V

CONF-830816--41

EGG- M-08483
PREPRINT

EGG-M--08483

DE84 000892

TMI-2 Core Damage: A Summary of Present Knowledge

D. E. Owen
R. E. Mason
R. D. Meininger
W. A. Franz

August 28 - September 1, 1983

International Meeting on LWR Severe Accident Evaluation

EG&G Idaho
Idaho Falls, Idaho 83415

DISCLAIMER

TMI-2 CORE DAMAGE: A SUMMARY OF PRESENT KNOWLEDGE[a]

D. E. Owen, R. E. Mason, R. D. Meininger, and W. A. Franz

EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415

INTRODUCTION

Analysis of the extent of core damage resulting from the March 1979 accident at the Three Mile Island Unit 2 reactor (TMI-2) began soon after the event and continues to this day. Based primarily on instrument data acquired during and immediately following the accident, computer code reconstructions of the accident scenario have been used to (a) explain the observed and measured reactor system responses and (b) predict key features of the accident for which little or no on-line data were obtained. While the TMI-2 damage analyses have been important, increasing effort has been placed on direct observation of the core damage or on measurements which allow inference of the extent of core damage. These TMI-2 core examination activities are important to both light water reactor (LWR) severe accident data acquisition programs and the TMI-2 accident recovery efforts. These core examination tasks contribute to the understanding of important LWR safety issues, including fission product release, transport, and deposition; severe accident damage processes; hydrogen generation; and containment integrity. In addition, these tasks provide core condition data to plan certain aspects of the TMI-2 defueling; for example, specialized tools and equipment needed to disassemble and remove the damaged core. The purpose of this paper is to review these recent findings and summarize what is currently known about the condition of the TMI-2 core.

CORE DAMAGE DATA ACQUISITION TASKS

Research tasks sponsored by the Department of Energy and performed by GPU Nuclear Corporation and its contractors are being performed to acquire a variety of data on the TMI-2 accident. Several of the research tasks have produced both direct and inferred data on the extent and nature of the core damage and on the postaccident condition of the TMI-2 core. These research tasks include:

- o Axial power shaping rod movement
- o Closed-circuit television camera inspection
- o In-core instrument evaluation
- o Leadscrew uncoupling
- o Makeup and purification system filter debris analysis
- o Leadscrew analysis.

The axial power shaping rod (APSR) movement test was one of the first tasks from which core damage information could be inferred. TMI-2 contains eight APSR clusters, symmetrically located at approximately the one-half core radius position. The APSRs are similar to control rods, except that they remain withdrawn when the reactor scrams. The APSR movement test consisted of driving the APSR clusters into the core to a full stop position while monitoring their movement electrically and acoustically. This was considered a sensitive operation because it was the first deliberate movement of material into what was believed to be a severely oxidized and fragile reactor core. Only two of the eight APSR clusters could be driven to their fully inserted position; three were partially inserted, and three could not be moved.

Soon after the APSR movement test, data were obtained from the in-core instrument evaluation. Resistance and time-domain reflectometry measurements made on the 52 in-core instrument strings [each containing one thermocouple and seven axially spaced self-powered neutron detectors (SPNDs)] suggested regions of severe in-core instrument damage and, by implication, severe fuel damage. These data indicated damage to the upper portions of a large number of fuel assemblies located in certain regions of the TMI-2 core.

The in-core instrument data were soon confirmed by the closed-circuit television camera (CCTV) inspection. The CCTV inspections determined that at least the top ~1.5 m of the central part of the TMI-2 core had fragmented into a rubble bed. The rubble bed surface consisted of granular debris with some larger, recognizable fuel cladding and structural pieces. The CCTV inspection also determined that local regions of the structural components at the top of some fuel assemblies reached stainless steel melting temperatures, and that the severe fuel rod damage extended radially outward to slightly beyond the one-half radius position.

Additional insight into the nature of the observed core damage has been obtained from the analysis of the makeup and purification system filter debris and the control rod drive leadscrews. A portion of the primary system water was diverted through the makeup and purification system following the accident. In-line filters, which plugged with core debris, were shipped to several remote handling facilities for analysis. Similarly, control rod drive leadscrews removed from selected core locations to provide CCTV access paths were

a. Work supported by the U.S. Department of Energy, Office of Terminal Waste Storage and Remedial Action, under DOE Contract No. DE-AC07-76ID01570.

analyzed. The nature of the filter debris and condition of the leadscrews, as well as the material deposited on them, have provided data from which core damage phenomena can be inferred.

Each of these tasks has provided some unique data on the nature and extent of TMI-2 core damage. The following section summarizes the information learned from these tasks and presents the current knowledge of the core damage generated during the accident and of the postaccident condition of the core.

TMI-2 CORE DAMAGE

Extent of Damage

The eight axial power shaping rod assemblies in TMI-2 each consist of a cluster of sixteen stainless steel cladding tubes containing Ag-In-Cd alloy neutron absorber material. The sixteen absorber rods are joined at the top to a common spider, which in turn is coupled to a leadscrew. The leadscrew is inserted or withdrawn by a rotor/stator drive mechanism. Each APSR cluster is inserted into a fuel assembly through guide tubes located within the assembly. Unlike control rods, the APSRs are not automatically inserted during a reactor scram. Thus, the TMI-2 APSR assemblies remained in a 25% withdrawn position following the accident. Complete insertion of the APSRs, or at least insertion to a hard stop position, is needed to uncouple the APSR assembly spiders from their drive leadscrews. Movement of the APSRs would also cause the rods, if they were intact, to pass through a portion of the reactor core and the reactor plenum structure (located immediately above the core). Thus, the APSR movement test was devised to both move the APSR assemblies to a fully inserted or hard stop position as a prerequisite to subsequent uncoupling, and to infer the condition of the TMI-2 core and plenum structure by the ease of APSR movement.

Following laboratory tests and tests on undamaged APSR assemblies from the TMI-1 reactor, the TMI-2 APSR assemblies were instrumented with acoustic transducers and electrical signal recording equipment to record the performance of their drive mechanisms. The acoustic transducers recorded the unique sound signatures of the basic features of APSR motion (e.g. drive mechanism latching, unlatching, motor pole slips, etc.), as well as any core disruption, such as fuel assembly breakage, caused by APSR movement. The electrical signal recorders monitored motor parameters (which can in turn be correlated with rod insertion force), as well as linear travel of the APSR drive leadscrew.

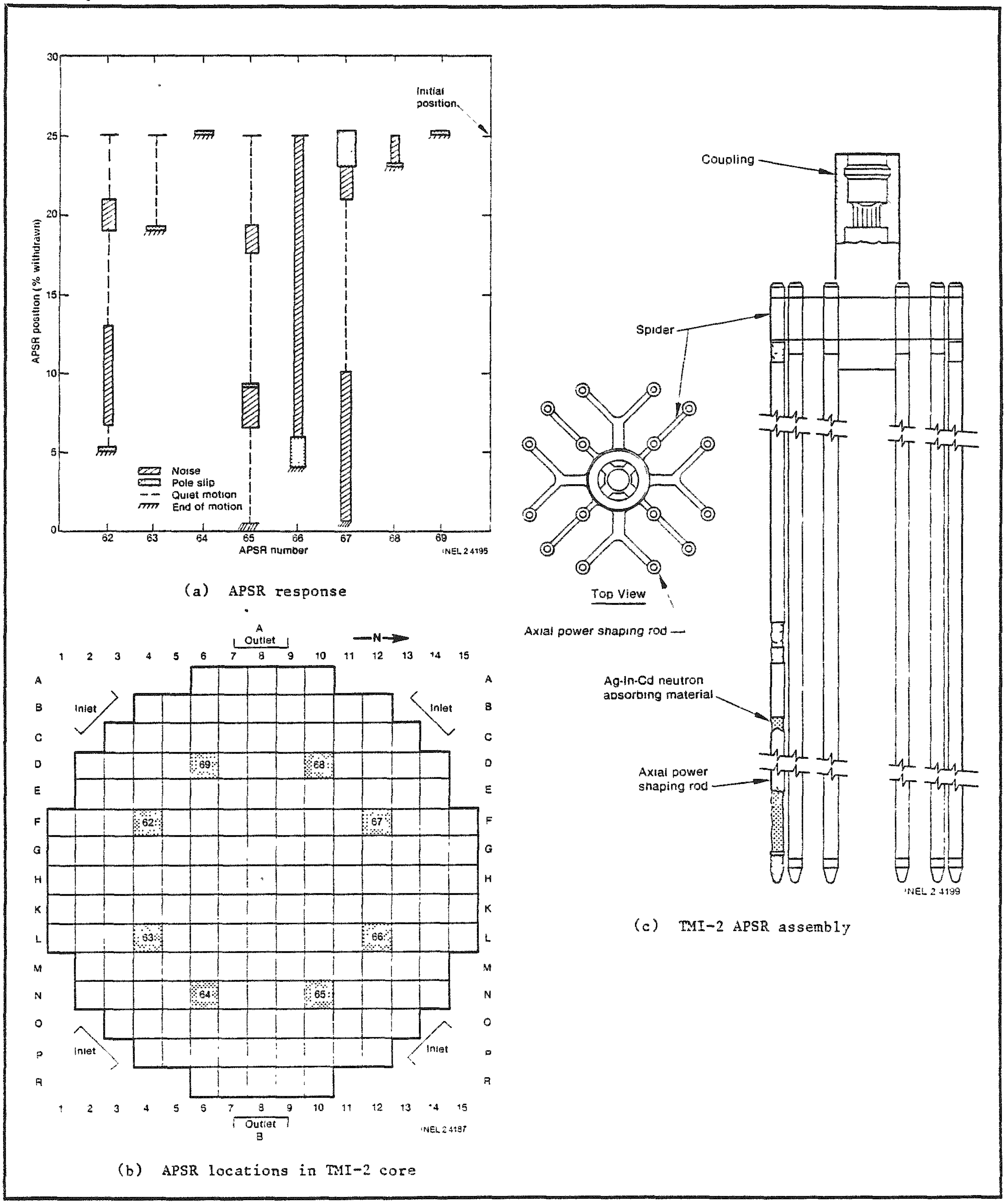
The results of the APSR movement test(1) are summarized in Figure 1(a). With all eight APSR assemblies starting from their normal shutdown position of 25% withdrawn, two of the APSRs were fully inserted, three were partially inserted, and three were essentially immovable. As Figure 1(a) indicates, APSR movement was generally accompanied by periods of acoustic noise atypical of APSR movement in an undamaged reactor. There were no noises, however, indicative of fuel assembly or plenum damage or disruption during any APSR movement. Examination of Figure 1(a) reveals that, although none of the acoustic profiles are exactly alike, there are several common areas in the APSR movement path associated with high acoustic noise or APSR obstruction. These zones, at about the 20% withdrawn position and the 5 to 10% withdrawn position, were the subject of additional analysis to determine whether the reasons for APSR motion interference could be identified and correlated with either APSR or drive mechanism damage caused by the accident.

When the APSRs are partially withdrawn, as was the case at the start of the APSR movement test, part of each rod assembly (∿75% of its length) is within guide tubes in the core and part (∿25% is within guide tubes in the reactor plenum region located immediately above the active core. In both locations, the vertical guide tubes are held in position by axially spaced horizontal alignment structures. In the core region, fuel assembly spacer grids provide the alignment, whereas in the plenum region, alignment is provided by guide tube assembly brazement plates. Analysis of the APSR movement test data revealed that damage or distortion of either of these alignment structures could explain APSR movement noise or stoppage, depending on the assumptions made about the extent of damage to the APSRs themselves. If the individual rods were still intact, then resistance to movement could be a result of guide tube distortion in the vicinity of the bottom two spacer grids in the fuel assemblies into which the APSRs are inserted. However, if those portions of the APSRs that were in the core were destroyed or broken off by the accident, then the resistance to movement would more likely result from the interference of the APSR stub assembly (the short length remaining in the plenum region) with distortion of the guide tubes in the vicinity of the bottom three guide tube brazements in the plenum. Since the actual extent of damage to the APSRs themselves was not known, the source of rod motion noise or rod stoppage could not be unambiguously determined. Thus, even though the response of the APSRs to the movement test implied some major damage or distortion, the implications for the extent of TMI-2 core damage were not clear.

Shortly after the TMI-2 APSR movement test, the TMI-2 closed-circuit television camera examination provided a partial answer to the ambiguous interpretation of APSR movement, as well as substantial additional information on specific core damage features. The CCTV examination provided direct observation of TMI-2 core damage by lowering a radiation-resistant TV camera into the core via openings created by the removal of selected control rod drive leadscrews. Core damage was viewed directly at the center of the core and at approximately the one-half core radius position. A third core inspection attempt at a position near the core periphery was blocked by the presence of the control rod assembly spider and, presumably, the underlying fuel assembly. [Specifically, CCTV inspections were made at core locations H8, E9, and B8; see Figure 1(b) for orientation.]

The results of the CCTV camera inspections have been previously reported.(2,3,4) Briefly, the inspections revealed:

- A large void exists in the upper center of the core due to fragmentation of the fuel and settling or redistribution of



(a) APSR response

(b) APSR locations in TMI-2 core

(c) TMI-2 APSR assembly

FIGURE 1. AXIAL POWER SHAPING ROD MOVEMENT TEST RESULTS.

the fuel debris. At the center of the core (position H8), the top 1.60 m of fuel is missing. At the specific half-radius position inspected (position E9), the top 1.52 m of fuel is gone.

- At the core center location, the debris bed was relatively flat and level and consisted of granular material with an apparent average size of ~0.5 cm. At the half radius location, the surface of the debris bed was irregular and the debris pieces were of larger average size, including cladding shards and fuel rod pieces many centimeters long. At several locations, small ([0.5 cm), apparently once-molten nodules were seen in the loose debris.

- As determined by probing with a steel rod, the rubble bed at both the center and half radius positions consists of loose, easily penetrated debris to a depth of at least 35.5 cm.

- At the half-radius location, there are some fuel assembly upper end-fittings hanging unsupported from the underside of the plenum that contain some damaged fuel rods and control rods. There is evidence of some melting of parts of the stainless steel end-fittings.

- The bottom of the reactor upper plenum assembly, including the control rod and APSR guide tubes and brazements, appears relatively undamaged.

A summary of the key CCTV camera inspection findings is presented in Figure 2. Figures 3 and 4 illustrate some of the observed TMI-2 core damage features.

The CCTV camera examinations confirmed earlier calculations[5] that the TMI-2 accident produced major oxidation of the upper central portion of the core, and that the consequent fuel rod cladding embrittlement caused fuel rod fragmentation and core slumping by thermal shock during the reflood stages of the accident. The examinations belied calculations that the embrittlement extended to essentially the core periphery. Calculations indicating that fuel liquefaction (UO_2 dissolution by molten zircaloy) occurred in the core can neither be confirmed nor refuted by the CCTV camera observations.

Examination of the top view of Figure 2 provides a partial explanation of the ambiguous nature of the APSR movement test results. The ring of APSR assemblies marks the approximate demarcation between major core damage and relatively intact fuel assemblies. It appears likely that damage to the APSRs was extensive enough that some, if not all, of the rods are missing or severely damaged. It is thus clear that the observed resistance to APSR assembly motion is not the result of rod interference with distorted guide tubes or spacer grids low in the core. Similarly, the observation of generally intact plenum assembly guide tubes implies that neither is the resistance to movement a result of rod stub interference with distorted plenum guide tubes or brazements. At this time, the most likely explanation is that high temperatures at the very

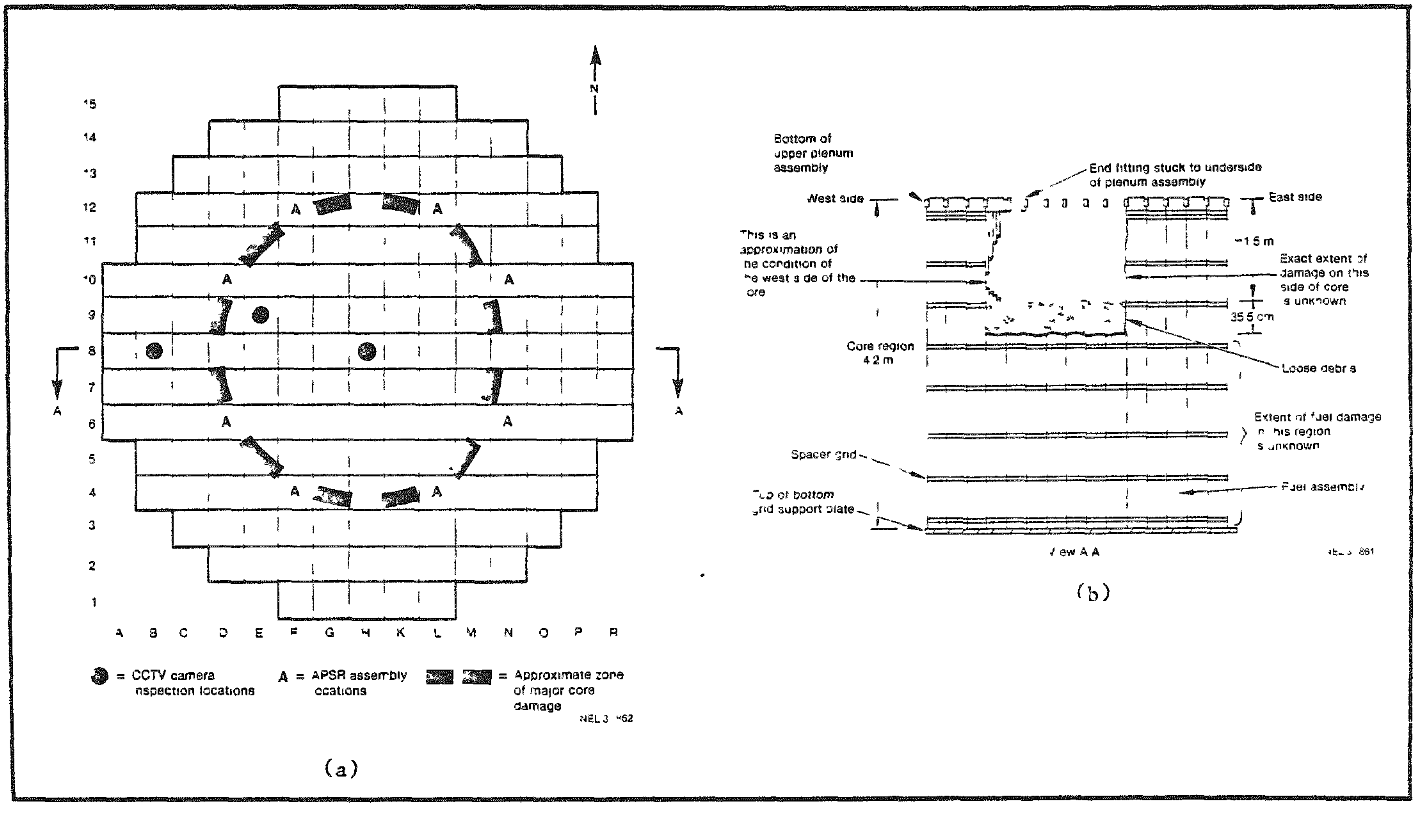


FIGURE 2. CORE DAMAGE AS REVEALED BY CCTV CAMERA INSPECTIONS.

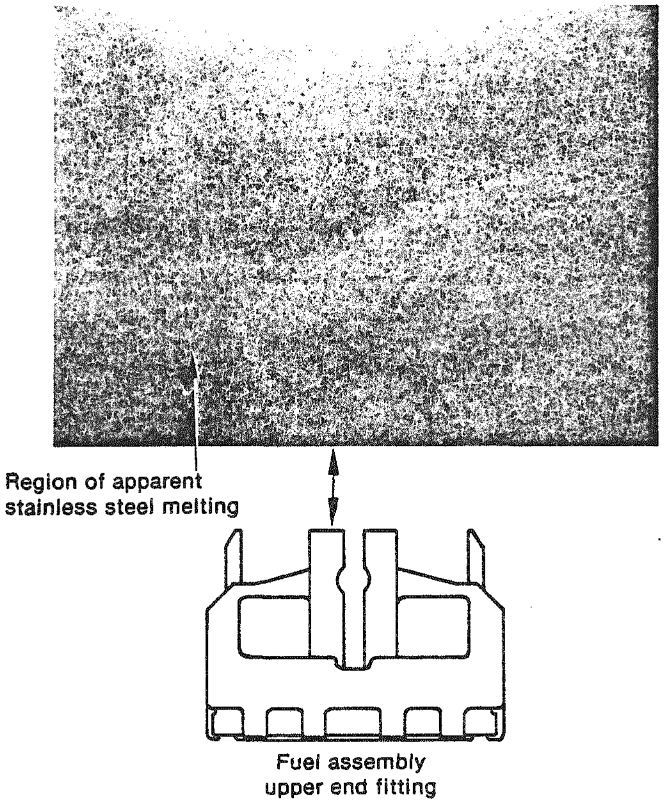


FIGURE 3. PARTIAL MELTING OF TMI-2 STAINLESS STEEL FUEL ASSEMBLY END FITTING.

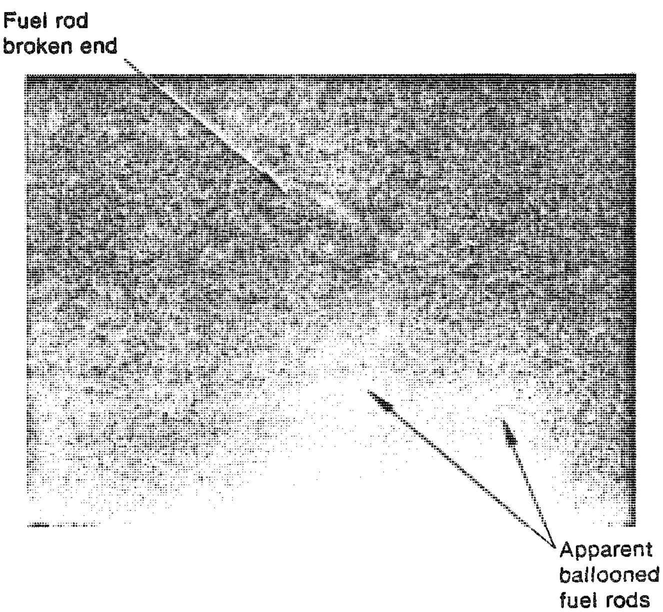


FIGURE 4. BALLOONED AND FRACTURED TMI-2 FUEL RODS.

top of the core (as evidenced by the observed partial melting of some stainless steel end fittings) severely distorted the APSR stubs or fused the APSR cladding to the upper end fittings.

Additional insight into the localization of TMI-2 core damage has come from the postaccident analysis of in-core instrumentation. The instrument strings pass up the center flow tube of 52 fuel assemblies. The seven SPNDs in each instrument string are approximately evenly spaced over the fuel length, and the thermocouple is located immediately above the active core in order to measure fuel assembly coolant exit temperature. Resistance and time-domain reflectometry measurements made on the in-core instruments following the TMI-2 accident were compared to preaccident reference data in order to evaluate incore instrument damage,(6) which presumably correlates well with general core damage. The relatively uniform array of instrument strings in the core was used to estimate the general extent, both radial and axial, of core damage.

Measurement of the postaccident thermocouple resistances revealed three distinct groups: Group 1 corresponded to an apparent average reduction in length of $\sim$6 m; Group 2 corresponded to an apparent average reduction in length of $\sim$3 m; and Group 3 consisted of thermocouples for which the data and, consequently, the thermal damage estimates, were inconsistent. (It should be emphasized that these relative length reductions are based on resistance changes; actual length reductions are uncertain because resistance changes are a function of initial conditions and of reduced length and high temperature reaction of the wire, sheath, and insulation.) Groups 1 and 2 are shown in Figure 5 as areas of "high apparent thermocouple damage" and "apparent thermocouple damage," respectively. Similar analysis of SPND data showed that almost all of the SPNDs in the upper part of

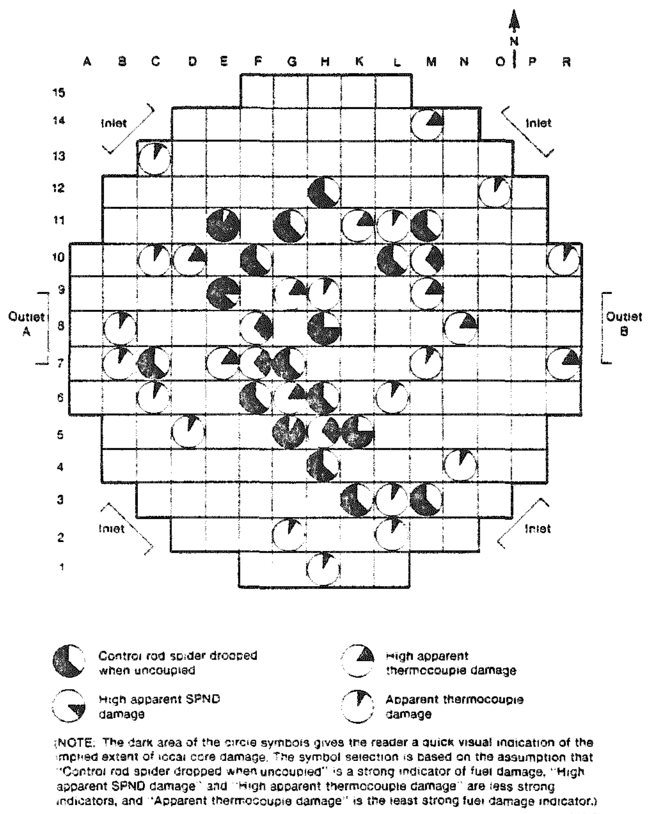


FIGURE 5. INDICATORS OF TMI-2 CORE DAMAGE BASED ON IN-CORE INSTRUMENT AND LEADSCREW UNCOUPLING DATA.

the core were damaged, regardless of radial location, implying widespread damage in the upper part of the core. In addition, a sub-group of instrument strings were identified in which all seven of the axially spaced SPNDs appear to be damaged, implying that core damage in these locations extends over essentially the entire fuel assembly length. These locations are shown as "high apparent SPND damage" in Figure 5.

Data with strong core damage implications are also available from the control rod drive leadscrew uncoupling task. This task involved manual uncoupling of the 69 control rod drive mechanism leadscrews and 8 axial power shaping rod leadscrews from the control element spiders to which they were attached. (Such uncoupling of the leadscrews is a prerequisite to reactor vessel head lift.) During the uncoupling process, it was possible to tell the behavior of the control element spider to which the leadscrew was attached. In some instances the spider dropped, indicating that the fuel assembly normally supporting the control element spider was either absent or damaged. If the spider dropped following uncoupling, it was not possible to determine exactly how far it dropped, other than it had to drop at least 5 cm, otherwise it would have been possible to reengage it. In the central region of the core where the CCTV camera revealed a core void, it is likely that the spiders fell down onto the rubble bed; in fact, the spider from the center core position (H8) was observed on the rubble bed during the CCTV camera inspection. At other core locations, it is not known whether the spider fell completely away or whether the underlying fuel assembly was only damaged, not absent, in which case the spider could have dropped only slightly. Regardless, the fact that the spider dropped at all during uncoupling implies significant damage to the underlying fuel assembly. Those control element locations at which the spiders dropped are also shown in Figure 5.

Comparison of Figure 2 (damage directly observed by CCTV camera inspections) with Figure 5 (damage zones implied by the analysis of in-core instruments and control element spider movement) indicates that core damage extends radially and axially beyond the obvious core void. Most accident scenario analyses also predict a gradation of fuel rod damage ranging from zircaloy cladding ballooning and rupture, to various stages of cladding embrittlement and fragmentation, through fuel liquefaction. Unless very sophisticated core debris sampling programs are developed, the full extent of core damage will not be revealed until reactor defueling.

Type of Core Damage

The tasks described above have helped reveal the extent of TMI-2 core damage. Other research tasks have provided data on the specific high temperature materials interactions that occurred during the TMI-2 accident. A portion of the TMI-2 primary system water was diverted through the reactor's makeup and purification system during and following the accident. In-line filters which plugged with core debris were analyzed. Analysis revealed that this small (average size ∿6 um) particulate debris was primarily composed of non-fuel-rod components. Stainless steel and Inconel alloying elements (from structural components and control rod cladding) were found in ∿70% of the particles examined, whereas Ag-In-Cd control materials were found in ∿60%. Most particles contained many elements, indicating extensive reaction among the fuel rods, control rods, and structural components of the core. The most spherical particles were small (average size ∿2 μm) and were primarily composed of control materials and, in some cases, appeared to be almost pure Ag or Cd. These observations are consistent with extensive melting of the control rod alloy--a likely occurrence since the melting point of the Ag-In-Cd alloy (1050 K) is substantially lower than the currently known minimum peak core temperature of 1720 K (the stainless steel melting point).

The concentration of certain fission products (Cs, Sb, Ru, and Sr) in the filter debris was greater than could be accounted for by the fuel content of the debris, which was only 6% U by weight. Released fission products may have been deposited on aerosols generated by the vaporization of core materials, and then transported out of the reactor vessel with the aerosols. Volatilized Ag-In-Cd alloy is the most likely aerosol source, and the sphericity and the small average particle size of these materials in the filter debris is consistent with this hypothesis.

Portions of the ∿7.3-m-long control rod drive leadscrew H8 (from the center of the core), which was removed to allow CCTV camera access to the core, were examined.[8] The sample subjected to the most thorough examination was located approximately 4.3 m above the bottom of the leadscrew at a reactor elevation just above the plenum assembly. This section, a threaded length of 17-4 PH (precipitation hardened) stainless steel, was found to have loose particulate debris on the surface and a multilayer corrosion film on the stainless steel. Mean particle size of the leadscrew deposits was 5.8 μm, approximately the same as the filter debris. As was the case with the filter debris, the leadscrew deposits indicated extensive core materials reaction. Leadscrew deposit particles bearing U and Zr (indicating fuel-cladding interaction) accounted for ∿10% of the particles analyzed. The presence of Zr-Ag bearing particles, which constitue ∿6% of the particle population, indicates that the low-melting-point Ag-In-Cd control material reacted with the zircaloy fuel rod cladding or guide tubes.

Metallography and microscopy revealed three distinct layers on the leadscrew. An inner ∿3-um-thick layer was identified as being a typical reactor water corrosion film. A second, Cr-rich layer 10 to 90 um in thickness was also identified. About 90% of the fission product cesium on the leadscrew sample was associated with this layer. The cesium was very tenaciously bound, requiring a HNO_3-HF acid soak for removal. The third and outermost layer, which ranged in thickness from 25 to 75 um, was readily removed by wire brushing. This layer contained ∿85% of the ^{90}Sr and over 90% of the U on the leadscrew section. An interesting observation was the presence of spherical Ag-In nodules adhering to the leadscrew. The nodules also contain some Sn, one of the alloying elements in zircaloy, indicating that the Ag-In-Cd control alloy probably reacted with the zircaloy fuel rod cladding or guide tube following control rod failure. The nodules, which ranged in size from 15 to 300 μm, were tightly bound to the leadscrew; they were not removed by wire brushing. Electron microprobe analysis indicated some diffusion of the Ag-In into the adherent, Cr-rich layer. It appears that the Ag-In nodules may have been molten when they contacted the leadscrew and were thereby brazed or bonded to the adherent layer. This indicates that, as also suggested by the filter debris analysis, the accident conditions produced Ag-In control material transport in an aerosol or fine particle form.

CONCLUSIONS

In summary, the research tasks described have produced the following description of TMI-2 core damage. Extensive fuel damage (oxidation and fragmentation) has occurred and the top ~1.5 m of the center portion of the TMI-2 core has relocated. The fuel fragmentation extends outward to slightly beyond one-half the core radius in the direction examined by the CCTV camera. While the radial extent of core fragmentation in other directions was not directly observed, control rod spider drop data and in-core instrument data suggest that the core void is roughly symmetrical, although there are a few indications of severe fuel damage extending to the core periphery. The core material fragmented into a broad range of particle sizes, extending down to a few microns. APSR movement data, the observation of damaged fuel assemblies hanging unsupported from the bottom of the reactor upper plenum structure, and the observation of once-molten stainless steel immediately above the active core indicate high temperatures (up to at least 1720 K) extended to the very top of the core. The relative lack of damage to the underside of the plenum structure implies a sharp temperature demarcation at the core/plenum interface. Filter debris and leadscrew deposit analyses indicate extensive high temperature core materials interaction, melting of the Ag-In-Cd control material, and transport of particulate control material to the plenum and out of the vessel.

The research activities described are part of an ongoing program to understand TMI-2 core damage. By continually building on previous studies, the details of core damage are becoming increasingly clear. These individual steps are helping to define the detailed TMI-2 core examination plan--the program to document, sample, transport, and examine core debris specimens. Ultimately, this process will lead to a definitive understanding of light water reactor core damage under severe accident conditions.

ACKNOWLEDGEMENTS

Many individuals and organizations have contributed to the TMI-2 data acquisition tasks described herein. The authors' gratefully acknowledge the contributions of selected individuals from Argonne National Laboratory, Babcock and Wilcox, the Department of Energy, the Electric Power Research Institute, GPU Nuclear, Los Alamos National Laboratory, and MPR Associates.

REFERENCES

(1) R. W. Garner, D. E. Owen, and M. R. Martin, An Assessment of the TMI-2 Axial Power Shaping Rod Dynamic Test Results, GEND-INF-038, April 1983.

(2) Bechtel Northern Corp., Quick Look Inspection: Report on the Insertion of a Camera into the TMI-2 Reactor Vessel Through a Leadscrew Opening, GEND-030-Vol. 1, March 1983.

(3) GPU Nuclear and Bechtel National, Quick Look Inspection Results, TPO/TMI-026, December 1982.

(4) W. A. Franz, N. M. Cole, W. E. Austin, and R. L. Rider, "The Quick Look at TMI-2," ANS Transactions, 43, November 1982.

(5) D. W. Croucher, Three Mile Island Unit-2 Core Status Summary: A Basis for Tool Development for Reactor Disassembly and Defueling, GEND-007, May 1981.

(6) M. E. Yancey and N. Wilde, Preliminary Report on TMI-2 In-core Instrument Damage, GEND-INF-031, January 1983.

(7) R. E. Mason et al., Interim Report on the TMI-2 Purification Filter Examination, EGG-TMI-6181, February 1983.

(8) G. M. Bain and G. O. Hayner, Initial Examination of the Surface Layer of a 9-Inch Leadscrew Section Removed from TMI-2, to be published.