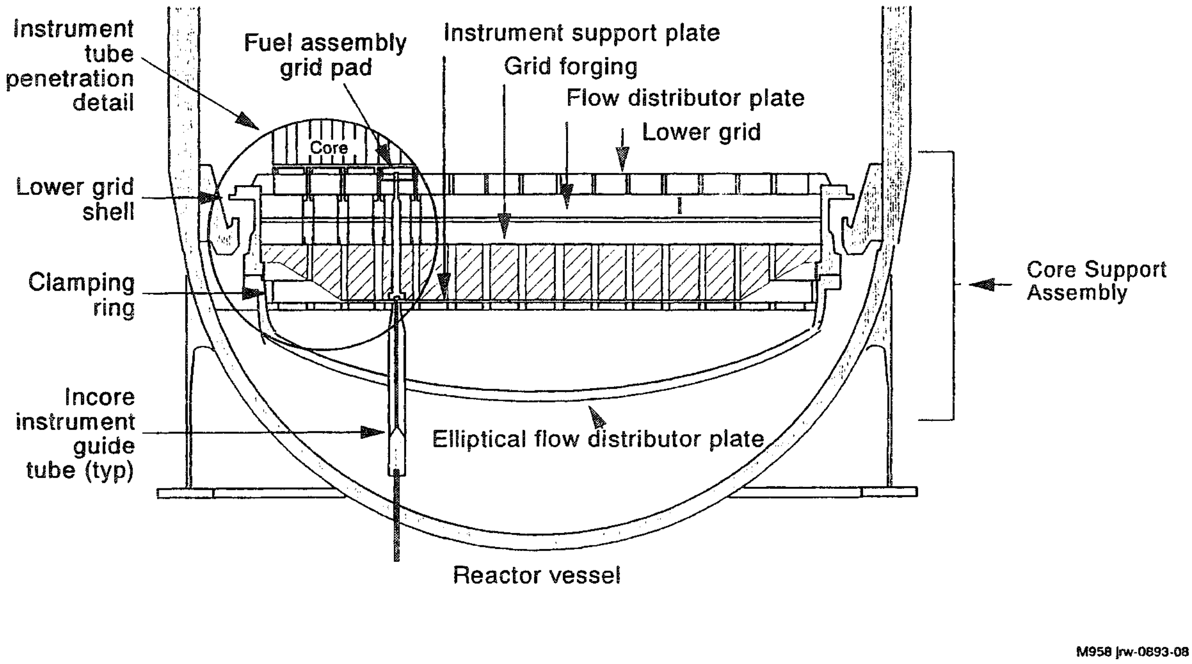

Figure 8-3. TMI-2 core support assembly.

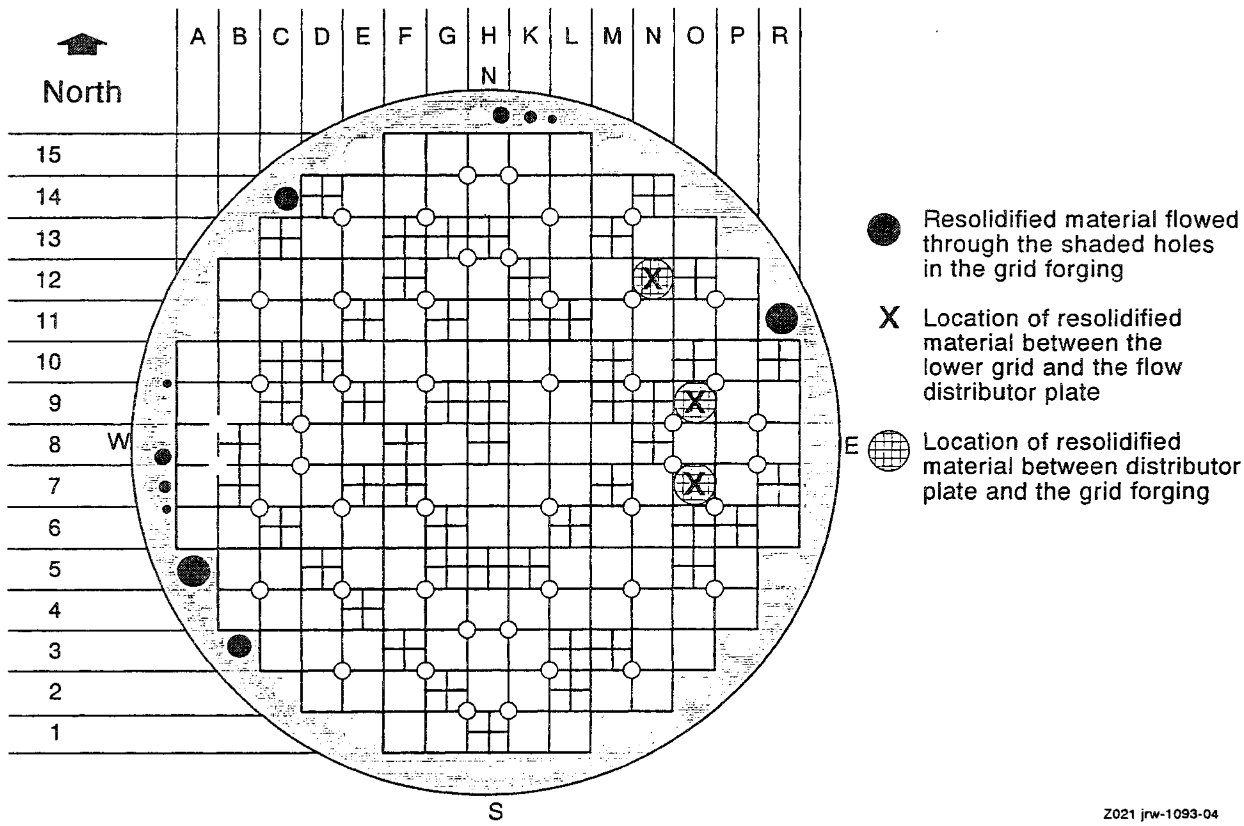

Figure 8-4. Solidified material in core support assembly.

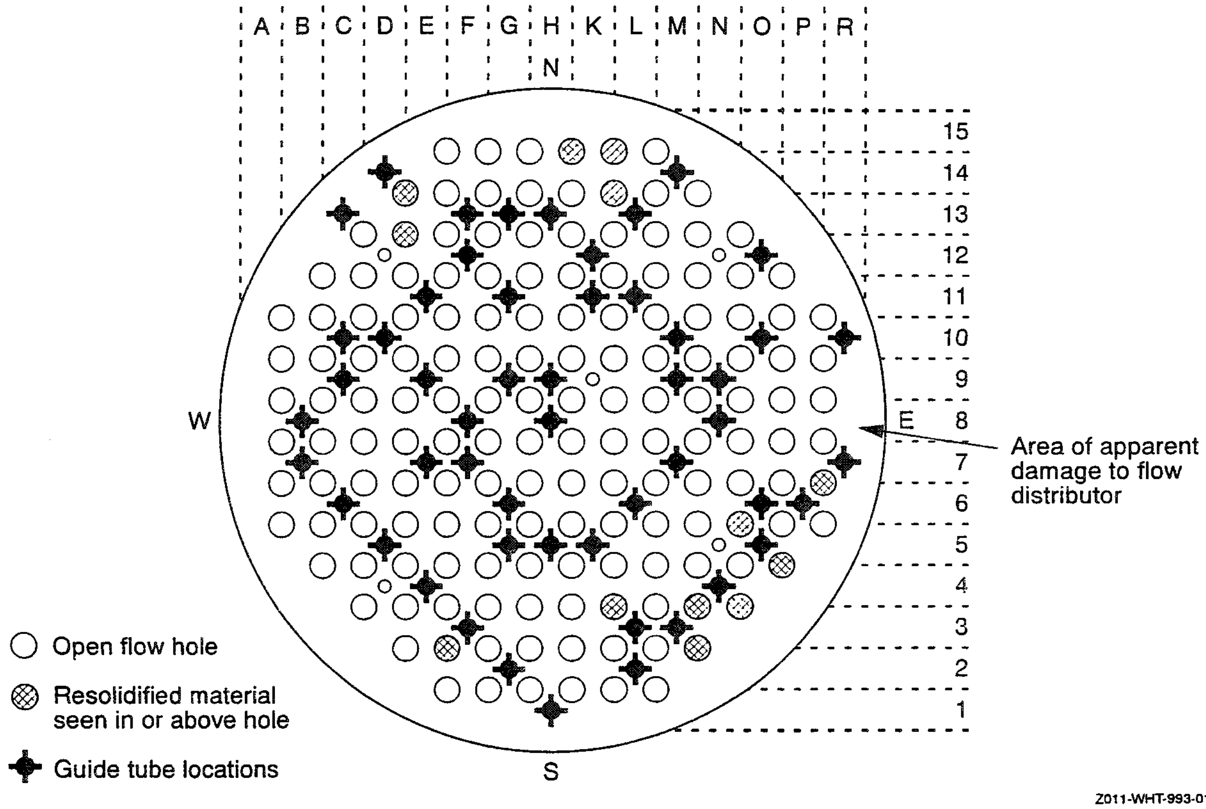

Figure 8-5. Solidified material in the elliptical flow distributor.

Some of the molten material solidified on the EFD and formed plugs in the flow holes at locations shown in Figure 8-5. The subsequent flow of material was probably diverted by the plugged holes and dropped onto the lower head from several different locations around the periphery of the EFD.

8.3.4 Movement of Molten Debris on the Lower Head

One of the most puzzling questions of the VIP program has been why the molten material that relocated to the lower head did not do more damage to the vessel itself and why some nozzles were completely buried in solidified debris but showed absolutely no damage while others were almost totally destroyed. It is postulated that when the initial portion of the continuous relocation flow reached the lower head, the combination of the heat sink provided by the nozzles and the vessel lower head itself, along with insufficient thermal energy in the molten flow, cooled and rapidly froze the initial portion of molten material that reached the lower head. This made it possible for the rapid formation of a thick ceramic crust, regardless of the temperature of the molten material. The rapid buildup of this crust resulted in the formation of an insulating ceramic layer that covered much of the lower head and also formed around many nozzles. Wherever the lower head and nozzles were covered by this insulating debris layer, they were protected from thermal damage.

As the initially cooler material fell onto the lower head from several different locations around the periphery of the EFD, the material effectively formed a cup-shaped basal crust structure that served to insulate the lower head structures in these areas. Then, hotter material flowed downward across the top of this basal crust and caused the nozzle damage pattern described in Section 6. The pattern of nozzle damage indicates that multiple flow paths existed and that the movement of molten material onto and across the lower head was not one massive unified flow.

The pattern of nozzle degradation observed at elevated levels for several nozzles is shown in Figure 8-6 and indicates the extent of the insulating ceramic debris layer that formed in the lower head and protected many of the nozzles and the lower head from extensive thermal damage. As the flow moved on top of the initial insulating debris layer, newly exposed molten fuel came in contact with the nozzles at elevated levels. These nozzles were melted at an elevation that is thought to be representative of the bottom of the molten fuel flow. Since the molten material flowed on top of the initial debris layer, this height is also representative of the thickness of insulating material that protected the lower head and the lower portions of many nozzles. As an example, examinations showed that the nozzle damage at M-9 was at about 25 cm above the lower head, and the damage to H-5 was about 15 cm above the head. Damage to nozzles around the M-9 and H-5 core locations, which have damage at elevations above the base of the nozzles, suggests that the insulating layer was approximately 25 cm thick at the M-9 location and 15 cm thick at H-5.

As the hotter molten material flowed across the top of the insulating ceramic debris layer, the cup-shaped structure that had initially formed on the lower head began to be filled. In the end, this resulted in what is known as the "hard debris layer," which is shown in Figure 8-7.[15] The debris depths shown in this figure were determined from mechanical probing of the hard layer during the defueling operation.

The last material to flow onto the lower head was what is known as the "loose debris layer." The depths of the loose debris layer are shown in Figure 8-8 and were determined before the defueling effort began.[16,17] The depths were determined by probing examinations and by analysis of video tapes taken of the lower head debris. Figures 8-9, 8-10, and 8-11 show cross sections of the hard debris layer thickness at several representative locations. As shown in these figures, there are relatively steep cliff-like areas along the periphery of the debris bed, and both full length and damaged nozzles are embedded in the debris.

8.3.5 Formation of the Hot Spot

In addition to damaging the nozzles on the lower head, the flow of the hotter molten material may have also resulted in the formation of the localized lower head hot spot. It is postulated that as the hotter material flowed down the sides of the cup-like shape that was formed by the initial insulating crust towards the bottom of the vessel, the insulating layer crust became progressively thinner. Eventually, the flow of hotter material reached an area where the basal crust thickness was insufficient to adequately insulate the lower head, and a localized hot spot formed. The location of the hot spot on the lower head is shown in Figure 8-12.

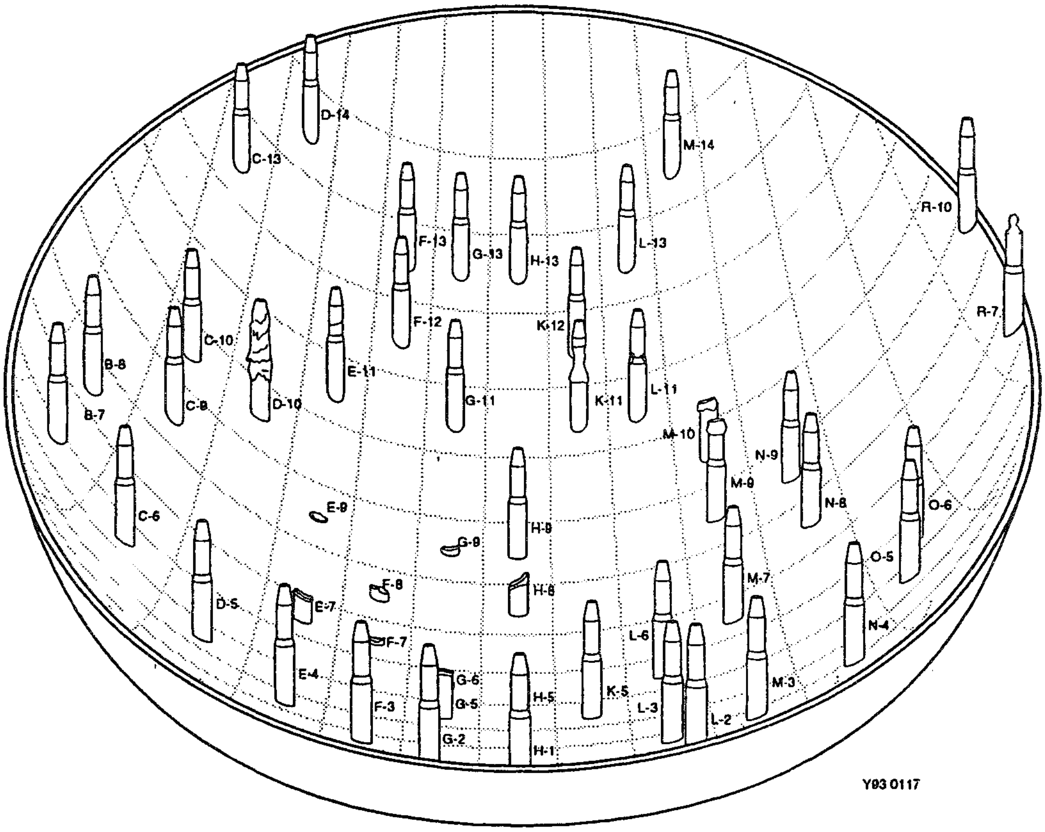

Figure 8-6. Nozzle damage profile.

The hypothesis that the hot spot was occurred beneath a crust that was of insufficient initial thickness to protect the lower head is consistent with the observation that the deepest debris was found in other locations of the vessel rather than over the hot spot. A progressively thinner crust was also indicated by data from the nozzle examinations, which showed that more of the nozzle length was melted in the vicinity of the hot spot. The region where the most severe nozzle damage occurred was consistent with the location of the hot spot and indicated that the insulating layer was thinnest in this area.

8.4 Lower Head Cooling

As was discussed in Section 7, thermal calculations that were based on coolant mass flow entering and exiting the reactor coolant system support the hypothesis that more lower head debris cooling occurred than would be expected, based on data from companion sample examinations. Metallurgical examinations presented in Section 4 indicated that at the hot spot location, the lower head was heated to peak temperatures of about 1,100°C and indicated that the temperature was maintained at that level for approximately 30 minutes before cooling rapidly (50°C/min).[18]

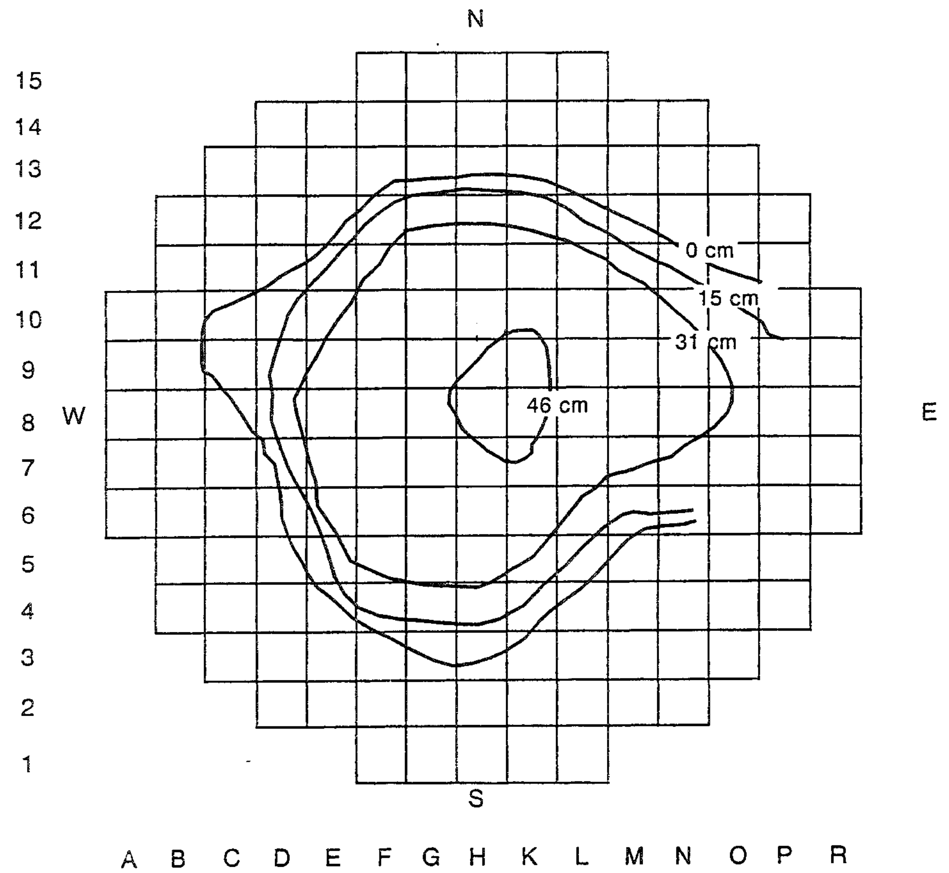

Figure 8-7. Hard layer debris depth. (Contour lines represent incremental increases, with the outside line equal to 0 cm and the inside equal to 46 cm.)

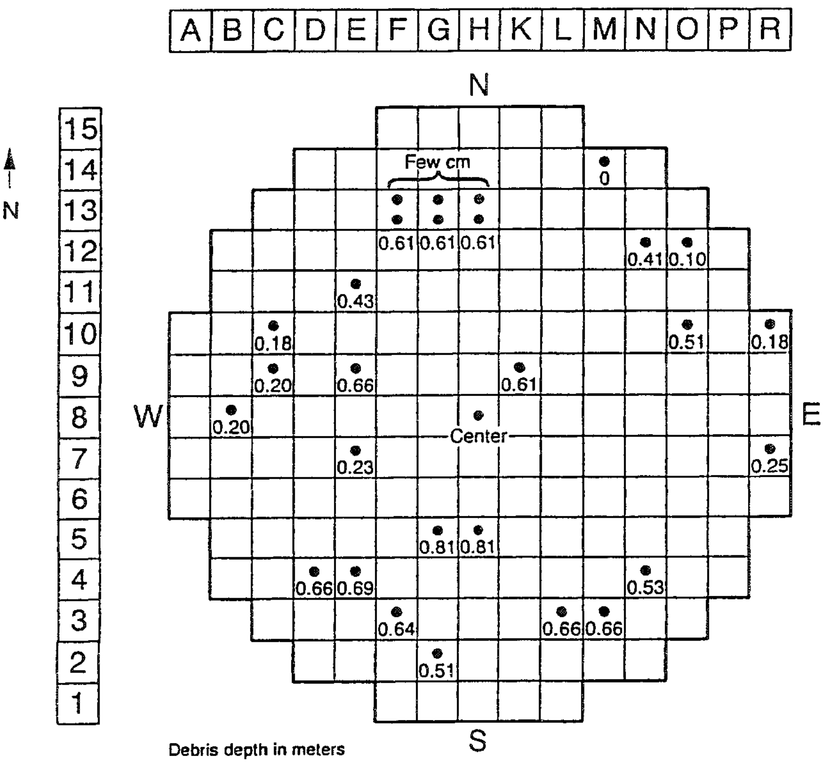

Figure 8-8. End state hard and loose layer debris configuration.

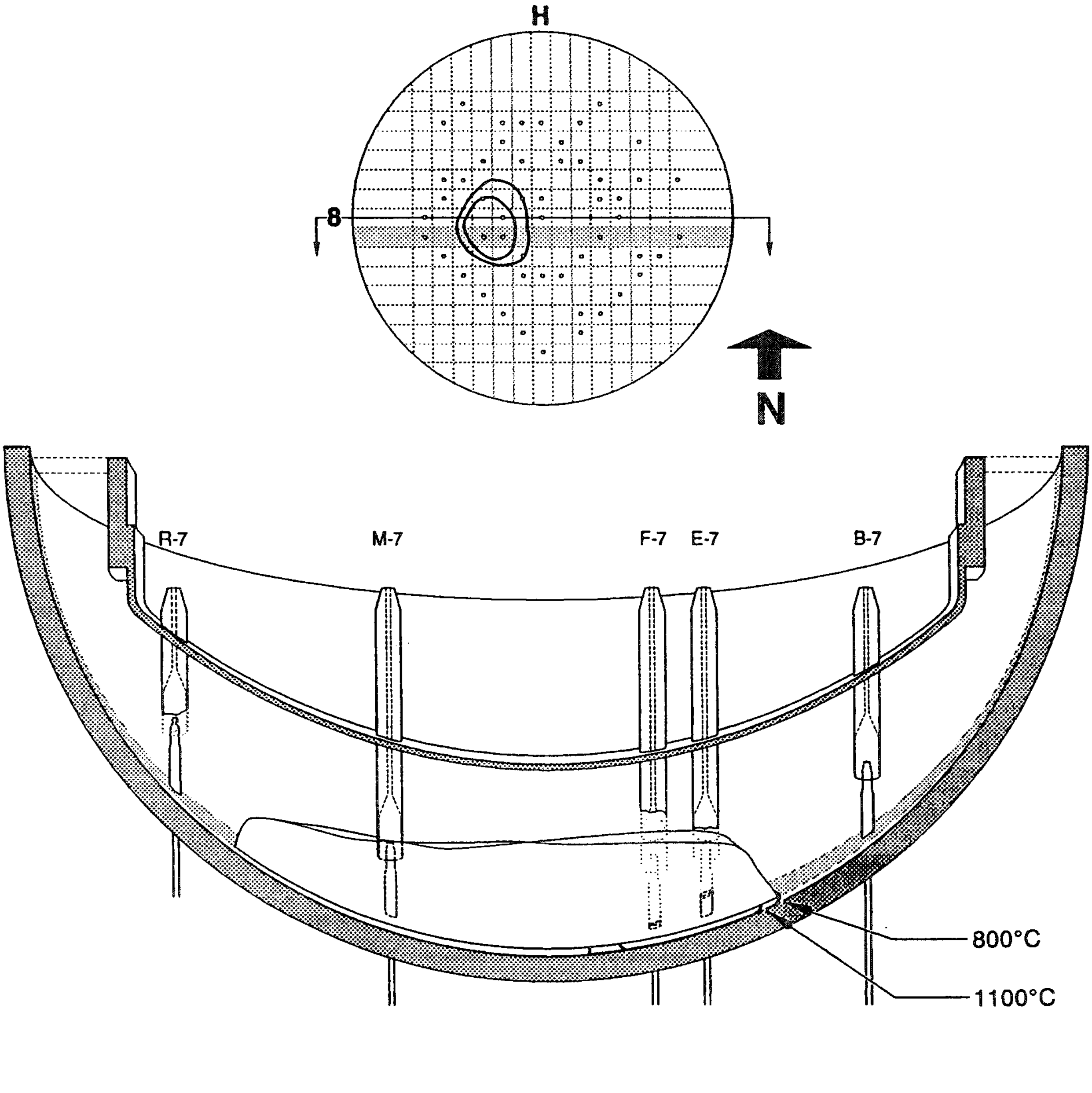

Figure 8-9. TMI-2 lower head cross section of hard debris, row 7.

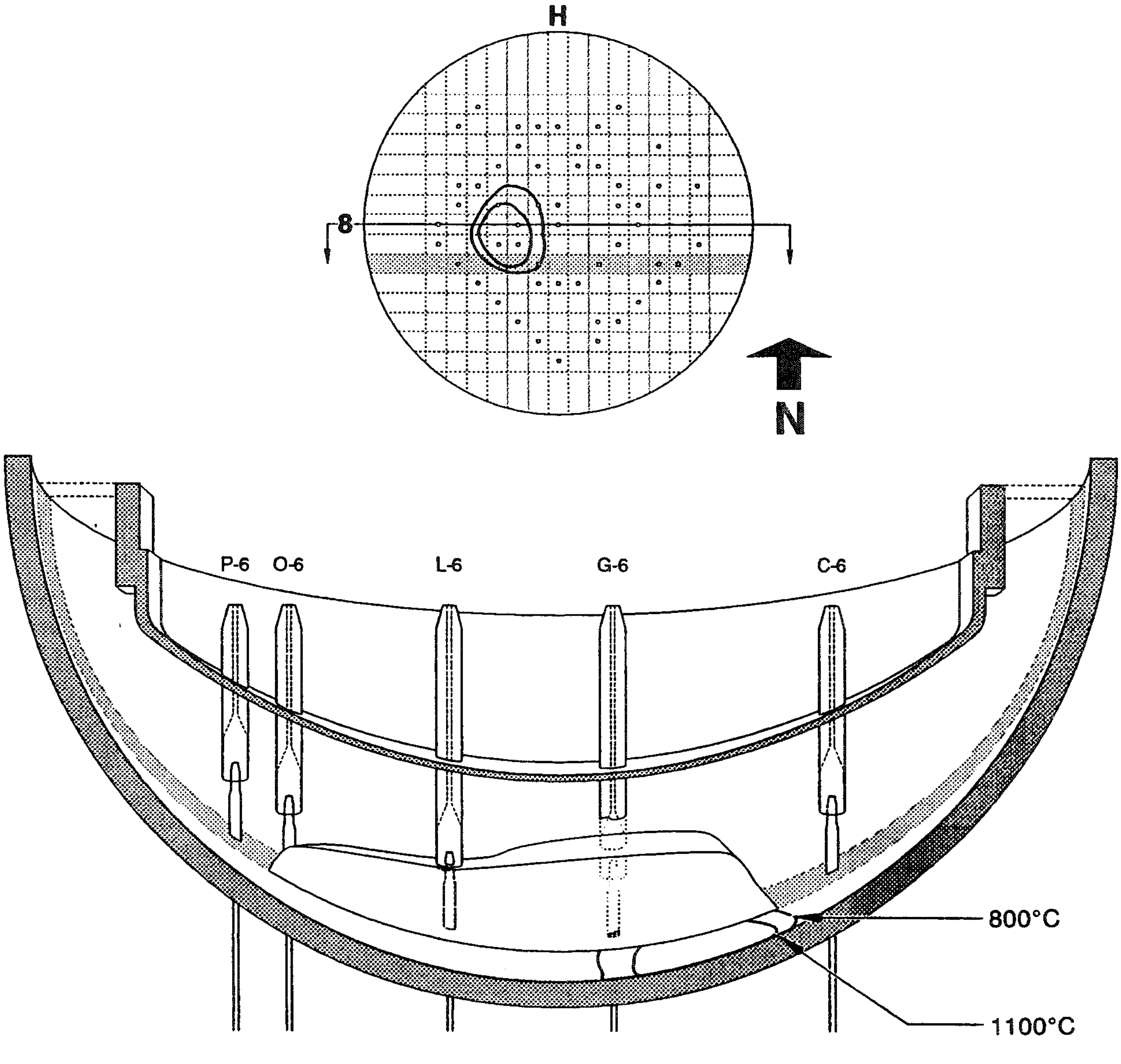

Figure 8-10. TMI-2 lower head cross section of hard debris, row 6.

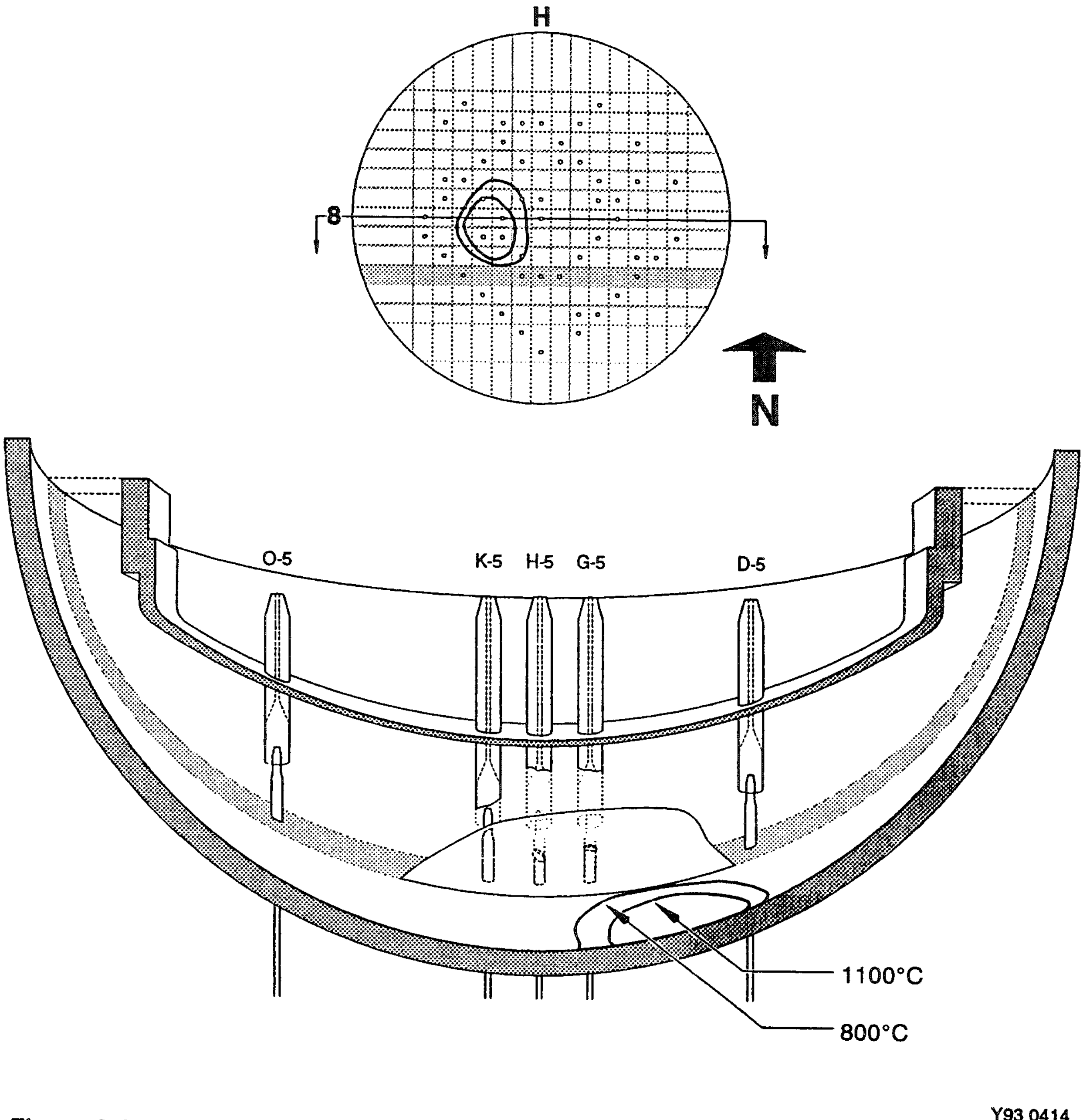

Figure 8-11. TMI-2 lower head cross section of hard debris, row 5.

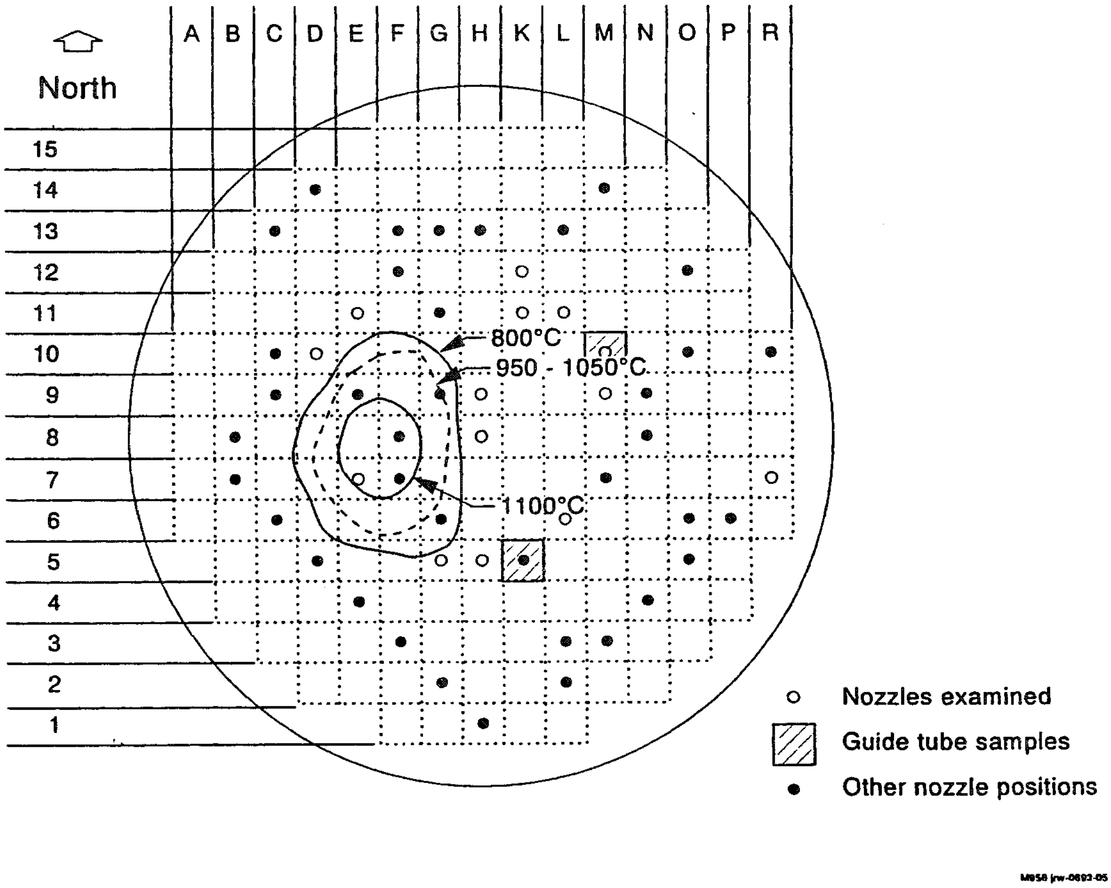

Figure 8-12. Lower head hot spot and nozzle/guide tube locations.

The mechanism that was responsible for the postulated rapid cooling of the lower head after 30 minutes has not been adequately explained. One proposed mechanism for this rapid cooling is the presence of interconnected flow channels within the debris and between the vessel and the debris layer. A considerable period of time (up to 30 minutes) would be required to adequately cool the peripheral portions of the debris before water could penetrate through to the hot spot location. Upon penetration of water through gaps between the debris and the vessel wall, the vessel steel could have cooled rapidly as indicated by the metallurgical examinations.

8.5 Relocation Scenario Conclusions

A scenario has been postulated based upon available plant instrumentation records and post-accident examination results. Although it is recognized that this scenario is not the only potential relocation scenario, it is consistent with information from plant data, VIP examinations, and analysis efforts. Key points of the scenario discussed in this section are summarized below:

- Relocating molten fuel flowed down through the core support assembly and onto the eliptical flow distributor plate.
- The initial molten fuel flow plugged holes around the periphery of the eliptical flow distributor plate, causing molten material to relocate from this plate to the lower head at several locations.
- The initial molten debris on the lower head cooled rapidly and formed an insulating layer of variable thickness that protected the lower head and many of the nozzles from damage.
- The pattern of molten material deposition on the lower head resulted in most of the vessel being insulated and protected from thermal damage. However, in the area just to the west of center (E-7, E-8, and F-8), the insulating layer was not sufficiently thick to protect the lower head, producing a localized hot spot.
- Effects, such as porosity in the insulating debris bed and cracking that occurred as the basal crust was formed, allowed water to penetrate into the debris bed to maintain some cooling.
- The hot spot remained hot for 30 minutes until water penetrated to the lower head between the crust and the vessel wall and caused rapid cooling of the vessel steel.

8.6 References

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9. CONCLUSIONS

Through the efforts of the VIP Signatories who supported the project, numerous significant contributions were made that dramatically increased the understanding of both the extent of damage to the vessel lower head and the margin of structural integrity that remained in the vessel. The principal results and conclusions from this project are discussed below.

- Vessel steel examinations indicated that a localized hot spot developed in the region of samples E-6, E-8, F-10, and G-8. In this region, the maximum temperature of the ferritic steel base metal near the interface with the stainless steel cladding was approximately 1,100°C. The steel may have remained at this temperature for as long as 30 minutes before cooling occurred. Temperatures 5 cm into the 14.2-cm-thick vessel wall (the thickness includes the cladding) were estimated to be 100 ± 50°C lower than the peak surface temperatures. Away from the vicinity of the hot spot, lower head temperatures did not exceed the 727°C transformation temperature.

- Even though a definitive scenario describing the movement of molten fuel and the formation of a localized hot spot during the lower head relocation process cannot be determined, there is evidence based on nozzle damage patterns to suggest that the initial flow onto the lower head formed an insulating layer that protected the lower head itself and several of the nozzles from extensive damage. Nozzle damage occurred in locations where the molten lava-like flow moved across the top of the insulating debris layer and contacted the nozzles in the areas where damage was found. The hot spot formed in a location where this debris layer had insufficient thickness to effectively insulate the lower head from the molten lava-like flow.

- Large margins to failure existed throughout the TMI-2 event for the failure mechanisms of tube rupture. Melt penetration calculations indicated that ceramic melt would not penetrate below the vessel head, which resulted in the margin to failure for this failure mechanism being extremely high. This effectively eliminated the possibility of an ex-vessel tube rupture.

- Lower head penetration weld failure calculations were performed, and results indicated that there was a considerable margin in the weld's integrity. Hence, the need for any tube ejection analysis was precluded, and the possibility of a tube ejection was eliminated.

- Jet impingement calculations indicated that the magnitude of the hot spot temperatures estimated in the metallurgical examinations were due to a longer-term heatup of the debris rather than from a jet impinging directly on the lower head.

- Analyses indicated that for a TMI-2 type accident, a localized effect such as a hot spot will shorten the overall global vessel failure time but is unlikely to cause vessel failure by itself as long as the background lower head temperatures (outside the area of the hot spot) remain cool.