POLICY ISSUE
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SECY-93-119

FOR: The Commissioners

FROM: James M. Taylor
Executive Director for Operations

SUBJECT: TMI-2 VESSEL INVESTIGATION PROJECT

PURPOSE:

To provide the Commission with a summary of the major conclusions and accomplishments of the TMI-2 Vessel Investigation Project.

BACKGROUND:

In October 1988, the NRC, in cooperation with 10 foreign countries under the auspices of the Organization for Economic Cooperation and Development's (OECD) Nuclear Energy Agency, began a joint research program to examine and analyze material samples from the lower head of the TMI-2 reactor pressure vessel. The objectives of this program, called the TMI-2 Vessel Investigation Project (VIP), were to (1) investigate the condition and properties of materials extracted from the lower head of the TMI-2 reactor pressure vessel, (2) determine the extent of damage to the lower head by chemical and thermal attack, and (3) determine the margin of structural integrity that remained in the pressure vessel.

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NOTE: Due to limitations on the distribution of reports under the OECD TMI-2 Vessel Investigation Project, and the fact that the draft VIP Integration Report is still undergoing review by the VIP participating countries, this Commission paper should not be distributed outside the NRC until after the final report has been issued and the TMI-2 VIP has been completed.

NOTE: SENSITIVE INFORMATION - LIMITED TO NRC UNLESS THE COMMISSION DETERMINES OTHERWISE

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Prior to the initiation of the VIP, the Department of Energy (DOE) had supported extensive post-accident examinations and analyses of the TMI-2 damaged core. The primary objective of the DOE TMI-2 Accident Evaluation Program was to develop an understanding of (1) core damage progression in the upper core region, (2) heat-up, and the formation and growth of the molten central region of the core, (3) relocation of approximately 20 tons of debris to the lower head, and (4) release of fission products to the reactor vessel and the containment.

The principal conclusions from the DOE program were that the TMI-2 core damage progression involved the formation of a large consolidated mass of core material surrounded by supporting crusts, the failure of the supporting crusts, and finally, the long-term cooling of a large volume of molten core material. The TMI-2 accident demonstrated that at least for one severe accident scenario, the accident can be terminated and confined to the reactor pressure vessel by cooling water before the failure of the lower head. However, there was no quantitative information that could be used to determine how close the vessel was to failure.

The examinations that were performed under the OECD NEA VIP go beyond the work performed during the previous TMI-2 examinations. Specifically, the VIP plan was to obtain and examine samples of the lower head steel, instrument penetrations, and previously molten debris that was attached to the lower head and use this information to estimate the vessel margin-to-failure. A summary of the major results and conclusions of the TMI-2 VIP is presented in the discussion section below.

A draft of the final TMI-2 VIP Integration Report was issued on March 31, 1993, to the participants in the OECD VIP for review and comment. Comments will be discussed at the upcoming VIP Program Review Group and Management Board meetings to be held from May 17-19, 1993, at Argonne National Laboratory. Based on the comments received and subsequent discussions, Idaho National Engineering Laboratory (INEL) will issue the final report by June 30, 1993, at the conclusion of the VIP. The OECD, in cooperation with the NRC, is planning a conference from October 20-22, 1993, in Boston, Massachusetts, to present the results, conclusions, and accomplishments of the TMI-2 VIP to the world-wide reactor safety community.

DISCUSSION:

The draft TMI-2 VIP Integration Report presents the major findings and conclusions that were developed during the VIP. Discussions on the various elements of the project are integrated into this report to present in a single document a comprehensive understanding of the results of this research. These major project elements include: sample selection and acquisition; metallurgical examinations and mechanical properties; companion sample examinations (i.e., previously molten debris near the reactor pressure vessel lower head); examinations of nozzles and guide tubes; lower head core debris relocation scenario; and margin-to-failure analysis. Each of these topics is discussed in greater detail in separate reports that were completed under the VIP.

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 during the TMI-2 accident. The principal results and conclusions from this project are summarized below:

- Vessel steel examination indicated that a localized hot spot developed in an elliptical region approximately 2½ by 3 feet. In this region, the maximum temperature of the ferritic steel base metal near the interface with the stainless steel cladding was approximately 1100°C. The steel may have remained at this temperature for as long as 30 minutes before cooling occurred. Temperatures 1¼ inches into the 5⅜-inch thick wall 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.

- Nozzle examinations and post-accident visual examinations indicated that the major lower head relocation flow path for molten material was from the northeast and southeast quadrants of the vessel lower head towards the hot spot location in the western sector.

- 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 considerable evidence indicating that the lower head was insulated by a debris layer (deposited both before and during the relocation event) containing both ceramic and metallic material. The hot spot formed in a location where this 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 accident for the failure mechanisms of tube rupture and tube ejection. In fact, calculational results indicated that tube rupture and ejection can essentially be eliminated as potential failure mechanisms.

- Without modeling enhanced cooling of the debris and lower head, the margin-to-failure scoping calculations that were based upon data from companion sample examinations indicated that vessel failure should have occurred when the reactor system was repressurized by plant operators at about 300 minutes. Thus, the importance of properly accounting for enhanced cooling of debris by existing water in the vessel lower head is emphasized.

- VIP contributions to reactor safety emphasized the importance of possible severe accident mitigation techniques such as ex-vessel flooding (to enhance heat removal from the lower head) and RCS depressurization. Since the lower plenum remained filled with water throughout the accident, either of these mitigation techniques could potentially eliminate the conditions that lead to the calculated vessel failure, namely the condition of elevated global vessel temperatures in conjunction with relatively high RCS pressures. VIP results also indicated that an additional safety margin, not currently considered within severe accident analyses, may occur due to coolant circulating within channels or cracks within the debris and within channels or gaps between the debris and the vessel. If relocated debris contains these channels, as it appears was the case during the TMI-2 accident, debris coolability is greatly enhanced, and lower head vessel failure is less likely. Additional research would be necessary to confirm the efficacy of these strategies to maintain vessel integrity during a severe accident for designs and conditions other than TMI-2.*

A more detailed summary of the major conclusions and accomplishments of the TMI-2 VIP is presented in the enclosure to this Commission paper.

Prior to the TMI-2 VIP Conference in Boston, the staff will brief the Commission more fully on the results of this Project. At that time the staff will also present results of follow-on analyses to address postulated questions and issues that are beyond the specific scope of the TMI-2 VIP. For example, one question might be, what would the resultant containment loads have been if the TMI-2 reactor vessel had failed and what would have been the margin to containment failure?

James M. Taylor
Executive Director
for Operations

Enclosure:
1. Major Conclusions and Accomplishments
   of the TMI-2 Vessel Investigation Project

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* Ongoing and planned experiments at the Russian Research Center's RASPLAV facility will address the capability of external flooding of the reactor cavity to retain molten core material in the reactor vessel lower head. The NRC is currently supporting this research project, and a cooperative international effort (under the auspices of the OECD) is currently under discussion to expand the RASPLAV project.

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Enclosure

Major Conclusions and Accomplishments of the TMI-2 Vessel Investigation Project

Results of the TMI-2 Vessel Investigation Project (VIP) contributed significantly to increased understanding of the extent of damage to the reactor vessel lower head and the margin of structural integrity that remained in the vessel during the TMI-2 accident, as well as lower vessel head behavior during severe accidents in general. The major elements of this project were: sample selection and acquisition; metallurgical examinations and mechanical properties; companion sample examinations (i.e., previously molten debris near the reactor pressure vessel lower head); examinations of nozzles and guide tubes; lower head core debris relocation scenario; and margin-to-failure analysis. The major conclusions and accomplishments of each of these elements is presented below.

Sample Acquisition

The initial phase of the VIP was devoted to developing the techniques and hardware necessary for removing the steel, nozzle, and guide tube samples. Removing the samples from the lower head of the TMI-2 vessel was a unique challenge that required the development of specialized cutting tools. Under the direction of MPR Associates, Inc., different tools were developed for each of the three types of samples (vessel nozzle penetrations, guide tubes, and vessel steel) that were extracted from the lower head.

The criteria and constraints that were considered in developing the extraction tool included:

- Obtaining the largest number of samples possible during the 30-day window that was available for the extraction process,
- Not breaching or significantly weakening the reactor vessel, and
- Working on a shielded platform mounted 40 feet above the lower head and remotely extracting the samples that were covered by highly borated water.

The cutting technique that was selected for extracting samples of the lower head steel was a metal disintegration machining (MDM) process.* This process uses a series of electric arcs to melt a small amount of material in the cutting area. Water pumped through holes in the cutting electrode cools the molten material and flushes the resulting particles away from the cutting area.

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* In SECY-92-276 the staff informed the Commission that the MDM cutting tool and other artifacts from the TMI-2 VIP will be included in a permanent exhibit on Science in American Life at the Smithsonian Institution's National Museum of American History.

Although only a limited number of samples could be extracted, different regions of the lower head had to be sampled. The following areas were selected for extracting samples.

- As close as possible to the area directly beneath the primary relocation path of molten core material to the lower head,
- Toward the radial center of the lower head underneath the maximum debris thickness,
- In the quadrant of the lower head where a "wall" of consolidated debris similar to a lava front had been observed,
- In an area of the lower head not contacted by the molten core material to act as a "control" sample, and
- Areas that include one or more instrument penetrations, especially in the areas noted above.

Since this was a first-of-a-kind process using a specially designed MDM cutting head, the exact number of samples could not be predicted in advance. It was hoped that from 8 to 20 samples could be obtained. As it turned out, the sample extraction was very successful, and 15 reactor vessel steel specimens, 14 incore nozzles, and 2 incore guide tubes were extracted from the lower head over a 30-day period ending March 1, 1990. The location of these samples is shown in Figure ES-1. The prism-shaped vessel steel samples extended approximately one-half way through the 5⅛-inch thick reactor vessel wall.

Vessel Steel Examinations

Argonne National Laboratory (ANL) coordinated the metallographic examinations and mechanical property tests of the vessel steel samples. All the lower head steel samples were visually examined, decontaminated, sectioned, and sent to eight of the VIP member countries for testing. The participants that examined the vessel steel samples were Belgium, Italy, Finland, France, Germany, Spain, the United Kingdom, and the United States. Examinations performed by the project participants included tensile, creep, and Charpy V-notch impact tests, microhardness measurements, micro and macro photography, and chemical composition. The primary purpose of these tests was to determine the lower head steel's mechanical properties over the temperature range experienced during the accident. Optical metallography and hardness tests were performed in order to estimate the maximum temperature various portions of the lower head reached during the accident.

The results of the wide range of inspections, mechanical property determinations, and metallographic examinations of the lower head vessel samples revealed important and previously unknown facts relating to the degree of thermal attack on the lower head. Overall, these examinations revealed that a localized hot spot formed in an elliptical region on the lower head that was approximately 3 ft x 2.5 ft as shown in Figure ES-2. The hot spot was located in the area where visual observations made during the defueling process indicated that the most severe nozzle damage had occurred. Metallographic examinations of samples taken from this region indicated that the inner surface of the vessel steel reached temperatures between 1075 and 1100°C during the accident. At this location, temperatures 1¼ inch into the vessel wall were estimated to be 100 ± 50°C lower than the peak inner surface temperature.

Temperatures in the hot spot were considerably higher than the surrounding region of the lower head. Generally, the vessel temperature away from the hot spot did not exceed the 727°C ferrite-austenite transformation temperature for the A533B pressure vessel steel. The results of metallographic examinations could not determine an estimate for the steel temperature away from the hot spot, only that the 727°C transition temperature was not reached.

The steel examinations were also able to provide data on the cooling rate of the lower head hot spot. Microstructural and hardness observations in the as-received state for two samples in the hot spot reflected the austenitizing heat treatment and the subsequent relatively rapid cooling of this material during the accident. Cooling rates were estimated to have been in the range of 10 to 100°C/min through the transition temperature. By comparing results of the TMI-2 lower head sample examinations with results from similar metallurgical examinations of heat-treated samples from an equivalent steel, it was determined that samples in the hot spot remained at their peak temperature for as long as 30 minutes prior to being cooled.

Mechanical property tests performed on the vessel steel samples produced a wealth of high temperature mechanical property data, which not only provided information on the present condition of the lower head, but also provided input to the margin-to-failure analysis. Creep tests performed at 600 to 700°C indicated no significant differences in behavior between samples that exceeded a maximum temperature of 727°C and those that did not. Tensile tests for specimens that exceeded 727°C showed significantly higher strengths at room temperature and at 600°C when compared to those that did not exceed 727°C. The tensile tests at lower test temperatures further confirmed the hardness measurements which showed that the material from the hot spot had been austenitized and subsequently cooled rapidly.

During the sample removal effort, tears or cracks were found in the cladding of the vessel around four nozzles. Vessel steel samples containing these cracks were analyzed by ANL. It was found that the crack did not propagate into the base metal. The cracks were attributed to hot tearing of the cladding caused by differential thermal expansion between the stainless steel cladding and the carbon steel vessel that occurred during vessel cooling. Furthermore, the presence of control assembly material (Zr, Ag, Cd, and In) within the cladding tears and into the grain boundaries on the surface of some sample locations indicated that a layer of debris containing metallic material was already present on the lower head when the major relocation of ceramic molten core material to the lower head took place at 224 minutes after the initial reactor scram.

Nozzle Examinations

Fourteen nozzles and two guide tube specimens were removed from the vessel by being cut off as close to the lower head as possible. Several nozzles were melted off almost flush with the vessel and could not be removed. All nozzle and guide tube samples were shipped to INEL, and six were then shipped to ANL for examination. Examinations included micro and macro photography, optical metallography, scanning electron microscope measurements, gamma scanning, melt penetration measurements, and microhardness. There were two primary purposes for these examinations. First, these examinations would help to determine the extent of nozzle degradation to evaluate the thermal challenge to the lower head. Second, they would provide information on the movement of molten fuel onto and across the lower head during the relocation. Portions from selected INEL nozzles and guide tubes were later sent to CEA Saclay, France, where similar examinations were performed.

Examinations performed on the nozzles and guide tubes, conducted primarily at ANL, provided insights into the accident progression. Damage to several nozzles indicated that their end-state condition was caused by molten core material coming in contact with the nozzles at an elevation ranging from 5½ to 10½ inches above the lower head. Surface scale found on the nozzles below their melt-off points suggested that this molten material flowed on top of a crust of preexisting solidified fuel debris that had been cooled below its solidus temperature.

During the examinations, it was estimated that nozzle temperatures varied widely as a function of location and elevation above the lower head. They ranged from 1415°C, which is the Inconel 600 nozzle's liquidus temperature, to 1000°C at elevations of 5½ in. and 2½ in. above the lower head, respectively. The penetration of fuel debris downward into the nozzles was influenced by the temperature of the fuel at the time of entry, debris composition (and hence its fluidity), and the temperature of the nozzle itself. Temperature was found to greatly affect the solidification of fuel and also the degree of interaction between the debris and the nozzle.

Examination results also indicated the presence of Zr and Ag-Cd on nozzle surfaces, which interacted with the material. The presence of this material indicated that control rod material had relocated prior to the primary fuel relocation. The early movement of control material to the lower head was substantiated by the presence of control assembly material that was found in the cladding tears. However, the examinations were unable to determine the quantity of these materials that had relocated.

Companion Sample Examinations

The debris samples examined as part of the VIP were known as companion samples since they came from the same hard layer that was in contact with the lower head. Hence, they were "companions" to the lower head steel samples. Results of the companion sample examinations made it possible to determine the debris composition and the lower head decay heat load. During the defueling process, it was discovered that the hard layer was indeed extremely hard and had to be broken into pieces for removal. However, there was virtually no adherence of the material to the lower head itself. Because the hard layer had to be broken into pieces during sample acquisition, information on the sample location was limited to identifying from which quadrant the sample was obtained.

The primary constituents of the companion samples were uranium, zirconium, and oxygen $(U, Zr)O_2$ with only small percentages (<1 wt%) of other structural material such as iron, nickel, and chromium. Control rod materials such as silver, indium, and cadmium were present in low (<0.5 wt%) concentrations. The average sample debris density was 8.2 ± 0.6 g/cm^3 with an average porosity of $18 \pm 11\%$. Based on the debris composition, it is quite probable that the molten material reached temperatures greater than 2600°C in the central core region prior to relocation. The temperature of the debris when it reached the lower head is not known, but the material reached the lower head in a molten state.

Radiochemical examinations indicated that the primary radionuclides retained in the debris bed were medium and low volatile constituents. Almost all of the radiocesium, radioiodine, and radioactive noble gases volatilized from the molten core before it relocated to the lower head. Knowledge of the retained fission products is critical to calculating the debris decay heat and the resulting heat load on the lower head. Decay heat calculations indicated an overall heat load of 0.13 ± 20% W/g of debris when the relocation occurred at 224 minutes after scram and 0.096 ± 20% W/g at 600 minutes after scram. At the time of relocation, the total decay heat load was approximately 2.47 MW for the estimated 19,000 kg of material that relocated to the lower head.

Lower Head Relocation Scenario

A key element of the VIP was to develop a better understanding of the mechanisms involved in the relocation of molten fuel to and across the lower head. However, a definitive relocation scenario that accounts for both the molten fuel movement and the formation of the hot spot could not be determined because of the extremely complex interactions that took place during the accident and the limited data available from the TMI-2 plant instrumentation. There is evidence from the ANL nozzle examinations and the geometry of the debris bed layer, which support earlier visual observations, that the relocation flow path was generally from the northeast and southeast sectors of the reactor towards the hot spot located in the western sector of the lower head.

When molten fuel debris moved across the lower head, the lower plenum was filled with water throughout the accident, and molten fuel movement took place through a water-filled volume. The nonplanar upper surface of the hard debris layer is consistent with a scenario where a relatively viscous lava-like flow moved through water. The crust that surrounded the molten flow as it moved through the water-filled lower plenum continually broke up and reformed. This action exposed new molten material as the flow moved across the lower head.

The pattern of nozzle degradation observed at elevated levels for several nozzles supports the idea of an insulating debris layer (e.g., basal crust) that formed around the lava-like flow as it moved across the lower head. The pattern of nozzle damage is thought to have occurred because as the lava-like flow moved over the top of the 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 a 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.

The nozzle examinations also provided insights into what caused the localized hot spot found on the TMI-2 lower head. One possible explanation is based on the pattern of nozzle degradation and damage. As the viscous lava-like flow moved across the vessel towards the location where the hot spot occurred, the insulating debris layer crust became progressively thinner. This is consistent with the observation that the deepest debris was found in other locations of the vessel rather than above the hot spot. A thinning crust was also indicated by data from the nozzle examinations, which show that more of the nozzle length was melted as flow moved towards 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. As the lava-like flow reached the uphill side of the lower head, a hot spot could have formed because molten fuel had broken through the continually reforming frontal crust and came to rest almost directly on the lower head. At this point, the preexisting basal crust thickness was insufficient to adequately insulate the lower head, and a localized hot spot formed.

Margin-to-Failure Analysis

The final element of the VIP, the margin-to-failure analysis, was performed to investigate mechanisms having the potential to threaten the integrity of the reactor vessel and to help improve understanding of events that occurred during the accident. Analyses addressed mechanisms that could result in lower head penetration tube and vessel failures. Specific failure modes examined were instrument tube rupture, tube ejection, localized vessel failure, and global vessel failure.

Margin-to-failure calculations relied upon three major sources of VIP examination data: (a) nozzle examination data for characterizing melt composition and penetration distances within instrument tubes, (b) companion sample examination data for characterizing debris properties (such as decay heat and material composition), and (c) vessel steel examination data for characterizing peak vessel temperatures, duration of peak temperatures, and vessel cooling rate.

The margin-to-failure analysis has provided significant insights into potential failure mechanisms of the TMI-2 lower head. Results from these calculations eliminated tube rupture and tube ejection as potential failure mechanisms during the accident. Melt penetration results indicated that ceramic melt did not penetrate below the lower head, which effectively eliminated an ex-vessel tube rupture as a failure mechanism. Analyses also indicate that the instrument tube weld would remain intact even if the peak reactor coolant system (RCS) pressure was conservatively assumed to occur at the same time the hot spot formed. As a result, tube ejection was also eliminated as a potential failure mechanism.

Jet impingement calculations indicated that the amount of breakup occurring as melt relocated to the lower plenum was insignificant. Calculations also indicate that the magnitude and duration of hot spot temperatures estimated in TMI-2 vessel examinations could not have been caused by an impinging jet. Rather, hot spot temperatures were due to a sustained heat load from debris on the lower head. The limited area estimated to have experienced hot spot temperatures suggested that this region was subjected to a localized heat source, such as might occur with an nonhomogeneous debris bed or a localized region with enhanced debris-to-vessel contact as was postulated in the discussion on the relocation scenario.

The potential for the vessel to experience a global failure was evaluated for temperature distributions obtained from thermal analyses with best estimate and lower bound input assumptions for parameters such as debris decay heat, outer vessel heat transfer coefficient, and the debris-to-gap heat-transfer resistance. Calculations based on these assumptions indicated that global failure due to creep rupture was predicted to occur within the first two hours after debris relocation because of the sustained high vessel temperatures when the RCS was repressurized. This rise in RCS pressure occurred when the plant operators closed the block valve for the power operated relief valve (PORV) at 320 minutes.

Localized vessel failure analyses indicated that the predicted time to vessel failure was reduced when a localized hot spot was superimposed upon the calculated best estimate temperatures discussed above. However, these localized calculations also indicated that it is possible to withstand the 1100°C hot spot temperatures for the 30-minute time period inferred from the vessel steel examinations, provided that the rest of the vessel remained relatively cool.

Taken together, the localized and global vessel failure calculations indicated that the background metal temperature behavior, which is highly dependent on the heat load from the relocated debris in the lower head, was key to predicting failure from either of these mechanisms. Cool background vessel temperatures have the potential to reduce structural damage and preclude global vessel failure even at high pressure and in the presence of a localized hot spot.

Initial thermal response results, and subsequent structural analysis results, were dominated by input assumptions based upon companion sample examination data, which indicated that the debris experienced relatively slow cooling over a period of several days. However, differences between these analysis results and data from the metallurgical examinations indicated that the lower head must have cooled within the first two hours after debris relocation. These initial results showed that initial cooling must have occurred, which is not indicated by companion sample examinations. Hence, calculations were performed to quantify both the magnitude of the cooling and the debris configuration required to support this cooling. A thermal analysis that considered coolant mass flows entering and exiting the vessel confirmed that the debris must have cooled in the time period between relocation and vessel repressurization.

Two forms for enhanced debris cooling were investigated that have the potential to produce more rapid vessel cooling during the first two hours after debris relocation: a slow cooling mode in which it was assumed that water slowly removes heat as it travels through channels or "cracks" within the debris, and a rapid cooling mode in which it was assumed that coolant rapidly removes heat as it travels through channels or "gaps" between the vessel and the debris. Slow-cooling analysis results indicated that coolant traveling through a relatively insignificant volume of cracks within the debris (i.e., less than 1% of the debris volume) will remove sufficient heat to preclude vessel failure. Rapid cooling analysis results indicated that coolant traveling through a gap of minimal size (i.e., as small as .04 in.) will remove sufficient heat to allow the vessel to experience cooling rates consistent with metallurgical examination data.

Conclusions

Through the efforts of the VIP signatories who supported the project, numerous significant contributions were made that dramatically increased the understanding of the extent of damage to the vessel lower head, the margin of structural integrity that remained in the vessel during the TMI-2 accident, and our general knowledge of lower vessel head behavior during severe accidents. The principal results and conclusions from this project are summarized below:

- Vessel steel examinations indicated that a localized hot spot developed in an elliptical region approximately 2½ by 3 feet. In this region, the maximum temperature of the ferritic steel base metal near the interface with the stainless steel cladding was approximately 1100°C. The steel may have remained at this temperature for as long as 30 minutes before cooling occurred. Temperatures 1¼ inches into the 5⅝-inch thick wall 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.

- Nozzle examinations and post-accident visual examinations indicated that the major lower head relocation flow path for molten material was from the northeast and southeast quadrants of the vessel lower head towards the hot spot location in the western sector.

- 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 considerable evidence indicating that the lower head was insulated by a debris layer (deposited both before and during the relocation event) containing both ceramic and metallic material. The hot spot formed in a location where this 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 accident for the failure mechanisms of tube rupture and tube ejection. In fact, calculational results indicated that tube rupture and ejection can essentially be eliminated as potential failure mechanisms.

- Without modeling enhanced cooling of the debris and lower head, the margin-to-failure scoping calculations indicated that lower head temperature distribution based upon data from companion sample examination data would have resulted in vessel failure when the reactor system was repressurized by plant operators at about 300 minutes.

- VIP contributions to reactor safety emphasized the importance of possible severe accident mitigation techniques such as ex-vessel flooding (to enhance heat removal from the lower head) and RCS depressurization. Since the lower plenum remained filled with water throughout the accident, either of these mitigation techniques could potentially eliminate the conditions that lead to the calculated vessel failure, namely the condition of elevated global vessel temperatures in conjunction with relatively high RCS pressures. VIP results also indicated that an additional safety margin, not currently considered within severe accident analyses, may occur due to coolant circulating within channels or cracks within the debris and within channels or gaps between the debris and the vessel. If relocated debris contains these channels, as it appears was the case during the TMI-2 accident, debris coolability is greatly enhanced, and lower head vessel failure is less likely. Additional research is needed to confirm the efficacy of these strategies to maintain vessel integrity during a severe accident for designs and conditions other than TMI-2.

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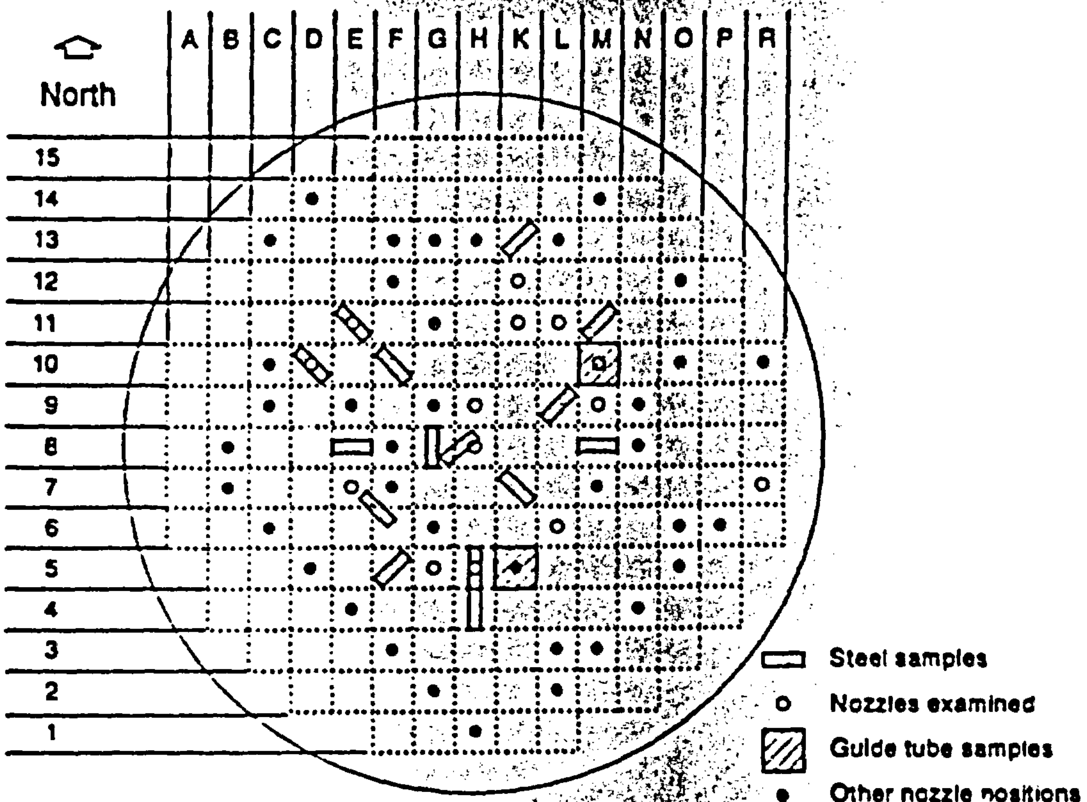

Figure ES-1. Location of lower head steel, nozzle, and guide tube samples.

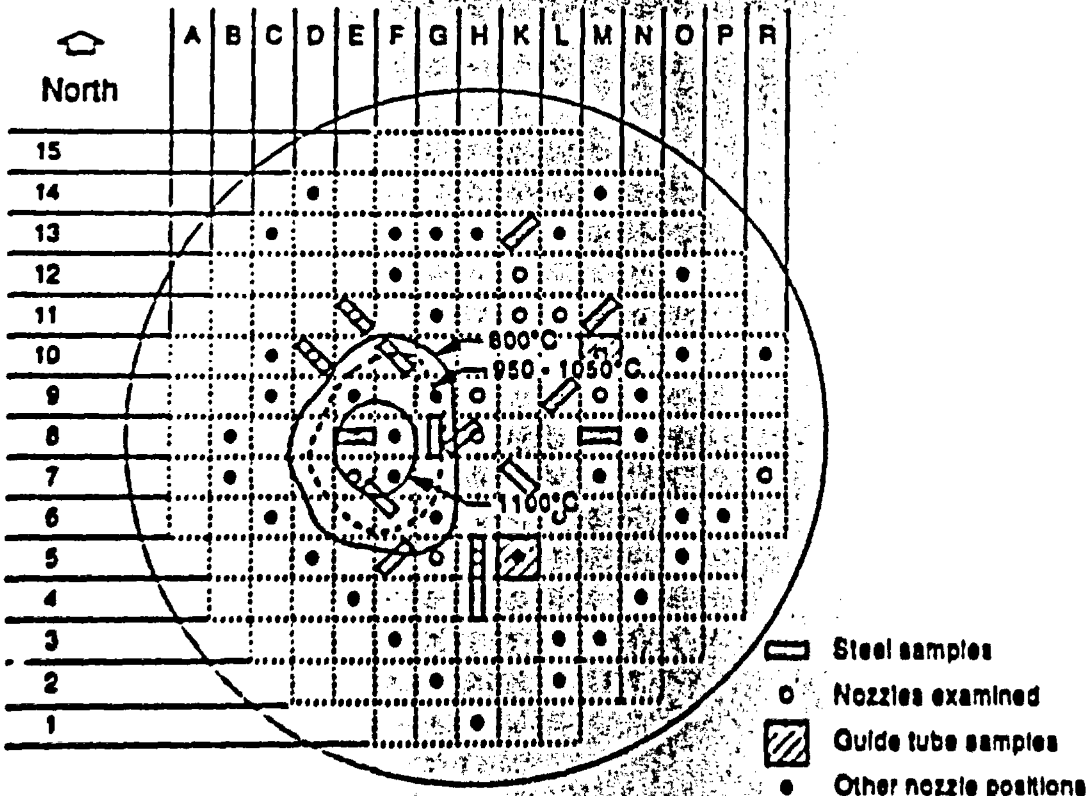

Figure ES-2. Lower head hot spot location.