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Three Mile Island—New Findings 15 Years After the Accident

By A. M. Rubin and E. Beckjord[a]

Abstract: *On March 28, 1979, the Three Mile Island Unit 2 (TMI-2) nuclear power plant underwent a prolonged small-break loss-of-coolant accident, compounded by human errors and equipment failures, that resulted in severe damage to the reactor core. The accident, the most severe that has occurred in a commercial pressurized-water reactor, resulted in a partial melting of the reactor core and significant release of fission products from the fuel into the reactor vessel and the containment building. The progression of the TMI-2 accident was mitigated by the injection of emergency cooling water.*

A great deal has been learned about the TMI-2 accident since it occurred 15 years ago. Much of our knowledge about the accident has evolved over time as cleanup, defueling, examinations inside the reactor vessel, and analyses have been completed. In October 1993 a 5-year major research project on the damaged reactor, called the TMI-2 Vessel Investigation Project (VIP), was completed. This article summarizes the views of the accident over the past 15 years, what we have learned from the VIP, and the broad significance of these findings. In particular, the VIP has added significant insights about the TMI-2 accident in the areas of reactor vessel integrity and issues related to accident management.

By the time the Kemeny Commission released its report to President Carter in October 1979 the circumstances that led to the accident, the course of events, and the actions taken by plant operators were clear for the plant systems for which measurements and records were available: these were the systems outside containment and inside to a lesser extent. As an observer attempted to focus attention on the reactor coolant system and the reactor vessel, clarity vanished, and he or she could only attempt to speculate on events and final conditions by inferring from external measurements and judgment. An article published in the *Spectrum* of the Institute of Electrical and Electronics Engineers (IEEE) gives an excellent account of the widely held view in the months after the accident: " . . . .This was because most of the core damage was to the cladding, which primarily yields noble gases. Iodine is released by damage to the fuel pellets, and this damage was minimal at Three Mile Island."[1]

The article identified the 100-minute mark after the main feedwater pumps tripped, which was the start of the accident, as the point of time before which there was the possibility of recovery to prevent a severe accident and after which core damage was unavoidable. Notice especially, too, the statement that most of the damage was to the clad, and the fuel pellets themselves experienced minimal damage. Four years passed before the error of this latter view came to light. This change in view is marked in a second *Spectrum* article: "What is now known is that most of the 177 fuel assemblies . . . were nearly completely destroyed in the upper quarter of the reactor core. What exists now is a void measuring 9.3 cubic meters. . . . Other material from the core void is believed to be at the bottom of the reactor vessel."[2] The suggestion that "resolidified mass from the molten

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material could exist below the cavity in the core" represents a drastic change in the view of the accident in comparison with the October 1979 IEEE *Spectrum* article.

By 1987 the Three Mile Island (TMI) research had advanced considerably, and the investigators had developed a much better understanding of the accident sequence on the basis of the location and condition of core materials, fragments, and once-molten core materials that had resolidified. On the basis of this research, knowledge of the end-state condition of the TMI-2 reactor vessel and core is shown in Fig. 1. A central cavity existed in the upper portion of the core approximately 1.5 m above a loose debris bed. A previously molten region that was contained by partly or fully metallic crust layers was found below the loose debris layer. Overall, at least 45% (62 metric tons) of the core had melted. Video examinations also indicated that approximately 19 000 kg (19 metric tons) of molten material had relocated onto the lower head of the reactor vessel.

Information presented in a paper entitled "A Scenario of the Three Mile Island Unit 2 Accident"[3] describes the accident in seven periods: (1) the first 100 minutes of the loss-of-coolant accident, (2) initial core heat-up, (3) formation of the upper core debris bed, (4) growth of a pool of molten core material, (5) injection of emergency core coolant system water, (6) failure of the crust supporting the molten pool and flow of molten material to the bottom of the vessel, and (7) finally quenching and cooling of the lower debris bed and eventual stabilization of conditions.

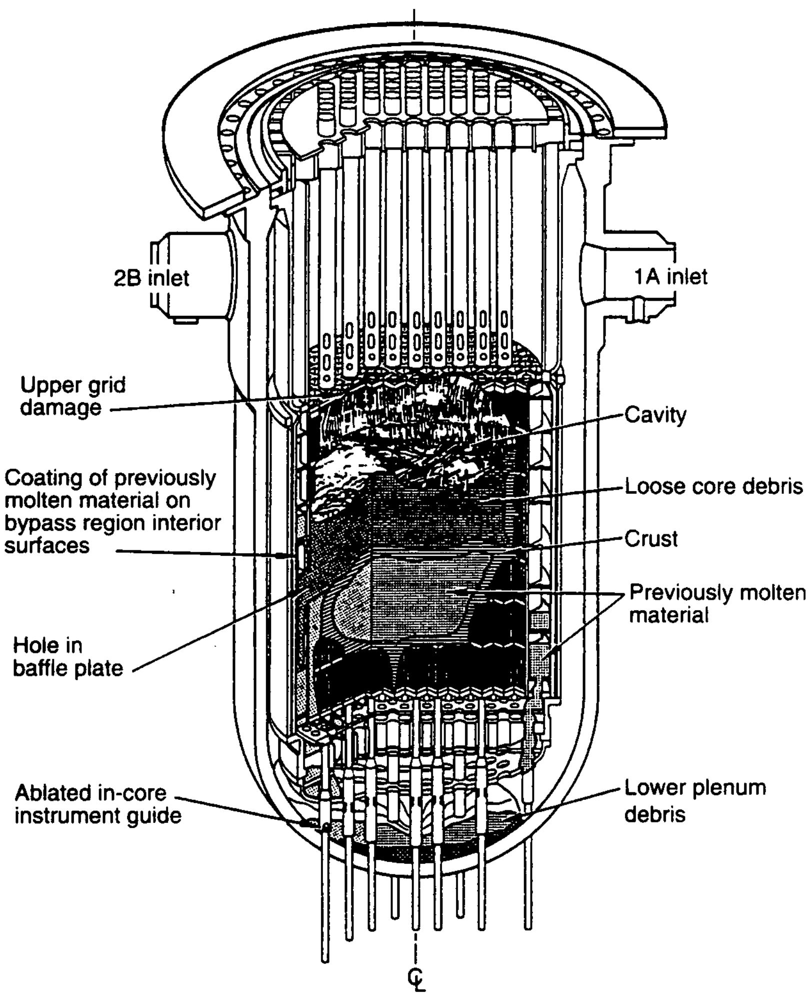

Fig. 1 TMI-2 reactor vessel end-state configuration.

The change indicated in the 1987–1989 views, compared with the views of 1984, is in the condition of the vessel, with the suggestion of "possible thermal ablation of the reactor vessel lower head." At the same time, the scenario confirms the view of the first 100 minutes of the accident that was presented in the 1979 *Spectrum* article. So the 1979 view of the first 100 minutes has stood the test of time, whereas the view of what subsequently took place within the vessel has changed drastically.

It is interesting to reflect on the long time (i.e., 8 to 10 years) that it took to develop the final view of the TMI core conditions. Did the initial erroneous view extend the time required to obtain the facts? Probably not. The long lead time required to develop the means of discovery and solve myriad technical problems associated with the removal of reactor internals, core, and fuel debris under difficult working conditions played the major role in extending the effort.

INITIATION OF THE TMI-2 VESSEL INVESTIGATION PROJECT

As researchers gained more information in the early and mid-1980s concerning the extent of damage to the TMI-2 reactor, they realized that cleanup of the reactor would take several years and would require the cooperation of both private industry and government agencies. As a result, an organization named GEND, which included General Public Utilities Nuclear Corporation (GPUN), the Electric Power Research Institute (EPRI), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Department of Energy (DOE), was formed. GEND gave technical and financial assistance to the owner of the TMI-2 reactor, GPUN was responsible for ongoing plant cleanup operations, and DOE was responsible for providing transportation and interim storage of the core until permanent disposition was decided. DOE also supported an extensive research program, the TMI-2 Accident Evaluation Program (AEP), to develop a consistent understanding of the accident. The primary objective of the DOE AEP was to develop an understanding of (1) core damage progression in the upper core region, (2) the heat-up and the formation and growth of the molten central region of the core, (3) the relocation of approximately 19 metric tons of debris to the lower head, and (4) the release of fission products to the reactor vessel and the containment.

The AEP was focused primarily on core damage progression and the mechanisms that controlled fission-product behavior. Observations made during the latter portions of the defueling effort, however, indicated that the accident progressed even further than was envisioned when the AEP was established. Molten core materials were found to have moved laterally through the east-side core baffle and former plates and into the core bypass region between the core-former wall and the core barrel. Visual observation also indicated the presence of a large hole approximately 0.6 m wide and 1.5 m high extending across the lower portion of three core-former plates. The 1.9-cm-thick core-former plates and sections of three 3.2-cm-thick horizontal baffle plates were melted in this region. Molten material from the core region flowed through this hole and into the upper core support assembly. Loose debris was found in the area behind the baffle plates and extended completely around the core region. It was estimated that 4200 kg of core debris was in the upper core support region. Closed-circuit television pictures indicated evidence of thermal damage to instrument structures in the lower plenum and around flow holes in the elliptical flow distributor.

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 lower head fails. However, there was no quantitative information that could be used to determine how close the vessel was to failure.

In October 1987 the NRC proposed that a joint international cooperative program be formed that would be sponsored by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA-OECD). This program would conduct further investigations of potential damage to the TMI-2 reactor vessel lower head from the relocation of molten fuel to that region. A steering committee was established to determine if there were sufficient interest from the OECD member countries to warrant formation of such a program. The OECD efforts led to issuing the "Agreement to Investigate the Three Mile Island-2 Reactor Pressure Vessel" in June 1988. Signatories to the project, commonly called the Vessel Investigation Project (VIP), included Belgium, Finland, France, Germany, Italy, Japan, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

As described in the formal project agreement, the objectives of the VIP were to do the following: Jointly carry out a study to evaluate the potential modes of failure and the margin to failure of the TMI-2 reactor vessel during the TMI-2 accident. The conditions and properties of material extracted from the lower head of the TMI-2 pressure vessel will be investigated to determine the extent of damage to the lower head by chemical and thermal attack, the thermal input to the vessel, and the margin of structural integrity that remained during the accident.[4]

The examinations performed under the VIP went beyond the work that had been 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. The schedule for the VIP was determined by the tasks required for fuel removal, the development of the cutting tools to remove lower-head samples, the laboratory metallurgical work, and finally the study and analyses of results. It took nearly 5 years to carry out the project, during which time nearly all the objectives were accomplished.

PROJECT ORGANIZATION

The management and organization of the VIP were defined in the 1988 formal agreement that established the project. Overall control and direction of the VIP were vested in a Management Board that consisted of one member designated by each of the signatories. The primary function of the Management Board was to approve the overall VIP work scope and budget, including the allocation of tasks among the signatories.

A Program Review Group was also formed that consisted of one member designated by each signatory. The primary function of the Program Review Group was to act as the technical advisor to the Management Board for both ongoing activities and future work. The Program Review Group was also chartered to provide technical advice and recommendations to the VIP operating agent, NRC, which was responsible for implementing project objectives in accordance with the project agreement and directions from the Management Board.

MAJOR PROJECT ELEMENTS

The VIP objectives were realized through a combination of several major activities that included extraction of vessel steel, nozzle, and guide tube samples from the lower-head region; examinations of the extracted material; and analyses to determine the structural integrity that remained in the vessel. Various project members examined the steel samples, along with the nozzles, guide tubes, and previously molten debris that were found in the lower-head region to determine the condition and properties of the samples and the extent of damage to the lower head during the accident. The results of these examinations were used to assist in quantifying potential reactor vessel failure modes, to estimate the vessel steel temperatures in the lower head during the accident, and to develop physical and mechanical property data to support the analysis effort. In the area of analysis, scoping calculations and sensitivity studies were performed in an effort to quantify the margin to failure for different reactor failure modes and to identify which modes had the smallest margin to failure during the accident.

The significant conclusions and accomplishments of each of the major project elements are discussed in the following text. Additional details on each of the major VIP elements and project results and conclusions are provided in a series of reports that were issued under the VIP.[5–12]

SAMPLE ACQUISITION

One of the major accomplishments of the VIP, accounting for approximately one-half of the total cost of $9 million, was the recovery of samples from the TMI-2 vessel lower head. This task, which was performed under the direction of MPR Associates, Inc., required careful planning because only a 30-day window was available at the site to set up the equipment and remove the samples. Specialized extraction tools had to be developed and tested before the actual sample removal.

One of the unique challenges in removing the samples was that the reactor vessel could not be breached or significantly weakened. Also, work had to be performed on a shielded platform mounted 40 feet above the lower head while samples that were covered by highly borated water were extracted. Because this was a first-of-a-kind process and the available time was limited, the exact number of samples removed could not be predicted in advance. It was hoped that 8 to 20 samples could be obtained. Despite extensive mock-up testing of the cutting tools, which used an electrical discharge metal disintegration process for cutting, a number of unexpected problems arose during the first half of the time for working in the reactor vessel, and no samples were taken during that time. The effort was very successful in the last half of the window, however, and 15 vessel steel samples, 14 nozzles, and 2 guide tubes were removed from the vessel in February 1990. The location of these samples is shown in Fig. 2. The prism-shaped vessel steel samples extended approximately half way through the 13.7-cm-thick reactor vessel wall.

GPU Nuclear provided access to the reactor during this window at its cost, and the VIP paid only the incremental cost of sample cutting and removal. An extension of the 30-day window would have added greatly to the cost of the project and was not financially possible for the VIP.

VESSEL STEEL EXAMINATIONS

Argonne National Laboratory (ANL) in the United States 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, in the United States, ANL and Idaho National Engineering Laboratory (INEL). 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 mechanical properties of the lower-head steels over the temperature range experienced during the accident. Optical metallography and hardness tests were performed to evaluate the microstructure to estimate the maximum temperature of 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 several 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 1 m by 0.8 m, as shown in Fig. 3. The hot spot was 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

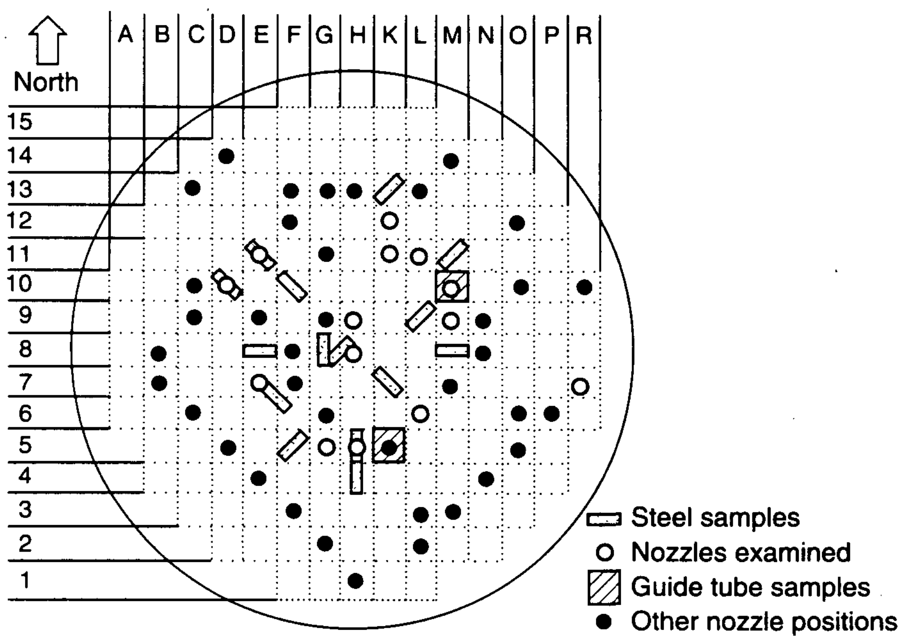

Fig. 2 Location of lower-head steel, nozzle, and guide tube samples.

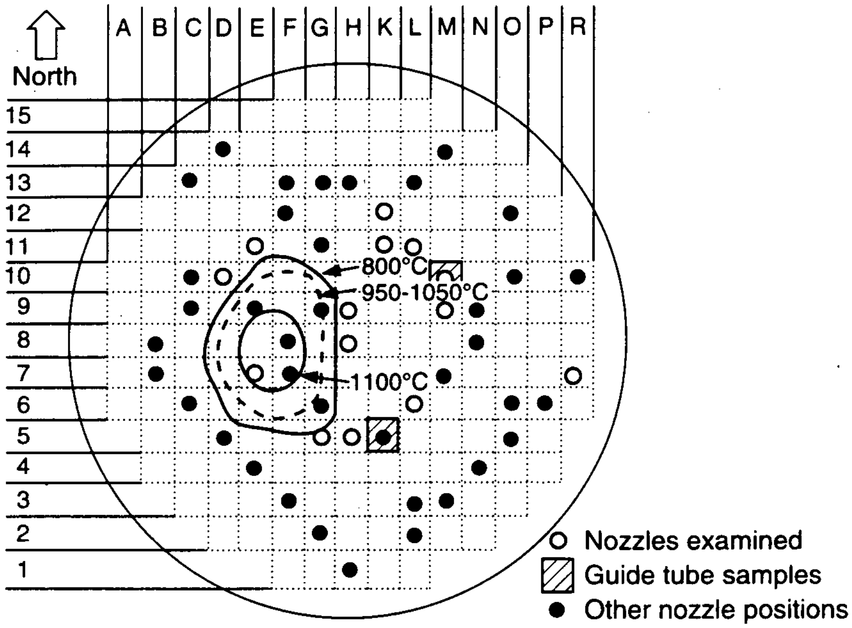

Fig. 3 Lower-head hot spot location.

location, temperatures 0.45 cm into the vessel wall were estimated to be 100 ± 50 °C lower than the peak vessel inner surface temperature.

By comparing results of the TMI-2 lower-head sample examinations with results from metallurgical examinations of heat-treated samples from an equivalent ("archive") steel from the Midland reactor, the vessel steel temperatures, time at temperature, and cooling rate were estimated. Standards with known thermal histories were prepared from the Midland archive material and later from actual as-fabricated TMI-2 material. The standards provided a means for comparing a similar material with a known thermal history to TMI-2 material with an unknown thermal history. As the standards were prepared and examined, various metallurgical observations revealed a stepwise process that could be used in determining thermal histories of the TMI-2 samples. G. Korth[6] constructed a diagram (shown in Fig. 4) that illustrates the metallurgical changes with time and temperature of the Midland and TMI-2 lower head A 533 B steel with a 308L stainless weld clad. Because the vessel was stress-relieved at 607 °C after the weld clad was added, no thermal effects from the accident could be detected at or below this temperature, and therefore the diagram shows only metallurgical observations for temperatures above this point. The lowest temperature indicator, above the stress relief temperature, was the ferrite–austenite transformation, which starts at 727 °C and is complete by about 830 °C. Variations in the typical as-fabricated hardness profile were evident when this temperature threshold was exceeded. The next indicator is the dissolution or dissipation of a dark feathery band at the interface between the base metal and the stainless steel clad; this occurs between 800 and 925 °C, depending on the time. The next indicator of increasing temperature is the appearance of small equiaxed grains, which formed in the A 533 B steel adjacent to the interface at temperatures between 850 and 900 °C and disappeared between 1025 and 1100 °C as they were consumed by grain growth in the low-alloy steel. Grain growth in the A 533 B steel becomes significant above approximately 950 to 1075 °C, depending on the time involved. The highest temperature indicator shown on the diagram is the change in morphology of the δ-ferrite islands in the stainless steel cladding. In the approximate range of 975 to 1000 °C at 100 minutes or 1100 to 1125 °C at 10 minutes, the δ-ferrite islands begin to lose their slender branch-like morphology and become spherical. Additional details on how these indicators were used to estimate the TMI-2 vessel steel sample temperatures are provided in Ref. 6.

Temperatures in the hot spot were considerably higher than those in the surrounding region of the lower head.

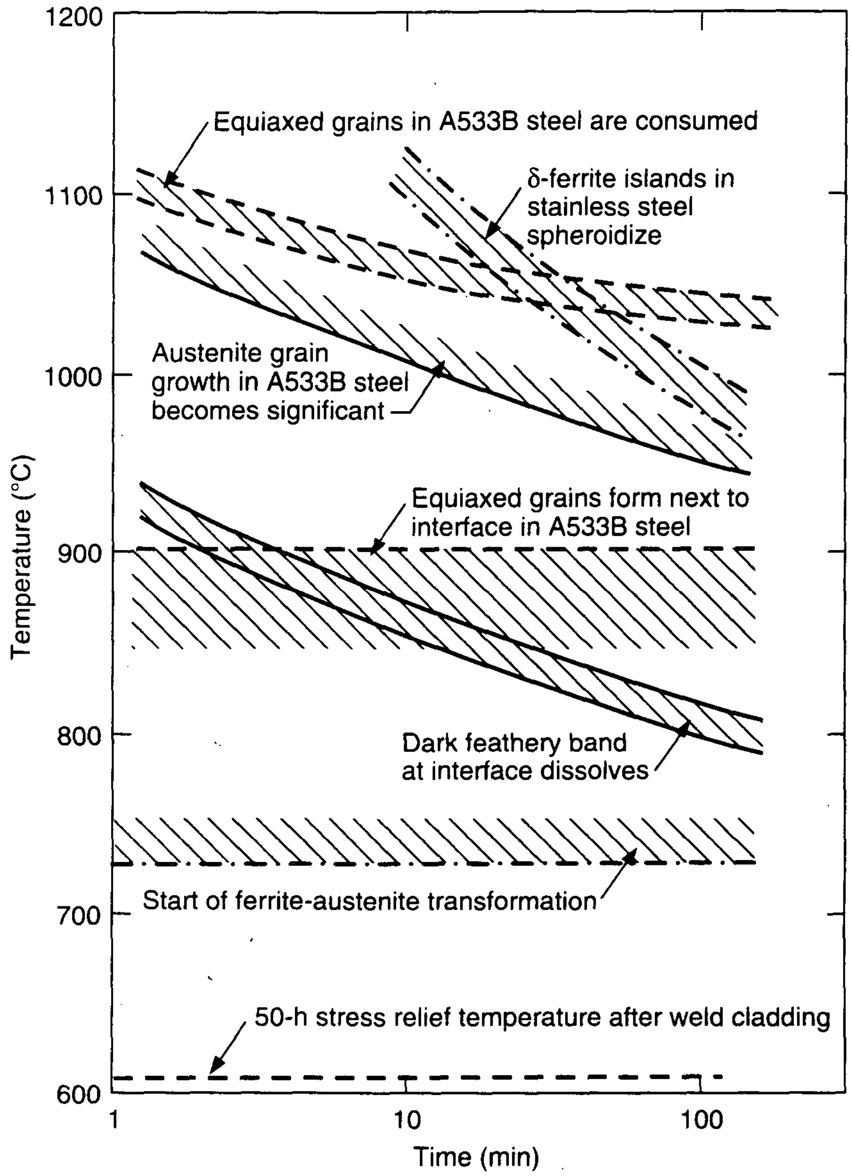

Fig. 4 Diagram of time–temperature observations of A 533 B pressure vessel steel clad with type 308L stainless steel.

Generally, the vessel temperature away from the hot spot did not exceed the 727 °C ferrite–austenite transformation temperature for the A 533 B pressure vessel steel. The results of metallographic and hardness examinations could determine whether the 727 °C transition temperature in the steel was exceeded. However, because microstructural and associated hardness changes in the steel do not occur below 727 °C, it was not possible to estimate how far below 727 °C the vessel steel temperature was away from the hot spot. Therefore there is a large uncertainty in the actual vessel steel temperature away from the hot spot. The temperature of the vessel inner surface in this region during the accident could have ranged from a minimum of 327 °C (normal plant operating conditions) to a maximum of 727 °C.

The hardness profiles of most of the TMI-2 samples had the typical characteristic profile of as-fabricated material, as shown in the shaded band in Fig. 5; but

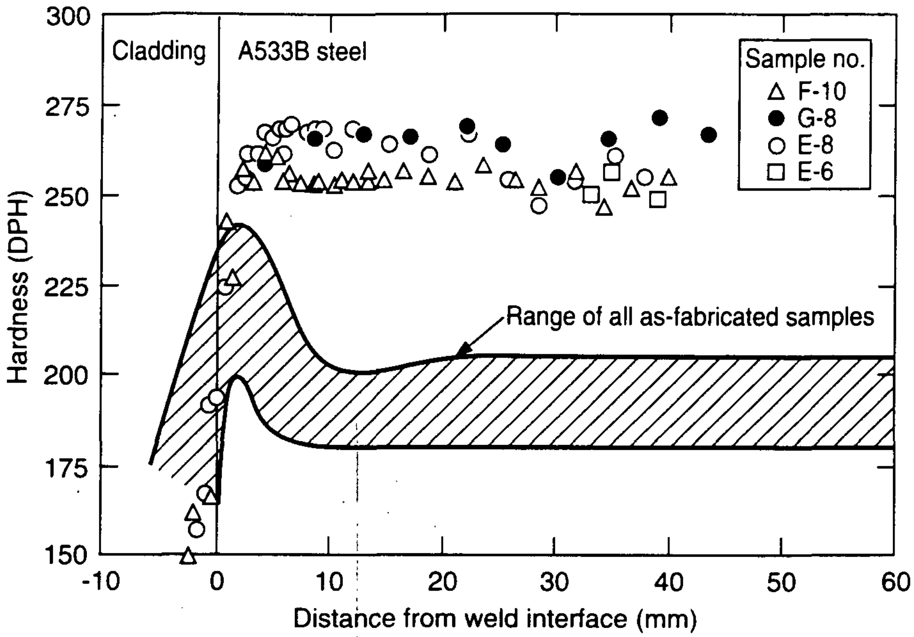

Fig. 5 Hardness profiles of samples F-10, G-8, E-8, and E-6 compared to the as-fabricated samples.

the hardness profiles from sample locations E-6, E-8, F-10, and G-8 (see Fig. 2) were markedly different from all other samples, as shown in this figure. In these four samples the characteristic hardness profile through the heat-affected zone near the clad weld interface had risen sharply to much higher levels and was then sustained throughout the full sample depth. Heat-affected bands from the weld cladding were not evident in these four samples but were completely eliminated by the thermal effects of the accident. Two other samples (H-8 and F-5) also showed anomalies in the hardness profiles. Results of these hardness profile measurements indicated which samples exceeded the 727 °C transformation temperature.

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 transformation temperature. It was also determined that samples in the hot spot may have remained at their peak temperature for as long as 30 minutes before being cooled.

Mechanical property tests performed on the TMI-2 vessel steel samples produced a wealth of high-temperature mechanical property data. Results of these tests, along with observations of the samples, provided information on the postaccident condition of the lower head as well as 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 which did not. Tensile tests for specimens that exceeded 727 °C showed significantly higher strengths at room temperature and at 600 °C when compared with those which 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 three nozzles. ANL analyzed vessel steel samples containing these cracks and found that the cracks penetrated only superficially 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 intergranularly 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 extracted from the vessel by being cut off as close to the lower head as possible. Four nozzles in the hot spot region were melted off almost flush with the vessel and could not be removed. The damage states of the nozzles and guide tubes and their location with respect to the hot spot are shown in Fig. 6.

The nozzles and guide tubes were removed and shipped to INEL; 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 core material 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

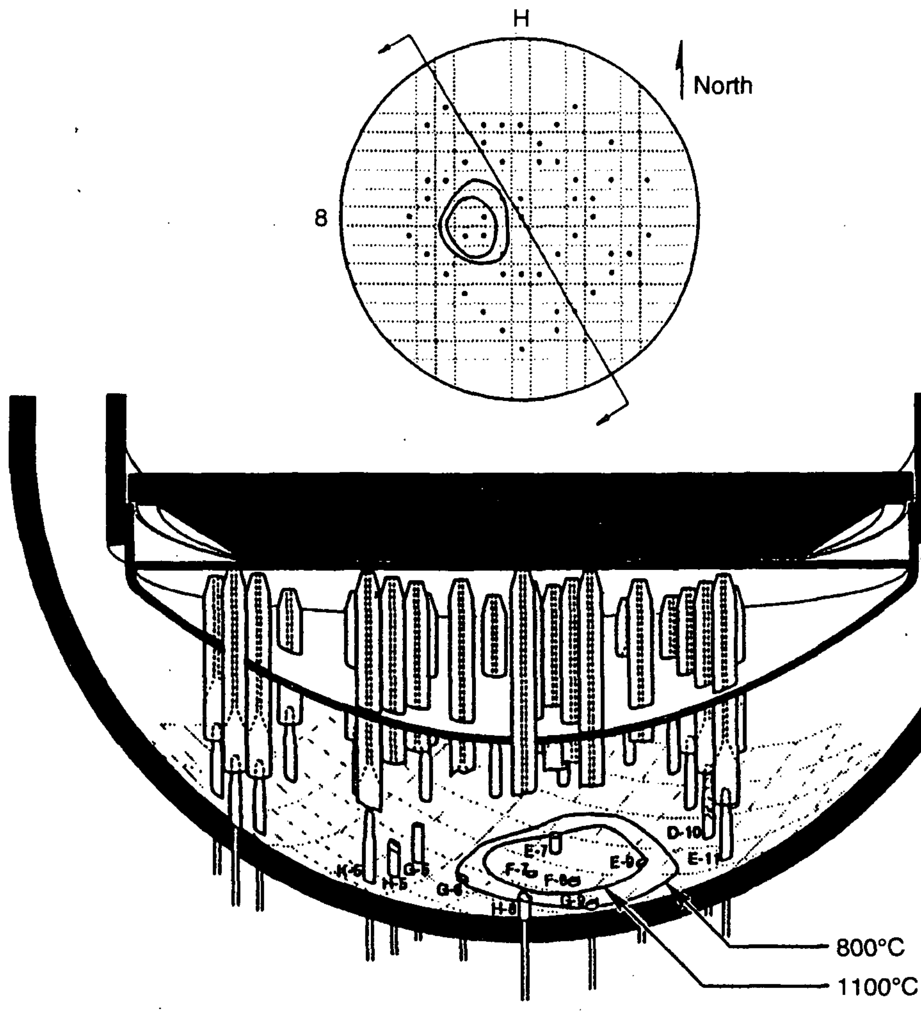

Fig. 6 TMI-2 lower head, southwest section.

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 140 to 270 mm 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 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 140 and 64 mm above the lower head, respectively. The penetration of debris downward into the nozzles was probably influenced by the temperature of the molten material 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 molten debris 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 before the primary fuel relocation. The early movement of control material to the lower head was substantiated by the presence of control assembly material found in the cladding tears. However, it was not possible 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 because they came from the 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 were used to determine the debris composition and to estimate 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 the quadrant from which 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 Fe, Ni, and Cr. Control-rod materials such as Ag, In, and Cd were present in low (<0.5 wt%) concentrations. The average sample debris density was 8.4 ± 0.6 g/cm^3 with an average porosity of $18 \pm 11\%$. Overall, the examinations indicated that the companion samples were relatively homogeneous with small variations in composition and density.

On the basis of the debris composition, it is quite probable that the molten material reached temperatures greater than 2600 °C in the central core region before relocation. The temperature of the debris when it reached the lower head is not known. However, the material reached the lower head in a molten state, and results of the examinations suggest that portions of the debris cooled slowly over many hours.

Radiochemical examinations indicated that the primary radionuclides retained in the debris bed were medium and low volatile constituents. Almost all 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 estimating the debris decay heat and the resulting heat load on the lower head. Decay heat calculations indicated an overall heat load of $0.13 \pm 20\%$ W/g of debris when the relocation occurred at 224 minutes after scram and $0.096 \pm 20\%$ 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.

The average burnup of the TMI-2 core at the time of the accident was relatively low. If the accident had occurred with the core near its end of life, the debris would have had a higher decay heat load. Although more volatile fission products would be retained in higher burnup fuel, calculations indicate that the decay heat for relocated fuel from a full burnup core would increase by less than 20% above that for the TMI-2 accident for the time period of concern (i.e., the first 16 hours after reactor scram).[11] Such a change in decay heat level would not have significantly altered the results of the margin-to-failure analysis or the conclusions of the VIP.

MARGIN-TO-FAILURE ANALYSIS

The final element of the VIP, the margin-to-failure analysis, was performed to investigate mechanisms that could potentially 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: (1) nozzle examination data for characterizing melt composition and penetration distances within instrument tubes; (2) companion sample examination data for characterizing debris properties (e.g., decay heat and material composition); and (3) vessel steel examination data for characterizing peak vessel temperatures, duration of peak temperatures, and vessel cooling rate.

The margin-to-failure analyses provided significant insights into potential failure mechanisms of the TMI-2 lower head. Results of 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 ex-vessel tube rupture as a failure mechanism. Analyses also indicated that the instrument tube weld would remain intact even if the peak reactor coolant system (RCS) pressure were 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.

Calculations indicated 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.

Because of insufficient available data, it was not possible to come up with a best-estimate quantification of the margin to failure for global or local creep rupture of the lower head. Such failures would be associated with high temperatures on the lower head coincident with high reactor coolant system pressure. However, an extensive series of analyses and calculations was performed[10] with the best available information to try to scope the issue as described in the following text.

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 such parameters as debris decay heat, outer vessel heat-transfer coefficient, and the debris-to-gap heat-transfer resistance. Calculations for both of these cases indicated that global failure caused by creep rupture was predicted to occur within the first 2 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 at 320 minutes after reactor scram.

Localized vessel failure analyses 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 (i.e., outside the area of the hot spot) remained relatively cool. Localized calculations also indicated that the predicted time to vessel failure was reduced when a localized hot spot was superimposed on the calculated best-estimate background temperature (i.e., outside the hot spot).

Taken together, the localized and global vessel failure calculations indicated that the background vessel steel temperature behavior, which greatly depends 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 can potentially reduce structural damage and preclude global vessel failure even at high pressure and in the presence of a localized hot spot.

Thermal and structural analysis results were dominated by input assumptions on the basis of companion sample examination data, which suggested that the debris experienced relatively slow cooling over a period of many hours. However, differences between these analysis results and data from the vessel steel examinations indicated that the entire lower head cooled within the first 2 hours after debris relocation. An energy balance that considered coolant mass flows entering and exiting the vessel supported the hypothesis that the debris cooled in the time period between relocation and vessel repressurization.

Although there are insufficient data to quantitatively determine the exact mechanisms that caused this cooling, scoping calculations were performed to investigate possible mechanisms that could provide this cooling. In these analyses it was assumed that the simultaneous presence of cracks and gaps within the debris provided multiple pathways for steam release (e.g., water may travel down along the gap and boil up through cracks). Results of these calculations indicated that a minimal volume of cooling channels within the debris and a minimal size gap between the debris and the vessel could supply the cooling needed to obtain vessel temperatures and cooling rates determined in metallurgical examinations. Such cooling is not currently modeled in severe accident computer codes. Also, there are uncertainties in models that estimate the cooling of debris as it breaks up and relocates to the lower plenum through water. Some questions also remain regarding the best failure criterion to be used for predicting vessel failure. However, the uncertainties in the amount of debris cooling on the lower head appear to be more significant for quantifying the margin to failure of TMI-2 vessel than either the vessel failure criterion or cooling of debris as it relocates to the lower plenum. Because of these uncertainties, results of the margin-to-failure analysis should be viewed as providing insights into areas such as identifying the failure mode with the smallest margin during the TMI-2 event and emphasizing areas in which additional research may be needed in severe accident analysis.

CONCLUSIONS

Through the efforts of the VIP signatories who supported the project, numerous significant contributions were made that dramatically increased both the understanding of 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 examinations indicated that a localized hot spot developed in an elliptical region approximately 1 m by 0.8 m. 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 0.45 cm into the 13.7-cm-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 postaccident 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 toward the hot spot location in the western sector.

• 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.

• Analyses results indicated that a localized effect, such as a hot spot, can shorten the overall vessel failure times caused by creep rupture. However, by itself it is unlikely to cause vessel failure for the temperatures and pressures that occurred in the vessel during the TMI-2 accident.

• 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 after reactor scram.

• Even though a definitive scenario describing the movement of molten debris and the formation of a localized hot spot cannot be determined, considerable evidence indicates that a debris layer containing both ceramic and metallic material insulated the lower head. The hot spot formed in a location where this layer had insufficient thickness to effectively insulate the lower head from the molten flow.

SIGNIFICANCE OF THE VIP FINDINGS

One of the most important implications of the VIP conclusions relates to accident management. The TMI-2 accident began with the main feedwater pumps' trip, an anticipated event. It was compounded by closure of the auxiliary feedwater system block valves, a human procedural error, and by the failure of the pressurizer relief electromatic valve to close after the proper relief of excessive primary system pressure, an electromechanical fault. The operator action of reducing the high-pressure safety injection system flow turned the event in a very serious direction. The operator had erroneously interpreted the indication of rising pressurizer water level to mean that the reactor coolant system was nearly filled with water, whereas in actual fact it was becoming a saturated system with steam formation caused by the loss of primary coolant. The operators failed to regain control of events in the first 100-minute period short of severe damage, which was the first opportunity for accident management. However, the operators were successful in discovering and opening the auxiliary feedwater system block valves early in this period, a necessary condition for final stabilization and recovery. In the intervening period of time since the TMI-2 accident, the total set of actions carried out to improve the interface between control room person and machine, to increase emergency safety system reliability, to develop emergency symptom-oriented procedures, and to improve reactor operator training makes a repetition of such a failure very unlikely.

In the subsequent severe accident phase of TMI-2, the operators, though halting and inexperienced in an unknown field of reactor operations, were finally successful in stabilization and recovery. They isolated the stuck-open pressurizer relief valve and reactivated the high-pressure safety injection pumps, which were also necessary conditions, and thus enabled restoration of cooling water and heat removal in the primary system. This was the second and more difficult opportunity for accident management. The operators had cooling water and emergency power and pumps at their disposal, and they used them. The core was not cooled immediately when cooling water flow was restored. A crust surrounded the molten ceramic pool and prevented water from penetrating and cooling the material. The ceramic pool and surrounding crust continued to grow for about 25 minutes after high-pressure injection cooling water flow was restored until the crust broke through at its side at 224 minutes into the accident. The molten core material subsequently cooled after flowing to the vessel lower head. The experience at TMI-2 thus validates the importance of accident management and perseverance in a strategy of delivering cooling water. But it is also now clear as a result of the VIP that the reactor vessel provided a previously unrecognized defense in depth for a severe accident that was, of course, essential to success.

To pursue this point further, the VIP has also shown that global creep failure of the reactor vessel could occur under conditions of high vessel temperature and high pressure. Therefore accident management procedures should recognize the following: (1) the importance of cooling water not only for the reactor core but also for limiting the reactor vessel wall temperature and (2) the need for controlling pressure to avoid vessel creep failure. There should be here a word of caution about energetic fuel–coolant interactions (FCI) that could challenge pressure vessel integrity. We know that such an interaction did not occur at TMI-2 (Ref. 3), but some work on FCIs indicates an increased potential for triggering an FCI at low pressure.[13] Nevertheless, most experts today believe that depressurization should take priority over the FCI concerns. Work separate from the TMI-2 VIP is under way to address remaining questions about energetic FCIs.

As a follow-up to the TMI-2 VIP, additional research can confirm the conditions under which reactor vessel integrity is likely to be maintained during a severe accident. The cooling of the external reactor vessel, by flooding the cavity surrounding the lower part of the reactor vessel, could reduce the potential for reactor vessel failure. Analysis of the effects of ex-vessel cooling or plant-specific design features, such as vessel support structures or insulation that could restrict the flow of coolant or steam around the lower head, were not part of the VIP. However, several logical follow-on programs to the VIP, both internationally and at NRC, are currently under way or are in the planning stages to address reactor vessel failure issues. Additional research could also improve the understanding and quantification of the cooling of debris by water on the lower head.

The participants among the NEA-OECD countries examined the evidence, analyzed it, and reached conclusions about the accident as far as was possible. The international support and cooperation among the project participants, both technical and financial, helped make the TMI-2 VIP a success. For example, independent examinations of the vessel steel samples at laboratories around the world corroborated the estimated steel temperatures in the hot spot, which added credibility to the findings and conclusions of this project. Analysis of the accident shows that the TMI-2 reactor vessel was more robust than experts believed 15 years ago when the accident occurred and that this fact has broad implications for the accident management and safety of light-water reactors.

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