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TMI-2 Core Examination

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DISCLAIMER

TMI-2 CORE EXAMINATION[a]

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ABSTRACT

The examination of the damaged core at the Three Mile Island Unit 2 (TMI-2) reactor is structured to address the following safety issues: fission product release, transport, and deposition; core coolability; containment integrity; and recriticality during severe accidents; as well as zircaloy cladding ballooning and oxidation during so-called design basis accidents. The numbers of TMI-2 components or samples to be examined, the priority of each examination, the safety issue addressed by each examination, the principal examination techniques to be employed, and the data to be obtained and the principal uses of the data are discussed in this paper.

INTRODUCTION

The damaged core of the TMI-2 reactor contains a wealth of information that will aid in understanding the behavior of light water reactor (LWR) cores under severe accident conditions. Improved understanding of the damage phenomena and, especially, the release of fission products from the fuel and their transport and deposition within the primary system, will contribute to the resolution of the principal LWR safety issues.

The development of an examination plan for the TMI-2 core has taken place over a considerable period of time with input from many sectors of the nuclear community: reactor vendors, utilities, architect/engineering firms, national laboratories, consulting firms, government institutions, and universities. The starting point was the recommendations[(1)] of the TMI-2 Examination Planning Groups 7.2 and 7.4. The assessment by Croucher[(2)] of the damage state of the TMI-2 core has been a useful guide, along with early results from inspections and measurements of TMI-2 reactor components reported by Owen et al.,[(3)] at this meeting. Progress on the TMI-2 core examination plan was reported earlier,[(4)] and the final plan[(5)] will be published in late 1983 after review by the TMI-2 Core Damage Assessment Technical Evaluation Group, an independent advisory group representative of the nuclear community.

The examination of the TMI-2 core is structured to address the principal safety issues facing the light water reactor industry. These issues and the contributions of the TMI-2 core examination are discussed first, followed by a description of the recommended examination. This material was developed, in part, through the efforts of a Technical Evaluation Working Group whose members are acknowledged at the end of this paper.

SAFETY ISSUES

The principal safety issues, and the data that can be obtained from the TMI-2 core to impact the issues, are listed in Table 1.

Fission product release and transport is clearly the most fundamental safety issue and underlies all others because radionuclides present the primary risk to the public from reactor accidents. Calculations of fission product release from a light water reactor primary system during a severe accident are generally overestimated. Such calculations do not fully account for the significant retention of fission products within the primary system by deposition on surfaces within the reactor vessel and dissolution within any remaining liquid coolant.

The TMI-2 core examination can contribute to this issue by measuring fission product retention in the fuel and deposition on the core and plenum surfaces. All forms of fuel encountered (intact rods, broken rods, loose debris, liquefied fuel, etc.) will be investigated. The role of vessel internal surfaces, particularly the upper plenum and fuel assembly upper end fittings, in fission product retention will be determined. Information on the distribution within the pressure vessel of ^{129}I, ^{134}Cs, ^{137}Cs, ^{90}Sr, ^{106}Ru and ^{106}Pd, stable Te, ^{144}Ce and ^{144}Nd, and U and Pu will be sought. Reactor vessel internal components will be examined by gamma spectrometry, radiochemistry, scanning electron microscopy, and other surface analysis techniques.

The issue of a loss of core coolability leading to a core melt, vessel failure, and possible containment breach has been a safety concern for many years. The TMI-2 accident confirmed that even a severely disrupted reactor core could remain coolable. Yet the accident simultaneously raised questions as to exactly how the core reconfigured, and whether that reconfigured core could have reached a noncoolable or difficult-to-cool geometry. Data from TMI-2 are required to show how the core damage event developed and whether or not there were unexpected phenomena. These data can best be obtained by a thorough sampling of the full range of core debris encountered during defueling. The first goal of this sampling will be to document the location and the extent of damage features throughout the core. Material relocation; general debris characterization (permeability, porosity, packing density, stratification, etc.); extent of oxidation of cladding and other core components;

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TABLE 1. MAJOR NUCLEAR SAFETY ISSUES AND THEIR UNDERLYING DATA NEEDS

1.	Fission Product Release, Transport, and Deposition	a. Retention in fuel b. Chemical states (particularly I, Cs, Te, Ru, Sr, U, Pu) c. Aerosol generation d. Temperature distribution in the core and upper plenum e. Fuel relocation in the primary system f. Deposition on core surfaces g. Deposition in balance of reactor coolant system and other parts of the plant.
2.	Core Coolability/Understanding Damage Processes of Core and Internals	a. Material relocation b. General debris characterization (permeability, porosity, packing density, stratification, etc.) c. Extent of oxidation d. Melting and liquefaction e. Fragmentation and embrittlement f. Deformation g. In-core instrument survivability
3.	Containment Integrity	a. Extent of oxidation b. Presence of major melting c. Evidence of major accumulation of core materials in the lower plenum d. Lower head integrity
4.	Recriticality/Segregation of Fuel and Control Materials	a. Location and configuration of fuel and control materials
5.	Chapter 15 (Appendix K) Issues	a. Ballooning b. Oxidation

NOTE: The five major nuclear safety issues are prioritized based on their relative order of importance. The underlying data needs associated with each major safety issue are not prioritized.

melting of cladding, spacer grids, and control materials and liquefaction of fuel; fragmentation and embrittlement of fuel rods and other core components; and deformation of core components will be investigated.

The loss of containment integrity and the timing of that loss strongly influence the potential for radiological releases to the environment as a result of a severe core damage accident. The maintenance of containment integrity during the TMI-2 accident helped to keep the release of radioisotopes to the environment extremely low. However, hydrogen gas released from the metal-water reaction in the core did reach the TMI-2 containment building where it ignited. The principal questions the TMI-2 core examination can help answer are: What was the extent of hydrogen generation by the steam oxidation of reactor vessel components, and did major melting or liquefaction present a threat to the integrity of the reactor vessel? Thorough sampling of the TMI-2 core, followed by analyses of the extent of metal oxidation (both zircaloy and stainless steel components), will permit calculations of the amount of hydrogen generated, which in turn will complement calculations based on the measured containment building pressure pulse during the hydrogen burn.

The question--could the segregation of fuel and control materials during a severe damage accident cause recriticality and further damage the reactor vessel and containment, causing a release of fission products to the environment--is an issue that can also be addressed by the TMI-2 core examination. The principal means will be the determination of the location and configuration of the fuel and control materials within the reactor vessel, especially the lower plenum and the core.

The examination of the TMI-2 core also offers a unique opportunity to provide fuel rod cladding ballooning and oxidation data from a large-scale accident. The ballooning issue is: what is the extent of coplanar flow blockage during so-called design basis accidents resulting from fuel rod ballooning and rupture? With the exception of the TMI-2 core, data on rod ballooning are available only from small-scale experiments, in which cold wall effects are always a concern. Information on rod ballooning will be obtained through hot cell examination of intact assemblies removed from the core periphery. The oxidation issue is: Do cladding temperatures in excess of the 1477 K specified in Appendix K of 10 CFR 100 lead to severe core disruption and significantly reduced core coolability? The TMI-2 core examination affords an opportunity to study the influence of oxidation phenomena on core damage progression in a full-sized reactor. Oxidation will be studied primarily by hot cell metallographic examination of fuel rods, debris, and other core components.

RECOMMENDED EXAMINATION

The recommended examination presented in Table 2(a) shows the numbers of reactor components or samples to be examined, the examination priority, and the safety issue addressed; Table 2(b) presents the data to be obtained and the principal

TABLE 2(a). TMI-2 CORE EXAMINATION RECOMMENDATIONS

Reactor Component or Sample[a]	Examination Priority[b]	Safety Issue to be Addressed[c]	Principal Examination Techniques
Leadscrew guide sleeves from the reactor vessel dome.	Moderate	Fission product R, T, and D (b, c, d, f).	Gamma scan, radiochemistry, surface analysis, metallography.
Plenum cover debris.	Low	Fission product R, T, and D (a, b, e); Coolability/damage processes (a, e).	Chemical analysis, SEM, radiochemistry, particle size.
Plenum cover specimens.	Low	Fission product R, T, and D (b, d, f).	Radiochemistry, surface analysis, metallography, gamma scan.
Radiation mapping of plenum.	Moderate	Fission product R, T, and D (f).	Gamma scan.
Control rod leadscrews.	Very high	Fission product R, T, and D (b, c, d, f).	Gamma scan, surface analysis, radiochemistry, metallography.
Split-tube sections.	Very high	Fission product R, T, and D (b, c, d, f).	Surface analysis, gamma scan, radiochemistry, metallography.
Control rod guide tube assemblies.	High	Fission product R, T, and D (b, c, d, f).	Photo/visual, gamma scan, surface analysis, radiochemistry, metallography.
Control rod spiders.	High	Fission product R, T, and D (d, f).	Photo/visual, surface analysis, metallography, radiochemistry.
Fuel assembly end fittings.	High	Fission product R, T, and D (d, f).	Photo/visual, surface analysis, metallography, radiochemistry.
Intact fuel assemblies.	High	Fission product R, T, and D (a, b, d); Coolability/damage processes (c, f); Recriticality (a); Appendix K (a, b).	Photo/visual, gamma scan, metallography, radiochemistry, surface analysis.
Damaged fuel assemblies.	Critical	Fission product R, T, and D (a, b, c, d, e); Coolability/damage processes (a, c, d, e, f); Containment integrity (a, b); Recriticality (a); Appendix K (a, b).	Photo/visual, neutron tomography, metallography, chemical analysis, SEM, particle size, radiochemistry, microprobe, STEM.
Loose debris specimens.	Critical	Fission product R, T, and D (a, b, d, e, f); Coolability/damage processes (a, c, d, e, g); Containment integrity (a, b); Recriticality (a).	Photo/visual, metallography, chemical analysis, SEM, particle size, radiochemistry, microprobe, physical properties, STEM.
Crust debris specimens.	Critical	Fission product R, T, and D (a, b, d, e, f); Coolability/damage processes (a, b, c, d, e); Containment integrity (a, b); Recriticality (a).	Photo/visual, metallography, chemical analysis, SEM, radiochemistry, microprobe, physical properties, STEM.
Fuel stub assemblies.	Very high	Fission product R, T, and D (a, b, d, e); Coolability/damage processes (a, c, d, e); Recriticality (a).	Photo/visual, neutron tomography, metallography, radiochemistry, SEM, and microprobe.

TABLE 2(a). (continued)

Reactor Component or Sample[a]	Examination Priority[b]	Safety Issue to be Addressed[c]	Principal Examination Techniques
Loose debris from lower vessel.	Moderate	Fission product R, T, and D (e); Coolability/damage processes (a, b); Containment integrity (c, d); Recriticality (a).	Photo/visual, metallography, chemical analysis, SEM, particle size, radiochemistry, microprobe, physical properties, STEM.
Core former wall.	Moderate	Fission product R, T, and D (d, f).	Metallography, radiochemistry, surface analysis, gamma scan.
Filter debris.	High	Fission product R, T, and D (a, e, g); Coolability/damage processes (a); Recriticality (a).	Photo/visual metallography, chemical analysis, SEM, particle, size, radiochemistry, microprobe, physical properties.
Debris specimens from balance of reactor coolant system.	High	Fission product R, T, and D (a, b, c, e, g); Coolability/damage processes (a); Recriticality (a).	Photo/visual, metallography, chemical analysis, SEM, particle size, radiochemistry microprobe, physical properties.
General documentation of large-scale condition of the reactor vessel and core.	Critical	Fission product R, T, and D (a, e, f); Coolability/damage processes (a, b, d, e, f); Containment integrity (a, b, c, d); Recriticality (a).	Photo/visual, closed circuit TV, core topography mapping.

a. Listed by physical location within the reactor vessel, proceeding from the top of the vessel down.

b. The examination priorities for each type of reactor component or sample are a measure of the impact of the examination data on the combined nuclear safety issues described in Table 1.

c. Lower case letters refer to specific data needs listed in Table 1.

TABLE 2(b). TMI-2 CORE EXAMINATION RECOMMENDATIONS

Reactor Component or Sample[a]	Data Obtained	Principal Data Uses	Comments
Leadscrew guide sleeves from the reactor vessel dome.	Fission product plate-out, metal temperatures, extent of oxidation.	Fission product transport codes, source term determination, core internals temperature estimates.	Three guide sleeves required from center, midradius, and periphery. This exam will complement measurements made by EPRI for reactor vessel head requalification.
Plenum cover debris.	Debris composition and particle size, fission product content of debris.	Core debris relocation models, fission product transport codes, source term determination.	One sample required if there is significant accumulation observed by CCTV inspection.
Plenum cover specimens.	Fission product plate-out, metal temperatures.	Fission product transport codes, core temperature codes, plenum temperature estimates.	Five specimens required (punchings or cuttings)--locations based on visual examination.

TABLE 2(b). (continued)

Reactor Component or Sample[a]	Data Obtained	Principal Data Uses	Comments
Radiation mapping of plenum.	Isotopic radiation levels as a function of position in the plenum.	Fission product transport codes.	This exam needed to guide later sampling of plenum. Recommend be performed after head removal by lifting and gamma scanning 11 leadscrews. Could be done by alternate technique after plenum removal.
Control rod leadscrews.	Fission product plateout, component temperatures, extent of oxidation.	Fission poduct transport codes, plenum temperature estimates, core exit steam temperature calculations.	The three leadscrews removed in 1982 are probably adequate.
Split-tube sections.	Fission product plateout, component temperatures, extent of oxidation.	Fission product transport codes, plenum temperature estimates, source term determination.	Short sections cut from selected split-tubes at 11 radial locations and 2-3 axial locations. These specimens will provide an early, thorough mapping of fission product plateout on plenum.
Control rod guide tube assemblies.	Fission product plateout, peak temperature estimates, extent of component deformation and melting.	Fission product transport codes, source term determination, core and plenum temperature codes.	Three complete assemblies from center, midradius, and peripheral positions should be obtained at the time of plenum disassembly.
Control rod spiders.	Component temperatures, extent of oxidation, fission product plateout.	Core temperature codes, H_2 generation estimates, fission product transport codes.	Six spiders concentrated at the core center and midradius positions.
Fuel assembly end fittings.	Fission product plateout, component temperatures, extent of oxidation.	Fission product transport codes, source term determination, core exit steam temperature calculations, H_2 generation estimates.	Six fittings from same locations as spiders.
Intact fuel assemblies.	Cladding, fuel and control rod temperatures, oxide distribution, cladding deformation, flow blockages, fission products retained in the fuel, fission product plateout.	Appendix K issues (zircaloy oxidation and embrittlement, hydrogen generation, and zircaloy cladding ballooning and flow blockage); fission product retention; fission product plateout, source term determination.	Three assemblies required, one from core periphery.

TABLE 2(b). (continued)

Reactor Component or Sample[a]	Data Obtained	Principal Data Uses	Comments
Damaged fuel assemblies.	Cladding, fuel and control rod temperatures, extent of oxidation, extent of eutectic melting and fuel liquefaction, flow blockage, fuel rod fragmentation and relocation, UO_2 oxidation, fission product release from fuel, relocation of control materials.	Core temperature codes, core debris relocation models, H_2 generation estimates, fission product transport codes, source term calculations, recriticality analysis, flow blockage models, liquid material movement models.	Three assemblies required, one without control rods, one with control rods, one with burnable poison rods.
Loose debris specimens.	Fuel and structural material reactions, relocation of core materials, extent of fragmentation, extent of oxidation, retained fission products, nature of debris stratification, peak core temperatures, in-core instrument damage.	Debris bed coolability models,fission product transport codes, core debris relocation models, source term determination, H_2 generation estimates, in-core instrument survivability analysis, recriticality analysis.	Forty specimens of mtls., such as fuel and cladding pieces, control mtls., spacer grids, fuel rod springs, liquefied mtl., in-core instruments, structural mtls. Efforts will be made to acquire some specimens in a manner which preserves stratification so that the sequence of damage events can be reconstructed.
Crust debris specimens.	Molten material relocation; fuel, control, and structural material reactions; extent of oxidation; retained fission products; peak core temperatures; control material relocation.	Core debris relocation models, fission product transport codes, debris bed coolability models, H_2 generation estimates, source term determination, recriticality analysis.	Ten specimens of core debris in which significant quantities of once-molten material is present.
Fuel stub assemblies.	Microstructure of of damage transition zones, extent of oxidation, retained fission products, relocation of core materials.	Liquid level boildown models, fission product codes, core debris relocation models, H_2 generation estimates, recriticality analysis.	Three stub assemblies, one from the small number of gadolinia-bearing experimental assemblies in the core.
Loose debris from lower vessel.	Estimate of total quantity, particle size distribution, extent of once-molten debris, fission product content.	Core debris relocation models, fission product transport codes, vessel breach models, recriticality analysis, debris bed coolability.	Five samples of debris on the various horizontal surfaces below the core, particularly the bottom head. Sample selection should be based on CCTV inspection.
Core former wall.	Fission product plateout, peak metal temperature, extent of oxidation.	Fission product transport codes, radiative heat loss models.	Two punchings or cuttings adjacent to an intact assembly.

TABLE 2(b). (continued)

Reactor Component or Sample[a]	Data Obtained	Principal Data Uses	Comments
Filter debris.	Retained fission products, particle size distributions, fuel control material and structural material reactions, relocation of core materials.	Fission product transport codes, fuel fragmentation models, core relocation models, source term determination, recriticality analysis.	Refers to analysis of samples from Makeup and Purification System filters which plugged with core debris during the accident.
Debris specimens from balance of reactor coolant system.	Retained fission products, particle size distribution, core materials reactions, relocation of core materials.	Fission product transport codes, core relocation models, criticality analysis, source term determination, mass balance determination.	Debris in filters, tanks, pipes, containment sump, etc., should be quantified. Partial overlap with EPRI responsibilities for requalification.
General documentation of large-scale condition of the reactor vessel and core.	Core damage symmetry, core void size, total volume and mass of debris, stub assembly elevations, extent of liquefaction, transition zone configurations, major coolant channels.	Core relocation models, recriticality analysis, core coolability models, mass balance determination, molten material relocation models, nature of debris stratification.	These data will assist in planning and conducting all other examinations.

a. Listed by physical location within the reactor vessel, proceeding from the top of the vessel down.

uses of the data. Both nonfuel components, primarily in the upper plenum, and fuel materials from the core region are addressed.

Examinations have already begun on two of the components (control rod leadscrews and makeup and purification system filter debris) listed in Table 2. Preliminary results from these examinations are presented at this meeting in a paper by D. E. Owen et al.(3) As an example of the logic used in Table 2, the examination of damaged fuel assemblies will be discussed.

Three damaged assemblies, one with control rods, one without control rods, and one with burnable poison rods will be examined. The examination of damaged assemblies is the highest priority because these assemblies are expected to reveal the entire range of damage experienced in the the TMI accident and, therefore, be most instructive in the study of the accident progression and release of fission products. These assemblies are expected to be found at the edge of the cavity in the core and to contain a gradation of damage from intact, ballooned, and ruptured rods on the outside of the assembly, to rods facing the cavity that have experienced severe oxidation and embrittlement toward the top of the assembly and show cladding melting and fuel liquefaction, and relocation of the liquefied material at the middle and lower elevations, respectively. Because of the range of damage expected, the examination of these assemblies is expected to contribute to all the major safety issues discussed above.

In the case of the fission product release, transport, and deposition issue, the examination of damaged essemblies is expected to produce data on the amount and chemical states of the fission products remaining in the fuel, plateout of fission products on the colder rods and the upper end fittings, aerosol generation, temperature distribution in the core, and fuel relocation. Coolability and damage processes will be addressed with data on material relocation, general debris characterization, the extent of oxidation of cladding and other materials in the assemblies, melting and liquefaction, fragmentation and embrittlement, and deformation of assembly components. Containment integrity will be impacted by the extent of oxidation and the degree of melting. Recriticality will be addressed by determining the location and configuration of fuel and control materials. Finally, Chapter 15 (Appendix K, 10 CFR 100) issues will be investigated by assessing the magnitude of rod ballooning and the extent of cladding oxidation.

The principal examination techniques to be employed will be photo/visual documentation of the condition and damage of the assemblies; neutron tomography to reveal the nature and distribution of the damage internal to the assembly (e.g., regions of fuel liquefaction and relocation, rod fragmentation, and loose debris); metallography to study the extent of oxidation, the maximum temperatures reached by phase identification, fuel-cladding chemical interaction, fuel liquefaction, control rod material melting and interactions with steam and assembly components, etc.; chemical analysis to determine the elemental makeup of the major components remaining in the assembly; scanning electron microscopy to reveal the morphology and elemental composition of surface deposits, debris particles, molten materials, and fracture surfaces; particle size analysis to measure the particle size distribution of debris in the assembly; radiochemistry to measure the retention on surfaces of ^{129}I, ^{90}Sr, and fissile materials; and electron microprobe to perform quantitative elemental analyses of debris particles and various structures revealing materials interactions.

The principal uses of the data generated from the examination of damaged assemblies will be the assessment of computer codes used to calculate core temperatures under severe damage accident conditions, core debris relocation models, hydrogen generation estimates (from the extent of oxidation), fission product release and transport codes, source term calculations, recriticality analysis, flow blockage models, and models for the movement of liquefied fuel and other molten materials.

The TMI-2 core examination is divided into three phases. The first phase, pre-defueling examinations, is intended to provide early documentation of the postaccident condition of the core. This is to be accomplished by additional closed-circuit television camera inspections of the core and ultrasonic mapping of the core cavity. Core debris washed to the top of the vessel and small samples of the fuel debris will be obtained prior to lifting the reactor pressure vessel head. Radioisotopic mapping of the plenum is recommended after head removal by lifting and spectral gamma scanning eleven lead screws.

The second phase is core examination during defueling. The most important activity at this stage is the selection of representative core debris samples for later examination. Guidelines for sample selection are presented in Table 2. Actions will be taken to ensure preservation of the samples during handling and shipping. Additional in-core photography and ultrasonic topography measurements to document core conditions during defueling will also be performed.

The final phase of the core examination is the remote investigations to be carried out at hot cell facilities. It is these investigations that will reveal the details of the core materials interactions, the maximum core and plenum temperatures, and the fission product release, transport, and deposition.

SUMMARY

The core examination is a comprehensive study of the damage in the TMI-2 reactor vessel designed to address specific reactor safety issues. The examination will produce unique data that will have a significant impact on these major safety issues confronting the light water reactor industry.

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