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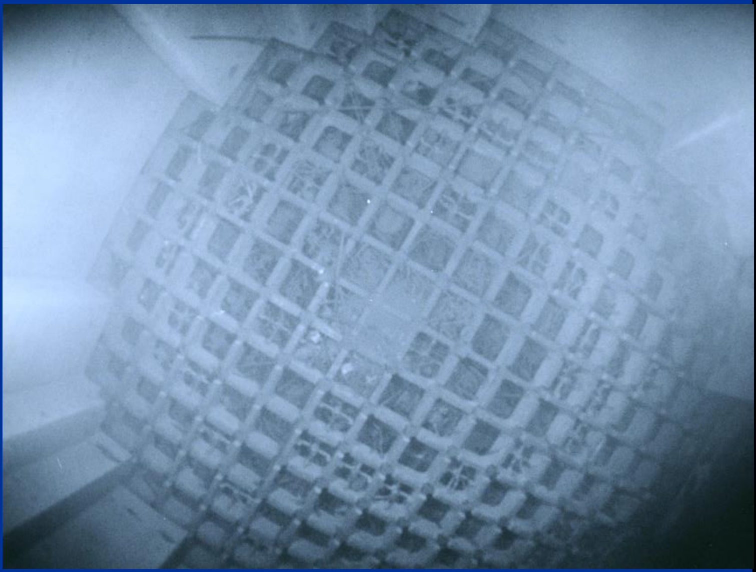

Three Mile Island Accident of 1979 Knowledge Management Digest

The Cleanup Experience
A Literature Review

NUREG/KM-0001, Supplement 2
Office of Nuclear Regulatory Research

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Figure on Front Cover: The view of lower core support structure inside the reactor vessel with fuel debris removed from the core region. Still filled with reactor coolant, the next defueling activities were the lower reactor vessel head region (debris can be seen under the grid structure) and behind the core baffle plates of the core former.

Figure on Back of Front Cover: Mosaic panorama of the reactor core cavity from comprehensive video mapping in April 1984. Shown are hanging control rod assemblies, and broken fuel rods and control rod upper end fittings on top of the rubble bed.

Figure on Page vi: TMI-2 ventilation stack and the top rim of the reactor containment building. Ventilation exhausts from the containment building and auxiliary and fuel handling building were processed by filtration systems before released to the stack (also see the following figure).

ACKNOWLEDGEMENTS

The editors of this knowledge management supplement greatly appreciate the contributions from the following individuals and organizations in their pursuit to preserve knowledge and experiences of the cleanup of Three Mile Island Nuclear Station, Unit 2 (TMI-2). The *knowledge* contributors listed below contributed historically important reports, papers, video tapes, presentations, and supplemental information. These individuals were actively involved with the cleanup effort while employed by the licensee (employee, contractor), U.S. Nuclear Regulatory Commission, and U.S. Department of Energy. The *management* contributors assisted in the drafting, reviews, and fact checking of this supplement. Many legacy documents and videos related to the TMI-2 cleanup are accessible from the *document collections* list below.

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1 INTRODUCTION

1.1 Purpose

The safe, expeditious stabilization, defueling, and cleanup [a] of Three Mile Island Nuclear Station, Unit 2 (TMI-2), including removal of the fuel from the accident-damaged reactor, were necessary for the long-term protection of public health and safety and the environment. The goal of the cleanup campaign was to ensure that the TMI-2 site would not become a long-term or permanent waste repository. The recovery activities that unfolded at TMI-2 in the weeks and months (and then years) after the March 28, 1979, accident were the result of a multiorganizational effort that included hundreds of dedicated and highly skilled individuals. About $2.4 billion (in 2019 dollars) [1] were spent by the time the defueling was nearing completion in 1989.

The purpose of this supplement is to catalog many of the experiences and insights documented in numerous reports and papers spanning the 1980 to 1993 cleanup period at TMI-2. The experiences in this report focus on those aspects of TMI-2 relating to long-term plant stabilization, cleanup, and defueling. The description of these experiences are based on an extensive review of a wide range of reports, papers, presentations, and interviews with personnel formerly from the key organizations involved in the cleanup. Many insights were taken from discussions during a workshop that was organized by the U.S. Department of Energy (DOE) and the Idaho National Laboratory (INL) in 2016. This workshop brought together many alumni involved with the TMI-2 cleanup and research, and 31 invited guests from 7 Japanese organizations involved with the cleanup of the Fukushima Dai-ichi Nuclear Power Station.

To keep the number of cleanup experiences and insights to a manageable size, the list was limited to those previously documented in reports, papers, and presentations. Text searches using key words, such as “lesson,” “problem,” “insight,” and “concern,” helped to sift through over 120,000 pages of documents to identify notable insights. Discussions with those involved in the cleanup significantly helped to identify documented experiences, lessons, and insights. The transportation of radioactive wastes and the long-term post-defueling monitored storage of the plant are not within the scope of this report.

1.2 How To Use This Report

Experiences and insights from TMI-2, Chernobyl, and Fukushima Dai-ichi revealed that each severe accident behaves differently, and the subsequent cleanup will also be different. Nevertheless, experiences and lessons from these accidents

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[a] The term “recovery” is used in this NUREG/KM to mean actions taken to keep the plant in a stable condition and to prevent the inadvertent release of radioactivity. The term “cleanup” is used to mean action taken to decontaminate and defuel the plant and dispose of radioactive waste. These two terms are often used interchangeably for certain actions.

and other large-scale cleanup programs can be adapted to most such programs, especially programmatic experiences.

This supplement is a continuation of Supplement 1 to NUREG/KM-0001, "Three Mile Island Accident of 1979 Knowledge Management Digest: Recovery and Cleanup." [(2)] Supplement 1 includes summary descriptions of structures, systems, components, and activities associated with the recovery and cleanup at TMI-2. Most importantly, most open-source references cited in this supplement can be found in the DVDs associated with Supplement 1. The document collections from these DVDs can be accessed at this time through the Idaho National Laboratory Research Library Digital Repository (https://tmi2kml.inl.gov).

Thorough overviews of the TMI-2 recovery and cleanup, including many experiences and lessons, can be found in the series of publications by the American Nuclear Society, Electric Power Research Institute (EPRI), International Atomic Energy Agency (IAEA), DOE, and NRC. Section 10 of this report lists these publications. The reader is strongly encouraged to refer to these excellent sources for details associated with the experiences summarized in this report, as well as additional experiences and insights. Each experience or insight has a numbered source, which is listed in the reference section of this report.

The reader should be cautioned that, while the experiences documented in this report came from largely previously published sources, they may have been superseded by subsequent experiences at TMI-2, lessons from other cleanup projects, and research results, as well as changes in regulatory requirements. Contributions to this report by knowledge providers and their organizations should not be considered as endorsements of the contents of this report.

1.3 Report Organization and Readability

Experiences are organized into major subjects with a brief background section to orient the reader to that subject. The subjects are divided into subtopics, each with a brief discussion and a series of experiences. The experiences are brief, and each is preceded with a keyword phrase to highlight its specific topic. References are given so that the details of the experience can be further investigated.

To improve readability, abbreviations were minimized [(b)] and others that were frequently repeated were spelled out in the section that contained them. The text was structured using past tense, except for text describing this supplement.

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[b] Abbreviations used throughout this supplement: as low as reasonably achievable (ALARA); *Code of Federal Regulations* (CFR); U.S. Department of Energy (DOE); Electric Power Research Institute (EPRI); General Public Utilities Nuclear Corporation (GPU); Idaho National Engineering Laboratory (INEL, now called INL); International Atomic Energy Agency (IAEA); U.S. Nuclear Regulatory Commission (NRC); programmatic environmental impact statement (PEIS); and Three Mile Island Unit 2 (TMI-2).

Footnotes provide editorials and additional clarifications not specific to the historical record. Some terms, which varied in use across documents and time, were standardized. The text uses the unit of measure (in English units or the International System of Units) in the original source document (in some cases, the source provided both). A conversion chart is provided on the back cover. End notes refer to the source reference. The end note number at the beginning of the subsection (or bullet) refers to the entire subsection; the number at the end of a paragraph refers to that paragraph; the number in a sentence only applies to that sentence. Due to limitations in word processing, end notes embedded in figure captions are listed in the last endnote (see Section 10).

Section 2 provides experiences of the high-level management and planning of the overall cleanup program, with further descriptions included in the first subsection of subsequent sections. Section 3 describes unique experiences of the NRC's regulatory oversight of the TMI-2 recovery and cleanup activities. Experiences from regulatory oversight of the TMI-2 cleanup had not been widely documented previously. Sections 4 through 8 describe experiences from an assortment of topics, including long-term stabilization; defueling, packaging, and onsite storage of radioactive waste; the front end of the fuel debris transportation campaign; decontamination of the auxiliary and fuel handling building and containment building; personnel protection; and onsite waste management. Section 9 is a bibliography of important resources that preserved the decisions made and associated consequences during the TMI-2 cleanup. The final section, Section 10, lists the references cited in this report. The format of most references provides the file name of those documents included on the DVDs for NUREG/KM-0001, Supplement 1.

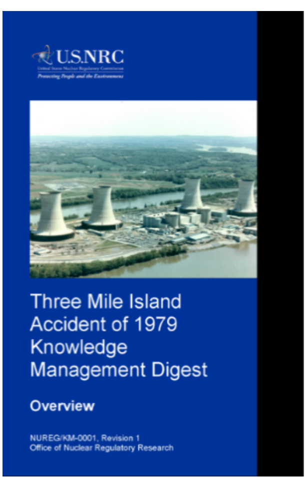


Figure on Next Page: Temporary filtration system for the auxiliary and fuel handling building installed on the auxiliary building roof. TMI-2 containment building in the background; fuel handling building at center right.

2 MANAGEMENT AND PLANNING

Many technical decisions considered issues on funding, public perception, and the regulatory environment. Each decision also involved a choice among several strategies, such as manual or robotic techniques to defuel the reactor; demineralization, evaporation, or solidification to process radioactive water; and gross decontamination or dose reduction to support the other cleanup work. The most important technical influence on decisionmaking was the relevant data available when a decision was made. In many cases, limited data or inaccurate assumptions about conditions were serious handicaps to both planning and operations. A central lesson of the TMI-2 cleanup was the importance of proceeding methodically to understand conditions, to develop a simple engineering approach to handle known conditions, and then to repeat this sequence until recovery operations were complete. (3)

The section covers experiences on organizations, project and work planning, and the retention of knowledge.

2.1 Organizations

Organizations that supported the licensee included the original architect engineers of Three Mile Island Nuclear Station (TMI), Units 1 and 2 (Gilbert Associates and Burns and Roe, respectively); the TMI-2 nuclear steam supply system vendor (Babcock & Wilcox); many volunteers from other nuclear power plants; the U.S. nuclear industry; universities; research laboratories; and several international organizations. (4) The licensee's two principal support contractors were Bechtel Northern Company (architect engineer and construction) and Bechtel National, Inc. (decontamination and technical support). (5)

The licensee instituted several review and advisory groups that focused on cleanup activities. In 1983, the NRC approved a change in the licensee's organization that created an onsite safety review group for independent review and audit. Although not required by regulatory requirements, other corporate review groups were established by the licensee to provide independent technical oversight on safety and cleanup technology issues, such as the Technical Assessment and Advisory Group and the Safety Advisory Board. (6, 7)

The DOE provided the technical assistance needed to enable removal and evaluation of the damaged reactor core and to perform other safety and severe accident research for the benefit of nuclear power technology. GPU, EPRI, the NRC, and the DOE formed a collective group called GEND to jointly sponsor and participate in the DOE's TMI Information and Examination Program. (8)

- ***Program Uniqueness***. All organizations involved in the cleanup of TMI-2 realized early in the cleanup effort that the stabilization, defueling, decontamination, and decommissioning of an already damaged reactor were unique and unlike anything previously encountered in U.S. commercial nuclear power reactors. The cleanup required special efforts to bring together all the resources needed to ensure worker and public safety. Past regulatory practices alone were neither sufficient nor appropriate. All organizations required a documented, unified common goal of a safe and prompt cleanup of TMI-2. The licensee, support organizations, and the NRC had clearly defined and documented roles, responsibilities, and authorities. [9]

Expertise from external organizations was needed because many aspects of the cleanup were beyond the expertise of the licensee. The cleanup required skills and special facilities from the DOE and its national laboratories that did not exist elsewhere. Expertise from other utilities, service companies, and universities provided valuable resources. Combining these outside experts with the onsite work force was difficult; however, the combination brought much needed technical support, new ideas, and a channel to the worldwide technical community. [10]

- ***Safety Review Group***. [11, 12] In 1983, the NRC approved a change in the licensee's organization that created an onsite safety review group (SRG) for independent review and audit. The SRG was a permanent, full-time group of qualified individuals designated to perform this function, replacing pre-accident review committees which convened periodically and sometimes with rotating personnel. The staff were assigned onsite and reported to the TMI-2 licensing and nuclear safety director. The SRG conducted an ongoing program to evaluate the technical adequacy of those procedures and design changes important to safe operation of the plant as required by regulatory requirements and implementing procedures. Additionally, the SRG reviewed results of audits conducted by the quality assurance department and made recommendations, as appropriate. The SRG operated independently from both plant operations and engineering and had the charter to advise the director of TMI-2 on all safety matters. The SRG manager had the authority and the responsibility to bring to the attention of the licensee president any issues that were not being addressed with adequate consideration of nuclear or radiological safety. The SRG consisted of a manager and at least 5 engineers with a bachelor's degree in engineering or physical sciences and 5 years of experience in the nuclear power field, or 9 years of appropriate experience. In addition, several technical analysts were included in this group to conduct operational trending analyses.

The safety review topics included: (•) written safety evaluations of changes to the facility, procedures, or tests and experiments, as described in the final safety analysis report, technical evaluation reports, or select system descriptions; (•) proposed changes in the facility, procedures, or tests and experiments, of which involved a change in the technical specifications or an unreviewed safety question; (•) proposed changes to technical specifications; (•) violations, deviations, or select reportable events to the NRC; (•) investigation of all violations of the technical specifications, as well as recommendations to prevent recurrence; (•) special reviews, investigations or analyses and reports, as requested; (•) summaries of audit reports of activities listed in the TMI-2 recovery quality assurance plan; (•) recognized indications of an unanticipated deficiency in some aspect of design or operation of structures, systems, or components, that could affect nuclear safety or radioactive waste safety; and (●) any other matters involving safety operations which the SRG deemed appropriate for consideration, or which was referred to the group.

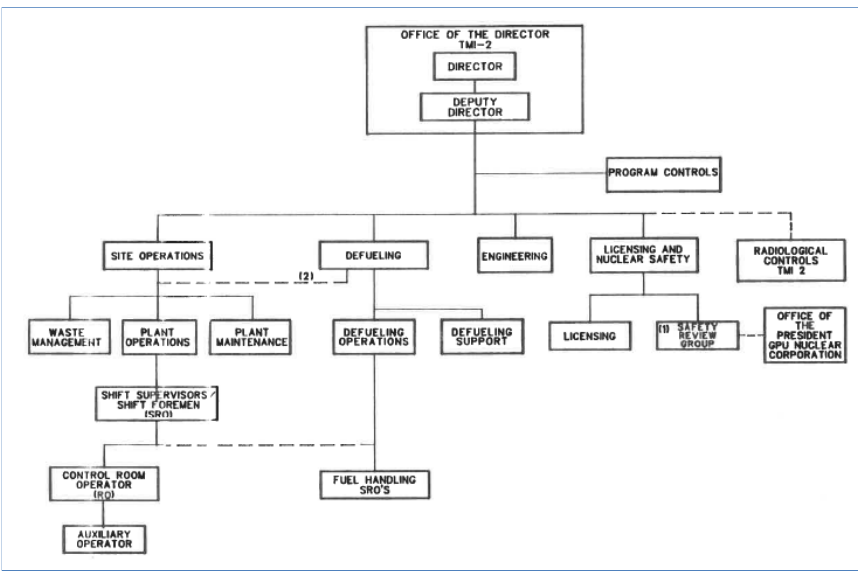
- ***Independent Advisory Committees***. The licensee voluntarily established two subsequent advisory groups: Technical Assessment and Advisory Group (TAAG) and Safety Advisory Board. The TAAG provided technical critiques of plans and operations, and the Safety Review Board reviewed safety practices. These two functions were kept separate to ensure clear definition of purpose; however, both groups were aware of each other's activities. Thus, the technical group considered safety aspects in its recommendations, and the safety group was aware of the technical practicality of its recommendations. Both groups reported to the licensee's corporation president. The NRC and the DOE observed meetings of both groups.

  - *Technical Assessment and Advisory Group*. The TAAG evaluated the cleanup in terms of experience and techniques that proved successful in other industries as well as the nuclear industry. This group ensured that approaches to the various cleanup and defueling operations were technically adequate and that consideration was given to keeping radiation exposures at "as low as reasonably achievable" (ALARA) levels. The TAAG consisted of about 10 permanent members with a broad range of experience and additional ad hoc members when their special expertise was needed. The group responded to specific requests from the licensee's recovery organization, the NRC, and the DOE. The DOE funded the group's work through INEL. [13]

  - *Safety Advisory Board*. The safety advisory board, which was different from the safety review group, evaluated the cleanup with a focus on public and worker health and safety. The board membership was composed of nationally and internationally recognized specialists in the fields of nuclear science, engineering, physics, economics, government and medicine. Members were drawn principally from university faculties and government research laboratories. The first chairman, Dr. James Fletcher, was former Administrator of NASA and returned to that position in 1986 following the Space Shuttle Challenger accident. Dr. Robert. Marston, who succeeded him, was former Director of the National Institutes of Health and former President of the University of Florida. The board met every 3 months and reviewed many aspects of the recovery activities, including regulations; nuclear criticality safety; worker and public safety; risk assessment; project organization; project financing; project procedures; technical planning; public communications; and conflict resolution. The board's final report [14] summarized its activities from its establishment in 1981 through its final meeting in December 1989. [15]

- ***Integration of Licensee Organizations***. In September 1982, the licensee integrated its two principal support contractors, Bechtel Northern Company (architect engineer and construction) and Bechtel National, Inc. (decontamination and technical support), directly into its organizational structure. This reorganization reduced redundancy and concentrated the licensee's resources on completing the cleanup and supporting the restart of Unit 1. Integration occurred at all levels, with licensee workers reporting to Bechtel managers and vice-versa. The organizational hierarchy remained flexible. For example, replacement of a licensee manager who left the organization by a Bechtel employee was possible, depending on who was best qualified to fill the opening. Many organization charts did not even refer to the parent company of the employee. This lack of emphasis on corporate identity helped to create a TMI-2 team feeling. The team approach included contractors that provided much of the union manpower for the cleanup activities. However, experience at TMI-2 showed that the integration was not achieved to the same degree within all parts of the organization. In addition, jurisdictional and organizational disputes were not always eliminated. Nonetheless, for the companies involved, there was a general lack of corporate posturing and competition. [16, 17, 18]

- ***Separation of Operations and Research***. [19, 20] A clear demarcation of responsibilities and the creation of onsite organizations for coordination and cooperation allowed plant cleanup and research to proceed efficiently and to complement each other. Throughout the TMI-2 cleanup, the DOE was primarily



The licensee's organizational structure at the beginning of defueling operations as described in the TMI-2 organization plan (supplement to the recovery technical specifications). The manager of the safety review group (different from the safety advisory board not shown on the chart) reported to the director of TMI-2 with the responsibility and authority to notify the licensee's president of inadequate consideration of nuclear and radiological safety issues. (481.1) responsible for conducting research, with EPRI providing research direction in a few specific areas. The DOE assembled, over time, a large team at TMI and at the national laboratories to support various research programs. While the licensee's staff was essential to assisting the DOE and performing many of the research tasks, the success of the research program was due, in large measure, to the division of research and operations responsibilities.

The licensee's management was focused on the accident cleanup and sometimes development of the tools, systems, and procedures needed for cleanup and sample acquisitions. The DOE's management was focused on the research. Each could devote most of its resources to its area of responsibility, with the necessary integration occurring primarily at working levels within the two organizations at the TMI-2 site. In addition, the licensee allowed DOE contractor personnel access to the TMI-2 facilities and permitted them, in special instances, to perform research and data acquisition tasks.

Additionally, in a cooperation agreement [21, 22] between the DOE and 17 Japan nuclear power organizations, the Japanese research staff at TMI-2 and DOE national laboratories worked in almost every area of the TMI-2 cleanup project during a 5-year period in the latter 1980s.

- ***The U.S. Department of Energy***. [23] The uniqueness of the accident recovery and cleanup provided significant opportunities for reactor safety research and the DOE and its contractors were best suited fully to exploit them. In recognition of these opportunities, it was decided to establish a four-party coordination agreement among the licensee (GPU), EPRI, the NRC, and the DOE, collectively referred to as GEND. Accordingly, in March 1980, 1 year after the accident, the four parties signed a basic agreement in which each agreed to cooperate in areas of common research and to disseminate fully the results of the TMI-2 recovery operations to the world.

  - *The DOE's Contributions*. As its contribution to the effort, the DOE agreed to help develop the unique technology needed to enable removal and evaluation of the damaged reactor core and to perform other safety and severe accident research. In 1982, the DOE role in waste immobilization and reactor evaluation was substantially augmented in recognition of the unique capabilities of the U.S. Government for ensuring safe isolation and disposal of radioactive waste materials, as well as to conduct associated research and development that would be of general benefit. The DOE also agreed to accept the damaged core and transport it to its Idaho site for temporary storage and research. The DOE selected the INEL to manage its research and development program and to conduct a substantial part of the work at its laboratory in Idaho. In addition, many other DOE laboratories and contractors participated in the program, including Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Hanford Operations, Sandia National Laboratories, Los Alamos National Laboratory, and Brookhaven National Laboratory.

- *Technical Integration Office*. In 1980, the DOE established a Technical Integration Office at TMI-2 to provide an onsite presence to carry out the DOE's work more efficiently. Over the cleanup period, the office served as the DOE's primary data gathering and distribution group. Its primary tasks included: (●) providing technology support to the licensee for recovery operations; (●) supporting the core debris shipping program through onsite preparations and monitoring; (●) providing samples and other data in support of the accident evaluation effort; and (●) disseminating technical information to the public, industry, and scientific community.

  For most of the cleanup, the DOE maintained a relatively small department staff and a somewhat larger contractor staff at the TMI-2 site. These onsite technical personnel had routine access to the plant and were permitted to work directly with the organizations conducting the cleanup. The DOE manager at TMI-2 reported to the DOE's Idaho Operations Office but had considerable personal budget authority and the latitude to discuss issues directly with DOE headquarters officials in Washington, DC. The DOE developed most of the specialized equipment for data acquisition and recovery off site and thoroughly tested it in mockup facilities before using it at TMI-2.

- *TMI-2 Research Budget*. The total cost of the DOE TMI-2 research and development program was about $188 million (or $382 million in 2019 dollars). Direct funding of research and development at TMI-2 was approximately $78 million. Offsite technology support cost an additional $29 million, with the remaining $81 million devoted to research on the accident and its consequences.

- *Key Experiences*. The 10-year involvement of the DOE and its national laboratories in the TMI-2 cleanup and research programs yielded many lessons of value for nuclear power programs around the world. Some of the key experiences included the following: (●) Success at TMI-2 was generally a result of innovative engineering applied to existing technology, rather than due to the development of entirely new approaches. (●) Data acquisition sometimes conflicted with production line work; however, data acquisition findings contributed to key program successes. (●) New and improved technologies for collecting, concentrating, transporting, and disposing of accident-generated radioactive wastes were developed and applied at TMI-2. (●) Concern for worker protection during decontamination resulted in a variety of innovations, including new surface cleaning techniques; new radiation survey equipment to quantify contamination levels; improvements in protective clothing; techniques for reducing worker heat stress; and improvements in beta dosimetry. (●) Documentation processes captured unique technologies developed during the cleanup. [c]

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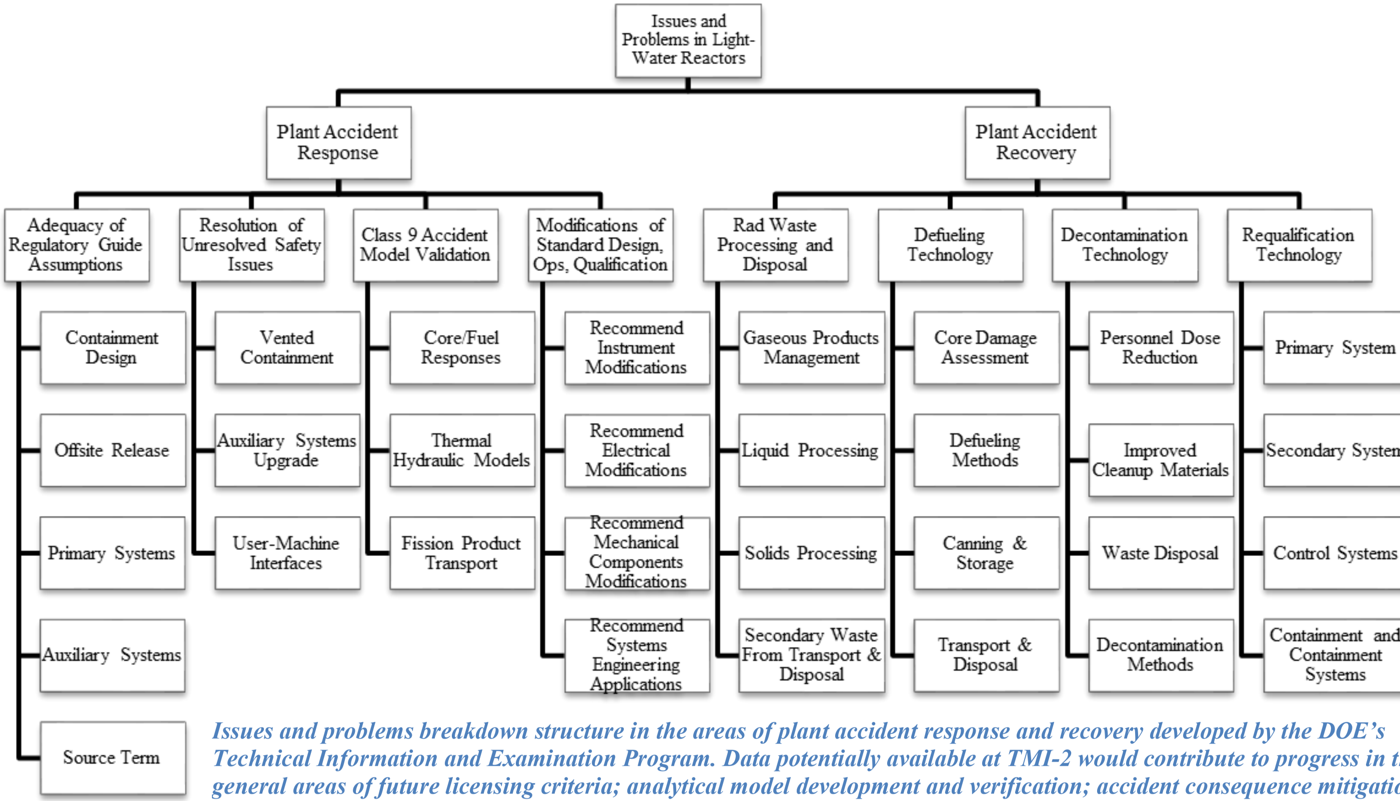
[c] Editor's Note: Documentation is also important for long-term cleanup programs that may span one or more generations of technical support.



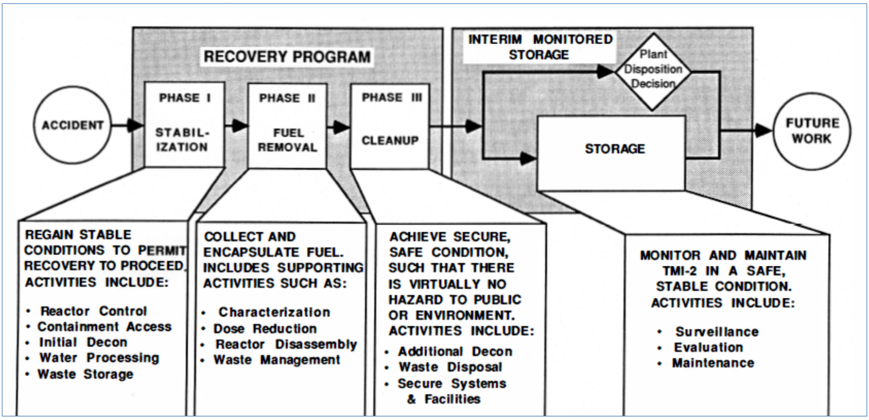
Issues and problems breakdown structure in the areas of plant accident response and recovery developed by the DOE's Technical Information and Examination Program. Data potentially available at TMI-2 would contribute to progress in the general areas of future licensing criteria; analytical model development and verification; accident consequence mitigation; safety system design; system operation; system reliability; and requalification of key light-water reactor components and equipment. (481.2)

2.2 Program Planning

The first plan for the decontamination and defueling of TMI-2 [(24)] was developed at the request of Congress and issued in December 1979. However, this early plan did not have the benefit of information from the first manned containment building entry in the summer of 1980 and the first "Quick Look" camera inspection of the damaged reactor core in the summer of 1982. The licensee's "TMI-2 Program Strategy Technical Plan" [(25)], issued in June 1984, defined the recovery program in three phases: stabilization, fuel removal, and cleanup. The details of the plan evolved in view of new data, available technology, regulatory guidelines, and financial constraints. The "Strategy for Recovery Program Completion and Post-Recovery Configuration" plan [(26)], issued 2 years later, added a fourth phase for interim monitored storage. Many task forces and planning studies evaluated options and provided recommendations in every aspect of the cleanup campaign. [(27)]

- ***Time at Risk***. The cleanup operation involved many risks; however, the time that radioactive materials remained outside the fuel cladding was an important safety consideration. The risks associated with the cleanup activities to place the once-melted fuel radionuclides into engineered containers needed to be balanced against the risks associated with fuel debris not contained in an engineered containment system for an extended period of time. Both the licensee and the NRC balanced these competing risks in a proper manner to assure public health and safety. The longer that the once-melted fuel remained in an unengineered condition, the greater the general overall risk. [(28)]

- ***Conservatisms***. Experience at TMI-2 showed that excessive conservatism applied to reducing defueling risks could lengthen the time that the damaged fuel remained in an undesigned condition. This delay could increase overall risks when compared with proceeding with timelier defueling using more moderately conservative criteria. A proper judgmental balance had to be achieved for overall



Four phases of the TMI-2 postaccident plan: stabilization, fuel removal, cleanup, and interim monitored storage. (481.3) societal benefit. [29]

- ***Innovative Applications of Existing Technology***. Success in the TMI-2 cleanup generally resulted from innovative engineering applied to existing technology. Building on existing technology allowed the cleanup to proceed in small, steady, incremental steps. In most instances, this proved to be faster and to cost less than engineering entirely new approaches to problems. The approach at TMI-2 was to try to use existing technology in a creative manner. This produced some simple and clever solutions to intimidating problems. The small step at a time or "learn as you go" approach was successful because there were so many surprises throughout the cleanup program. [30]

- ***Accommodation of Uncertainties***. No one knew all the engineering challenges of a cleanup following a severe accident—TMI-2 was not a traditionally plannable decommissioning project. TMI-2 showed that uncertainties were large and there were many "unknown unknowns" in making "a priori" decisions. Licensee and NRC decision processes required a flexible, adaptive, and iterative (step-by-step) approach that included constant organizational self-reflection to gather lessons learned from previously performed steps. Classical conservative deterministic criteria alone were not completely sufficient. [31]

Although formal risk-informed processes did not exist at the time of the TMI-2 cleanup, risk-informed aspects that focused on contamination and radioactive materials controls were the predominate safety concerns at TMI-2. Traditional reactor regulation focused on core cooling and protection aspects. To accommodate uncertainties, practical and basic safety precautions, such as monitoring and hold points, were established to minimize the time duration of the at-risk situation of the damaged core being in an unengineered configuration. Parallel engineering on difficult cleanup issues and evolutions provided readily available alternatives for the "unknown unknown" situations. [32, 33]

- ***Importance of Data Acquisition***. [34, 35, 36] Balancing data-gathering tasks against production tasks was one of the most difficult challenges during the cleanup. Because of the DOE's involvement in the TMI-2 cleanup, there was considerable emphasis on research that would benefit the nuclear industry. Early in the TMI-2 cleanup, the plant operations staff objected to the delays resulting from research tasks. However, it was recognized that advance survey data about conditions inside the reactor vessel, containment building, and many locations of the auxiliary and fuel handling building were important for cleanup planning.

Data acquisition became such an important part of the overall cleanup program that a group was created within the TMI-2 organization to support the DOE's data acquisition needs. This group acquired and interpreted its own data that specifically benefited the cleanup program. Competition for resources never allowed for the complete elimination of disagreements over the value of data acquisition tasks, obtained at extra effort, time, and exposure. Nonetheless, there was a general recognition that the cleanup, and the condition of the damaged core, held so many potential surprises that data acquisition was an important part of each step in the program.

- ***Focus on Water Processing***. The potential for TMI-2's accident-generated radioactive water to leak into the Susquehanna River, contaminating both the river in Pennsylvania and the downstream Chesapeake Bay, was a major concern for the licensee leadership, the leaders and residents of communities downstream, and the State and local governments in both Pennsylvania and Maryland. The importance and urgency of removing the contaminated water from the entire TMI-2 site, as well as the TMI-2 containment building basement, became very significant. There was enormous focus on water processing throughout the entire TMI-2 cleanup. Decontaminated (processed) accident-generated water was temporarily stored on site and reused as radiation shielding in the spent fuel pools inside the fuel handling building and the deep end of the refueling canal inside the containment building. This water was reprocessed and evaporated over a 2.5-year period at the end of the cleanup campaign. (37)

- ***Focus on Defueling***. Early in the planning stages of recovering from the accident, the licensee envisioned returning TMI-2 to operation. As the extent of the damage to the reactor core and the expense of refurbishment became evident, a decision was made to work without regard to the final disposition of the plant. This decision focused available resources on immediate tasks. (38) In March 1984, the licensee changed its main focus at TMI-2 by advancing a "fast track" defueling concept to begin removing fuel within a year, with significant fuel removal planned to begin in April 1985 (although actual early defueling did not begin until later that year). In addition, the licensee focused efforts on modifying regulatory requirements to TMI-2 conditions, which involved significantly different safety controls and a different public risk profile. The concept focused available resources on near-term issues. (39)

- ***Conflicting Requirements.*** Potential sources of conflict developed early in the TMI-2 program because of differences in regulations and quality assurance (QA) practices followed by the licensee, the DOE, and the NRC. To promote smooth operations, it became necessary for each party to acknowledge the proper role of the other organizations and to sometimes accept the preeminence of another's practices. For example, though many projects were research related, NRC regulations (which govern nuclear utilities) generally superseded those of the DOE when working with the licensee. When fabricating research equipment, the DOE's QA requirements were generally followed. However, when the equipment was brought to TMI-2, the equipment was generally operated under the licensee's QA requirements. (40)

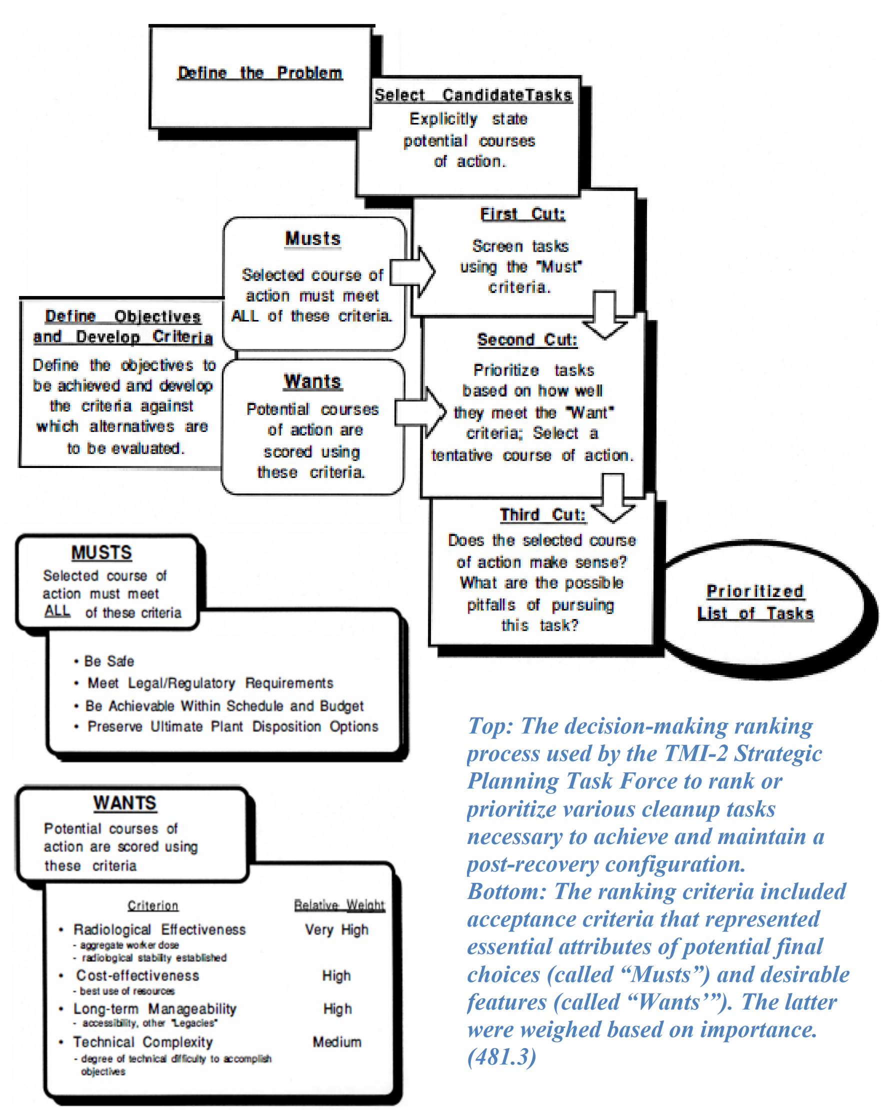
Another example of a conflict that occurred early in the cleanup involved the shipment of abnormal waste from TMI-2 to INEL for research. The DOE required a task-oriented process for QA. TMI and other NRC licensees used a programmatic approach to QA. The DOE required the licensee to develop and use special procedures and checklists that were specific to the abnormal waste item instead of using more generic documentation and procedures, which were used for NRC-regulated activities. Further, DOE requirements were different from the regulations of the U.S. Department of Transportation and the NRC. For example, DOE definitions of fissile material and accountable materials included additional radioisotopes. [41]

- ***Plan with Available Resources***. Considerations of bankruptcy and an order from the Pennsylvania State Public Utility Commission impacted the schedules and planning of cleanup activities. The licensee had to consider whether to remove the reactor vessel head before all resources (e.g., financial, engineering, personnel, training) were available to complete the effort or to reinstall the reactor head, if necessary. In late 1980, the public utility commission would not allow the use of any operating revenues for cleanup and restoration costs at TMI-2 that were not covered by insurance. However, the NRC Commissioners emphasized, in their policy statement that was attached in a subsequent letter [42] from the NRC Chairman to the licensee, that the licensee had to fully comply with all NRC health, safety, and environmental requirements applicable to TMI-2, regardless of whether these requirements appeared to conflict with the utility commission's order. Further, the Chairman's letter listed the activities required to be performed during the period of ongoing discussions between the licensee and the State agency. The list provided the minimum activities required to maintain the TMI-2 reactor in a safe-shutdown condition and to ensure public and worker health and safety and environmental protection in the near term. In addition, the list provided some activities required for reducing the intermediate and long-term threats to public and worker health and safety and the environment. Although the licensee was already performing the listed activities, this list (Table 1) was an early "roadmap" for protecting public and worker safety. [43, 44, 45]

- ***Project End State***. Toward the end of the cleanup, some questions arose about the end state of the TMI-2 site. The NRC's independent Advisory Panel for the Decontamination of TMI-2 urged the NRC staff to produce a third supplement to the programmatic environmental impact statement to address the topic of the final end state. The NRC Commissioners directed the staff to produce the supplement. [46]

The project end state, known as "post-defueling monitored storage," differed from any of the then-NRC-approved decommissioning modes, reflecting the fact that none of the established decommissioning end states would be achievable and appropriate for TMI-2. Post-defueling monitored storage was determined to be beneficial for the following reasons: (•) Occupational dose in the plant would be reduced during monitored storage because of natural decay of radioactive contamination (the remaining amount of cesium-137 would be 29–50 percent and cobalt-60 would be 1.9–13 percent). (•) A monitored storage period would allow time for continued development of decontamination technology. (•) Further reduction of occupational exposure would be achieved using advanced robotic technology, automatic cleaning and chemical cleaning techniques, and advanced waste treatment methods. (•) Developing technology for radioactive waste packaging and volume reduction could result in a reduction in the total volume of radioactive waste generated following post-defueling monitored storage. In addition, the licensee had stated that placing the TMI-2 facility in storage would eliminate any possible impact of TMI-2 decontamination and decommissioning efforts on the operating TMI Unit 1 facility. [47, 48]

- ***End State Specification Criteria***. An IAEA working group developed an example of end-state specification criteria for the postaccident cleanup end state, with examples taken from TMI-2 (see Table 2). [49]



Top: The decision-making ranking process used by the TMI-2 Strategic Planning Task Force to rank or prioritize various cleanup tasks necessary to achieve and maintain a post-recovery configuration.
Bottom: The ranking criteria included acceptance criteria that represented essential attributes of potential final choices (called "Musts") and desirable features (called "Wants'"). The latter were weighed based on importance. (481.3)

Table 1. NRC staff list of activities required in 1981 to be performed by the TMI-2 licensee. [50]

1. Maintain adequate control and confinement of radioactive materials. (Note 1)
2. Minimize the volume of water used in cleanup activities, maximize reuse of processed water, and reduce cross-contamination of processed water to the maximum practicable extent. (Note 1)
3. Maintain the facility and perform surveillance activities required by the technical specifications. Included in this activity was the performance of a test to verify stable core cooling by losses to ambient. (Note 1)
4. Perform necessary maintenance, including minor modifications, of equipment and facilities (i.e., winterization of the containment building cooling system). Included in this activity was the associated training of operators, and minor modifications identified as being desirable based upon design reviews and initial operating experience. (Note 1)
5. Decontaminate the auxiliary building as necessary to facilitate maintenance and operation of safety-related equipment. (Note 1)
6. Process radioactive waste generated by activities in this list, including handling and packaging for offsite disposal. Continue shipments for disposal of radioactive material. (Note 1)
7. Perform radiological controls necessary to support activities in this list, including: surveillance of work in radiation areas; in-plant surveys and monitoring; personnel exposure, measurement, and documentation; maintenance and calibration of equipment; emergency response capability; and training. Included in this activity was a continuation of the upgrading of the radiological controls program to meet revised performance standards which had resulted from the TMI-2 accident. (Note 1)
8. Perform measurement, analysis and documentation of the environmental impact of the facility. (Note 1)
9. Perform engineering functions (e.g., review of plant procedures) incident to conduct of required operation and surveillance of conditions of plant equipment, systems, and facilities. (Note 1)
10. Administer the technical and administrative interface with the regulatory agencies of the federal and state governments, including maintaining knowledge of current and proposed regulatory requirements. (Note 1)
11. Provide technically oriented services to implement quality assurance, training, emergency preparedness, and independent safety assessment programs. (Note 1)
12. Provide minimum required services in various support functions (e.g., security). (Note 1)

Table 1. NRC staff list of activities required in 1981 to be performed by the TMI-2 licensee. (Continued)

13. Provide repair or replacement of the failed source range neutron monitor. Continue efforts to achieve improved monitoring of core neutronics, utilizing other instruments. (Note 1)

14. Perform decontamination efforts inside the containment building necessary to support required maintenance activities. (Note 1)

15. Complete, subject to NRC approval, an interim solid waste storage facility. (Note 1)

16. Support finalization of the Draft Programmatic Environmental Impact Statement. (Note 2)

17. Develop the capability to decontaminate the radioactive water within the containment building sump and the reactor coolant system. (Note 2)

18. Continue the technical planning effort, including the gathering of data on conditions inside the containment building and the development of criteria to be applied to cleanup activities. (Note 2)

19. Provide engineering to support licensing and completion of base line engineering documents. (Note 2)

20. Complete development, engineering, and design efforts necessary to obtain NRC approval for construction and operation of a system for solidification of EPICOR II liners or propose alternative methods for the stabilization of these wastes. (Note 2)

21. Continue decontamination of the auxiliary building. (Note 2)

22. Continue to improve the company's management control programs. (Note 2)

23. Continue operation of the EPICOR II system on an as needed basis. (Note 2)

Notes:

(1) Minimum activities required to maintain the TMI-2 reactor in a safe shutdown condition and to insure public and worker health and safety and environmental protection in the near term.

(2) Activities required for reducing the intermediate and long-term threats to public and worker health and safety.

Table 2. Example of end state specification criteria for the postaccident cleanup end state. *[51]*

Criteria subjects	Criteria statements (examples based from TMI-2)
Structural and boundary integrity	Structural and boundary integrity will be such that: (a) inspection personnel are safe, (b) contamination or hazardous materials remaining in the facility are contained, and (c) intrusion by unauthorized personnel, as well as animals and plants, are prevented.
Nuclear materials and criticality	Nuclear fuel and debris will be removed to the extent practical. Residual fissile material must be reduced to a level such that criticality cannot occur.
Hazardous materials	Hazardous materials and chemicals will be removed in accordance with environmental regulations. Fixed in place hazardous materials remaining in the facility will be contained in limited areas or stabilized to prevent release. The amount and location of remaining hazardous materials will be documented.
Process systems and equipment	Process systems and equipment have been abandoned in place, isolated or sealed off for the safety of future personnel, or removed where there is a compelling reason to do so.
Service and utility systems and equipment	Only systems required to support the SAFSTOR state and maintain the stable condition are operational. Other utility systems will be abandoned in place, isolated or sealed off for the safety of personnel, or removed where there is a compelling reason to do so.
Personnel safety	Inspection personnel are safeguarded by stable conditions, postings and written procedures established in accordance with standard procedures for radiological protection and industrial safety practice.
Waste and liquid effluents	Waste will have been removed to the extent practical. Waste may remain if removal is extremely difficult. The only liquids remaining are minor quantities that cannot be readily removed with installed equipment.
Radiation protection	Established in accordance with standard procedures. In particular, the periodic inspection path will be subjected to ALARA review. Contamination remaining in the facility will be contained in limited areas or stabilized to prevent release.
Housekeeping and miscellaneous materials	Valuable materials will be removed. Rubbish and non-contaminated furniture, loose equipment, etc. will be removed.

2.3 Documentation

- ***Target the Audience***. Documenting the DOE research at TMI-2 was largely done by and written for the national laboratory audience. However, the DOE research had many practical applications and benefits for nuclear utilities, and the utility audience required a completely different documentation approach. Technical detail and background were less important than specific direction on the practical aspects of implementing the results derived from the DOE research. Generally, reports for the utility audience were required to be concise and stress the cost, performance, or productivity improvement that could be expected. [(52)]

- ***Consolidate Reporting***. The DOE published many research reports as "GEND" documents, even though the work was done by a variety of organizations that had their own technical documentation systems. GEND was the acronym for the principal participants in the TMI-2 research program: the licensee (GPU), EPRI, NRC, and DOE. The GEND reports came to be recognized as an important definitive source of TMI-2 data and results. This system allowed multiple organizations to publish TMI-2 information in a standard format. GEND reports are publicly available with no copyright restrictions. [(53,54)]

- ***Archived Data***. In 1980, the DOE established a microcomputer database that eventually indexed about 20,000 documents on the TMI-2 research and cleanup programs. The database was designed to be easily accessed by researchers throughout the country. Periodic reviews of the database contents, particularly in the early stages of development, were important for ensuring that the most useful documents were being included. The reviewers included both technical and documentation support staff. [(d, 55, 56)]

- ***Repositories of TMI-2 Knowledge***. With the advances of information technologies since the TMI-2 days, document collections can be easily captured and stored for future use by all interested stakeholders. The challenge today is organizing the vast amounts of electronic media for easy retrieval. The technical aspects of the TMI-2 cleanup were well documented. Key sources of TMI-2 cleanup experiences include the following: [(57)]

  - *American Nuclear Society* (ANS) (www.ans.org) maintains an extensive collection of its journal articles and proceedings on every aspect of the TMI-2 accident. ANS published the proceedings of the topical meeting, "The TMI-2 Accident: Materials Behavior and Plant Recovery Technology," held in

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[d] Editor's Note. The TMI-2 database is no longer available for the obvious technical reason that the database platform is obsolete. Future endeavors to capture knowledge for long-term and future decommissioning projects like Fukushima Dai-ichi and Chernobyl should be mindful of changes in information technologies as well as changes in organizational ownerships. Further, existing nondigital information (reports, photographs, and videos) from TMI-2 and other past cleanup programs should be converted to digital format before being lost or degraded beyond use.

Washington, DC, in 1988 in Volume 87 (58) of the *Nuclear Technology* journal. The papers in the proceedings and other papers may be purchased from the ANS Web site (free for ANS members).

- *Electric Power Research Institute* (www.epri.com) (EPRI) made available on its Web site many of its research reports that supported the cleanup and understanding of the accident. This collection is copyright protected. Six comprehensive reports on the accident, recovery, and cleanup include, "Analysis of Three Mile Island—Unit 2 Accident" (59); "The Cleanup of Three Mile Island Unit 2, A Technical History: 1979 to 1990" (EPRI-NP-6931); "TMI-2 Waste Management Experience" (EPRI-TR-100640); "TMI-2 Post-Accident Data Acquisition and Analysis Experience" (EPRI-NP-7156); "Radiation Protection Management Programs at TMI-2: Noteworthy Practices and Accomplishments" (EPRI NP-5338); and "Decontamination Experience During the Cleanup of Three Mile Island Unit 2" (EPRI-NP-7157).

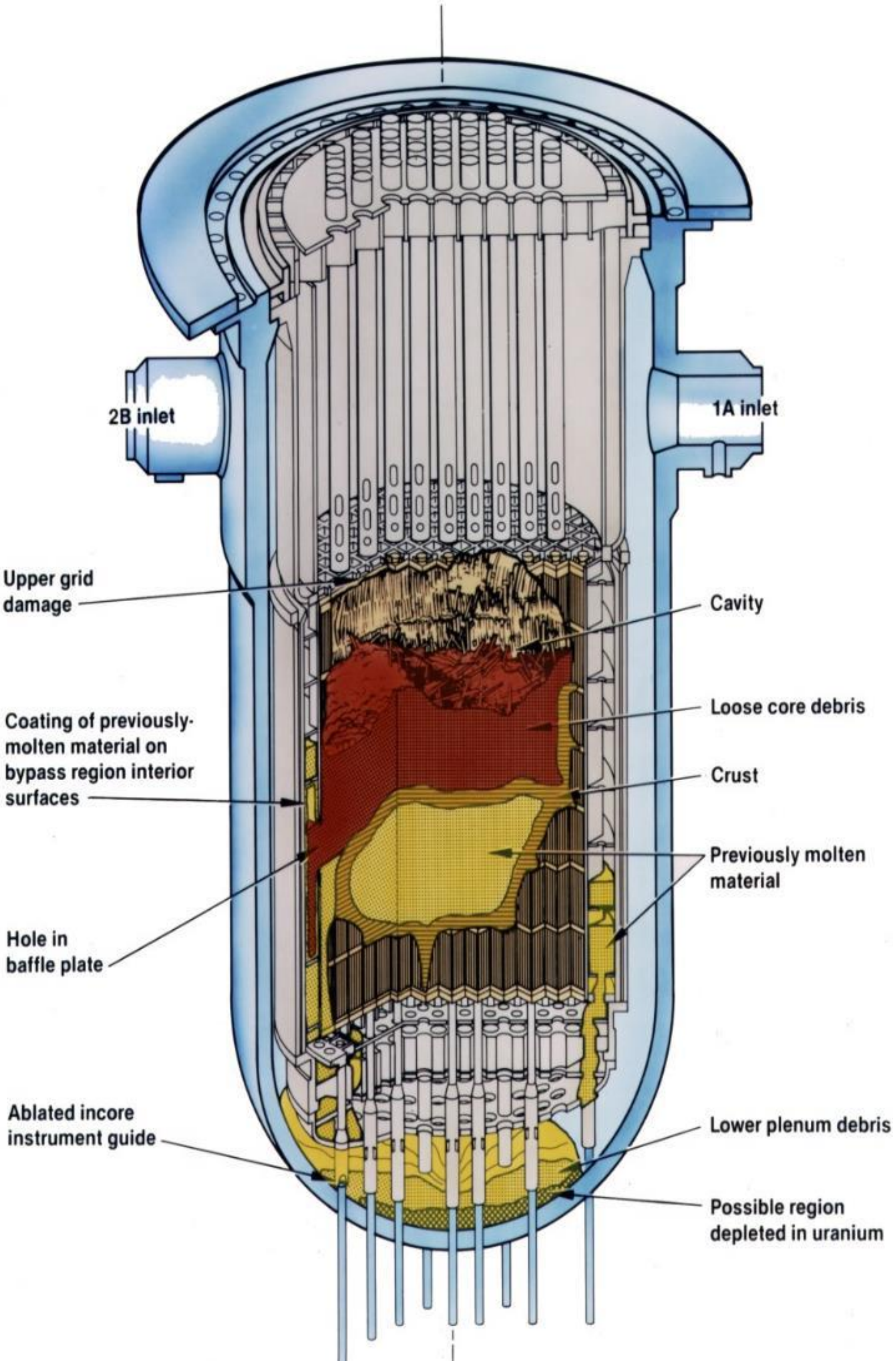
- *Idaho National Laboratory* (INL) (https://inldigitallibrary.inl.gov) maintains a collection of research reports in its INL Knowledge eRepository, including the GEND report collection. Most of these documents are on the DVDs for NUREG/KM-0001. The contents of the DVDs are posted on INL's Web site (https://tmi2kml.inl.gov).

- *Pennsylvania State University libraries* (www.libraries.psu.edu) maintain the TMI-2 Recovery and Decontamination Collection that contains several thousand videotapes of the recovery and cleanup during the 1979–1990 time period, as well as a few reports and photographs. GEND cosponsored a project with the university to catalog and maintain the extensive videotape library for future researchers. However, very few of the 3,000 video tapes are digitized, and these tapes are deteriorating at an alarming rate.

- *The DOE Office of Scientific and Technical Information* Web site (www.osti.gov) contains over 1,000 electronic full-text reports and papers relating to DOE-funded research in support of the recovery and cleanup efforts at TMI-2. Most of these documents are on the DVDs for NUREG/KM-0001.

- *The NRC* (www.nrc.gov) made available all its correspondence and safety evaluations with the licensee in microfiche format and an electronic cataloging system (the first electronic system for the NRC). Over 25,000 documents were preserved on microfiche. The electronic catalog platform has been kept up to date throughout the years and is available online for public access; however, only a very few documents captured on microfiche have been digitized. About 4,000 of the key documents from the NRC collection are on the DVDs for NUREG/KM-0001.

Figure on Next Page: The INEL report "TMI-2 Accident Scenario Update" (EGG-TMI-7489, December 1986) identified four regions within the original core volume: upper cavity void region, debris bed region, previously molten region, and partially standing fuel assemblies (or "stubs") region.


2B inlet
1A inlet
Upper grid damage
Cavity
Loose core debris
Coating of previously-molten material on bypass region interior surfaces
Crust
Previously molten material
Hole in baffle plate
Ablated incore instrument guide
Lower plenum debris
Possible region depleted in uranium

3 REGULATORY OVERSIGHT

The NRC realized that the recovery and cleanup of an already damaged reactor were unique and unlike anything encountered before. Special efforts were required to bring together all resources within the NRC and NRC technical support contractors. Past regulatory practices alone were neither sufficient nor appropriate. [(60)] Notable successes in the NRC's oversight of the cleanup program can be attributed to the programmatic environmental impact statement (PEIS); the onsite and offsite NRC TMI project offices; the NRC concept of operations for the TMI-2 cleanup; the recovery technical specifications; and the Advisory Panel for the Decontamination of TMI-2. Experiences from these topics are presented below.

3.1 Programmatic Environmental Impact Statement

In their November 21, 1979, policy statement [(61)], the NRC Commissioners directed the NRC staff to prepare a PEIS on the decontamination and disposal of radioactive waste resulting from the accident. The Commissioners' decision was influenced by a lawsuit about 6 months earlier from the City of Lancaster and others concerning the proposed operation of the EPICOR II system and by NRC discussions with the Council on Environmental Quality, within the Executive Office of the President. This holistic review (a thousand-page final PEIS document) was needed because the National Environmental Policy Act (NEPA) required a complete review of the environmental impact of an action—the TMI-2 cleanup in this case—and not a piecemeal approach. A piecemeal approach would have only looked at incremental impacts, which could be small individually but in total could be large. External stakeholders were concerned about these incremental impacts, as well as the lack of documented consideration of alternative approaches for the cleanup. The PEIS provided the bases for the environmental impact assessment for all cleanup activities. [(62, 63, 64)]

- ***Scope of the PEIS***. [(65)] The PEIS was intended to provide an overall evaluation of the environmental impacts that could result from the various cleanup activities. These activities began when the plant conditions were stabilized after the accident and continued through the completion of the cleanup. Impacts included the transportation of radioactive wastes and fuel debris to offsite storage locations. The PEIS included an overall description of the activities and a schedule for their completion, along with a discussion of alternatives considered and the rationale for choices made.

    - *Public Meetings*. The NRC discussed the proposed scope of the original PEIS with representatives of the President's Council on Environmental Quality, the licensee, and several State agencies. Early in the process of developing the draft PEIS, scoping sessions with the public took place in Harrisburg and Middletown, PA, and in Baltimore, MD. After publication of the draft PEIS for comment, the staff held 31 meetings with the public, local officials, and interested organizations to obtain, first hand, the comments and concerns of meeting participants and to foster an interchange of ideas.

- o *Uncertainties*. Because they were programmatic in nature, the reports were not intended to provide a step-by-step work plan. However, the most probable sequences and methods for cleanup had been assumed to predict the resulting environmental impacts. The best available information had been used and documented in these impact analyses. Where uncertainties existed, conservative assumptions had been made and documented in the main text and appendices as appropriate. If, when more information became available (for example, conditions inside the reactor building and reactor vessel), proposed activities were found to be significantly beyond the scope of these assessments, the NRC would issue appropriate supplements to the PEIS.

- o *Scope Expectations*. The ultimate disposition of the facility, whether to decommission or restore it to a condition acceptable for licensed operation, was not within the scope of the original PEIS. In addition, in their policy statement of April 27, 1981, which approved the NRC staff's use of the PEIS, the Commissioners wanted to decide on the disposition of accident-generated water at a later date. Later supplements to the PEIS further addressed these two exceptions.

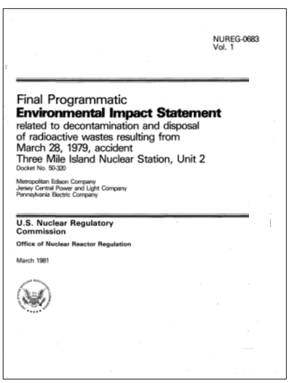
• ***Supplements to the PEIS***. The PEIS (NUREG-0683, "Final Programmatic Environmental Impact Statement Related to the Decontamination and Disposal of Radioactive Wastes Resulting from March 28, 1979, accident, Three Mile Island Nuclear Station, Unit 2," issued March 1981) had three supplements that were considered part of the original PEIS:

- o *Supplement 1, "Final Supplement Dealing with Occupational Radiation Dose*." The original PEIS stated that the most significant environmental impact of cleanup activities at TMI-2 would result from the radiation dose to the cleanup work force. This supplement, issued in October 1984, reevaluated the occupational radiation dose and resulting health effects from cleanup and addressed additional alternative cleanup approaches using information gathered since the PEIS was prepared in 1980. Higher estimates resulted from a more accurate characterization of radiation fields in the reactor building based on numerous worker entries. [(66)] However, by the end of 1989, with the fuel debris about 99 percent removed, the collective dose to all workers fell within the range estimated in the original PEIS. [(67)]

- o *Supplement 2, "Final Supplement Dealing with Disposal of Accident-Generated Water*." This supplement, issued in June 1987, updated the environmental evaluation of accident-generated water disposal alternatives published in the original PEIS, using more complete information. The supplement also included a specific environmental evaluation of the licensee's proposal for water disposition. [(68)]

- o *Supplement 3, "Final Supplement Dealing with Post-Defueling Monitored Storage and Subsequent Cleanup."* This supplement, issued in August 1989, evaluated the licensee's proposal to complete the cleanup effort and place the facility into monitored storage for an unspecified period of time. The supplement provided an environmental evaluation of the licensee's proposal, as well as several alternative courses of action, from the end of defueling efforts to the beginning of decommissioning. However, it did not evaluate the environmental impacts associated with decommissioning. [69]

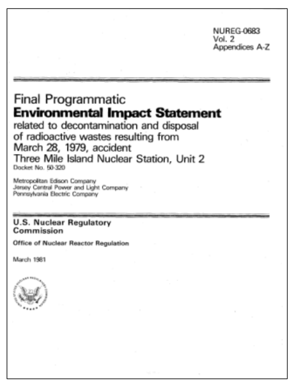
- ***Approval of Cleanup Proposals: NRC Staff.*** The NRC Commissioners' policy statement that endorsed the PEIS provided the staff with the authority to approve most cleanup activities. The Commissioners stated that, as the licensee proposed specific major decontamination activities, the NRC staff would determine whether these proposals, and the associated impacts that were predicted to occur, were within the scope of those already assessed in the PEIS. Except for the disposition of processed accident-generated water (which the Commissioners wanted to decide on later), the staff was allowed to act on each major cleanup activity without the Commissioners' approval if the activity and the associated impacts were within the scope of those assessed in the PEIS. [70]


NUREG-0683
Vol. 1

Final Programmatic
Environmental Impact Statement
related to decontamination and disposal
of radioactive wastes resulting from
March 28, 1979, accident
Three Mile Island Nuclear Station, Unit 2
Docket No. 50-320

Metropolitan Edison Company
Jersey Central Power and Light Company
Pennsylvania Electric Company

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
March 1981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Vol. 2
Appendices A-Z

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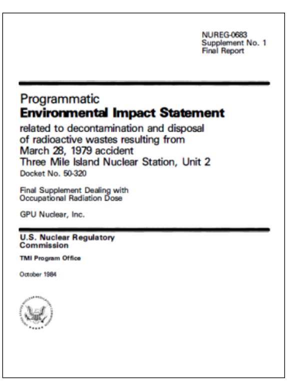
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Supplement No. 1
Final Report

Programmatic
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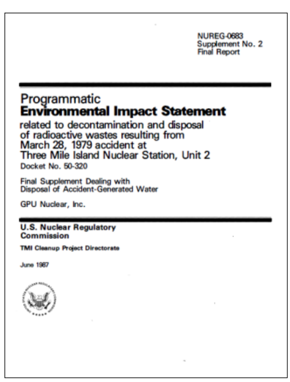
related to decontamination and disposal
of radioactive wastes resulting from
March 28, 1979 accident
Three Mile Island Nuclear Station, Unit 2
Docket No. 50-320

Final Supplement Dealing with
Occupational Radiation Dose

GPU Nuclear, Inc.

U.S. Nuclear Regulatory Commission
TMI Program Office
October 1984


NUREG-0683
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Final Report

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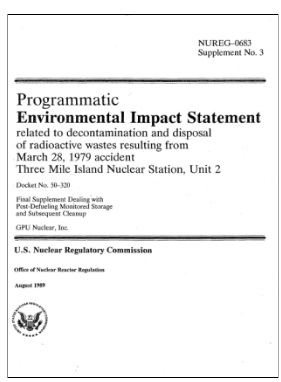
Final Supplement Dealing with
Disposal of Accident-Generated Water

GPU Nuclear, Inc.

U.S. Nuclear Regulatory Commission
TMI Cleanup Project Directorate
June 1987


NUREG–0683
Supplement No. 3

Programmatic
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related to decontamination and disposal
of radioactive wastes resulting from
March 28, 1979 accident
Three Mile Island Nuclear Station, Unit 2

Docket No. 50-320

Final Supplement Dealing with
Post-Defueling Monitored Storage
and Subsequent Cleanup

GPU Nuclear, Inc.

U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
August 1989

The Programatic Environmental Immpact Statement (PEIS) had three supplements that were considered part of the original PEIS.

- ***Approval of Cleanup Proposal: NRC Commissioners***. In the year following the accident, the NRC Commissioners approved radiological effluent criteria for the interim period before the issuance of the PEIS for radiological releases from data-gathering and maintenance operations. Following the issuance of the PEIS, if a cleanup task was evaluated to be outside the scope of the PEIS, then the NRC TMI-2 project office (TMIPO) would recommend to the NRC Commissioners either their approval of the task or the development of a supplement to the PEIS. This action was never necessary. The licensee never submitted a proposal for a cleanup activity that TMIPO determined would result in an environmental impact outside the scope of the PEIS and its supplements. (71)

- ***Success of the PEIS***. The TMI-2 PEIS became a bounding safety case analysis document and served as an envelope within which cleanup operations could be efficiently approved by the onsite NRC staff. The NRC TMI project office was able to approve proposals, sometimes within days instead of the months that would have been needed had the reviews required NRC Commissioner approvals. The determination to develop a PEIS that covered the entire cleanup process, rather than separate environmental assessments for each major activity, helped to expedite environmental reviews. The PEIS' success was based on the following additional contributions: (●) The requirements and intent of the National Environmental Protection Act were compiled using a programmatic approach to assessing impact. (●) The PEIS summarized the various components of the TMI-2 cleanup that had appeared in many documents. (●) The document was written to be understood by members of the public. (●) The PEIS evaluated alternatives to the various evolutions. (●) The PEIS included technical information on the cleanup, including estimates of the impact on the environment, workers, and the public. (●) Development of the PEIS encouraged and factored in public involvement, including 31 meetings with the public, local officials, and interested organizations. (●) The PEIS was a living document that ultimately had three supplements. (●) Both the industry and the public considered the PEIS to be a comprehensive assessment. (72, 73)

- ***PEIS-Like Document for Other Cleanup Programs***. The PEIS satisfied the requirements of the National Environmental Protection Act and then became the basis for the NRC staff's approval of cleanup proposals. The latter use of the PEIS can be applied to other severe accident cleanup programs. A PEIS-like document could be useful in the following ways: (●) Represent a national-level comprehensive document that addresses impacts from all segments of the cleanup. (●) Consider and incorporate input from all stakeholders, including the public, the licensee, and government agencies. (●) Evaluate alternatives. (●) Improve public understanding of the complexity and difficulty of the cleanup. (●) Be a living document, with the publication of supplements, as needed, with public input. (74)

- ***PEIS Delayed at TMI-2***. The NRC did not decide to prepare a PEIS until nearly 8 months after the accident. An earlier decision to prepare this document would have allowed the PEIS to be published earlier than March 1981, which would have facilitated some of the early cleanup activities, including an earlier startup of the submerged demineralizer system to remove contaminated water on the containment building floor. [75] The potential for this radioactive water to leak into the Susquehanna River, contaminating both the river and the downstream Chesapeake Bay, as well as downstream drinking water supplies, was a major concern for the licensee's leadership, the leaders and communities downstream, and the State and local governments in both Pennsylvania and Maryland. [76]

3.2 Technical Specifications

Within a year following the accident, the NRC issued an order that established the new "recovery technical specifications" (Appendix A to the facility operating license) that considered the condition of plant systems at that time. The purpose of these new technical specifications was to ensure that the damaged plant would remain in a safe and stable condition during the recovery mode. The then-existing preaccident technical specifications imposed for the protection of the environment (Appendix B to the facility operating license), including the established limitations on effluent releases and discharges, were unchanged and were to remain in effect except as provided in the order. [77]

- ***Recovery Technical Specifications***. One important lesson from the cleanup was that many of the administrative inefficiencies were related to the constraints of the preaccident TMI-2 technical specifications. [78] As a result of the core and equipment damage, various requirements set forth in the preaccident technical specifications governing operations were no longer appropriate. For example, certain equipment that was required to be operable was no longer operable as defined in the technical specifications. Other systems not generally relied on for safe shutdown of the reactor maintained the facility in a stable mode of heat removal. High radiation levels in the containment building, reactor coolant, and certain areas throughout the plant had limited personnel access to certain components or had limited the ability to operate certain systems or components in their original design mode. Several systems and components had been modified to respond to the initial emergency condition. The postaccident recovery technical specifications saved time and resources that would have been needed to modify the facility license for each change to the plant's technical specifications. [79]

- ***Recovery Operations Plan***. The "recovery operations plan" defined the surveillance requirements to be performed to ensure equipment operability as required by the recovery technical specifications. This plan was included as Section 4 of the recovery technical specifications. However, the plan was not considered a part of the technical specifications. As such, the NRC staff approved changes made to surveillance requirements without the need to modify the facility license, which changes to the technical specifications would have required. [80]

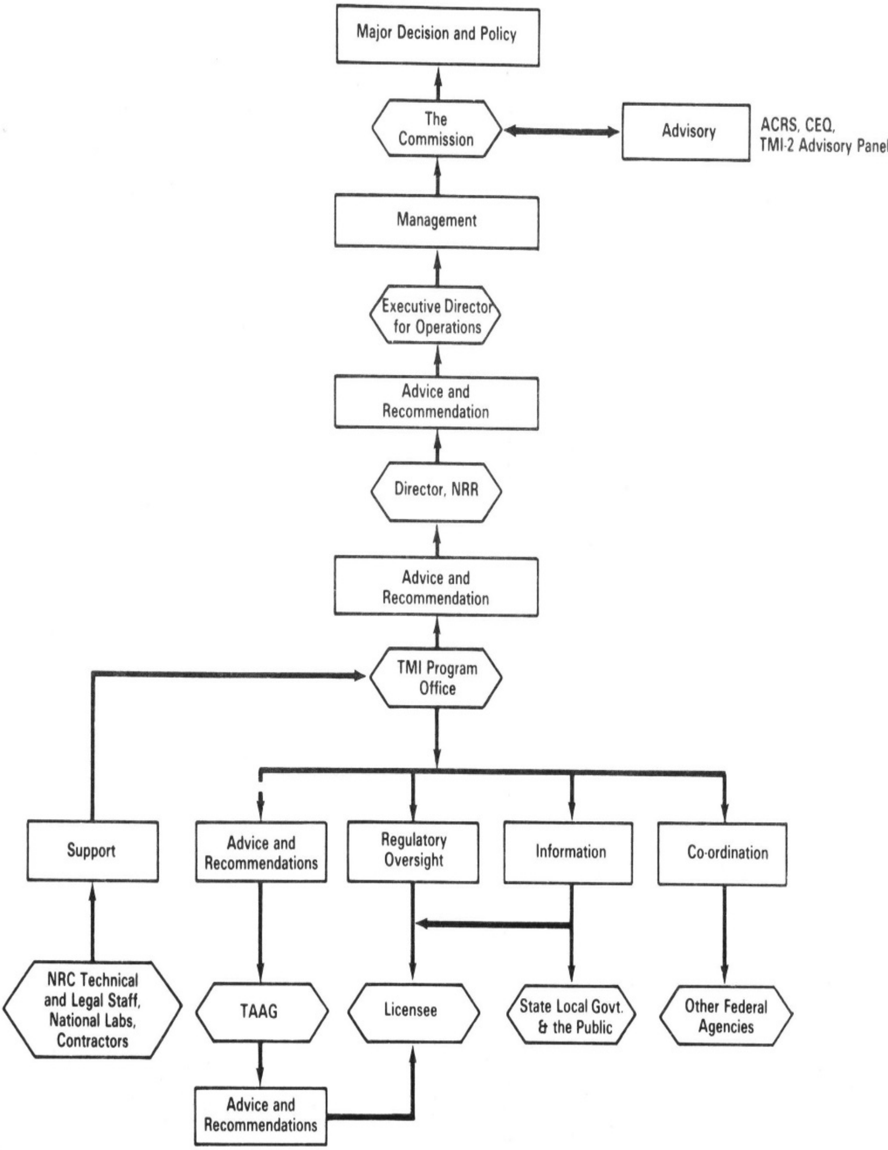
- ***TMI-2 Organization Plan***. The licensee's organization plan provided the organizational structure (e.g., charts) for managing the TMI-2 recovery operations, including the support functions of engineering and administration. The plan was cited in the organization section of the proposed technical specifications. The NRC approved the licensee's concept of providing charts of the TMI-2 recovery management in the organization plan, instead of in the recovery technical specifications, so that future changes could be made effective in a timely manner. Changes made to the organization plan required NRC approval, but most changes did not require a modification of the recovery technical specifications. [81]

- ***Recovery Procedures***. The recovery technical specifications also imposed a requirement that the NRC would approve recovery mode implementation procedures. The specific procedures affected by this requirement were those that: (●) specifically related to core cooling; (●) could cause the magnitude of releases to exceed limits established by the NRC; (●) could increase the likelihood of failures in systems important to safety and radioactive waste processing or storage; or (●) could alter the distribution or processing of significant quantities of contaminated water stored or being released through known flowpaths. The implementation of the procedure approval requirement necessitated a high degree of involvement by the NRC's onsite staff in planning operations. During the first 5 years of recovery operations, the NRC approved over 1,000 procedures, including revisions. [82]

3.3 Conduct of Operations

Soon after the creation of the TMI-2 project office, the office staff issued NUREG-0698, "NRC Plan for Cleanup Operations at Three Mile Island Unit 2," in July 1980. This plan defined the functional role of the NRC in cleanup operations at TMI-2 to ensure that agency regulatory responsibilities and objectives would be fulfilled. The plan outlined NRC functions in TMI-2 cleanup operations in the following areas: (●) functional relationship of the NRC to other government agencies, the public, and the licensee to coordinate activities; (●) functional roles of these organizations in cleanup operations; (●) NRC review and decisionmaking procedures for the licensee's proposed cleanup operation; (●) NRC/licensee estimated schedule for major actions; and (●) the NRC's functional role in overseeing implementation of approved licensee activities. The NRC revised the plan in 1982 and 1984. [83, 84]

- ***Adjustments to Meet Challenges***. As the cleanup progressed, it became apparent that TMI-2 should be treated more like a waste management facility than a reactor facility. This required different skills and different mind sets. Sometimes traditional reactor safety perspectives were counterproductive. The NRC's oversight responsibilities at TMI-2 required special delegated authorities and accountability requirements. The NRC required technical staff who possessed excellent communication skills. Decisions were generally more effective when made at the local site versus at NRC Headquarters or NRC Region I, although NRC Headquarters expertise was often used. The issues under consideration were very technical and site driven. [85]



Key: Advisory Committee for Reactor Safeguards (ACRS), President's Council on Environmental Quality (CEQ), Nuclear Reactor Regulation (NRR), Technical Advisory and Assistance Group (TAAG)

Major NRC functional roles in TMI-2 cleanup operations in 1984. (481.4)

- ***Regulatory Goals***. The NRC's regulatory goals for TMI-2 cleanup operations were well understood and documented in NUREG-0698. The NRC kept the plan current with subsequent revisions and included the following objectives: (●) ensure reactor safety and control of radioactivity [e]; (●) ensure minimal environmental impacts; (●) maintain the radiation exposures of workers, the public, and the environment within regulatory limits and at ALARA levels; and (●) achieve interim safe storage and disposal of radioactive wastes from the cleanup operation. [86]

- ***Onsite Presence***. The NRC had a daily onsite presence with prompt, open access to all information. Information exchanges between the licensee (and its contractors) and the NRC included preliminary planning and scheduling. This information involved more than just being aware of daily plant status; it also included being part of the intellectual planning aspects. The licensee decided what activity was to be proposed and determined when the proposed activity was safe enough to move forward. Additionally, the NRC staff monitored licensee planning meetings to keep the agency's managers informed of upcoming activities, including those with possible safety or regulatory issues. This information fostered more complete and faster safety evaluations by the licensee and the NRC. In all cases, for both organizations, the dominant criterion was to do what was best for public and worker safety. [87]

- ***NRC TMI Project Office (TMIPO)***. [88, 89, 90, 91] At TMI-2, the normally separate NRC functions of regulatory approval of proposed changes and the inspection of operations to ensure compliance with approved license requirements were combined in a single group. Most of NRC staff who conducted the regulatory reviews and inspections were physically located onsite in mobile trailers. Some NRC reviewers and inspectors of unique activities were occasionally loaned to the site from NRC Region I or NRC Headquarters. In this manner, the staff could accomplish the review and approval process of proposed activities in a matter of days instead of months, and it could inspect all the activities immediately.

  - *Authority and Capabilities*. The NRC Commissioners gave TMIPO unprecedented authority and capabilities to meet regulatory responsibilities. These included ample staffing and sufficient funding for technical support to use outside experts (national laboratories, consultants) and access to NRC technical experts at NRC Headquarters and regional offices. This organization was also unique because it combined in one unit both the management and professional staff necessary to carry out safety and environmental reviews and the direct inspection of nearly all aspects of the cleanup.

  - *TMIPO Locations*. TMIPO had a strong onsite presence, with two offices at TMI and a staff of about 20 individuals. The offices included a public office in

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[e] Editor's Note: "Radioactivity" was a legacy term used during the TMI-2 period to mean most things radioactive, such as radioactive materials, contaminated waste water, surface contamination, and area sources of radiation.

Middletown and an onsite working office. The onsite office was staffed by Headquarters and regional inspectors and technical staff, clerical staff, foreign assignees, part-time cooperative students, and summer students. This office was responsible for the day-to-day review of all licensee activities that pertained to the cleanup and information flow to other NRC offices, interested government agencies, and the public. The town office provided opportunities for the public to stop by and speak to public affairs and technical staff about the status of the plant and cleanup, including voicing their concerns about public safety. (The office included a rug for use by the children of visiting mothers.) An additional TMIPO office at NRC Headquarters, located in Bethesda, MD, functioned as the liaison with the Commissioners, executive managers, and NRC Headquarters offices.

- *Staffing and Support*. TMIPO had an integrated onsite staff for analysis, licensing, operations, inspections, and public communications. TMIPO also had strong support at NRC Headquarters for Federal interfaces, legal expertise, and special issues (e.g., transportation, health physics, environmental). National laboratories and contractors contributed special expertise to the NRC site office. Within the first 3 years following the accident, the NRC assigned 30 to 40 staff members to the TMI-2 cleanup, initially divided equally between the site and NRC Headquarters offices. This level of staffing allowed for a high level of NRC scrutiny of the unique cleanup activities, including the review and approval of the detailed procedures for implementing the cleanup. As the project progressed, the NRC gradually reduced its staff and the level of staff review of detailed cleanup activities.

- *Public Outreach*. Public communication was most visible through weekly plant status reports on the cleanup; notification reports of unusual occurrences; participation in several public and civic group meetings every week; and interviews with the local news media. The reports provided to the public and media were the same ones distributed within NRC Headquarters.

- ***Roles, Responsibility, and Authorities***. The NRC staff involved in the regulatory oversight at TMI-2 required clearly defined and documented roles, responsibilities, and authorities on the cleanup, including regulatory interactions with all involved organizations, while maintaining regulatory independence. NUREG-0698 documented the NRC's role in cleanup operations at TMI-2 and its regulatory responsibilities in fulfilling this role. [92]

The purpose of this NRC plan was to (●) define the functional role of the NRC in cleanup operations to ensure that agency regulatory responsibilities and objectives were fulfilled and (●) provide a general schedule of major cleanup actions and the NRC's role in meeting these milestones.

The plan outlined NRC functions in the following areas: (●) relationship of the NRC to other government agencies, the public, and the licensee for coordinating activities, (●) review and decisionmaking process for the licensee's proposed cleanup activities, and (●) roles in overseeing implementation of approved licensee activities. The NRC issued two revisions of its plan. [93]

- ***Sharing Information***. All organizations at TMI-2 proactively shared information while maintaining their respective responsibilities and duties. Open discussions of mutual concerns and options were encouraged so that all organizations could understand the others' views. Differing professional opinion discussions were welcomed and resolved promptly with an established management process. Constant self-assessment was necessary; operational feedback reflection was an important part of the never-ending improvement learning process. [94]

- ***Regulatory Independence***. The NRC TMI project office (TMIPO) used DOE national laboratories extensively to conduct independent confirmatory safety and environmental reviews relative to the cleanup. For example, Argonne National Laboratory supported the development of the PEIS, and Pacific Northwest Laboratory measured the nuclear fuel remaining in the reactor coolant system and the reactor vessel after defueling. In such cases, the NRC was careful to avoid the appearance of a conflict of interest, ensuring that when a specific national laboratory did work for the NRC, it did not work on that same subject for the licensee. This practice helped maintain independence. [95, 96]

On only one occasion was the use of separate laboratories not practical. That occasion required the use of two experts, who were the only ones highly specialized in fuel measurement, and both came from the same national laboratory. The licensee contracted one expert to assess the remaining fuel in the reactor vessel following defueling. TMIPO contracted the other specialist to review this assessment. Luckily, both experts came from different organizations within the laboratory, and the laboratory established a special "firewall" to separate the two to prevent collaboration and organizational influences in their work. The NRC found this arrangement acceptable. [97]

- ***Independent Research***. The NRC signed a coordination agreement with the DOE, the licensee, and EPRI in 1980 to jointly sponsor and participate in the DOE's TMI Information and Examination Program. This program (known as "GEND") was established to acquire data to improve the understanding of nuclear plant accidents and the phenomena that contributed to those accidents. Like other research agreements that the NRC had with industry organizations on non-TMI-related research collaboration (e.g., EPRI, owners' groups), all parties agreed upon the data collection methods and procedures before work began, and participating organizations used the impartial results independently to meet their individual needs. Since NRC TMI project office (TMIPO) observed daily meetings of the various cleanup groups, the NRC staff was responsible for reviewing the data acquisition tasks to ensure that they were implemented in coordination with the ongoing cleanup schedule. In addition, TMIPO ensured that the acquired data were used for the benefit of the cleanup to the maximum possible extent. [98]

3.4 Advisory Panel for the Decontamination of TMI-2

In October 1980, the NRC established a 12-member TMI-2 advisory panel to consult with and advise the Commissioners and staff on major activities related to the decontamination and cleanup of TMI-2. The panel consisted of State employees of the Commonwealth of Pennsylvania, local government, the scientific community, and residents near TMI. The TMI-2 project office acted as a liaison between the NRC and the panel and provided information to the panel on the status of the cleanup. Panel meetings were open to the general public, and transcriptions were produced for the public record. Panel members traveled to Washington, DC, at least once a year to meet with the Commissioners and report on panel activities. The panel held its last meeting, the 78th overall, in September 1993. (99)

- ***Lessons Learned from the Advisory Panel***. (100) NUREG/CR-6252, "Lessons Learned from the Three Mile Island Unit 2 Advisory Panel," issued August 1994, included observations and lessons based on interviews of former members and reviews of transcriptions of public meetings. All 36 individuals interviewed for NUREG/CR-6252 considered the advisory panel a success, particularly its effectiveness in accomplishing its mission. The following summarizes some key observations from that document on the achievements of the panel:

  - The panel established a communication channel between the public and the NRC Commissioners and helped to defuse hostility among the stakeholders.

  - The panel provided a way for the NRC and the utility to report on the progress of the cleanup and to gauge the public's reaction to various alternative actions.

  - The panel kept the importance of the cleanup before the NRC Commissioners through periodic public meetings.

  - The consensus was that the panel had an influence on cleanup activities, although not in the form of technical advice or guidance.

  - The most crucial panel influence on cleanup activities was the increased public scrutiny of both NRC and licensee decisions and activities. The panel facilitated communication with the public for both the NRC and the licensee. This communication helped sensitize the NRC and the licensee to public concerns.

  - The panel encouraged the licensee and the NRC to fully consider alternatives and to carefully think through cleanup activities and how these activities would be presented to the community.

- ***Success of the Advisory Panel***. (101) The panel held 78 meetings over 13 years. Panel members were dedicated to their appointments (and not paid, except for nominal travel reimbursements). The success of the panel could be attributed to the following:

- The NRC had a genuine interest in opening two-way communications with the public. The licensee recognized the value of openness in dealing with the regulatory agencies, employees of the Commonwealth of Pennsylvania, and the public. The NRC consistently supported the panel.

- Although funded by the NRC, the panel enjoyed a great deal of independence. Periodic meetings with the NRC Commissioners lent legitimacy to the panel.

- The panel was led by two chairpersons who were outstanding in their ability to deal with complex technical issues in a highly charged public environment. These chairpersons were fair, effective, and concerned when leading the meetings. A good chairperson was an absolute necessity for success.

- The makeup of the panel was balanced and represented all stakeholders. Panel members ranged in expertise and perspectives. This makeup contributed to the perception that the panel was a credible and legitimate forum for discussion of the cleanup activities. Longevity of panel membership allowed the development of the technical understanding required to ask the right questions and understand the answers.

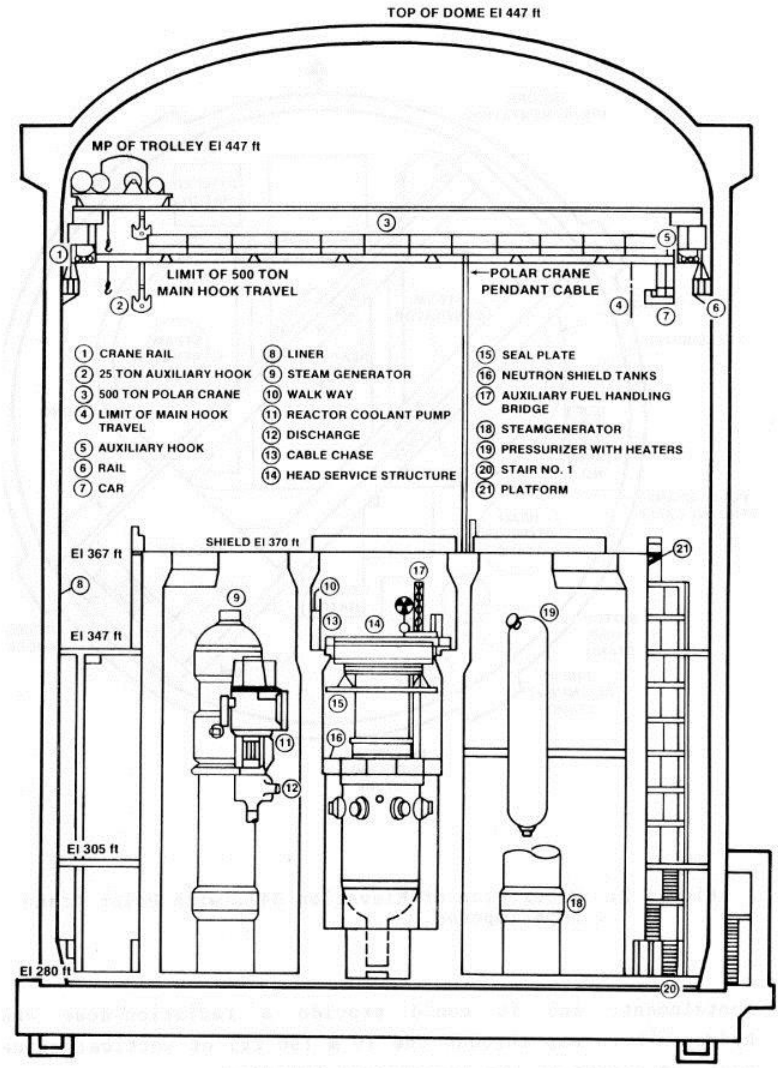
- The structure of meetings was effective. The agenda for each meeting was predictable, time constraints were followed, and time was scheduled for all parties to speak.

- Panel members were committed and willing to spend the time between meetings to prepare. Having the meetings in the early evening made the meetings more accessible to the public; it also had the benefit of allowing the panel members to dine together, which markedly improved their understanding of each other's concerns.

- Transcribing the meetings was important in that people were careful in what they said. Additionally, the transcription provided a historical record of the cleanup as told by all the stakeholders.

- Frequent news media coverage of the panel meetings disseminated cleanup information to a wider audience than was reached through the panel meetings themselves. Media coverage encouraged high-quality presentations about the cleanup.

- Members from the licensee's Safety Advisory Board frequently attended panel meetings. This also helped inform cleanup planning.



Key to Figure on Next Page:
Workers on the defueling work platform.(a) camera operator; (b) tool operator; (c) crane operator; (d) probably the camera controller acting as an assistant to the tool operator; (e) radiation control technician; (f) step stool for disconnecting tools from the jib crane when tied off in the slot; (g) hydraulic control skid used to power long-handled tools; (h) long-handled tool tied off in the slot; (i) stepoff pad to the defueling water cleanup equipment; (j) small long-handled tools tied off in the slot; (k) long-handled tools tied off along the fuel canal wall; (l) monitor console; (m) rack containing disposable booties and gloves; (n) possibly a container of discarded booties and gloves awaiting transfer; and (o) camera control console and radio repeater equipment. (481.5)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4 DEFUELING

The 10-year overall defueling effort at TMI-2 expended a collective manpower effort of over 3.6 million person-hours. The reactor vessel defueling operations alone spanned a 5-year period, from October 1985 through January 1990, and involved over 2 million person-hours. The 5-year effort removed a total of about 133,000 kilograms of fuel, cladding, and structural and control materials from the reactor vessel. In July and August 1991, the reactor vessel was drained to make final measurements of the residual fuel remaining in it. The estimated residual fuel quantity that remained in the reactor vessel following defueling was approximately 1 percent of the original 94,000 kilograms of uranium oxide fuel inventory. (102) The total quantity of residual fuel (uranium dioxide) was estimated to be less than 1,125 kilograms, distributed in four major plant locations as follows: (●) auxiliary and fuel handling buildings (less than 17 kilograms); (●) reactor building, excluding the reactor coolant system (less than 75 kilograms); (●) reactor coolant system, such as steam generators, pressurizer and surge line, and other low points, excluding the reactor vessel (less than 113 kilograms); (●) reactor vessel (less than 900 kilograms). (103)

The following defueling topics include safety; planning; predefueling activities; the defueling work platform; work inside the containment building; defueling tools; defueling canisters; and defueling operations.

4.1 Defueling Safety

The near-term cooling of the reactor core was stable within the first week after the accident. However, many technical issues involving safety and control were considered in the following weeks and months. Other unique safety concerns and solutions were identified during the defueling years. The list below presents a brief overview of these concerns related to defueling activities. More thorough descriptions appear in EPRI-NP-6931 and NUREG/KM-0001, Supplement 1.

- **Defueling Safety Concerns**. When preparations for defueling began, each proposed activity required NRC approval, in accordance with requirements in the recovery technical specifications. The licensee's safety analysis report of a proposed activity and the NRC's safety evaluation report considered a list of safety concerns, along with any mitigation measures related to the proposed activity. The typical list of safety concerns addressed in these reports included: (●) criticality (in-vessel, ex-vessel, and containment building sump); (●) decay heat removal; (●) hydrogen evolution; (●) pyrophoricity; (●) heavy load handling and load drops; (●) fire protection; (●) impacts on TMI-1 and TMI-2 plant operations; (●) submerged combustion; (●) instrument interference; (●) reactor pressure vessel integrity; (●) electric shock; (●) worker exposure; and (●) release of radioactivity, including offsite exposure. (104)

- ***Criticality Concerns***. The licensee instituted the necessary controls to prevent the damaged reactor core from achieving a critical condition during defueling operations. The reactor vessel at TMI-2 remained intact, allowing the use of boric acid in the reactor coolant for criticality control. Analysts predicted how much fuel would be at each location (in-vessel and ex-vessel), and they conservatively estimated the amount of boron required to preclude inadvertent criticality at each location. Safety evaluations included every possible scenario that could result in an inadvertent boron dilution. Numerous criticality analyses included conservative assumptions to account for the unknowns about the condition of the core. Further, there was reasonable assurance that the necessary controls were in place to prevent an inadvertent criticality. The NRC's independent analyses supported its approvals of all cleanup activities that could impact subcriticality. [105, 106]

- ***Boric Acid for Criticality Control***. Six elements (boron, cadmium, gadolinium, lithium, samarium, and europium) were studied for potential addition into the coolant system to maintain the neutron multiplication factor (k_{eff}) below 0.95. Boron (as boric acid) was found to have a variety of advantages, including minimum impact on water cleanup systems, lack of serious materials compatibility problems, and lower costs. In addition, boron could be added to the coolant system using existing chemical addition equipment. The dissolved boron minimum level of 4,350 parts per million was found to be adequate to maintain the TMI-2 core debris subcritical under all feasible configurations. Boron additions had to be made before lowering water in the vessel because, once the water level was lowered, gas pockets (at the tops of the steam generators) would prevent mixing of the boron throughout the reactor coolant system. [107, 108]

- ***Boration Dilution Concerns***. [109] Licensee evaluations considered that unborated or underborated water could be unintentionally injected into the reactor vessel, resulting in boron dilution and possible inadvertent criticality. The underborated water could come from several sources, such as demineralized water used in the plant or "slugs" of water trapped in pipes since the accident. All proposed cleanup activities at TMI-2 were analyzed for boron dilution and mitigation.

  - *Analysis*. The boron dilution analysis typically included the following steps: (1) Identify the potential points of water injection into the reactor coolant system (RCS) (e.g., core flood tanks, pressurizer, reactor coolant pump seals, steam generator secondary side, reactor vessel nozzles, top of the open reactor vessel). (2) Track each potential RCS injection point connected from potential dilution sources (e.g., tanks, coolers, demineralizers, evaporators, heaters, closed cooling water systems, spent fuel pool). (3) Identify isolation barriers for each dilution source (e.g., removed spool pieces, closed valves, heat exchanger or pumps with elevation or head differences). (4) Determine the probability of failure of the isolation barrier configuration due to hardware faults and human error. (5) Estimate the total plant boron dilution potential by considering the number of injection paths, the reliability of each isolation barrier, and the potential for operator error, or failure, in identifying and terminating a boron dilution event.

- *Mitigation*. Credit for mitigation was heavily dependent on the detection capability. At TMI-2, the means of detecting a boron dilution event included monitoring: (●) reactor coolant level; (●) levels of dilution sources (e.g., tanks); (●) mass balance of the RCS; (●) status of the positions of valves, pumps, and breakers by using equipment checklists; (●) neutron detection with operable source range neutron detectors; and (●) RCS boron concentration by routine sampling.

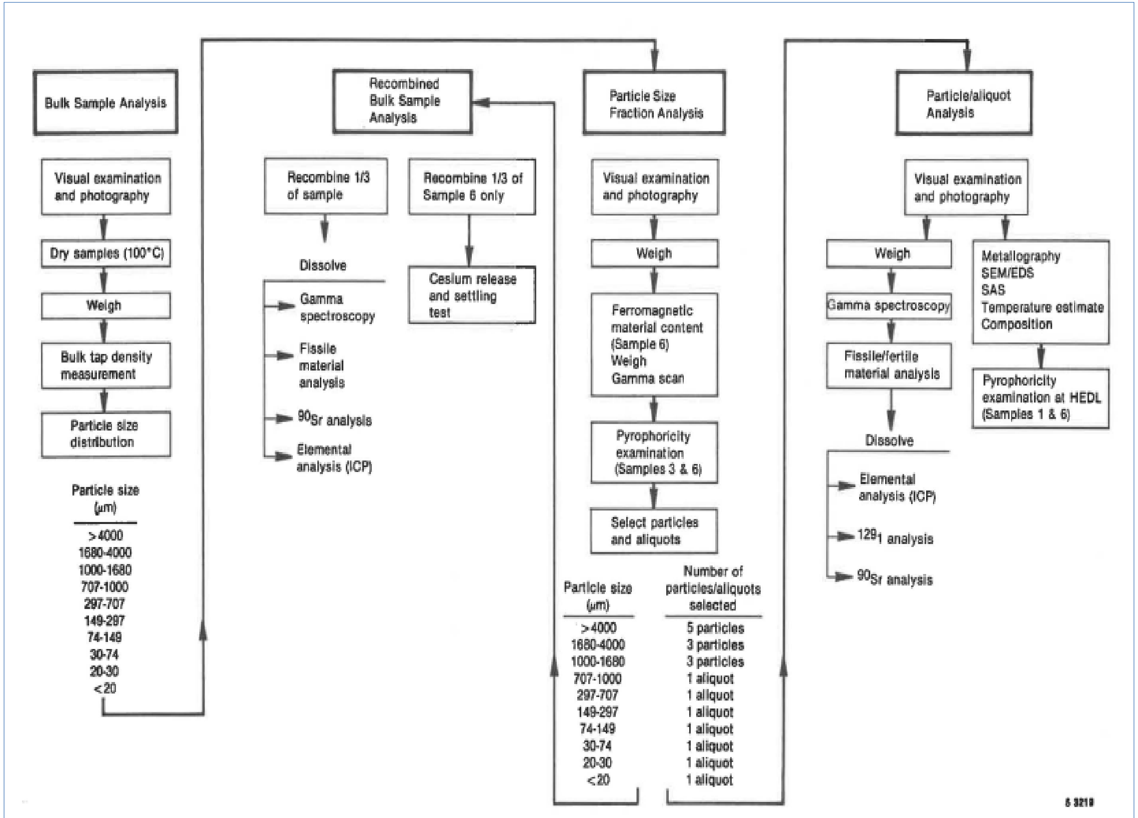
- ***Pyrophoric Reaction Concerns***. Finely divided metallic Zircaloy is pyrophoric. Even though evidence showed that most of the Zircaloy fuel rod cladding had been oxidized by the accident, the fact that it had fragmented caused concern over a pyrophoric reaction (and a consequent large metal fire) if core debris were exposed to air. Various studies were performed in which samples of fine core debris were subjected to ignition tests. The studies indicated no potential for pyrophoric reactions. When the water level was subsequently lowered to the top of the plenum assembly before head lift (thereby uncovering fine debris resting on the top of the plenum) and air was allowed into the system, no pyrophoric reactions occurred. Nor were any such reactions observed during the entire reactor defueling operations, including sawing and plasma arc cutting of core materials. (110)

4.2 Planning

The TMI-2 experience demonstrated that damaged fuel could be safely handled and stored in a practical and effective manner. (111) However, the uncertainty about the scope of the defueling tasks and the unfounded hope that damage was minimal were the major shortcomings of early defueling planning. (112)

- ***Data***. One lesson to come from the cleanup was the importance of accurate data about conditions inside the containment building, reactor vessel, and reactor coolant system. The licensee recognized this need and created an engineering organization responsible for data acquisition and analysis. The licensee's Safety Advisory Board believed that data acquisition and analysis played an important role in the final success of the cleanup. However, the Board concluded that the licensee did not always assign adequate time or resources to the acquisition of accurate data and that this hindered many cleanup plans and subsequent operations. One impact of a lack of adequate knowledge about core conditions was the difficulty in planning for adequate tooling. Because data were often insufficient or not timely, tooling requirements were poorly defined. Defueling safety was not compromised by tooling difficulties, but the project schedule was probably delayed to some extent. (113)

- ***Examinations***. Defueling could not be completely engineered at the start. Instead, a novel approach was required: engineering to gather data first and to take initial steps; gathering more data; engineering to defuel; and then repeating the steps as new areas and information were encountered. (114) Data on core conditions were obtained by the following in-containment activities: (●) camera examination



Flow diagram showing the examinations performed on core debris grab samples. (481.6) of the upper core region ("Quick Look"); (●) uncoupling of all control rod drive mechanism leadscrews; (●) removal of three control rod drive mechanism leadscrews and analysis at offsite laboratories; (●) a probe insertion into the core debris bed; (●) core topography examination and explorations using ultrasound equipment; (●) underhead characterization program (visual inspections, radiation measurements, pyrophoricity tests); (●) axial power shaping rod assembly insertion test; (●) core debris grab samples; (●) solid-state track recorder measurements of the lower head region; (●) lower head visual examination; (●) debris samples from the lower head; (●) operating experience from defueling; (●) core void video mapping; (●) in-core instrument probing; (●) in-core thermocouple and self-powered neutron detector data; (●) core bore samples and video inspections; and (●) core bore machine data (i.e., depth, rotation speed, torque) to interpret elevation and thickness information on penetrated material. [115]

- ***Planning Study***. [116] Within a few months prior to the start of preliminary defueling, the licensee planning study, "Core Conditions Design Basis," issued in March 1985 [117] and revised in July 1986 [118], identified physical conditions that had a reasonable probability of being encountered during fuel removal operations. This study provided the design bases for the development of techniques and tools to remove core material. The report described core conditions that were based on fuel condition data obtained from various inspections and defueling operations performed in the reactor vessel.

  - *Study Inputs*. The combination of investigations and methods included: (●) initial defueling experience; (●) visual and ultrasonic examination of the reactor vessel internals; (●) physical and chemical examinations of materials removed from the reactor vessel; (●) examination of materials transported throughout the RCS and containment system components; (●) interpretation of the response of online instrumentation during the accident; (●) calculations of accident damage and fission-product behavior using severe-accident analysis codes; and (●) first-principle engineering calculations of specific phenomena.

  - *Actual Conditions*. Actual core conditions experienced throughout the defueling operations included: (●) loose debris; (●) fused debris; (●) intact assemblies; (●) a partially embrittled zone; (●) guide tubes and instrument tubes; (●) fused adjacent fuel assemblies; (●) fuel assembly/core former interface; (●) a lower core monolith; (●) lower reactor vessel head debris; and (●) end fittings stuck in the lower grid.

- ***Research Topics***. Planning required testing, evaluation, and resolution of safety concerns. The DOE's Hanford Operations evaluated safety concerns in GEND-051, "Evaluation of Special Safety Issues Associated with Handling the Three Mile Island Unit 2 Core Debris," issued June 1985 [119], such as pyrophoricity, radiolytically generated hydrogen and oxygen, and the potential for steam generation in core debris canisters from an accidental fire during a transportation accident. Various other organizations conducted criticality studies. Recommendations drawn from these results included the following:

(●) Hydrogen-oxygen recombiners should be installed in each core debris canister. (●) Water could be removed from each canister by drip drying (no vacuum pumping was required). (●) The maximum weight of the loaded, dewatered canisters and the minimum volume of gas/vapor in each canister should be controlled and measured by weighing before and after dewatering. (●) A cover gas of approximately 2 atmospheres of argon should be added to each canister. (●) Each canister should be weighed and pressure checked before shipping. (●) The shipping cask [f] should be designed to limit the temperature of the canister contents after the standard hypothetical accident (fire), such that the design pressure of the canister or cask would not be exceeded. (●) Provisions should be made for canister venting during long-term storage and for cask venting in the event of an overpressure condition resulting from an "extended" fire. (●) Some pyrophoricity testing of samples should be conducted during defueling to assure adequate safety-related information during canister opening. [(120)]

- ***Evaluation of Uncertainties***. [(121, 122)] The NRC PEIS for the cleanup of TMI-2 and design of the defueling systems were developed before the extent of core damage and radiological conditions were fully understood. The PEIS was based on NSAC-1, "Analysis of Three Mile Island—Unit 2 Accident," [(123)] issued in March 1980. The early defueling designs were based on INEL's GEND-007, "Basis for Tool Development for Reactor Disassembly and Defueling," [(124)] issued May 1981, which compiled the core damage estimates previously performed by five independent groups. Neither study had the benefit of visual inspections inside the reactor vessel nor grab samples from the "Quick Look" program.

  - *Worst Case Estimate*. To compensate for uncertain core conditions, the PEIS postulated best and worst case core conditions. GEND-007 went further to identify the minimum and maximum bounds of damage and established a "reference" description for the status of the damaged core. The different degrees of damage present in the reference core were considered during planning of contingency tooling and procedures for reactor disassembly, fuel removal, core inspections, and fuel sample acquisitions.

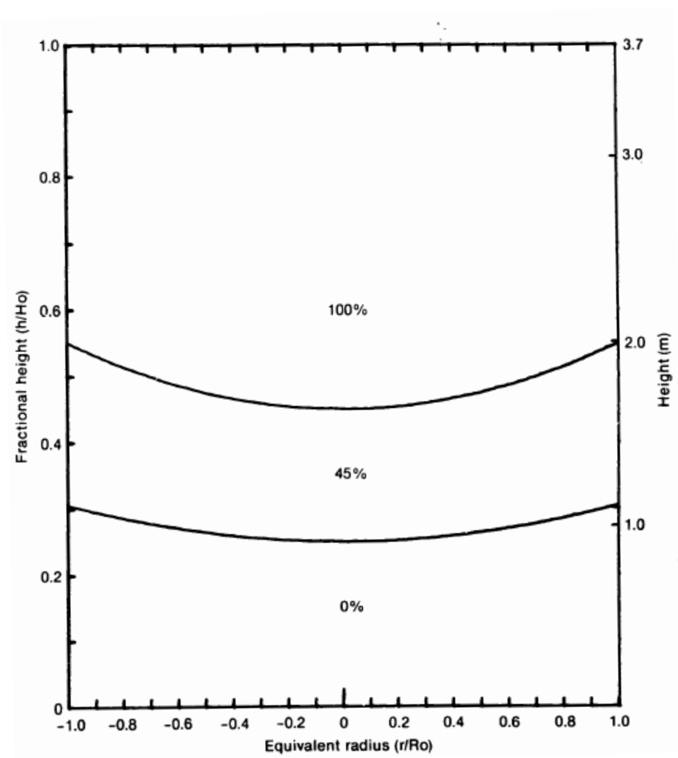
  - *Observed Damage*. The true extent of damage was not understood until after video inspections and sonar mapping of the rubble bed in 1983, video inspections of the lower head region in 1985, the core sample drilling program in 1986, and video inspections behind the core former walls in 1987. During

[f] Editor's Note: While referred to in the documents as a shipping cask, the terminology in the regulations for both the NRC (Title 10 of the *Code of Federal Regulations* (10 CFR) Part 71, "Packaging and Transportation of Radioactive Material") and the U.S. Department of Transportation (49 CFR 173, "Shippers—General Requirements for Shipments and Packagings," Subpart I, "Class 7 (Radioactive Materials") is package, or transportation package (or packaging when referring to only the shipping cask and not to the container and its contents). See also the definitions in the IAEA's transportation regulations, Specific Safety Requirements No. 6, "Regulations for the Safe Transport of Radioactive Material," 2012 Edition.

early planning through 1982, GEND-007 was adequate to bound the core damage for tool development, at least to the extent necessary to start defueling.

- ***Unsuccessful Data Acquisitions***. Some data collection activities at TMI-2 were not conclusive. These activities included the following: (•) Insertion test of axial power shaping rods to the fully inserted position to ascertain core conditions; control rods were not connected to the control rod drive mechanism leadscrew. (•) Vertical gamma profiles of the reactor vessel's lower head region via the in-core tubes; tubes were blocked. (•) Use of solid-state track recorder neutron dosimetry in the reactor cavity between the vessel and biological shield for nondestructive assessment of fuel distribution; results were questionable. [125, 126]

- ***Systems Integration***. The integrated design of the fuel removal, transfer, storage, and cask loading system was vital to defueling success. Defueling handling and processing changed little throughout the cleanup. The notable exception was the use of new and modified fuel debris removal equipment in the reactor vessel (e.g., variations of handheld and pneumatic tools, core bore machine, plasma arc cutting torch). These changes were made as defueling progressed and unexpected conditions were encountered, such as a solidified lower



Maximum damage configuration of the TMI-2 core as estimated in 1981. The graph shows regional average fuel cladding oxidation. (481.7) core region, solidified core melt in the lower core support structure, and significant debris behind core baffle plates. [127, 128]

- ***Mockups***. [129] The typical progression of activities at TMI-2 involved procurement, design, testing, development, shipment, more testing and development, training, assembly, and finally operation. The latter stages of development and training used mockups extensively. Used before every major cleanup activity, the mockups proved effective in improving work efficiency and minimizing radiation exposure. Mockups ranged from partial workspace arrangements to a more expensive detailed re-creation of an entire work area and activity. Detailed mockups were developed for activities in radiation areas that involved limited stay times, high collective doses, critical paths, routine tasks by many workers, complex tasks, or use of special equipment. Structures, systems, and components were also staged in a mockup setting in the turbine building before being reassembled in the containment building. The advantages of the use of mockups included the following:

  - *Effective Planning Tool*. Planners used mockups to identify necessary tools, materials, and services; to provide walk-throughs by planners, developers, and workers; to identify real and potential problems; and to plan and train for the use of robots. Tools that were tested in noncontamination conditions and did not work as expected could be disposed of as nonradiological waste.

  - *Effective Development Tool*. Developers used mockups for fabrication, operating, and contingency procedures; to test equipment and tools; to check intersystem interfaces; and to check for tooling clearances and interferences.

    For example [130], the INEL staff based in Idaho performed the bulk of the development work for the core bore drilling machinery. The staff designed, procured, assembled, and tested the equipment in an old unoccupied containment building at INEL. The facility provided full-scale testing of the equipment and the writing and validation of (verbatim compliant) procedures. The final core bore operating procedure contained 300 pages.

  - *Effective ALARA Tool*. Radiation protection specialists used mockups to evaluate dose reduction measures and to reduce the time required in a radiation area, thus reducing worker exposure.

  - *Effective Operations Tool*. The operations staff used mockups to facilitate maintenance; increase the efficiency of operations; assess impacts on work schedules; simulate upset conditions; and solve operational problems.

    For example [131], after initial operations, trouble shooting, and repairs, the core bore system full-scale mockup at INEL was used for data acquisition. Because the TMI core was an unknown environment, a data base was developed that consisted of drilling through a variety of materials (end fittings, standing glass rods, vertical metallic tube arrays, ceramic plates, carbon steel plates, stainless steel plates, sand, and even voids) to characterize the core locations drilled. The resultant data base allowed researchers to categorize materials drilled from the core, by comparison of the known data with parameters coming from actual core drilling.

- ***Contingency Planning***. Contingency plans were formulated to address credible events that could impede the timely completion of the plenum assembly lift and transfer operations. Many subsequent contingency plans were a direct result of lessons learned during reactor vessel head lift operations. (132)

- ***System Checkouts***. A checkout program for the plenum lift equipment identified several needed modifications. Special equipment was operationally and functionally checked out as part of an integrated system before use in the containment building. The onsite checkout was performed under conditions that closely simulated the actual interfacing conditions the equipment would be

Safety Advisory Board inspecting the mockup in the TMI-2 turbine building of the rotating defueling work platform used to train defueling operators and test new equipment.

subjected to during use in the containment building. [133]

- ***As-Built Dimensions***. Inspections revealed that the as-built dimensions of the reactor vessel internals were not consistent with the designed dimensions. These lessons showed that inspections for as-built dimensions should be made at critical interface locations between reactor intervals (and perhaps all nuclear steam supply system equipment) and specially designed recovery equipment well in advance of final manufacture to avoid reworks or unusable equipment. [134]

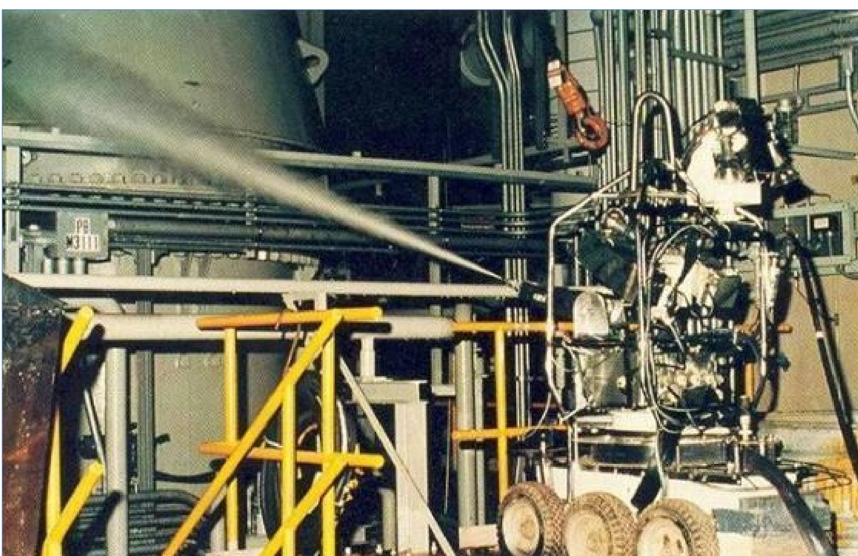
- ***Use of Video to Survey the Damaged Core***. The use of video equipment for reactor vessel characterization was extremely effective for seeing the conditions in the vessel. This information was eventually used to develop methods for fuel removal. The use of video cameras had some problems, such as the effects of the intense gamma radiation fields in the reactor vessel on the video camera and the challenge of relating the information obtained from viewing a small area to a larger area. To overcome the challenge of dimensional interpretation, objects of known dimensions in the reactor vessel were used as benchmarks to scale up the video image to the larger area. The effects of water clarity and shadows on the black-and-white video images (high-resolution color video technology was limited at the time) also presented problems. The use of auxiliary lights greatly improved the quality of the video. A little extra effort in properly positioning these lights helped eliminate the distracting shadows and provided a clearer image. [135]

- ***Single Defueling Contractor***. As early as 1981, the DOE urged the TMI-2 project management to select a single contractor to design and supply defueling tools and to pursue the post-head-removal defueling operation. Advantages of a single contractor included the following: (•) Cradle-to-grave responsibility would help ensure a thorough and competent job. (•) Relevant defueling experience could be applied to reduce the time and resources needed to develop a satisfactory level of expertise. (•) Because no one right approach existed, the process of selecting a single contractor would focus attention on the earliest possible selection of a defueling approach, which would then have a champion in the contractor proposing it. (•) One contractor would better ensure that tradeoffs between one defueling subsystem and another (e.g., one to control contamination in defueling water) were coordinated. (•) A single contractor could ensure the integration of equipment, procurement, installation, and operations. In the spring of 1983, the licensee decided to retain Westinghouse Electric Corporation as the defueling contractor because of its experience in the areas of tool design, robotics, and nuclear fuel handling. The licensee retained control over the tool development program and produced performance specifications. [136]

- ***Remote Defueling***. [137] One of the key questions facing planners was the use of remote equipment for defueling. An alternative defueling method that was considered was to convert the entire core into vacuumable rubble and transfer it directly into canisters in the fuel handling building, instead of transferring the fuel debris into shipping containers in the vessel or the fuel transfer canal. This approach proposed a remotely operated service arm (ROSA), a large shredder, and a debris vacuum/transfer system. ROSA was a computer-controlled and programmable electro-servo-powered arm.

- *Advantages*. The advantages of a remotely operated service arm included the following: (●) Avoided the time-consuming process of placing fuel into shipping canisters within the confines of the reactor vessel and then transferring the canisters into the fuel handling building. (●) Minimized in-containment work associated with preparing for or conducting defueling activities. (●) Reduced the number of in-containment work hours and could reduce the need for decontamination. (●) Reduced water clarity problems because ROSA could be programmed to work blind, thus reducing the volume of water to be processed. (●) Eliminated problems associated with tools long enough to be operated from an elevation above the reactor vessel. (●) Avoided material handling problems associated with moving shipping canisters inside the containment building.

- *Challenges*. One of the most technically challenging elements of the approach was the development of the shredder. Technical concerns with the shredder/slurry system centered on the development and licensing of an unproven technology. In addition, the uncertainties surrounding the release rate of radionuclides during the shredding process were a concern. The pumping of debris outside of the containment building without packaging it first was a further concern. Developing this technology was determined to require an estimated 3-year engineering development program. Other concerns expressed during the review of the proposed system [138] included delays caused by maintenance issues and the uncertainty as to whether the system would work.

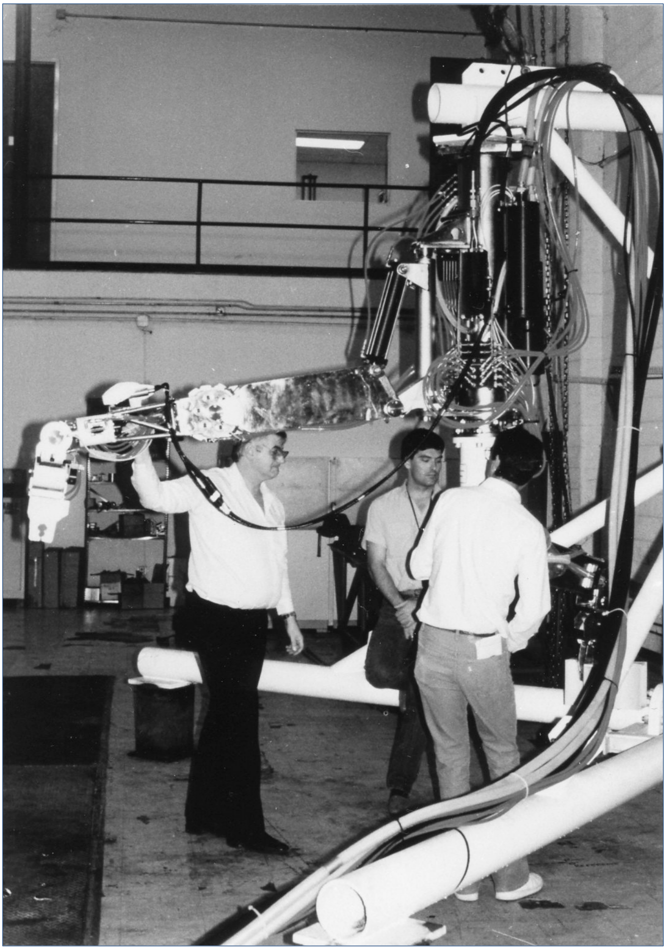


The remote reconnaissance vehicle called Rover operated in the containment building basement throughout the cleanup campaign.

- *Manual Defueling*. Manual defueling would be more flexible. The ability of the program to reduce doses would be effective; therefore, the need to use robotic equipment would not be necessary

- *Decision*. Rather than attempting to minimize the theoretical overall time necessary to defuel (which was the promise of this alternate approach), the licensee wanted a method to start defueling as soon as possible. Otherwise, the success or failure of a complex system using unproven technology would not be known for 2 to 3 years.

• ***Use of a Robotic Arm***. An automated cutting equipment system was originally conceived to work with a robotic service arm, called MANFRED, which would have deployed tools and handled pieces of the lower core support assembly. This equipment was on site; however, it was never used because of concerns about the



The MANFRED robotic service arm was on site; however, it was never used because of concerns about the complexity of operation.

complexity of operation and the vulnerability of cables and hoses to accidental severance. MANFRED would also had been extremely difficult to decontaminate when it had to be removed from the vessel. [(139)]

- ***Integration of Core Examinations with Defueling Plans***. The DOE became concerned about the effects of one of the potential defueling methods under consideration at the time on its research and development objectives focused on the effects of the fuel melting. This method was completely robotic and involved conversion of the entire core into vacuumable rubble that would be transferred directly into canisters in the fuel handling building. If the core was ground up and sluiced into canisters, all the spatial information on fission products and control material would be lost. As a result, the DOE developed a core sampling program that used a core boring machine to retrieve 8-foot-long bore samples from the damaged reactor core. [(140)]

- ***Use of Water for Shielding***. [(141)] Reprocessed accident-generated water was used to fill spent fuel pool "A" to shield the highly radioactive submerged demineralizer system vessels, pool "B" to shield the defueling canisters, and the deep end of the fuel transfer canal inside the containment building to shield defueling canisters being staged for transfer to the fuel handling building.

The volume of water was minimized to reduce decontamination. Lessening the volume of water was crucial to accelerating the start of defueling by minimizing equipment development and logistics. The fuel transfer canal was only flooded in the deep end where the fuel transfer mechanisms were located. A dam was installed in the deep end of the fuel transfer canal to provide the water to shield the plenum and the transfer of fuel canisters, which were to be loaded inside the vessel. This arrangement allowed the fission products in the reactor coolant to be retained in the minimum volume of water. Further, to simplify the water cleanup, the water in the fuel transfer canal and in the reactor vessel was separated to minimize cross contamination.

4.3 Quick Look

The first video inspection of the upper reactor core region took place on July 21, 1982. This activity was the first major planned activity inside the containment building. A camera 1.5 inches in diameter and 12 inches long was inserted through an empty leadscrew support tube (inside a control rod drive mechanism), and then into a central control rod guide tube (inside the upper plenum). As the camera was lowered into the upper core region, it revealed a bed of rubble approximately 5 feet below the normal location of the top of the fuel assemblies.

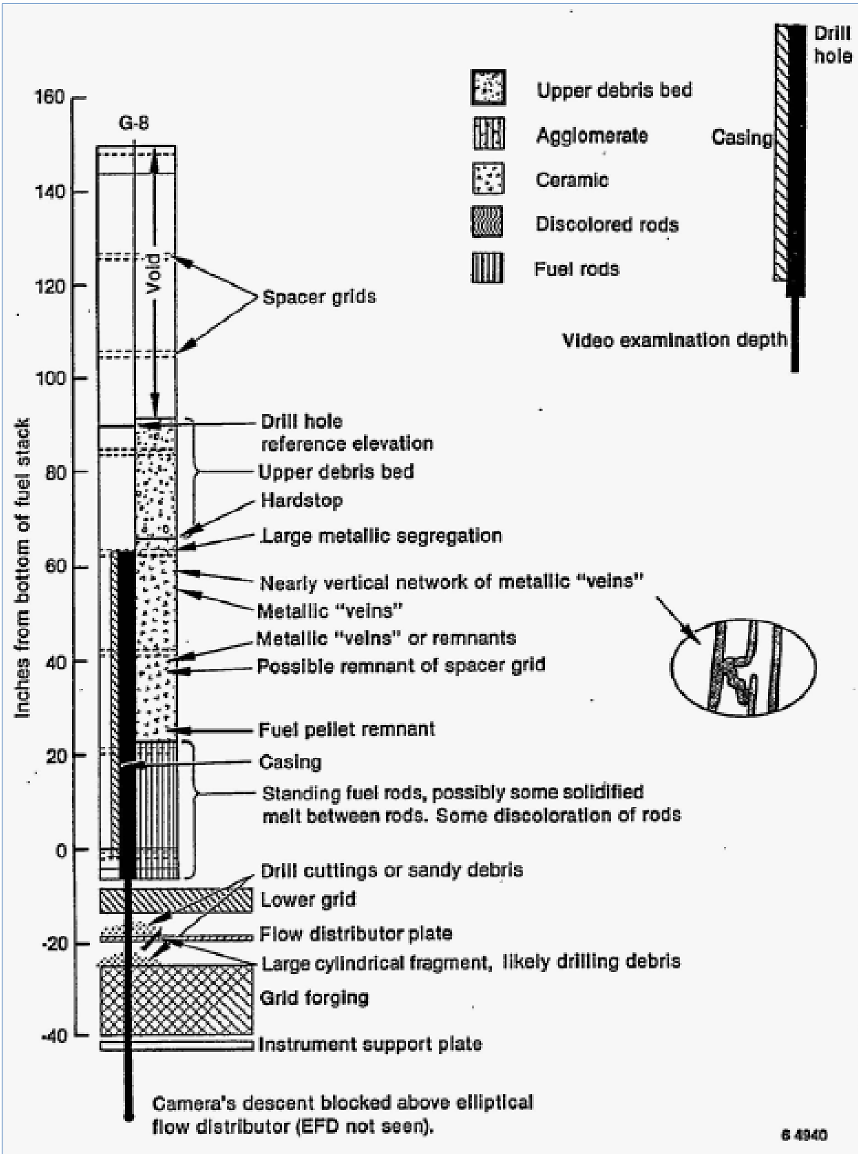
- ***Quick Look—The Pathfinding Examination.*** Quick Look provided solid evidence that the core had been severely damaged. Until the video inspection of the core cavity in 1982, the licensee hoped that the TMI-2 plant could be refurbished and restarted as early as 1985. By one account, it was Quick Look that galvanized the attention of all organizations and provided the common focus that was needed to move forward with core debris removal. The licensee could not hope for a reactor restart. [142]

Another account called the Quick Look inspection a “pathfinding” examination. Such an examination could not answer all the basic questions; however, once information and experience from the examination became available, it was possible to develop more sophisticated examination equipment with a more realistic set of functional and operational requirements. [143] Follow-on examinations included the reactor vessel underhead video and radiological survey in the summer of 1983; reactor core topography program in August 1983; retrieval of “grab” samples from the debris bed in October 1983; and reactor core video mapping in April 1984. These and other examinations paved the way for the removal of the reactor vessel head on July 25, 1984, and the removal of the upper plenum assembly on May 15, 1985. [144]

The experience gained from this inspection supported the consideration of a manual defueling concept for removing the core and its debris. Further, the observation that the reactor internals were essentially intact, and that opening and working in and around the reactor vessel head area was reasonable, provided the basic insight that supported a manual “dry defueling” concept without having to flood the refueling canal. [145] The manual dry defueling concept was decided 2 years later. [146]

- ***Quick Look Safety Evaluations***. Quick Look was the first complex activity inside the reactor vessel that required formal safety review by the licensee and approval from the NRC. The licensee’s 169-page safety evaluation report included a comprehensive criticality analysis for the proposed activities that could cause fuel rearrangements. The safety evaluations associated with the effects of Quick Look on safety functions included: (●) radiological environmental releases due to the release of krypton-85 from the reactor coolant system (RCS); (●) reactivity changes as a result of postulated fuel disturbances; (●) effects of the drain down of the RCS on decay heat removal capabilities; (●) boron dilution events from potential dilution paths; (●) releases of trapped hydrogen and krypton gases into the containment building atmosphere during the venting of the RCS; (●) potential for a combustible gas burn inside the containment building; (●) occupational exposures associated with decontamination or contamination control, rigging, RCS venting, installation of temporary power and lighting, removal of a control rod drive mechanism leadscrew, and inspection inside the reactor vessel; (●) RCS chemistry changes due to exposure of the RCS to the containment building atmosphere; and (●) fire protection. [147]

The onsite NRC TMI-2 project office reviewed the licensee’s proposal, safety evaluation report, and associated operating procedures. The NRC concluded that Quick Look could be conducted in a safe manner with the measures and precautions provided for each of the major activities (i.e., venting,

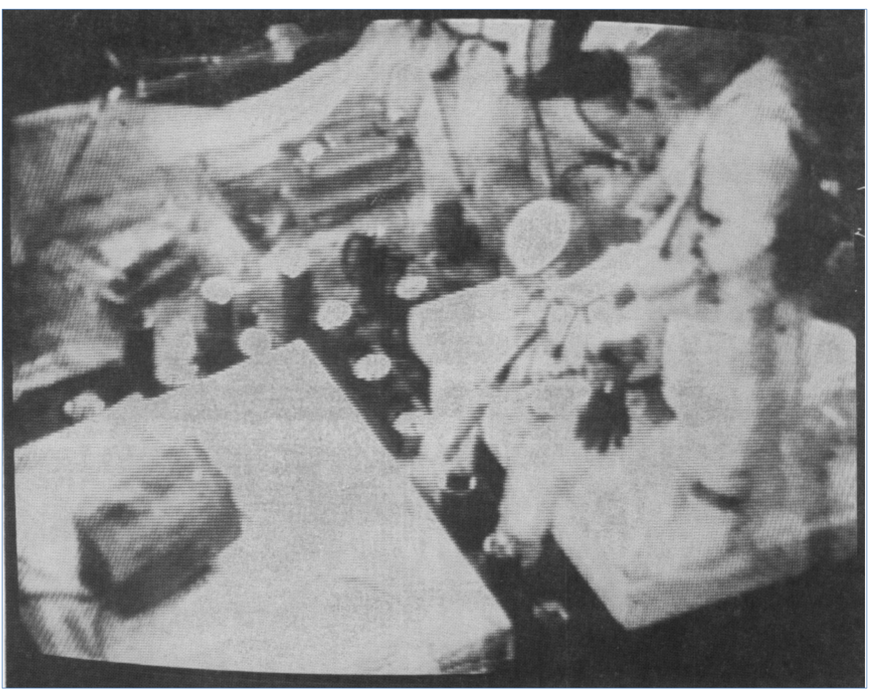


Observation summary from central core bore location (K9). Video data from the interior of the core bore holes revealed a region of previously molten material directly below the hard crust and a region of intact standing fuel rods extending from the bottom of the previously molten region to the bottom of the core. (481.8) depressurization, water-level lowering, lead screw removal, and camera insertion) associated with Quick Look. In addition, the NRC determined that conducting this program would pose little risk to the offsite public and the occupational workforce. Further, all the Quick Look activities were within the scope of those analyzed in the TMI-2 PEIS. [(148)]

- ***Other Quick Look Experiences***. The Quick Look inspection also provided the following experiences and insights that helped with planning future cleanup activities: [(149)]

  - *Preparation of In-Vessel Activities.* Experiences from the preparation work included the following: (●) Depressurization of the RCS and lowering the coolant level to prepare for the inspection were completed as planned. (●) The control rod drive mechanism drive shaft assembly was removed from the control rod without difficulty. (●) Cost in resources and time was high; 27 containment building entries with 243 person-hours spent in the containment building to prepare for and execute the operation. (●) Challenging technical work could be conducted in the reactor vessel.

  - *Radioactivity Control.* Observations from the radioactive contamination and exposure encountered during the preparation and conduct of the inspection



The first closed circuit video inspection of the upper reactor core region took place on July 21, 1982. A technician sitting on a platform positioned on top of the reactor vessel service structure is inserting a camera, 1.5 inches in diameter and 12 inches long, through an empty leadscrew guide tube.

included the following: (●) Airborne activity and surface contamination were not a problem. (●) Inspection equipment could be installed in the reactor core region and be satisfactorily decontaminated by simply wiping the equipment off, very much as was done in servicing operating nuclear plants. (●) Alpha contamination was not a problem. (●) A unique form of cesium contamination was discovered on the surfaces of the control rod drive mechanism leadscrew (examined at INEL) that was exposed to the accident environment inside the reactor vessel; this unique cesium surface contamination was very adherent and could not be removed easily. (●) Work could proceed in some areas of the containment building without excessive personnel exposure. (●) Work could be performed within the reactor vessel from a work platform under acceptable radiation levels with the potential to further reduce the radiation levels. (●) Actual exposure to complete the first Quick Look was 23 person-rem; the licensee's initial estimate of 1,600 person-rem had cancelled or delayed the inspection, but experienced members of the Technical Assistance Advisory Group (an external review group) estimated 45 person-rem (NRC estimate was 60 person-rem).

- *In-Vessel Visual Observations*. The following visual observations contributed to the consideration of other defueling concepts: (●) The observable extent of damage to the upper core was enveloped within one of the worst case predictions of core damage as described in GEND-007 [150], which showed that computer models predicting reactor core damage were at least partially correct. (●) Upper reactor vessel internals were essentially intact (more damage had been expected) and should be structurally sound for removal purposes. (●) Core debris was not found on the top cover of the upper plenum assembly. (●) Core debris was not plastered up against the underside of the reactor vessel head.

4.4 Crane Operations

Several cranes were located inside the containment building:
(●) 456,000-kilogram polar crane that was used to remove the reactor vessel head and plenum; (●) 23,000-kilogram auxiliary hoist that provided defueling support; (●) 4,500-kilogram service crane that was installed to support handling of the long-handled tools and other equipment; (●) wall-mounted jib crane above the reactor vessel head storage stand that was used to place the sand columns around the head storage stand; and (●) two jib cranes that were mounted on the rotating defueling work platform to aid the operators in manipulating the long-handled tools through a slot in the platform. Initially, the auxiliary hoist was not refurbished to avoid detracting from the critical path; however, the decision was later changed when defueling experience indicated the need to securely grapple core debris and to apply lift forces greater than those achievable with the service crane. [151]

- ***Crane Height***. Experiences from crane operations inside the containment building during TMI-2 defueling included the following: (●) Cranes and hoists should have had sufficient lift to handle the longest tool with allowance for the rigging, a load scale, and over-travel for the upper limit switch. (●) The service crane height should be high enough to handle tools that could reach to the bottom of the reactor vessel or the lowest possible point. (●) The jib cranes mounted on the rotating work platform should have had telescoping posts to provide more usable hook height. (152)

- ***Crane Load Tests***. The use of in-containment components for load testing cranes eliminated the need to bring other weights into the contaminated environment. The load test of the containment building polar crane consisted of removing the four 39,000-kilogram missile shields over the reactor vessel refueling canal and the 30,000-kilogram pressurizer missile shield. A stand was constructed to hold the missile shields after removal. (153)

- ***Crane Load Cells***. Based on experience, one account suggested that cranes should include load cells to detect tools that were hung up on debris or work platform equipment. (154)

- ***Crane Preventive Maintenance***. Two failures occurred during the head lift; failure of the polar crane pendant switch followed by failure of the relay in the polar crane hoist circuit. (155) As a result of the lessons learned from the head lift, the polar crane's yearly preventive maintenance was scheduled to be completed just before the beginning of the plenum lift evolution. (156)

4.5 Defueling Work Platform

The defueling work platform (also known as the shielded work platform), with a

Containment building polar crane load test using 40-ton missile shield blocks that are normally positioned over the reactor vessel service structure.

17-foot diameter rotatable surface and a 6-inch-thick steel plate shield, was installed 9 feet above the reactor vessel flange. By placing the work platform in the fuel transfer canal that had no water, the canal walls provided a shield from significant radiation in the lower levels of the reactor building. The platform provided a shielded work area for defueling operations; a support for manual, hydraulic, and mechanical defueling tools; and a method for removing defueling canisters. An adjustable slot and hand rail spanning the diameter provided access to the reactor core. The entire reactor vessel defueling effort was performed from this platform.

- ***Rotating vs. Stationary Platform***. A stationary work platform would had been simpler to build and install and would not have required any components with long lead times. However, a rotatable platform offered the advantage of a more precise alignment of tools and equipment over the desired section of the core. Loads could also be picked up in one radial core location and moved to another by rotating the platform. (157)

- ***Worker Safety***. Two safety issues were revealed from minor incidents that could had resulted in significant injuries to workers on the work platform:

  - In one case, the hoist on a jib crane came off the end of the jib arm I-beam on which it was being moved and slightly injured an operator. The jib crane hook, which was mounted on the defueling work platform, was moved along an I-beam by a hand-operated chain-driven gear. A mechanical stop was mounted at the end of the I-beam to prevent the jib crane from running off the end. The stop was mounted by a bolt in a set screw arrangement. This set screw came loose with excessive use. (158)

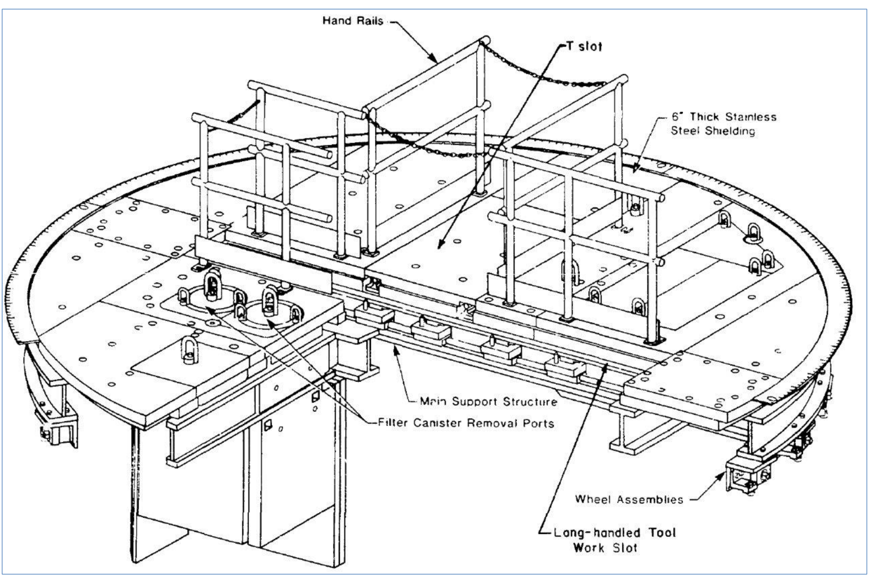


Diagram of the rotating defueling work platform. (481.9)

- In another case, a worker fell into the reactor vessel through an open access port on the platform. The port provided access to one of the five defueling canister sleeves on the canister carousel (canister positioning system) in the reactor vessel. The worker backed into the open port and fell into the reactor vessel while catching the platform by the upper arms and elbows. The worker's legs were submerged in the reactor coolant. Preliminary dose estimates indicated that the worker was expected to receive about a 200-millirad skin dose to the legs. The worker received only minor bruises and did not require any medical treatment. [159]

- ***Tool Wash***. A clean water wash system was installed on the work platform to provide clean borated water at a slow flow rate to wash off tools being lifted out of the coolant in the reactor vessel. [g] This helped to control contamination and hot particles. [160]

- ***Separation of Ground Fault Protection***. When more than one light was served by a ground fault interrupter (GFI), any lamp failure due to water in-leakage would trip the GFI, resulting in the loss of all lights. The effort to identify the defective light was substantial. Each permanently installed underwater light that was required to operate the equipment should have its own GFI. [161]

- ***Underwater Electrical Components***. Experience revealed that critical electrical components, such as limit or interlock switches, under water should be avoided. [162]

- ***Simplify Control Systems***. Complexity in control systems should be minimized, where possible. This would include minimizing the number of interlocks, protective circuits, and monitoring devices to those essential for ensuring safe operation. [163]

- ***Hydraulic Fluid***. The low-viscosity hydraulic fluid contributed to reduced reliability of the aluminum sandwich valves used for the low-flow circuits. Valve malfunctions would lock pressure in the hydraulic cylinders and cause the quick disconnect fittings to leak. [164]

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[g] Editor's Note: Current practice includes wetting or washing tools being lowered into (potentially) contaminated water to prevent the adherence of hot particles, radioactive particles, or contamination in pores and cracks in the tools. This practice facilitates ease of decontamination of tools along with the washing as the tools are removed from the (potentially) contaminated water. This is a common practice for moving spent fuel into storage casks and transportation packages at U.S. plants. This could apply to the tools and any other items (e.g., canisters, packages, casks) inserted into the reactor pressure vessel, spent fuel pool, or other containers of contaminated water.

4.6 Work Inside Containment

Work inside the containment building at TMI-2 was more challenging than activities during common outages at nuclear power plants. The basement floor and walls were covered with highly radioactive contamination. These contaminants produced increased background radiation levels throughout the containment building. Structures, systems, and components inside the containment building were contaminated during the accident with high levels of beta radiation. Various activities inside the containment building also generated airborne radioactivity. Heat stress was a problem during the early cleanup campaign before an air chiller was installed inside the containment building. All of these personnel safety issues presented unique challenges for work planning and implementation. Even the simple tasks common to routine outage work presented challenges at TMI-2. The licensee and others involved in the cleanup described the following experiences and insights:

- ***Equipment Supplies***. [(165)] The need for an adequate supply of reliable equipment, especially equipment that was essential to the critical path, was a primary lesson derived from the reactor vessel head lift operation. Some experiences from the reactor vessel head removal operations reported by the licensee (see GEND-044, "TMI-2 Reactor Vessel Head Removal," issued in September 1985) included the following:

  - *Inventory*. When making unscheduled containment building entries, improvements were needed to make sure that items were logged in and out so that the next crew was aware of what was already in the containment building and what needed to be taken into it. Based on this experience, an inventory accounting system and an adequate backup supply of equipment and tools should be maintained, based on conservative estimates of potential needs. Personnel protective equipment, such as vests, oversized hoods, and respirators, should be substantially stocked, and planning should provide for sufficient personnel to process the respirators at peak periods.

  - *Testing and Evaluation*. Measures should be taken to ensure that off-the-shelf equipment would perform satisfactorily. Procurement papers should be verified to include proper "Important to Safety" designations with quality assurance/quality control involvement. Testing should be performed, as applicable, before acceptance.

  - *Repairs*. Potential repair and maintenance tasks should be thoroughly evaluated before an activity to ensure that they could be conducted with a minimum impact upon the schedule if they needed to be done during the activity. All equipment should be supplied with scheduled (periodic) maintenance requirements and instructions.

  - *Backup and Spares*. The camera, which provided the polar crane operator with the information on the preplaced targets for crane location, failed before the start of the reactor vessel head lift. There was no installed backup for this camera, although a spare camera and spare parts were available on site. Contingency plans, procedures, backups, and spares should be readily available for all sorts of schedule-important support equipment. A repair team with spare parts should be readily available during critical operations, while assuring proper radiological controls. Preparations could reduce delays from failures to last only minutes instead of hours.

- ***Work Documentation***. [166] The documentation required for major operations was extensive, requiring multiple levels of review and approval. Planning was required to ensure that the operation followed procedures and that any changes could be expedited by available personnel. Some additional experiences from the reactor vessel head removal operations included the following:

  - *Approvals*. This system facilitated rapid review and approval of necessary changes from planned operations and to provide technical assistance. During the TMI-2 reactor vessel head lift, a task force of planners and staff members was available in the coordination center to expedite changes to procedures or work instructions. The individuals had signature authority for reviews and approvals. Because they were aware of actual operations, they were able to support alternative courses of action quickly. Based on experience, one account suggested that personnel should be on 12-hour shifts during operations to facilitate communication and maintain continuity.

  - *Procedures*. The procedures and documents for operations should be evaluated to ensure there are no duplicate steps. One action should not be controlled by more than one document, as this introduces the likelihood of overlooking details and increasing both the potential for conflicts and the effort required to make changes. This was a problem with the sequence document and the head lift procedure for TMI-2. Similar steps were in both documents.

- ***Worker Effectiveness***. Measures should be taken to keep morale high and to encourage teamwork. Some experiences from the reactor vessel head removal operations included the following: [167]

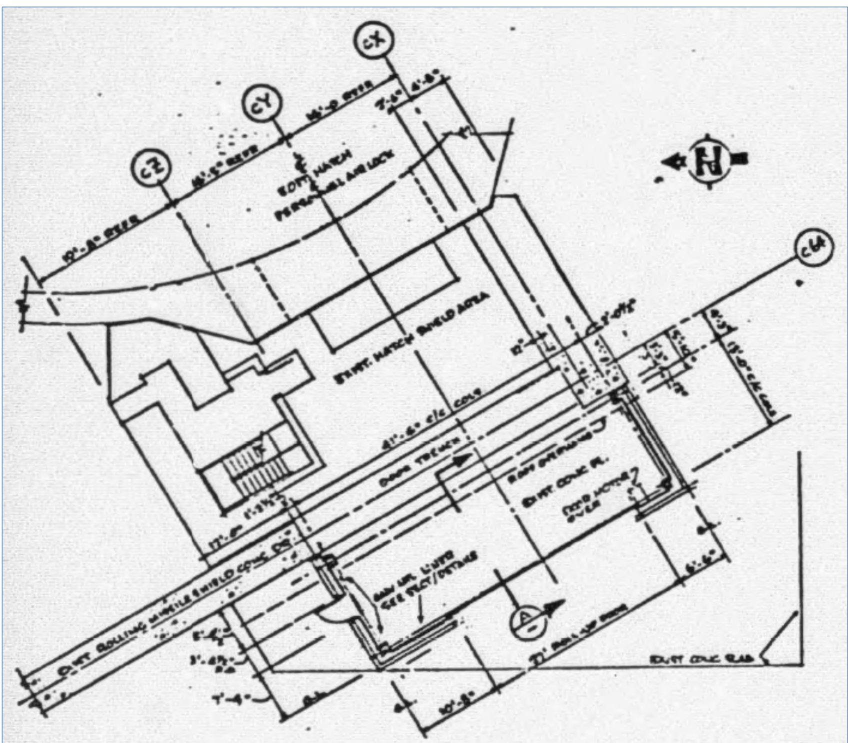
  - *Worker Fatigue*. Workers should be rested, cool, and calm before a containment building entry. Supervisors should be sensitive to the stress experienced by making entries.

  - *Shift Turnovers*. A single shift turnover meeting involving all participants should be held, and all personnel should work the same shift schedule to maintain a smooth flow of work.

  - *Coordination Center*. Too many people were in the Coordination Center during head lift; however, the question "Who is excess?" was the real issue. One possible arrangement to prevent or solve such an issue could involve the issuance of a limited number of passes or tickets per department. When that number of passes was in use, no other personnel could enter until someone from that department left. There should be no exceptions and no access lists beyond those authorized to hold passes. Individuals responsible for operations, by procedure, should make the determination.

- ***Training***. Workers should receive as much preliminary training as possible to familiarize them with the working conditions and required operations. Training on accurate mockups using the actual procedures and job walkdowns inside the containment building represented the most significant contribution to successful operations. During the walkdown, personnel were able to identify locations of potentially useful equipment for contingencies. They were also able to identify the location of equipment that could cause interference and thereby result in more time and cost due to the more severe radiological conditions. (168, 169)

- ***Electrical Maintenance***. Electrical equipment installed in the containment building or radiation areas should have easily accessible diagnostic points and simple component replacement. Decontamination activities should be conducted to avoid contaminating electrical equipment, which could complicate the maintenance of such equipment. (170)



Floor plan of the containment building air control envelope located outside the equipment hatch. (481.10)

- ***Moving Equipment into Containment***. Components that were too large to fit through a personnel airlock were designed in subassemblies. These subassemblies were assembled and tested, sometimes using a mockup, before being disassembled and transported into the containment building. Having assembled and tested the components outside the containment building, the reassembly required less time, minimized radiation exposure, and increased reliability and functionality. (171)

- ***Contaminent Building Air Control Envelope***. This was a controlled area outside the equipment hatch or emergency airlock where cleanup equipment and materials were assembled and staged before transfer into the containment building. This structure reduced worker stay-times in radiation areas, resulting in occupational exposure savings. The envelope also functioned as a staging area for contaminated material removed from the containment building, but it was not designed to be a storage area for radioactive wastes. (172)

- ***Equipment Hatch Removal***. The licensee asked the NRC for approval to remove the equipment hatch to the containment building on a contingency basis. The licensee considered that removal and reinstallation of the hatch could facilitate the movement of several pieces of large defueling equipment without the need for disassembly and reassembly inside the containment building, thus reducing time and radiation exposure. The NRC reviewed the licensee's safety analysis report; however, the licensee withdrew its request because improved access would not offset the resources, time, and worker exposure involved in removing, handling, decontaminating, and storing the hatch. (173, 174)

- ***Water vs. Sand Shielding***. Shielding around the reactor vessel head storage stand was used to attenuate radiation from the underside of the head. A shield wall consisted of fiberglass cylinders, each 0.6 meter in diameter and stacked 3.6-meters high. Each cylinder had a concave interlocking pattern for maximum shielding effect. Initially, these cylinders were filled with water; however, leaks occurred, and the cylinders were subsequently filled with sand. (175)

4.7 Defueling Tools

Unique systems and equipment were designed and used to remove damaged fuel and structural debris from the reactor vessel. In the early defueling phase, tools were designed for "pick-and-place," in which debris was picked up manually and placed into fuel containers (baskets) or specially engineered defueling canisters for shipping. Some long-handled tools had various hydraulically actuated fittings to tackle the larger pieces and smaller bits of debris. The core bore machine, previously used to obtain core samples, was used to bore holes in the resolidified mass of the previously molten material in the reactor vessel. This allowed the hard mass to be broken up. Combinations of tools to assist defueling the lower reactor vessel region included the core bore machine and plasma arc torch. (176)

- ***Designing Tools On Site***. Over 100 long-handled tools were used to remove most of the damaged reactor core at TMI-2. Tool design requirements changed as new challenges arose. The first set of tools was manufactured off site. Many tools needed modifying as core conditions became better understood. After the start of defueling, an onsite machine shop was established for quick response to the need for tools. Most long-handled tools were fabricated on site, increasing efficiency and applicability (because of the interaction of the machine shop staff with operators and engineers). Simple tools could be built within 2 days. Based on this experience, the tool design and fabrication processes were able to modify or redesign tools quickly. (177, 178, 179, 180)

- ***Tool Inventory and Control***. Experience revealed that tool inventory and control were essential to efficient operations. Spare parts should be provided for all tools that risked breakdown during normal defueling activities and that could cause a significant delay in defueling activities. Tools requiring maintenance should be segregated to prevent inadvertent use. (181, 182)

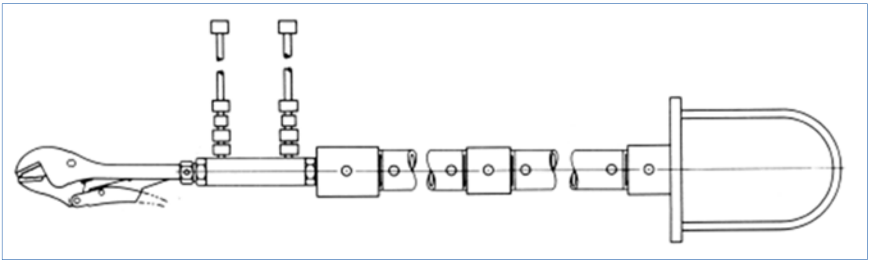
- ***Idle Tools***. The time required to move tools between the reactor and the tool storage racks was significant. Idle tools that were not removed from the reactor tended to interfere with ongoing operations. (183)

- ***Peters Tool***. A popular tool named after its vendor consisted of a very light aluminum rod and a vice-grip-like gripper on the end. The tool was operated by a mechanical lever at the top end. The tool was light and could be handled by hand without the use of a crane. These tools of various lengths were tied in the platform work slot for quick use. (184)

- ***Hydraulic Clam-Shell Tool***. The first defueling tool used to scoop up fuel debris on top of the core debris bed was a large hydraulic clam shell. This tool was ineffective because the debris bed was not very thick and contained partial fuel rods scattered across it. Additionally, the tool stirred up the fuel fines and eliminated all visibility. (185)

- ***Heavy-Duty Tools***. The center of gravity of the tool should be determined for use in rigging and positioning the tool for proper operation. Experience revealed that the heavy-duty tools were harder to handle. (186)

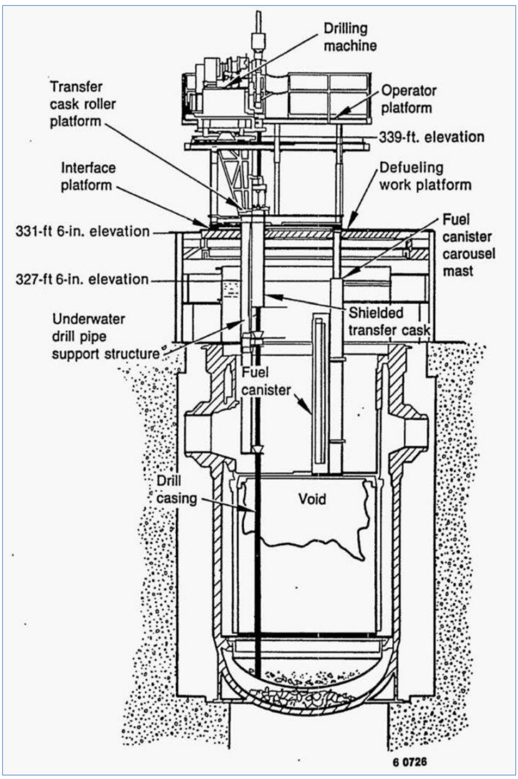
- ***Hydraulic Fluids***. Various fluids were tested for use in the defueling hydraulic system. After initiating defueling, a problem was encountered with the



Peters vice-grip tool. (481.11)

precipitation of boric acid crystals. To prevent further deterioration of the hydraulic fluid in the system and potential adverse effects on defueling tools, the hydraulic system was drained and flushed. Then the fluid was replaced with a tested substitution. When selecting a hydraulic fluid, several factors were considered: (●) the boron remaining mixed with the hydraulic fluid and (●) compatibility with RCS chemistry and processing, the canister recombiner catalyst, and the hydraulic system. (187, 188)

Another problem involving hydraulic fluid was encountered shortly after initiating defueling. The original hydraulic fluids were carbon based and contributed to microbial growth in the reactor vessel when hydraulic fluid leaked into the reactor coolant containing dormant microorganisms. The carbon-based borated hydraulic fluid used in the tools served as an unintended nutrient. To limit the growth of microorganisms, hydrogen peroxide was periodically added to the reactor coolant, and a water-based hydraulic fluid with a 5-percent organic addition was used in the long-handled defueling tools. (189) (The subsection on Defueling Operations, below, provides further details.)



Core bore machine, initially used to retrieve bore samples, was used to break apart once molten core and lower core support structure.

- ***Tool Connecting Joints***. Experience revealed that the use of flanges to join handling poles should be avoided to prevent hangups on hidden obstacles when raising or lowering the tool into position. (190)

- ***Useful Heavy-Duty Tools at TMI-2***. Two important defueling machines used at TMI-2 were an off-the-shelf oil-rig-type vertical drilling machine (called core bore) and the underwater plasma arc cutting device. These machines provided the primary means of delivering cutting energy to the resolidified fuel mass and reactor internals to break the material up into sizes small enough for manual and hydraulic (vacuum, water lift) removal. (191)

- ***Core Bore Design Tests***. Numerous bit styles and designs were tested using core-region mockups containing both actual materials and suitable substitutes in place of radiologically or economically prohibitive materials. The drilling mockup, located at INEL, included composite test samples consisting of Zircaloy-clad quartz rods, Inconel spacer grids, 300-series stainless steel end fittings, concrete blocks, ungraded 3/8-inch gravel, and hard-fired alumina plates. Information obtained from these tests was evaluated to select the drill bit cutter most appropriate for the work at TMI-2. Subsequent proof testing showed the bit to be successful in cutting all the anticipated material configurations. (192, 193, 194)

- ***Plasma Arc Cutting***. The underwater plasma arc cutting device was chosen to cut apart and remove the massive stainless steel lower core support assembly (LCSA) to access the debris on the reactor bottom. The arc torch was used previously to cut upper fuel assembly end fittings. (195) A broad range of techniques were evaluated to cut the LCSA. Some techniques were ruled out, but others required experiments under simulated TMI-2 conditions. Plasma arc cutting was chosen over spark erosion machining; thermic rod; cutting water jet; arc saw; mechanical shear; explosive cutting; oxygen burning; sawing; drilling/milling; ultrasonic disintegration; and laser cutting. An automated cutting equipment system was designed and installed in the reactor vessel to perform the task. The LCSA was cut into about 50 pieces; disassembly required about 1 year. Though actual cutting was quick, productivity was hampered by equipment failures, torch failures, and control system redesign. (196, 197)

- ***Plasma Arc Difficulties***. Torch burnouts and other problems (e.g., electronic failures, a seal failure on a servo-motor housing, a transformer failure, feedback circuitry difficulties, and position limit switch failures) initially affected system performance. Improvements and experience with the system reduced maintenance dependency. (198) Difficulty with the plasma arc cutting equipment slowed the cutting process for several reasons.

  - *Torch Burnouts*. Frequent torch replacements were required due to burnout (average torch life was about 10 cuts), arc starting problems, and mechanical damage in low visibility and restricted access areas. A common failure was loss of electrical conductivity caused by heavily borated vessel water leaking into the torch head. When failures occurred, the entire torch assembly had to be raised from the vessel and reconstructed on the defueling work platform. (199)

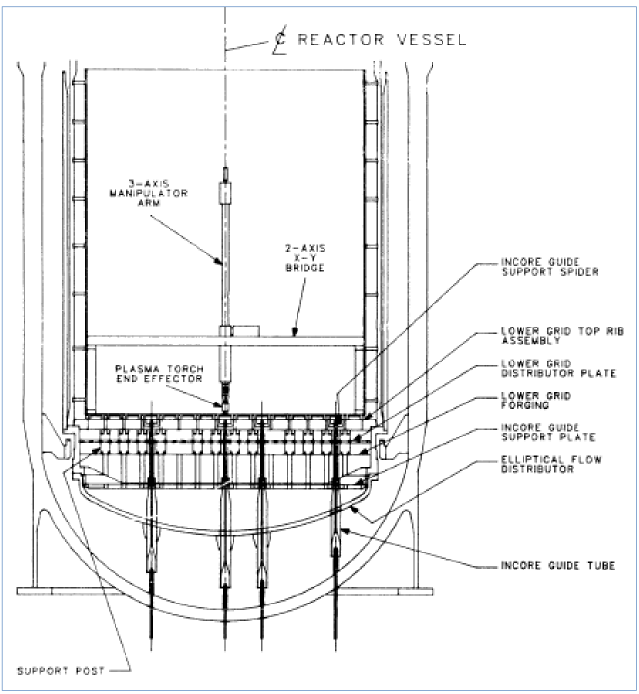
  - *Cutting Problem*. Fuel debris adhering to the lower core support assembly (LCSA) plates made cutting difficult. (200, 201)

  - *Turbulence*. Plasma cutting and cover gases acted as an airlift in the LCSA forging, which caused loose debris to move from the forging flow holes and to be deposited in the X-Y bridge drive system of the automated cutting equipment system. This required the cutting operation to be shut down; the bridge to be removed from the vessel; the bridge's various motors and positioning components to be disassembled, cleaned, lubricated, and reassembled; and the bridge to be reinstalled in the vessel. (202) Material suspended as a result of the airlift effect also interfered directly with the plasma arc cutting process, requiring recuts to be made. (203)

- *Contamination*. Bridge contamination impeded work progress. The bridge was extensively decontaminated before removal from the vessel. However, loose contamination levels increased as the liquid contamination dried on the bridge. This required extensive decontamination of the work areas where the bridge was handled during repairs. (204)

- *Krypton-85 Releases*. While performing plasma arc cutting, small amounts of krypton-85 gas were released when the ceramic fuel fragments were heated. The quantities released to the containment building and subsequently to the atmosphere through the monitored vent path were small and well within regulatory limits. (205)

- ***Plasma Arc Cutting Hazards***. One concern from the use of the plasma arc torch was toxic gas generation. By-product gases included fissile material vaporization; krypton-85; carbon monoxide; small quantities of hydrogen (less than 1/10 standard cubic feet per minute); nickel carbonyl vapor; and oxides of nitrogen. The principal oxides of concern were nitric oxides and nitrogen dioxide.

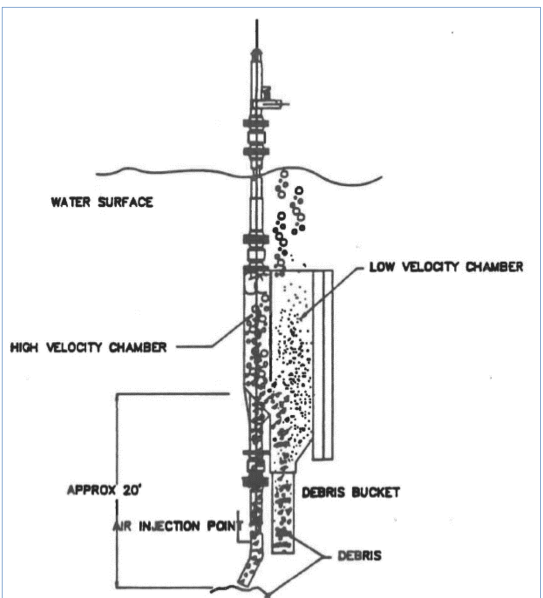


Schematic of the automated plasma arc cutting equipment system used to cut apart the massive stainless-steel lower core support assembly for removal from the reactor vessel. (481.12)

Safety evaluations concluded that gases that escaped from the water surface would be captured by the defueling work platform off-gas system. The gas was expected to be diluted to insignificant concentrations in the containment building near the plant purge system exhaust suction point, even during periods of no purge operation. Condensable gas products were retained in the water. Administrative controls were required to ensure that personnel access to the discharge areas inside the containment building was prohibited during plasma arc cutting. The safety department monitored the work area for by-product gas to ensure it did not exceed occupational exposure limits. (206)

- ***Plasma Arc Cutting Performance***. Several actions were taken to address concerns about automated (plasma arc) cutting equipment system performance: (●) improvements to increase the reliability of this system, (●) increase in the size of the pieces cut from the lower core support assembly to decrease the number of cuts, and (●) development of the core boring machine as a backup. (207)

- ***Vacuum and Air Lift Tools***. Inlet velocities of 1.5 to 3.0 meters per second were required to entrain and carry the fuel debris into the vacuum and air lift systems. The effective capture distance for entraining debris was less than the inlet diameter of the suction nozzle. (208) The major concern during airlifting was the continual loss of visibility and redistribution of small and medium particles over



Schematic of the air-lift system. A simple air-lift system injects air near the foot of the pipe: bubbles rise through the pipe; the liquid/air mixture within the pipe rises to the surface of the tank and draws water and solid debris through the opening at the foot of the pipe; and the debris eventually settles into a debris bucket. (481.12)

every horizontal surface in the vessel. This problem was addressed to some degree by modifications to the defueling water cleanup system's in-vessel filtration system, improving recovery time from 4 hours to 2 hours. [209] Based on a review of this experience, one account suggested that a series of filter devices could be used to capture all particulate material during similar defueling operations. Such a setup would require some additional filter changes but would also possibly improve defueling efficiency. [210]

• ***Air-Lift System***. The air-lift system (ALS) successfully loaded many thousands of kilograms of debris from the core region rubble bed and from the lower head region of the reactor vessel. Debris, water, and air separation techniques effectively packaged the debris into a debris bucket, which was then placed into a defueling canister. The ALS used compressed air to produce the motive force for effectively transporting fuel debris (ceramic-like rubble) from beneath the lower core support assembly (LCSA) into a standard debris bucket. Gravity caused the debris to separate from the transport stream. The entire method did not rely on moving parts. INEL performed a full-scale test of the ALS using a mockup section of the LCSA placed in the bottom of a tank containing lead shavings; cubes of lead measuring 2.5 centimeters; lead shot of various sizes; and sections of 1-centimeter-diameter stainless steel tubing that was 2–5 centimeters long. Tests demonstrated that the ALS could transport fuel debris from beneath the LCSA into a standard debris bucket at a minimum rate of 230 kilograms per minute. [211, 212]

4.8 Defueling Canisters

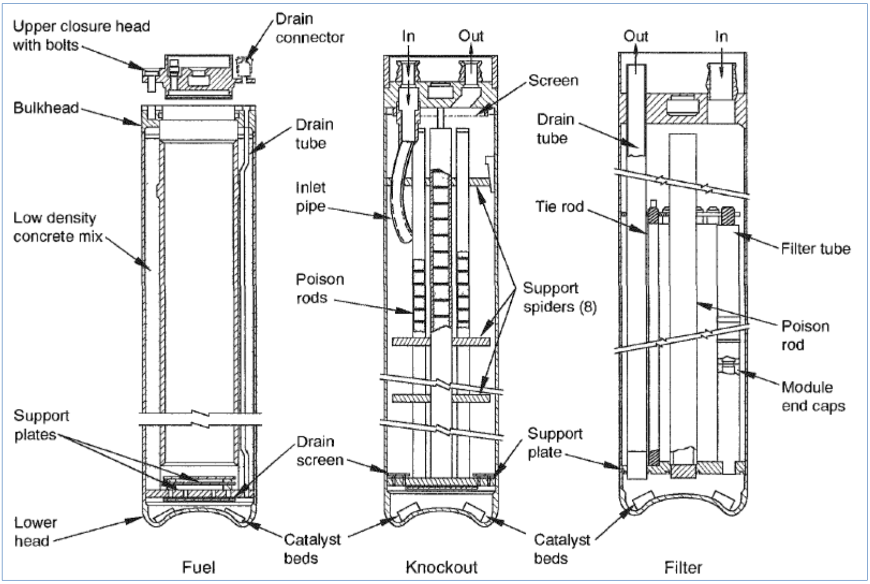
The defueling canisters were designed to accept and confine core debris ranging in size from particles (known as fines) of about 0.5 micron in diameter up to partial-length fuel assemblies of full cross section. The canisters were intended to provide confinement for offsite transport using a shipping cask and for long-term storage of core debris. Three types of defueling canisters were designed and fabricated: (●) The *fuel* canister was designed as a receptacle for large pieces of core material, which were picked up and placed either directly into the canisters or into another container that would then be inserted into the canister. (●) The *knockout* canister was designed for use in the fuel debris vacuum system to separate debris particles ranging from about 140 microns up to full pellet size or larger. (●) The *filter* canister was designed for use in the fuel debris vacuum system (particles that passed through the *knockout* canister), the defueling water cleanup system, and the canister dewatering system. [213]

• ***Design Factors***. Designers began work on the defueling canister in 1980 without knowing the physical details of the fuel debris. The final canister design influenced the designs of interfacing systems and the shipping cask, as well as the defueling process. Factors that influenced the design of the canisters included: (●) criticality safety; (●) structural integrity; (●) radiolysis of water; (●) ease in handling in the reactor vessel; (●) ease in loading; (●) limiting dimensions and weight restrictions of the fuel transfer system and shipping cask; (●) the weight restriction in the INEL storage pool; (●) the DOE requirement for canister vents;

and (●) considerations of whether to use multiple single-purpose canisters or a single, multipurpose canister (the single-purpose canister was selected). Finally, since the canisters were part of the NRC's certified transport package, they had to comply with NRC transportation regulations. (214, 215)

- ***Canister Diameter***. The canister design process determined that an increase in the outer diameter to 14 inches from an originally planned diameter of 13.25 inches was desirable. The increase in canister diameter considered the following factors: (●) The Boral plate shroud assembly for the fuel canister design would be an off-the-shelf-design item for a 14-inch diameter canister but would need to be redesigned for a smaller diameter canister. (●) A shroud for a 14-inch diameter canister would have had a relatively larger cross-sectional area than a shroud for the smaller diameter canister and would make loading of damaged fuel assemblies an easier task. (●) A larger diameter canister would have a larger volume per canister for loading fuel, and fewer canisters would be required to load the entire core. (●) A larger outer diameter would be needed for the hydraulic performance of the knockout canisters since smaller diameter canisters would have increased flow velocities and less settling of small particles. (216) It had been reported that the inside dimensions of the fuel canister should have been larger to better accept distorted debris and end fittings. Some debris had to be resized and some end fittings had to be placed in storage drums to avoid difficult resizing. (217, 218)

- ***Canister Length***. One important experience from TMI-2 was the potential for conflict between maintaining flexibility to redesign as conditions became known



Drawings of three types of defueling canisters. Canister design criteria included criticality control, hydrogen generation control, and survivability during a transportation accident. (481.13)

and the lead time required for design and safety assessments. [219] Some options to modify the canister design based on core conditions and operating experience would have been useful. [220]

An early (September 1981) study of fuel debris canister designs proposed one that could fit a full-length fuel assembly. [221] The sonar mapping of the core's topography in August 1983 indicated that few full-length fuel assemblies were left standing in the reactor vessel. This opened the possibility that the damaged fuel could be shipped in shorter length canisters, rather than full-length 431.8-centimeter (170-inch)-long canisters. The possible use of canisters that were only 330.2 centimeters (130 inches) long provided an opportunity to evaluate improvements in shipping economics and logistics using Government-owned M-130 rail casks, which had an inside cavity length of 330.2 centimeters (130 inches). After receipt of the cask proposals in June 1984, canister length was increased to 150 inches, which was the maximum length specified by potential suppliers. The slightly shorter length improved the ease of handling in the reactor vessel. [222] An even shorter canister design option (75 inches long) was considered to restrict the weight of the contents while maintaining a stack height of 150 inches, but other options were not discussed further in the literature. [223]

- ***Weighing of Canisters***. One major problem area that was encountered during the design stage was a simple and reliable way to measure the weight of the three different types of canisters while they were being loaded with debris in the reactor vessel. The total loaded dry shipping weight restriction was 2,800 pounds, which was a limitation of the canister storage pool at INEL (5 percent of the canisters could be up to 5-percent overloaded or 2,940 pounds). Several factors that contributed to the difficulty in developing a practical system for weighing fuel canisters in the reactor vessel included the following: (•) the expected wide variation in the debris density; (•) the mechanical and operational conditions during which the weighing system needed to be able to function; (•) the multielevation positions of canisters on the carousel (canister position system); and (•) the rotational motion of the carousel. [224] Solutions included the following: [225]

  - *Knockout Canister.* The knockout canister was weighed during all vacuuming operations using the knockout canister connect assembly module, which was mounted to the underside of the defueling work platform.

  - *Filter Canister.* The filter canister was weighed continuously during all vacuuming operations by the filter canister weighing system, which was attached to the filter canister and suspended from the defueling work platform deck shielding plate.

  - *Fuel Canister.* The fuel canister was weighed on an as-needed basis using the canister grapple tool (an open fuel can lifting tool) and a typical weight scale in the rigging of the containment building service crane. Since fuel canisters were open topped during loading, visibility during loading permitted the operators to accurately judge the fullness of the canister, and thus the canister was only weighed once or twice for verification.

- *Dewatered Canisters.* All three canister designs were weighed following dewatering in either the containment building or the fuel handling building. Each canister was picked up and raised out of the water by the canister handling trolley. This allowed the load cell in the canister handling trolley to sense the canister out-of-water weight to within 35 pounds. Each canister was weighed before and after dewatering to determine the amount of water removed during dewatering and to demonstrate that the dewatered canister complied with the maximum shipping weight restrictions.

- ***Design Controls***. A detailed canister design interface control program document coordinated the numerous organizations involved in canister and supporting equipment designs. Key areas of design interfaces were established, and the lead design organization controlled all exchanges of design interface information. [226]

- ***Decontamination***. [227] The external radiation dose rates on most canisters were very high, which made hands-on smear wipes not possible at TMI-2 because of the licensee's efforts to keep worker doses ALARA. The focus at TMI-2 was decontamination. At INEL, the canisters were measured for contamination.

- *Measures at TMI-2*. In the fuel handling building at TMI-2, a decontamination spray ring with borated hot water was used to clean the loaded canister as it was being lifted from the spent fuel pool to be transferred to the shipping cask. The licensee conducted several experiments with an empty canister to improve the decontamination procedures. These included: (•) a high-pressure water spray ring system, which failed by a factor of 50 to meet the INEL criteria; (•) multiple soakings of a canister in hydrogen peroxide solutions followed by hydrogen peroxide solution spraying and hand wiping, which indicated that another factor of two for decontamination would be required; (•) hand wiping and cleaning with a bristle brush, which showed that hand wiping was the most effective but still did not meet the requirements; and (•) using a decontamination spray ring with cold water and heated water, which showed that heated water was best and came closest to meeting the requirements.

- *Measures at INEL*. INEL was able to use the hot shop overhead manipulator to take smears of the external surface of a canister remotely as each was removed from a cask. INEL provided feedback on surface contamination levels for the licensee to improve its decontamination process. The problem was never completely eliminated but was significantly improved by the licensee's efforts.

- ***Contamination Traps***. An evaluation of the design of the canister closure cover considered that the cover could trap contamination and carry it from the reactor to the spent fuel pool. [228] Each canister had process connections located on the lid of the canister for filling, closing, dewatering, inerting, and monitoring. (229)

- ***Lid Gasket Seal***. The metal gasket seal between the removable upper head (lid) and the bulkhead on the canister body was found to leak too easily during remote installation of the heads to the bodies using manual long-handled tools. Leaks occurred during defueling operations, even though the metal seals were able to pass the pneumatic pressure test of 150 pounds per square inch as required for an American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code-stamped pressure vessel. The seal material was changed to an elastomer with DOE approval. (230)

- ***Serial Numbering***. Recordkeeping of loaded canisters was a challenge for canister components with more than one serial number (e.g., lid and body). Since the fuel canisters were ASME-Code-stamped pressure vessels that had been pressure tested with a "matching" head and body (i.e., both head and body had the same number), INEL was concerned that interchanging heads would possibly negate the ASME Code stamp and complicate recordkeeping of the fabrication, documentation, and identification of canisters. The licensee determined that interchanging the heads did not negate the ASME Code stamp but committed to limiting the interchanging of heads and bodies to special situations only. (231)

- ***Canister Positioning***. The canister positioning system (CPS) supported the fuel and knockout canisters in the reactor vessel. The CPS had five canister holding positions (sleeves), a means for lowering canister positions into three preset vertical positions, and a manual rotational drive unit. Various handheld tools were used to facilitate operation. The CPS was mounted to the defueling work platform. The elevation of each canister in the CPS could be changed to minimize the canister height above the core debris bed as the bed level was lowered. The canister elevation was adjusted by using a long-handled tool to change the height of the support sleeves. (232)

Suggested improvements in the design of the CPS based on actual defueling included the following: (●) More adjustability for vertically positioning the canisters in the reactor vessel would have improved the working height above the rubble bed. (●) The canister and sleeve could have been designed to use a single handling tool to minimize tool changeouts. (233)

- ***Canister Filler Material***. A lightweight concrete was used to fill the void between the square inner shroud and circular outer shell. This filling provided continuous lateral support to both the outer shell and the shroud. This resulted in a distributed loading function for horizontal drops and only insignificant deformations in the shroud shape, thus preserving a safe physical dimension for criticality safety. The fill also provided weight to ensure that an empty canister would be nonbuoyant, a general canister design criterion. The low-density concrete mixture contained cement, glass bubbles, and demineralized water. (234) The water present in the concrete mixture was extremely difficult to remove during the drying process at INEL. Canister drying is needed for long-term storage of fuel canisters; therefore, in hindsight, the material was not a wise choice. Many debris components oxidized, leaving a net surplus of hydrogen that required venting. Other options for filler material could have been explored, such as aluminum or glass beads. (235)

- ***Materials Compatibility***. Water and materials that could come into contact with the canister's internal components were evaluated for potential impacts. Modifications to water cleanup systems and water inhibiters were also evaluated for impacts. For example, the TMI-2 project experienced problems with the premature plugging of filter canisters by microorganisms and fine core materials. A biocide (hydrogen peroxide solution), a diatomaceous earth body feed, and a coagulant were used to enhance performance of the filter coating. The DOE reviewed the use of these materials for both transportation and long-term storage at INEL. The NRC's transportation certification staff also reviewed and approved the potential impact of these materials on the safety of the shipments. Reviewers evaluated the effect of adding the body feed, coagulant, and biocide on the canister's catalyst hydrogen recombiners. (236)

- ***Quality Assurance***. A valuable lesson from TMI-2 was that production support functions, such as material traceability, documentation, quality control, and quality assurance (QA), should be sufficiently staffed to support the production schedule. (237) Based on this experience, QA involvement of the manufacturer of defueling canisters should have started upon receipt of the material. The NRC and the licensee identified substantial problems relating to the documentation of material used in the fabrication of defueling canisters. This led to serious delays in fabrication and narrowly avoided an adverse effect on the defueling schedule. It also highlighted the dangers of relying on one low-bid vendor for such difficult and important work. After a period of delays and uncertainty, the contract was withdrawn from the initial vendor and given to two new vendors that produced satisfactory canisters. (238)

The licensee's contractor QA department was responsible for manufacturing inspections during canister fabrication, and it was decided to establish a full-time inspector in the shop. The licensee's QA department provided periodic oversight. INEL (receiver of the loaded canisters) and the NRC conducted spot checks as well. (239) As a result of a DOE request, the NRC inspected defueling canisters during the fabrication process, which included welding observation, nondestructive examinations, and fitting of components. (240)

- ***Vendor Inspections***. (241) At the DOE's request, which was the receiver of loaded defueling canisters, the NRC expended about 782 inspection hours related to the TMI-2 defueling canisters and transportation casks. The focus during these inspections shifted from a previous "paper" review to a safety review that involved a more thorough examination of equipment and the implementation of the quality assurance (QA) program during the fabrication of components. The NRC interaction with vendor personnel was largely positive. The vendors responded to the inspection findings by promptly initiating corrective actions that addressed root-cause issues and gained a better understanding of, and insight into, the regulations. Because of the interactions during the inspection process, manufacturing and design controls were improved, thus resulting in an improved product. The NRC staff believed that this was a direct result of the shift in inspection focus to hardware and implementation of quality activities.

Based on reviews of the canisters and cask designs, the NRC's vendor inspectors identified fabrication processes to be inspected. Inspection plans identified the specific areas to be examined. Inspection areas included: (●) fabrication and inspection processes, such as welding and nondestructive examination; (●) material identification and nonconforming item control throughout the facilities to ensure that nonconforming items were not used; (●) fabrication and acceptance tests and test results to ensure that acceptability criteria had been met; (●) training and qualification records of welders, nondestructive examination inspectors, and QA inspectors; (●) material storage to ensure that the material was not exposed to adverse conditions; (●) a calibration program for measuring and test equipment to ensure that calibrations were performed as required, by qualified personnel, with standards traceable to the National Bureau of Standards (currently the National Institute of Standards and Technology), and with calibrated instruments; (●) a procurement program, including purchase orders, to ensure that materials were bought from qualified subvendors, that receipts were inspected, and that the vendor had some control over the QA program in place at the subvendor's facility; and (●) design and drawing control to ensure that changes were made in a controlled manner and all documents were the latest revision.

4.9 Defueling Operations

Removal of damaged fuel and structural debris from the reactor vessel started on November 12, 1985, 6.5 years after the accident. Numerous manual and hydraulic-powered long-handled tools were used to perform a variety of functions, such as pulling, grappling, cutting, scooping, and breaking up the core debris. Eventually, more powerful tools, such as the core bore machine, plasma arc torch, and water jet cutting system, were used to disassemble or cut apart reactor vessel components and break up resolidified core material. After breaking up and sectioning oversized debris, long-handled tools manually loaded debris into defueling canisters positioned underwater in the reactor vessel. The larger pieces of vessel internal components, such as lower core support assembly sections, were lifted out of the vessel by crane and stored in the modified core flood tank "A." Smaller pieces or "fines" were vacuumed into knockout canisters and filter canisters. Residual fuel remaining after defueling operations is listed in Table 3.

Other defueling activities included transferring the loaded defueling canisters from the containment building to the fuel handling building, dewatering the filled canisters, and placing canisters into the canister storage racks located in spent fuel pool "A." Removal of fuel and structural material from the reactor vessel was completed in stages. The plan for each stage incorporated experience gained from previous stages and activities, including visual in-vessel inspections and sample examinations. (242)

- ***Water Safety***. The Occupational Safety and Health Administration rules on longshoring and marine terminal operations were useful guidelines for worker safety over water. (243) Only one incident report involved a worker on the defueling work platform who slipped through an open service hole and fell partway into the reactor vessel. The worker had temporarily and inappropriately unhooked himself from a sling to accomplish a work task. (244)

- ***Personnel Contamination***. Workers experienced many instances of personnel contamination, which was most likely the result of reactor coolant spray or splash when tools were raised from and inserted into the reactor vessel. (245)

- ***Defueling Staffing***. Initially, the work was conducted by teams of five. These teams were later reduced to as little as two, due to improved skills and experience of the workers. The original team included a tool handler, camera handler, crane operator, radiation control technician, and camera controller. Eventually, the camera controller function was performed by the tool handler when the camera controls were moved closer to the work slot in the defueling work platform. The radiation control technician, with a high-range radiation detector, was only involved when tools were taken out of the work slot. Supplementary personnel included the polar crane operator and the construction work force to assist in the tool movements outside the canal area and to close the debris canister. The NRC-licensed defueling senior reactor operator, stationed in the command and control center located in the turbine building, was technically in charge of the defueling operations requiring reactivity manipulations and was in constant radio contact with the defueling team members. (246)

- ***Opening the Reactor Coolant System to Atmosphere***. Although the reactor head lift was found to be straightforward and was performed without technical difficulties, the operation required a great deal of planning and management resources because of concerns about opening the reactor coolant system to the atmosphere. The lift also drew considerable attention from the news media and public. (247)

- ***Hose Leaks***. Hose failures occurred several times during the defueling process. Failures were typically caused by cracked hoses and snagging while raising tools out of the vessel. Even rubber hoses of the highest quality and pressure rating were known to fail. Based on this experience, it was reported that the use of rubber hoses should be minimized. Applications with rubble hoses should consider the consequences of failure in the design and response procedure. (248)

- ***Microbial Growth***. Only a few months after defueling started, water clarity began to deteriorate. Video camera visibility was rapidly lost, and defueling was hampered. The problem turned out to be microbial growth (and, to a lesser extent, fine particulate debris) that first plugged the sintered metal filters in the defueling water cleanup system and then began accumulating in algae-like masses within the reactor vessel. It took more than a year to analyze the source, decide and gain approval for a method to prevent future occurrence, and then to completely restore clarity and visibility. Studies revealed that small amounts of hydraulic fluid from the defueling tools had leaked into the reactor coolant and provided the organic food source for the microorganisms. This was aided by the appropriate levels of water temperature and light intensity from the underwater video camera lights to promote growth. Ultimately, hydrogen peroxide was used to kill the growth and prevent recurrence. [249, 250]

- ***Biocide***. Considerable time was spent attempting to improve visibility inside the reactor vessel. Numerous techniques, with varying degrees of success, were evaluated serially to bring microorganism growth under control and to improve clarity by the end of 1986. One account suggested that, had potential solutions been investigated in parallel (instead of serially), the microbial growth issue could have been resolved earlier. [251] Insights from biocide evaluations and implementation included the following:

  - *Biocide Concentrations*. As the result of extensive research and testing, the NRC approved 200 parts per million hydrogen peroxide as the biocide. The NRC's evaluation concluded that the biocide concentration was compatible with the following: (•) the existing water chemistry in the reactor coolant system; (•) water processing systems (i.e., EPICOR II, submerged demineralizing system, reactor vessel filtration system); (•) the defueling canister's catalytic hydrogen recombiners; and (•) waste disposal

Microorganism growth in the reactor vessel slowed defueling to a halt within a month after defueling started. Shown is the vessel annulus region between the lower core support assembly and the vessel wall.

requirements. In addition, the biocide did not negatively affect criticality safety, given that hydrogen peroxide was borated to levels that complied with recovery technical specifications. The evaluation also concluded that the increase in reactor coolant activity levels due to the increase in the rate of cesium leaching from the debris bed caused by the hydrogen peroxide would not have a significant impact on worker safety with the use of normal radiological control practices. (252, 253, 254)

- *Initial Shock Treatment*. Industrial strength hydrogen peroxide (15 percent) was added to the reactor coolant in the reactor vessel and spent fuel pool where the defueling canisters were stored before shipment. About 750 gallons (2,800 liters) were added initially to provide a shock treatment, with smaller concentrations added thereafter. (255)

- *Gas Generation*. Large amounts of hydrogen peroxide produced large quantities of gas that had to be vented. This gas produced significant liquid carryover onto the defueling platform surfaces and fuel handling building floors that required aggressive decontamination. (256)

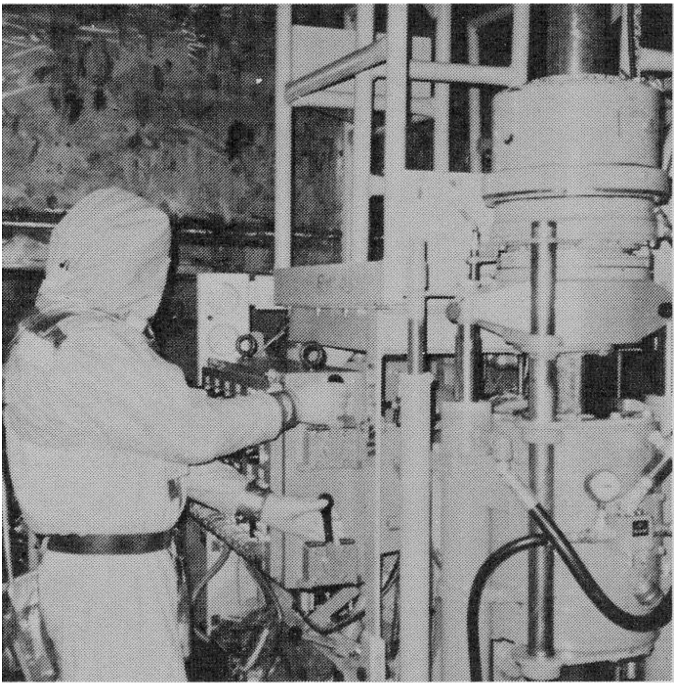
- *No Chloride-Induced Corrosion*. Hydrogen peroxide contained no chlorides that would corrode stainless steel and left no residue in the reactor coolant after oxidation. (257)

- *No Microbial-Induced Corrosion*. Inspections, corrosion studies, and laboratory tests found no microbial-induced corrosion of components and defueling equipment in the reactor vessel. (258)

- *Other Disinfection Approaches*. Disinfection, a process in which organisms are destroyed or inactivated, could be accomplished by several different physiochemical treatments, including thermal energy; ultraviolet, gamma, X-rays, and microwave irradiation; ultrasonic disruption; and chemical agents, with the latter the most common method of disinfecting water and waste waters. (259)

- ***Water Clarity***. One account indicated that the reactor vessel defueling water cleanup system could have been sized to restore water clarity more rapidly. Operation of underwater equipment with limited visibility greatly reduced productivity while increasing the risk of equipment damage and lost time. The design basis for water clarity should have been 0.1 nephelometric turbidity unit (ntu) (about 0.1 parts per million suspended solids) instead of 1.0 ntu for manual tool operation at depths of 6 to 10 meters. (260) Working inside the reactor vessel often resulted in the resuspension of very fine particulates, the mass of which precluded settling. This resulted in a smoky effect that reduced visibility from 12 meters of water shielding to less than 1 meter, and often much poorer. (261)

- ***Molten Material Formation***. Analysts had not predicted the extent to which the molten material had formed into a large monolith within the reactor vessel or understood the material's resistance to fracture. (In fact, fuel melt was first reported in 1985 after careful examination of the first "grab" samples from the damaged core, 6 years following the accident.) The molten material that formed in the TMI-2 core was a complex mixture of the major core constituents (uranium, zirconium, and iron) with lesser amounts of control rod material (silver, indium, and cadmium) and other alloy constituents (chromium and nickel). The molten material also contained a significant quantity of oxygen, making the solidified melt a highly refractory ceramic. A portion of the molten material solidified into a heterogeneous, funnel-shaped disk over a meter thick. The mass was located in the center of the reactor vessel below the plenum. Elsewhere in the reactor vessel, molten material flowed down between the baffle plates and the core barrel and solidified in the reactor vessel's lower head region. Both solidified masses weighed many tons. Heavy-duty defueling tools (impact chisels and wedges) were unable to break apart the monolith. A specialized drilling apparatus (core bore) was finally used to pulverize the material. [262, 263]



Technician at the controls of the core bore machine located on an elevated platform mounted to the defueling work platform. The core bore was used to drill large holes in the solidified molten core region. The drill string, which was mounted through the center of the motor, can be seen at the right. A drill bit was mounted at the end of the string; additional strings were fastened together as needed.

- ***Remote Coordination Center***. The remote coordination of defueling operations increased productivity and minimized radiation exposure. The defueling activities on the defueling work platform were monitored from a coordination center established in the nearby turbine building. Support staff observed the work teams using closed circuit video cameras mounted in the containment building. The camera pan, tilt, and zoom controls were remotely operated from the coordination center. Video monitors in the coordination center also displayed images from the in-vessel video cameras used by the defueling teams. In addition, the coordination center was in radio communication with each member of the defueling team. The center recorded the video and audio of the operations for archival purposes, analysis of the footage, and worker training. Support for the defueling operators (e.g., special data; engineering expertise; procedural changes; suggestions for solving problems; ALARA advice) came by communications from the coordination center rather than by sending additional workers into the containment building. (264, 265)

- ***Number of Canisters***. Estimating the number of canisters to be used in defueling evolved into a high art form and one with significant potential cost. The original estimate was 243. The first half of the INEL pool could store 288 canisters. The project's total estimate grew as defueling progressed because the weight loaded into each canister was usually less than anticipated. As important, the relative numbers of fuel, filter, and knockout canisters changed in response to the techniques used and unexpected conditions in the reactor vessel. The final estimate was between 349 and 360 canisters. (266) At the conclusion of the defueling effort, a total of 342 canisters of core debris, in 22 rail shipments, were transported to INEL. The total number of canisters included 286 fuel canisters, which contained partially intact fuel assemblies and large debris picked up from the reactor vessel; 12 knockout canisters, which contained core debris vacuumed from the reactor vessel and reactor coolant system; and 62 filter canisters, which contained fine debris that had passed through the knockout canisters. (267)

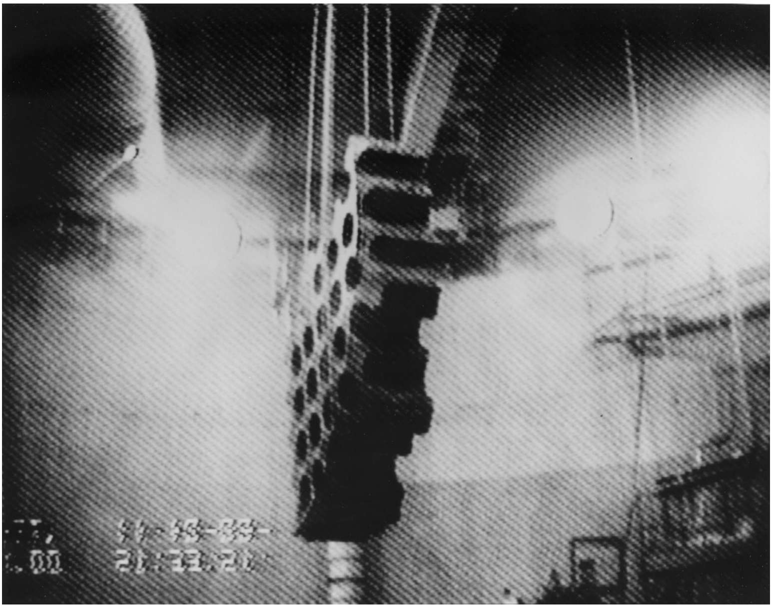
- ***Extraction of Standing Fuel Assemblies***. The outer ring of the core contained standing fuel assemblies of various lengths. Once the first assembly was removed by the lasso tool, the others came out easily. The tools that were developed for removing standing assemblies included hydraulic side grippers, spears, and long L-shaped assembly lifters. (268)

- ***Cutting Incore Guide Tubes***. The core boring machine proved very adept at cutting out in-core guide tubes and support posts, which was a weakness of the automated cutting equipment system. However, cutting was only effective when enough space existed for the chips to fall away. (269)

- ***Baffle Plate Handling***. (270, 271) Vertical baffle plates formed the peripheral boundary of the core. Roughly 4,000 kilograms of fuel debris relocated behind the baffle through one large hole in the baffle plates caused by the flow of molten core material from the core region. Several options were considered for removing the highly irradiated baffle plates (with an estimated peak contact gamma radiation field of approximately 3,000 roentgen per hour in air) to gain access to this debris.

- *Options*. The removal options included the following: (●) Cut the plates into small pieces and load them into fuel canisters or other specially designed containers. (●) Remove the small pieces of plates from the vessel and store them either in a remote location (e.g., the containment building basement) or in a modified core flood tank (sections of the lower core support assembly were stored in these tanks). (●) Cut the plates into large sections, rotate each section, and remove debris one plate at a time. The latter option, which was selected, required no plant modifications; resulted in lower radiation exposures; required minimum tool development; and did not introduce any new safety concerns (e.g., lifting and handling out of the vessel) or difficult failure scenarios.

- *Selection*. The plates were cut into eight sections using the plasma arc torch. A total of 864 bolts that held the baffle plates to the core barrel were removed using an untorquing tool and a drill tool. The 4-meter-long pieces of highly irradiated stainless steel were highly radioactive with an estimated peak of 3,000 roentgen per hour gamma. Baffle plate handling exposed the upper core support assembly for defueling of the core former area. Two of the eight baffle plate sections were removed and hung from vent valve seats. The exposed area was defueled before removal of the next plate section. A computer model of the vessel was used to help select how to shuffle the baffle plates from hanger to hanger in a manner that least affected defueling and required the least



Piece of the lower grid forging being removed from the reactor vessel. Pieces of the lower core support structure were moved in a modified core flood tank for storage.

handling. Each plate was essentially rotated 90 degrees from its original location to its final location.

- ***Defueling Incidents***. Very few incidents, two injuries, and a few other relatively minor incidents were reported during defueling operations:

  - *Dropped Canister*. On December 14, 1985, a load drop event occurred early in the defueling operations when a defueling canister and support sleeve fell into the reactor vessel. The licensee had been loading fuel assembly end fittings into a defueling canister when an end fitting became stuck in the canister. During attempts to reposition the stuck end fitting with the 1-ton jib crane, the defueling canister and support sleeve were dislodged from the canister positioning system and dropped 1.5 feet onto the top of the debris bed in the reactor vessel. The dropped load weight was 2,200 pounds; the jib crane was rated at 2,000 pounds. No increases in radiation levels and airborne activity were detected during the event and subsequent retrieval and recovery. [(272)]

  - *Dislodged Defueling Tool*. On May 22, 1986, the trolley on the number one jib crane on the rotating work platform disengaged and fell into the reactor vessel. An operator was struck by a portion of the falling apparatus and received a scalp laceration. Approximately one-half of the trolley was recovered from the vessel and examined to determine the failure mechanism. The trolley on the number one jib crane was replaced with another of a different design. [(273)]

  - *Dislodged Defueling Tool*. On August 19, 1986, a worker on the defueling platform was injured when a long-handled tool in the reactor vessel was dislodged from its temporary storage location and fell onto the worker's right hand, pinning it between the tool and the tool rack. The worker sustained an apparently severe laceration and possible fracture of one finger. [(274)]

  - *Worker Slipped into Reactor Vessel*. On May 22, 1988, a worker on the defueling platform slipped and fell partway into the reactor vessel through an open access hatch. The individual worker was installing equipment in the reactor vessel in preparation for the reinstallation of the plasma arc cutting assembly. The worker had temporarily unhooked himself from a sling to accomplish the work. The fall was broken when the worker grabbed the defueling platform. The worker's legs, up to his knees, were wet and contaminated. Protective clothing included a double protective clothing wetsuit and respiratory protection. Preliminary licensee dose estimates indicated that the worker was expected to receive about a 200-millirad skin dose to the legs. The worker received only minor bruises and did not require any medical treatment. [(275)]

  - *Workers in Contact with Fuel Debris-1*. A small section of a fuel rod was unknowingly withdrawn from the reactor vessel when the defueling tool was removed from the reactor vessel, and the section of fuel rod fell on the work platform. The piece measured 10 roentgen per hour on contact and was picked up with a Peters tool (vice grip) and dropped back into the vessel. (276)

- *Workers in Contact with Fuel Debris-2*. In another incident, in 1989, one worker received an overexposure of about 55 rem to the hand (which was in excess of regulatory limits) while unknowingly handling a piece of fuel debris in the TMI-2 containment building decontamination facility. A coworker received an unplanned exposure of about 13 rem to the skin on a hand. This facility was employed to repair, disassemble, and decontaminate equipment used in the defueling operation. During this cleaning evolution, one worker (without wearing a beta glove) picked up what he believed to be a piece of debris from the floor and threw it in the area of a trash container. This same individual then picked up the item a second time because he wanted the radiological controls technician to survey the item at the first opportunity. Shortly thereafter, the second worker picked up what was apparently the same piece of debris and briefly held it in his hand. Subsequently, in response to a concern raised by the first individual, the radiological control technician responsible for monitoring the cleanup activities in the facility surveyed the debris and determined that it was a highly radioactive fuel fragment. The radiation survey (277) of the material indicated contact does rates of 1,320 rem per hour of gamma radiation and 11,580 rem per hour of beta radiation. The technician assigned to monitor the work was unaware that either individual had picked up the fuel fragment and failed to investigate. An earlier radiation survey of the work area did not identify the fuel fragment because other debris on top may had shielded the fragment. (278)

  The NRC concluded that this incident demonstrated the need for (•) improved planning and preparation of work activities in contaminated or potentially contaminated areas, (•) improved radiological oversight and control of such work activities to ensure that such activities are conducted safely and in accordance with regulatory requirements, and (•) improved communications between the radiation protection personnel and the work crews they are monitoring. (279)

- *Inadvertent Core Alteration-1*. In March 1986, the defueling canister positioning system mounted in the reactor vessel was rotated with canisters containing core material without direct supervision of a licensed fuel handling senior reactor operator. This activity was classified as a core alteration in accordance with the recovery technical specifications. The lead engineer should have requested permission from the command center before initiating the core alteration activity. (280)

- *Inadvertent Core Alteration-2*. The air-lift vacuum system (ALS) used a debris bucket to collect debris. The debris bucket had a trap door that unloaded the bucket's contents into the defueling canister. In 1989, unlicensed defueling operators concluded that the ALS did not contain a significant quantity of fuel debris when the system was removed from the reactor vessel for eventual placement in temporary storage. Visual inspection of the debris bucket before its removal was hampered due to a lack of water clarity in the reactor vessel. To facilitate flushing of the bucket, the bottom door of the debris bucket was opened using an extension pole. Personnel stationed near the reactor vessel observed an unknown quantity of core debris fall from the debris bucket into the reactor vessel. This incident constituted an inadvertent and unplanned core alteration since a licensed fuel handling senior reactor operator did not authorize this action as required by the recovery technical specifications. The absence of a detectable increase in the weight of the debris bucket did not provide positive verification of the absence of fuel debris. The licensed operator and task supervisor should have assumed the presence of core debris in the debris bucket and classified this event as a core alteration before removal of the ALS. (281)

Defueling canister transfer cask positioned over a port hole in the defueling work platform. The canister transfer bridge raised the defueling canister inside the transfer cask, which was then moved to the deep end of the refueling pool.

Table 3. Residual uranium dioxide fuel (UO_2) remaining after defueling operations. [282]

Reactor Vessel	(kg UO_2)
Defueling Work Platform Region	
In-Vessel Filtration System	16.3
Canister Positioning System	13.7
Downcomer Region	
Cold Leg Flow Deflectors	11.9
Hot Leg Bosses in Core Support Structure (CSS)	26.6
Surveillance Specimen Capsule Holders	3.5
Thermal Shield Support Blocks (Top Surface)	15.2
Thermal Shield Inner Surface and Annular Gap	118.6
Core Catchers/Seismic Restraint Blocks	2.9
Internals Indexing Fixture (IIF) Region	
Reactor Vessel Flange, IIF Flange, CSS Flange	4.9
CSS Region	
Vent Valve Seats (Inner Surfaces)	8.7
Top of Lower CSS Flange	1
Upper Core Support Assembly Region	
Baffle Plate Inside Surface	17
Baffle Plate Outside Surface	17
Baffle Plate Flow Holes and Bolt Holes	10.5
Former Plates Top and Bottom Surfaces	39.9
Lower Core Support Assembly Region	
Lower Grid Rib Section (LGRS) [a]	41.3
Between LGRS and Lower Grid Distributor Plate (LGDP)	12.8 [b]
Between LGDP and Forging	48.2 [b]
Forging Peripheral Flow Holes	110.1
Inside Support Post Stubs	1.4
Between Forging and Incore Guide Support Plate (IGSP)[c]	174.3 [b]
Between IGSP and Flow Distributor	39.7 [b]
Bottom Head Region	
Head Surface	104.6
Incore Instrument Nozzles	29.4
Standing Incore Guide Tubes	17.6
Surface Film Deposits	2.1

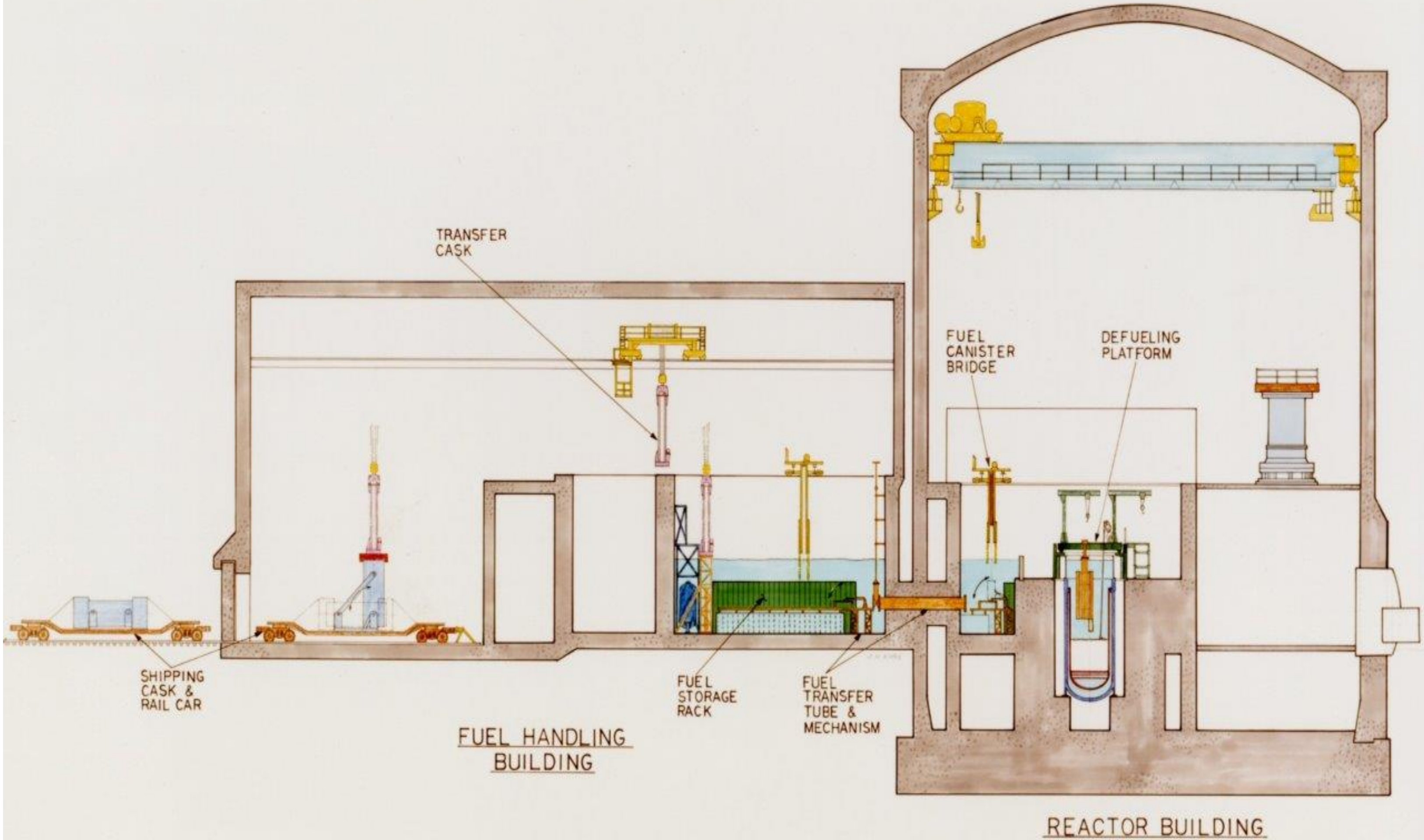
Table 3. Residual UO_2 remaining after defueling operations. (Continued)

Reactor Coolant System (Excluding Reactor Vessel)	(kg UO_2)
Decay Heat Drop Line	1.5
"A" Side Steam Generator	
Upper Tubesheet, Tube Bundle, Lower Head, and J-Legs	4.1
Cold Legs	34.1
"B" Side Steam Generator	
Upper Tubesheet, Tube Bundle, Lower Head, and J-Legs	51.7
Hot Leg	1.7
Cold Legs	21.3
Core Flood Line (Before Check Valve)	1.2
Reactor Coolant Pump	14.7
Reactor Building (Excluding Vessel and RCS)	(kg UO_2)
Fuel Transfer Canal	12.7
"A" D-ring	24.3
Storage Area, Upper Endfitting (55-Gallon Drums)	7.7
Letdown Coolers	3.7 (d)
Containment Basement and Sump	1.3
Defueling Water Cleanup System	2.3
Defueling Tool Rack	4.8
Temporary Reactor Vessel Filtration System	4.4
Containment Building Drains	5.1
Auxiliary and Fuel Handling Building	(kg UO_2)
Spent Fuel Pool "A"	4.9
Reactor Coolant Bleed Tanks	4.31
Subtotal: All Other Cubicles (Each < 1 kg)	7.79
Grand Total (Including Areas < 1 kg Not Shown Above)	**1120 kg**

Notes

a. Top surface and peripheral flow holes
b. Includes fuel pellets and fuel rod pieces
c. Includes IGSP flow holes
d. Below minimum detection level

Key to Figure on Next Page:
Defueling canister transfer process (right-to-left): (1) Workers on the defueling platform loaded fuel canisters. (2) A fuel canister bridge transferred a canister from the reactor vessel to the fuel transfer tube and mechanism inside the containment building. (3) The second fuel canister bridge in the fuel handling building loaded the canister into the fuel storage rack in the spent fuel pool. (4) The fuel transfer cask and building crane transferred the processed canister from the pool to the shipping cask loading station. (5) The Model 125-B shipping cask was lowered from its upright position onto the rail car and prepared for shipment.


TRANSFER
CASK
FUEL
CANISTER
BRIDGE
DEFUELING
PLATFORM
SHIPPING
CASK &
RAIL CAR
FUEL
STORAGE
RACK
FUEL
TRANSFER
TUBE &
MECHANISM
FUEL HANDLING
BUILDING
REACTOR BUILDING

5 FUEL DEBRIS TRANSPORTATION

Transport of the damaged core materials from TMI-2 to INEL for examination and storage presented many technical and institutional challenges. These challenges included: (●) assessing the ability to transport the damaged core; (●) removing and packaging core debris in ways suitable for transport; (●) developing a transport package that could both meet Federal regulations and interface with the facilities at TMI-2 and INEL; and (●) developing a transport plan, support logistics, and public communications channels suited to the task. The DOE's "Historical Summary of the TMI-2 Core Debris Transportation Campaign," issued 1993, provides a thorough historical summary of how the DOE addressed these technical and institutional challenges and transported, received, and stored the TMI-2 core debris at INEL. The scope of the experiences presented below is limited to the transportation preparations at TMI-2. (283)

5.1 Planning

- ***Coordination***. (284, 285) The close coordination of all organizations involved with the packaging and shipment of fuel debris from TMI-2 was required because of the broad scope, number of organizations involved, and required interfaces. In September 1983, INEL asked the licensee to consider a cooperative coordination effort for the TMI-2 core debris transport program. The TMI-2 Core Shipping Technical Working Team was formed to coordinate information among member organizations involved with the shipment of the TMI-2 core. This group solved major technical issues, such as hydrogen gas generation, canister criticality, canister design and testing requirements, and cask handling design requirements at both INEL and TMI-2.

  - *Membership*. All organizations involved with the transportation of fuel debris were members of the shipping working group. These organizations included those responsible for program management (DOE/INEL TMI-2 site office); core defueling coordination (licensee, Westinghouse); canister design coordination (licensee, Babcock & Wilcox); TMI-2 facility preparation (licensee, Bechtel); cask supplier (Nuclear Packaging, Inc.); hazards evaluations (Hanford Operations in Washington State); transportation technology (Sandia National Laboratory Transportation Technology Center); transportation support (INEL, TMI-2 site office); and INEL receiving facility preparation (Idaho). Other approving Federal agencies, such as the DOE, the NRC, and the Federal Railroad Administration, also attended most meetings and provided valuable input.

  - *Meetings*. The team provided a focal point for each program task, where activity status could be exchanged and potential problems could be identified for resolution in a timely manner. These principal organizations, and occasionally other special support organizations, attended the regularly held team meetings, during which many attendees would hear of progress on program tasks. The team approach was essential to the success of the program.

- ***Truck vs. Rail***. Truck versus rail shipments and wet versus dry loading were the principal alternatives evaluated before procuring the casks. For each alternative, the team determined the associated costs and schedules for the number of shipments necessary to move the complete core to INEL. Studies showed that the licensee's costs and INEL's unloading costs would be substantially less for rail casks compared to truck casks. Further, rail shipments could transport heavier and multiple casks. A rail cask could carry multiple defueling canisters, thus limiting the total number of shipments and reducing the chance of an accident. (286)

- ***Wet vs. Dry Loading***. The fuel debris handling studies performed by the licensee on truck casks showed that the use of a dry-loading method rather than a wet-loading method would reduce cask loading turnaround times at TMI-2. The wet-loading method was previously used for loading submerged demineralizer system liners into a shipping cask under water in the spent fuel pool. The dry-loading approach reopened the possibility that loading rail casks in the fuel handling building truck bay would be a viable alternative to the procurement of truck casks. (287, 288)

- ***Loading Approach***. (289) The licensee opted for dry loading of the cask instead of wet loading in the spent fuel pool. That decision was based on operational efficiencies, including the fact that much of the equipment dedicated to support of the cleanup effort occupied space in the pool. Safety considerations for dry loading of the cask included the handling of heavy loads and related accidents.

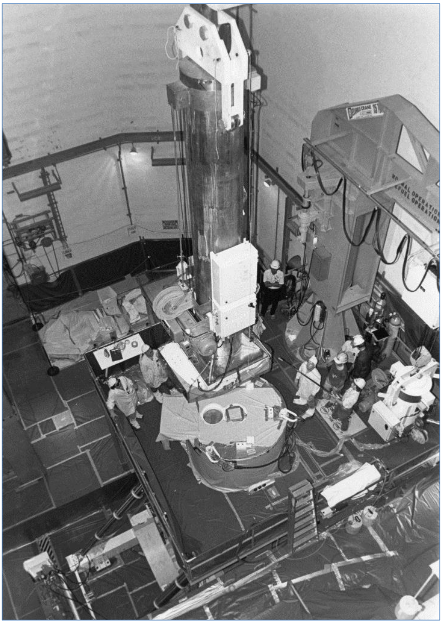
  - *Heavy Loads*. The major concern with cask loading activities was the handling of the heavy loads in the fuel handling building. TMI-2 had an NRC-approved heavy-load handling program that was expanded to allow for dry loading of the shipping cask. The program complied with the requirements of NUREG-0612, "Control of Heavy Loads at Nuclear Power Plants: Resolution of Generic Technical Activity A-36," (290) issued July 1980. Heavy-load drop concerns caused a major change in the dry-loading approach during development of the cask handling equipment. The hydraulic cylinders used to upright and lower the Model 125-B cask for loading at TMI-2 were a practical and safe method for allowing use of a cask that was too heavy for the existing overhead crane.

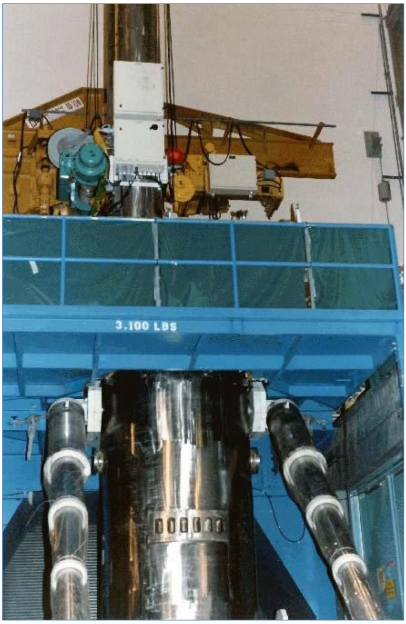
  - *Accident Analyses*. To be loaded, the shipping cask had to be rotated 90 degrees from a horizontal to vertical orientation. Accident analyses found that failure of the fuel handling building crane during cask rotation could result in dropping the cask onto the railcar, which had the potential to cause damage to the truck bay floor and fuel handling building systems in the basement (Unit 1 had redundant safety cables in the basement). The cask hydraulic lift assembly was built to upright the cask for loading and therefore eliminated the potential for failure of the crane during this operation.

  - *Dose Reduction*. The use of dry-loading equipment improved dose reduction and operational efficiency. In comparison to wet loading a cask, there was no need for hands-on decontamination of the exterior cask surfaces after removal from the water. With dose rates allowed by shipping regulations to reach 200 millirem per hour at a cask's surface, the potential savings in dose would be significant.

- *Cost Savings*. In addition to savings in dose, the dry-loading equipment would be cost effective for campaigns requiring many shipments. Many working hours would be saved per cask loading by eliminating underwater handling of a cask and its lid, draining, and external surface decontamination. Further, as previously mentioned, the TMI-2 fuel handling building crane would have required extensive modifications to permit the lifting of a large and heavy cask from the spent fuel pool to the loading bay.

- ***Loading Equipment Requirements***. The dry-loading equipment included some general requirements that were applicable to all components. These requirements included the following: (●) All lifting and handling equipment was designed to meet the requirements in NUREG-0612 and American National Standards Institute N14.6, "Radioactive Materials—Special Lifting Devices for Shipping Containers Weighing 10,000 Pounds (4500 kg) or More." (●) System components were designed with redundant safety and operating features to accommodate off-normal operating conditions (the cited reference did not provide examples). (●) System equipment was designed to fail in a safe manner assuming a failure would occur (fail safe). (●) Equipment included lead shielding to reduce personnel radiation doses. (●) System components were designed as modules to facilitate installation





Left: Fuel canister lowered into the Model 125-B shipping cask from a fuel transfer cask. Right: Shipping cask loading tower lowered the shipping cask to a horizontal position onto a skid that would be attached to the rail car.

and maintenance. (●) Equipment materials and coatings were selected to facilitate decontamination of radioactive materials. (●) Equipment to support and stabilize the cask was designed to withstand the seismic requirements for a safe-shutdown earthquake. (291)

- ***Keep Equipment Simple***. Most difficulties encountered during loading of the cask involved automated interlock systems (e.g., motor driven), particularly those in the fuel transfer cask. Many of these interlocks probably could have been designed for manual rather than automatic operation (the cited reference did not provide examples). Based on this experience, one account reported that, to avoid difficulties, equipment should be simple and, where practical, capable of manual operation. (292)

- ***Impact of Unrelated Events***. Events unrelated to the shipping activity had an unintended influence on the TMI-2 shipping campaign. Examples included the hazardous material train derailment in Pittsburgh (which led to the evacuation of approximately 15,000 people and occurred on the track used for TMI-2 shipments) and the bridge derailment near St. Louis (also on the track used for TMI-2 shipments). Even the Space Shuttle Challenger disaster in 1986 had an effect, raising concerns about the behavior of O-ring seals at low temperatures. O-rings; although different, were used to seal the lid of the shipping cask. (293)

- ***Neutron Sources***. Special attention was needed to identify and track neutron startup sources from the reactor core. Monitoring of a cask at INEL discovered one of the sources from TMI-2. Its presence was not documented in the canister shipping data and resulted in higher than expected radiation dose to personnel. Fortunately, the dose was well below acceptable levels. It was difficult to distinguish these sources from other debris while loading canisters and almost impossible to track them without neutron monitoring in all subsequent canister handling steps. (294)

5.2 Shipping Cask

- ***Cask Selection***. The DOE had primary responsibility for managing the design and certification of the shipping casks and their procurement. The following factors influenced the selection of a cask for transporting the core to INEL: (●) Core debris contained enough plutonium that, in accordance with 10 CFR 71.63, "Special Requirement for Plutonium Shipments," the material had to be transported in a separate inner container placed within an outer packaging (i.e., the package had to provide double containment). [h] That decision was reached in consultation with the NRC's transportation group. (●) Breached fuel

[h] Editor's Note: In a revision to the rule, published in the *Federal Register* on January 26, 2004 (69 FR 3698), the NRC modified 10 CFR 71.63 to remove the requirement for double containment of plutonium (see the discussion for Issue 17 in the cited *Federal Register* notice). Thus, since October 1, 2004, the effective date of the revised rule, NRC regulations no longer require double containment of plutonium.

rods could not be considered a level of containment. (●) Participants in the TMI-2 program decided that the defueling canisters would not be designed to provide a level of containment. The canisters needed removable lids and other loading features that made them difficult to qualify as a level of containment. Therefore, the decision was made that the shipping cask would provide both levels of containment. The canister design served other functions related to the integrity of the shipping cask as required by the regulations, such as criticality control and hydrogen and gas control. [(295)]

- ***Regulatory Coordination***. Each shipment was thoroughly inspected before leaving TMI. The DOE, the NRC, and the U.S. Department of Transportation ensured that cask, cargo, and railcar met all necessary Federal requirements for safe shipment. A thorough inspection of the railcar, including cask tie-down, was conducted to verify that it met the safety requirements of the American Association of Railroads. In addition, before transport, radiation surveys were conducted by the licensee and NRC inspectors from the NRC TMI-2 project office, as well as State inspectors at selected interchange stops enroute to INEL. Before the start of shipments, the Office of the Federal Railroad Administration inspected the entire rail route. [(296, 297)]

- ***Cask Fabrication***. The Model 125-B rail casks were fabricated in parallel with cask certification activities. The fabricator accepted the risk that the cask might not be approved as built. This risk was minimized by frequent meetings with the NRC to present the cask design as it evolved and by the successful completion of the quarter-scale cask model drop test program. Only long-lead-time materials (shells and forgings) were ordered before completion of the drop tests. Following the successful tests, fabrication of the cask components proceeded with some certainty that the cask design would not change. [(298)]

- ***Cask Certification***. Certification of the TMI-2 rail cask was completed in record time, 23 months from the first meeting with the NRC to receipt of the certificate of compliance. The TMI-2 Core Shipping Technical Working Team that represented all the involved organizations met monthly. [(299)] The NRC certified this cask only after complete review of the application for certification. This review included the safety analysis report for the cask; data from drop tests using a 1/4-scale cask model; data from drop tests of full-sized fuel and knockout

Left: Model 125-B rail shipping cask under fabrication showing internal structure without inner containment shell. Right: Outer containment shell. (481.14)

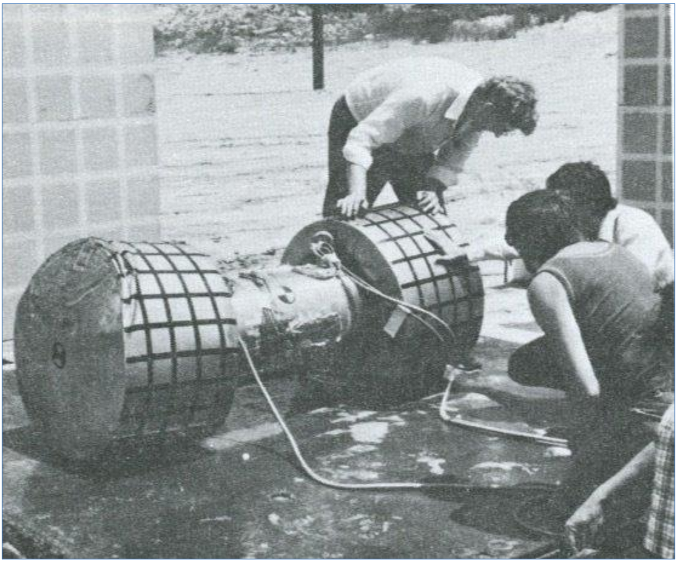
canisters; and resolution of many design-related and test-related questions from the NRC. Before the application was submitted to the NRC for review and approval, it was subjected to one of the most intense reviews in the history of transporting radioactive materials at that time. Reviewers included personnel from DOE national laboratories, the licensee, and several subcontractors. The scrutiny and analysis expended on the application by the NRC were as thorough as the agency has given to any application for any rail, or truck, spent fuel cask. [300]

- ***Cask Tests Beyond Requirements***. Computer modeling and analysis of certain structural design features of the TMI-2 cask system would have been adequate without drop tests. However, the DOE conducted drop tests of a 1/4-scale model of the cask and a full-scale model of the knockout canister to verify performance during simulated accidents. Although component fabrication was expensive and

Knockout canister inside a simulated shipping cask following a drop test. (481.14)

the testing costly, some estimates suggested that as much as a year was saved in acquiring certification. The drop test data and photographs were also helpful in reassuring the public that the TMI-2 transport system was safe. Conducting tests beyond the strict requirements of the regulating agency proved beneficial in licensing the equipment. (301)

- ***Integrated Cask and Equipment Tests***. The DOE procured two new rail shipping casks, railcars, and some of the cask support equipment. The licensee procured cask loading and facility interface equipment. The integrated test of the cask loading equipment at the Hanford Engineering Development Laboratory was very successful in identifying interface problems and training operators. Insights from these tests included the following: (●) The integrated test was conducted at Hanford away from TMI-2, which allowed small anomalies in installation and checkout of the equipment to be corrected more easily and at less cost than 3,000 miles away at TMI-2. (●) Several necessary mechanical and electrical modifications and equipment improvements were uncovered by the integrated test. Changes were engineered and implemented within hours and days rather than days or weeks, which would have been needed had the equipment been set up at TMI-2 initially. (●) The test enabled many TMI-2 operators to gain first-hand knowledge of the equipment's design and operation, including an understanding of the functional requirements, by direct discussions with shipping cask design engineers. This transfer of information was very valuable to the straightforward installation and use of the equipment at TMI-2. (●) The integrated test lasted a month, including initial system assembly, testing, disassembly, and packing for the shipment to TMI-2. The cost effectiveness of the integrated test was proven by the fact that equipment went from receipt at TMI-2 to NRC approval for use in less



Model 125-B rail shipping cask 1/4-scale model following a drop test. (481.14)

than 2 months. (302, 303, 304)

- ***Number of Shipping Casks***. In addition to the two shipping casks purchased by the DOE, the vendor built a third cask and leased it to the licensee to expedite the shipments to INEL. However, delays encountered during defueling operations slowed the rate at which canisters were loaded. The casks were often on site awaiting the generation of enough canisters for a shipment. (305)

- ***Cask Lid Seal***. The only cask-related delay in shipment occurred in 1988, when concerns over the O-ring material in the cask resulted in the material being changed to a different grade of elastomer. (306) The vendor identified a design test problem with the two O-rings used to seal the fuel shipment casks. The problem was that a design leak test of the cask with the existing O-ring material was not conducted at design cold temperatures (-40 degrees Fahrenheit). Design testing showed a potential for excess leakage using the existing Neoprene material at cold temperatures. (307, 308)

- ***Cask Improvements***. As a result of the comprehensive inspection and preventive maintenance program initiated on the Model 125-B casks and railcars, numerous improvements were made to the operations, thus reducing the maintenance efforts. Table 4 identifies items that required more maintenance on the casks and railcars than anticipated and the corrective actions that were taken to remedy the situations. (309)

- ***Single Transportation Incident***. The only rail shipment incident occurred in 1987, when the train traveling at slow speed struck a car. The driver of the automobile sustained minor injuries and received a traffic citation from local authorities. The train's engine received minor damage, but the shipping casks were not damaged. The carrier (Union Pacific Railroad) inspected the train's engine and determined that it could remain in service. (310)

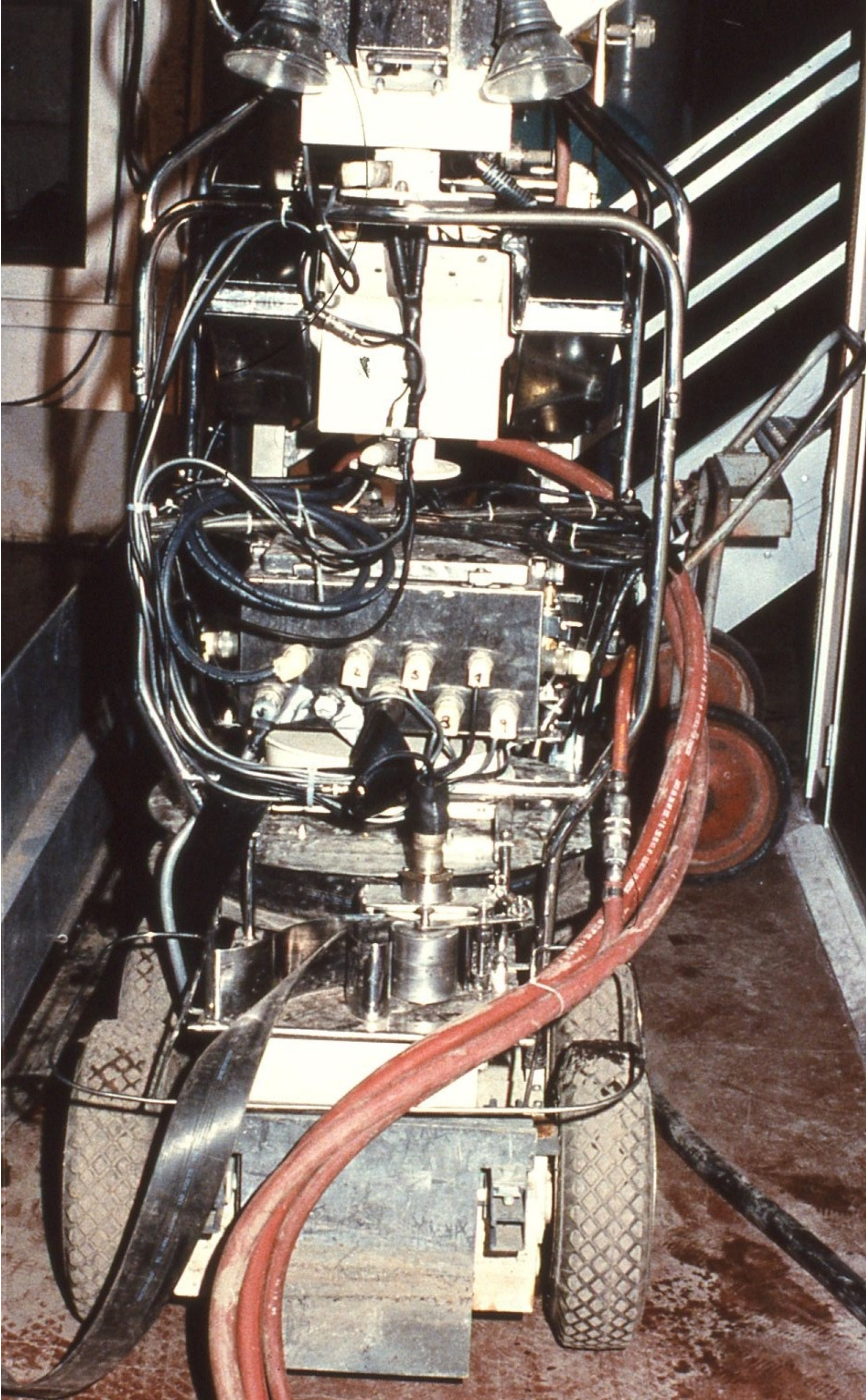
Rail shipment of three Model 125 B shipping casks containing defueling canisters. (481.14)

Table 4. Items of 125-B rail cask system requiring more maintenance than anticipated. [311]

Item	Initial situation	Improvement
Cask		
Internal impact limiters	Thin stainless-steel sheet around honeycomb energy absorption media failed at the adhesive joint and resulted in constant cleanup and repair.	Replaced the thin sheet with thicker sheet and welded the sheet in place.
Internal impact limiters	Removing water from the cavity of the cask's inner containment vessel required removal of the lower impact limiter.	A small-diameter tube was installed through the center of the lower impact limiter, allowing removal of water by pumping.
Lanyards on pins attached to the skid	Vinyl coating broke at crimp tie, allowing tie and coating to slide over cable, causing lanyard loop to open.	Replaced with uncoated stainless-steel cables.
Overpacks	Difficult to install bolts because they were heavy, long, and hard to maneuver into blind holes.	Added tapered lead-in collars around each bolt hole inside overpacks.
Railcar [(a)]		
Excessive brake shoe replacement	Pads on shoes cracked before wearing out. Brake shoes were faulty.	Ordered new brake shoes from another manufacturer. Improved controls for releasing brakes.
Span bolster center bowl wear ring cracking	Wear ring and attachment weld cracked.	Repairing and building up welds. Forged ring with machined press fit into center bowls was an alternative.
Tilt of railcar bed	Lube disks were too hard and failed to compress. Motion from railcar movement caused disk to tear at center pinhole and ball up, causing bed to tilt.	Replaced by lube material melted into bowl.
Wheels	Grade U wheels had excessive tread wear.	Replaced with harder Grade C wheels.

a. Due to space limitations in the fuel handling building, the 125-B rail casks were not centrally located on the rail car; they were placed closer to one end of the car. This could have contributed to the increased maintenance of the rail car. [312]

Figure on Next Page: Rover or remote reconnaissance vehicle (RRV) was used in the containment building's basement to perform video and radiation surveys, collect sludge samples from the floor, collect core samples from the wall surface, flush walls with high-pressure water, remove the surface of the walls using an ultrahigh-pressure scarification system, and remove sludge.



6 DECONTAMINATION AND DOSE REDUCTION

The loss-of-coolant accident exposed about 7,200 square meters of concrete surfaces within the containment building to liquid- and vapor-phase contaminants. Most of those surfaces were protected by coatings of epoxy-based, nuclear-grade paints. Cesium and strontium were transported to containment building surfaces in water droplets, and most of their measured surface activities were deposited after the nuclides had reached chemical equilibrium in the water in the basement. About 2.4 million liters of reactor coolant were deposited in the containment building basement during the accident. The water level eventually reached a depth of 2.56 meters, and quantities of radionuclides were absorbed into the concrete walls of the basement. The principal radionuclides in the basement were 310,000 curies of cesium-137 and 11,000 curies of strontium-90. [(313)]

The understanding of decontamination techniques and methods has improved significantly since the TMI-2 accident. Nevertheless, the TMI-2 cleanup provided a unique experience in the context of a severe accident.

The following experiences from decontamination and dose reduction activities include topics covering management planning; dose reduction; decontamination; radioactivity penetration in concrete and paint; and recontamination problems.

6.1 Management and Planning

The cleanup strategy was to first decontaminate as much as possible, referred to as "gross" decontamination. Presumably, the thought process was that first reducing dose rates throughout would lead to conducting work more easily later. With this strategy, decontamination became the major priority during the initial stage of the cleanup. After poor results from the gross contamination experiment inside the containment building, the priority was changed to decontamination on a case-by-case basis to support priority tasks for moving forward with defueling activities.

- ***Gross Decontamination Experiment***. The DOE funded the gross decontamination experiment in 1982 as part of its research and development charter to provide the industry with access to decontamination engineering and operational experience. In addition, the experiment documented effectiveness; criteria; techniques; and radiation monitoring activities. Key conclusions included the following: (●) Results were often inconclusive because not all the data for pre- and post-activity characterization were collected; some collected data were insufficient or not timely enough to accurately record the effects. (●) Radiation from other sources often masked the contamination reductions achieved during decontamination. (●) Knowledge about decontamination effectiveness had to be extrapolated or estimated with less precision than desirable. (●) Tested techniques were effective to varying degrees in removing surface contamination. (●) Some areas were recontaminated because of technique or procedure (see Section 6.5 of this document). (●) Organizational inefficiencies were revealed, including a complex review and approval process, as well as redundancy, duplication, and overlapping responsibilities in site procedures. (●) Knowledge about large-scale operations in the containment building was obtained, such as the movement of large numbers of workers in and out of the containment building, radioactive waste disposal, and communications and procedures for conducting in-containment work. (●) Decontamination training required rigorous standards. [314, 315, 316]

- ***Decontamination Sequence***. The proposed decontamination sequence, as described in the gross decontamination experiment report, included: (1) remove all the storage, trash, and waste; (2) decontaminate vertical and overhead surfaces, especially those surfaces that had not been decontaminated previously; (3) decontaminate floor surfaces; and (4) locate hot spots and shield, clean, or remove the source. [317]

- ***Plans and Priorities***. Following the completion of the gross decontamination experiment in the containment building (October 1981 to March 1982), the licensee proposed several decontamination and dose reduction plans to the NRC for approval. The key plans included the following:

    - *Reduce Respiratory Protection*. The decontamination efforts in September 1982 were directed toward the relaxation of respiratory protection and protective clothing requirements in the containment building, as appropriate. The objective was to increase worker efficiency by economizing person-rem resources, minimizing heat stress, and reducing waste volumes. In addition, expectations were that some reduction in area dose rates would be realized to the extent that superficial contaminants contributed to general area dose rates. The planned decontamination efforts included all levels of the containment building except the basement level. [318]

    - *Dose Reduction Task Force*. In early 1983, the recovery team realized that the effectiveness of dose reduction by means of gross decontamination techniques proved disappointing. The licensee formed the Dose Reduction Task Force to perform extensive radiological characterization to (●) identify the radiation sources that produced general area dose rates and (●) recommend actions to reduce dose rates from those sources in areas of intensive worker activities. [319]

    - *Strategic Decontamination and Dose Reduction*. [320, 321, 322] In mid-1984, the licensee's program for cleanup of the TMI-2 containment building, as presented in its TMI-2 Program Strategy plan [323] and the first supplement to NUREG-0683, the NRC's PEIS, changed the priority from a focus on gross decontamination in the containment building to strategic decontamination and dose reduction. The strategic objectives were twofold: (●) reduce the dose to workers in transit to and from their workstations on the 347-foot elevation (operating level) and defueling work platform and (●) reduce or eliminate the need for respiratory protection for routine reactor building entries. This new focus resulted in the greatest reduction in personnel exposures during defueling preparations and operations. The revised cleanup program entailed the same milestones as the initial schedule, but the sequence of tasks was altered as follows: (1) dose reduction to continue during reactor disassembly; (2) reactor disassembly and defueling; (3) defueling; (4) primary system decontamination; and (5) cleanup of the containment building, including equipment, and auxiliary building to proceed as resources allowed.

Reducing general area dose rates was achieved by installing shielding for specific sources of radiation including the enclosed stairwell and the floor hatch on the 305-foot elevation (entry level), and the aircoolers, floor drains, the open stairwell, and the seal table on the 347-foot elevation. Removal of fixed contamination on floors also contributed to reducing general area dose rates.

Initial efforts at dose reduction proved successful. The goals were achieved and, in some cases exceeded, at reducing: (●) the transit dose for personnel from air lock to work areas on the 347-foot elevation and returning to air lock from 0.4 to 0.18 millisievert (0.04 to 0.018 rem) and (●) the general area radiation levels on the 305-foot elevation from 3.5 to 2 millisievert/hour.

By attaining these early goals, the collective radiation does to workers was significantly reduced in the labor-intensive construction efforts in preparing for reactor vessel head lift and defueling. Later improvements in airborne contamination by decontamination of air-cooling units permitted manned access without respirators, allowing more effective use of limited personnel. Dose reduction efforts continued throughout the defueling period.

- *Support Reactor Disassembly and Defueling*. The TMI-2 Program Strategy plan [(324)] recognized that some decontamination activities would be required in the containment building during reactor disassembly and defueling to maintain surface and airborne radioactivity at acceptable levels. Additionally, the strategy recognized that some decontamination activities in the auxiliary building would be necessary to permit access for required safety surveillance operations and maintenance. Beyond these, incidental decontamination activities, such as small-scale demonstrations to support post-defueling activities, were to be conducted on a low-priority, noninterference basis. [(325)]

- *Support Long-Term Storage*. [(326)] The decontamination task force report [(327)], issued in December 1985, was prepared by a joint group of TMI-2 organization representatives to review the effort required to decontaminate TMI-2 and to evaluate the reduction in occupational exposure during post-defueling monitored storage. The report was prepared by a task force formed in 1985 to evaluate the problems and activities associated with achieving the final radiological completion criteria by mid-1985. The objective of the task force was to arrive at a consensus in the technical approach to each of the major areas of decontamination work in the containment. The major areas evaluated by the task force included: (●) remote equipment development; (●) sludge transfer and disposal; (●) steam generator D-ring shielding dose reduction and decontamination; (●) containment building basement recovery; (●) auxiliary and fuel handling building surface decontamination; (●) non-reactor coolant system decontamination; (●) containment building heating, ventilation, and air conditioning system modifications; (●) containment building Phase III (final) surface decontamination; (●) reactor coolant system decontamination; and (●) containment building Phase III decontamination waste management. The task force based its evaluations, technical approaches, and schedules on available technical plans.

The task force concluded that deferring decontamination for a period of 30 years would result in a potential occupational exposure savings in the range of 4,500 to 9,800 person-rem. This savings was based, in part, on reduction in radiation dose rates due to the natural decay of radioactive materials and to advances in both remote cleanup technology and chemical decontamination methods.

- ***Experienced Workers, Simple Tools***. Decontamination was labor intensive and required a range of skills. A mixture of skills and hands-on supervision by the licensee contributed to an effective range of capabilities. Simple, traditional tools used by an experienced work force contributed to the effectiveness of the decontamination work. The workforce provided feedback based on experience to improve existing tools, including the potential use of more sophisticated techniques when traditional tools were not effective in unique situations. Often, an improvement was a traditional tool mounted on a sophisticated delivery system. Feedback was important for every aspect of the recovery effort. [328, 329]

- ***Flexible Plans***. Planning the general approach was important; however, the plan needed to be flexible. Problems were approached in manageable segments. The specific task planning horizon at TMI-2 was 1 to 2 weeks, with changes occurring almost daily, based on the previous day's progress and events and new information. Too much planning for hypothetical situations consumed already limited resources. Accurate, timely data about conditions were vital for realistic planning. Analysis needed to be based on experience and hard data, not estimates; therefore, it was often necessary to start work and learn. [330]

- ***Plant Knowledge***. Knowledgeable personnel and accurate, as-built plant drawings were required for planning, efficient operations, and the effective use of resources. Knowledge of the TMI-2 plant was important to examine all interrelated aspects of decontamination operations, such as systems, cubicles, logistics of movement to avoid recontamination, and control of ventilation flowpaths to prevent recontamination. [331]

- ***Research vs. Operations***. Research and development needs often conflicted with decontamination activities due to time and resource constraints. On occasion, adequate baseline data were not obtained before completing a decontamination activity. Consequently, research and development could only produce marginally useful data to measure the effectiveness of a decontamination project. [332]

- ***Support Facilities***. New support facilities were required early in the decontamination program. Important facilities at TMI-2 included: (●) a changeout facility, called the coordinated personal access facility, for reducing skin contaminations while undressing as well as reducing time spent in entering and exiting radiation areas; (●) an onsite laundry and respirator cleaning facility; (●) small tool decontamination facility for reducing the number of tools needed, which decreased expenses, waste volume, and storage inside the containment building; and (●) the remote coordination center (located in the turbine building) for directing decontamination and defueling activities inside the containment building. [333, 334]

- ***Training and Staffing***. The gross decontamination experiment report [335] concluded that training must be completed to rigorous standards. Some training deficiencies occurred due to equipment shortages for training and poor instruction. During a few of the later entries, training occurred just before the scheduled entry. This resulted in no time for a review of training effectiveness. This schedule left the discovery of deficiencies to the task supervisor during the actual entry. An insufficient number of backup personnel were trained; as a result, considerable scheduling flexibility was lost. The number of crew changes for sickness, absenteeism, accidents, and other incidents for each entry was underestimated. One backup for every four crew members (laborers and crafts) performing decontamination work was shown to be optimal. [336]

The remote coordination center located in the TMI-2 turbine building contained the control functions for entry into the containment building with positions for safety; radiological engineering; operations; entry coordinator; and command center management. (481.15)

- ***Technique Selection***. The selection of decontamination techniques was based on the following attributes: (●) effectiveness; (●) resources; (●) time; (●) material compatibility with cleanup systems; (●) radioactive waste forms and constituents generated and associated disposability and disposal costs; and (●) personnel radiation exposure. [337, 338]

- ***Importance of Frequent Surveys***. Frequent surveys of the decontaminated areas were essential to tracking the progress made to reduce contamination and to identify recontamination sources. Though difficult, monitoring of surface contamination levels during the decontamination efforts by surveying surfaces during brief interruptions of the operation improved the effectiveness of decontamination. [339]

- ***Sample Analyses vs. Contact Surveys***. Cores from concrete surfaces at the containment building upper levels were extracted to determine the activity concentration on those surfaces. Results suggested that measurements of the contact beta and gamma exposure rates of a surface could be used instead of collecting samples from the surface. Because of the requirement that the survey instruments used for this purpose be highly collimated, the use of beta exposure rates was likely to be a more reliable method than one that used gamma exposure rates. [340]

- ***Radiological Survey Data***. [341, 342] Rigorous evaluation of the effectiveness of decontamination techniques required radiological survey data and a large database for source term characterization. Constraints on data acquisition included the following:

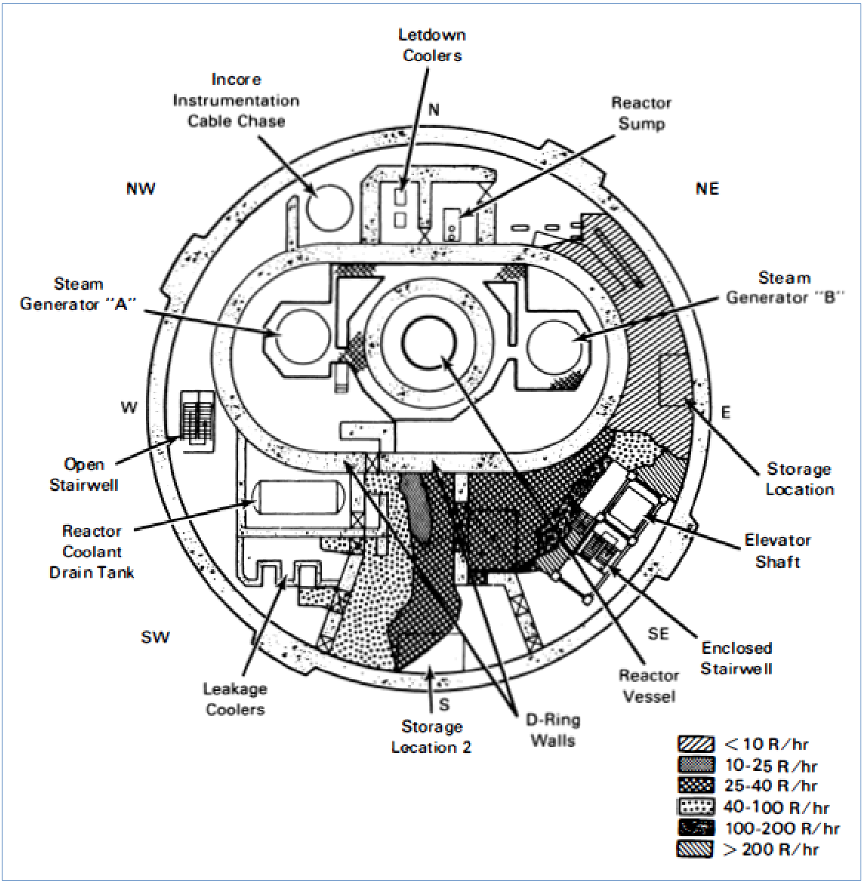
  - Factors that influenced the collection of radiological survey data included: (●) self-shielding effects of the survey technicians with different physical stature; (●) instrument variations causing different readings; (●) ongoing operations causing dynamic radiation fields in a specific area; (●) surveys not organized to systematically and precisely define the radiation field; (●) inconsistency of the surveyors; (●) and other varying factors with individual instruments creating uncertainties.

  - Problems in establishing a rigorous database included: (●) heterogeneity of containment building surfaces and coatings; (●) irregular geometry of equipment surfaces; (●) heterogeneity of the contamination pathway and resulting deposition patterns; (●) environment of multiple sources; (●) changing patterns of resuspension and deposition; and (●) high relative humidity.

  - The costs in resources and person-rem to collect and analyze samples and to interpret the data added constraints on the ability to statistically compare decontamination techniques.

- ***Radiological Survey Using Thermoluminescent Dosimeters.*** To resolve the problems associated with radiological survey data collection, strings of thermoluminescent dosimeters (TLDs) were used to characterize radiation profiles inside the containment building. The advantages included precise spacing and orientation of data collection points, reproducible measurements, and ability to use TLDs in high-radiation areas and through small openings (e.g., the containment building basement). The subsequent source term modeling of the containment building proved generally accurate and permitted later dose reduction efforts to be effective. [343]

- ***Communications***. Operational problems with radios (e.g., too few radios, inoperative equipment, poor transmission quality) caused a significant increase in the number of person-hours spent in the containment building and decreased the effectiveness of the decontamination tasks and data acquisition. [344]



Locations of thermoluminescent dosimeter (TLD) exposure rate readings at the 282-foot elevation (basement level) inside the containment building. Dosimeter data were obtained by lowering TLD strings at various points to define principal radiation sources such as the bathtub ring and the elevator shaft.

- ***Onsite Radiochemical Laboratory***. (345, 346, 347) The inability of the onsite laboratory facilities to accommodate high-activity samples proved to be a hindrance to efficient operation in terms of turnaround time and ALARA considerations. The DOE placed two mobile laboratories on site to reduce the time and capital expenditures required to analyze samples at TMI-2. The combined capabilities of the two laboratories greatly enhanced onsite analytical capabilities to analyze samples of fission products, fuel, transuranic, and elemental core debris:

  - *Radiochemistry Laboratory*. This laboratory, located in the TMI-2 fuel handling building, received and handled solid and liquid samples with activities up to 5 roentgen per hour. This laboratory, which had a sample hood, glove box, and analytical chemistry facilities, performed radiochemical separations and preparation of alpha, beta, gamma, and x-ray emitting radionuclides for quantification by instrumental analysis. In addition, the laboratory performed traditional wet chemical elemental analysis.

  - *Counting Laboratory*. This laboratory, located in the Unit 2 turbine building, received alpha, beta, gamma, x-ray, and elemental samples produced by the chemical separations in the radiochemistry laboratory. The counting laboratory handled very small quantities of material with activities of less than 1 milliroentgen per hour. The samples were analyzed instrumentally by spectroscopic techniques to produce quantitative analysis data.

Pre-accident construction-related equipment and materials stored inside the auxiliary building (top) containment building (bottom) became sources of radiation hot spots that complicated decontamination.

6.2 Dose Reduction

- ***Dose Reduction Program***. The effectiveness of dose reduction techniques in the containment building during the first 2 years of decontamination activities was reported to be disappointing. Dose reduction in the containment building proved to be a much more formidable task than in the auxiliary building. Source identification and characterization were difficult. The relatively congested physical arrangement of machinery, components, pipes, cable trays, and structural surfaces, all with potentially unique distributions of fission products, made the task of quantifying the discrete contributors to the overall high ambient radiation levels a complex puzzle. Gamma dose rates in the containment building remained at elevated levels despite substantial progress in gross decontamination and processing of contaminated water from the basement. Recognizing that the decontamination efforts would likely not result in significant reductions in general area radiation levels in the building, the licensee launched a dose reduction program at the end of 1982. [348, 349]

- ***Dose Reduction vs. Decontamination***. The dose reduction program emphasized dose reduction rather than decontamination in the containment building. The program identified radiological sources that were classified as principal or discrete; modeled the source and estimated its contribution to the general area exposure rates; and recommended actions to achieve dose reductions consistent with general exposure rate goals. *Principal* sources were physically large and had a major general area dose effect, such as the containment building basement, the enclosed stairwell, and the air coolers. *Discrete* sources were movable or had localized effects, such as floor drains, abandoned equipment, and trash. A list of source terms arranged in order of their contribution to the ambient radiation levels was essential in developing an efficient dose reduction strategy. [350]

- ***Radiation Sources***. [351] The dose reduction study classified radiological sources in the containment building as *principal* sources and *discrete* sources. The study also listed the major contributions of these sources. Sources and contributors are discussed below:

  - *Principal Sources*. Major principal contributors to gamma exposure in the containment building included the following: (•) The outer containment building walls in the basement consisted of a ring of contaminants, [i] located 8 feet from the floor. The ring on the poured concrete walls was caused by absorption into a 30-inch band of uncoated concrete 5.5 feet above the floor. Walls that were unpainted showed a marked increase in source strength over

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[i] The ring was residue as water from the basement was processed and resulted in lowering the level in the containment basement. This ring was the major contributor to dose rates within the upper containment. This was one reason for having the defueling platform inside the defueling water canal (without water) where the walls of the canal provided shielding for defueling workers.

painted surfaces. (●) The basement floor area consisted of sludge and water, both of which were assumed to be uniformly distributed over the floor. This slab source resulted in radiation fields that were as high as 1,000 roentgen per hour and made this area inaccessible to workers. (●) Reactor coolant system water was continually dissolving cesium. The reactor coolant system required periodic processing to remove radionuclides leaching from the fuel at a slow rate of 0.5 curie per day. (●) Areas of surface contamination included the containment building dome; polar crane; upper level (refueling deck) floor and walls; and the entry level floor, overhead, and walls.

- o *Discrete Sources*. Major discrete contributors to gamma exposure in the containment building included the following: (●) About 30 floor drains contained fixed contamination and presented high local area gamma exposure rates. (●) Trash consisted of materials that were in the containment building at the time of the accident. Trash was usually low-level waste; however, it masked gamma surveys and could mask other sources. (●) loss-of-coolant-accident ducts (both run up the wall of the containment building) were sources of exposure to personnel climbing up to the polar crane. (●) A resin column used to test the submerged demineralizer system ion exchange mixture had a contact dose rate of 12 roentgen (R) per hour. (●) Two welding machines that were in the containment building at the time of the accident had contact does rates of 2 R per hour. (●) Both discharge lines from the core flood tanks had dose rates of 2 R per hour at elbows and joints. (●) The in-core instrument service area (seal table) on the defueling deck had boron accumulation resulting in dose rates of 10 R per hour. (●) Polar crane components were not decontaminated due to their sensitivity to decontamination agents or techniques and so had high contact dose rates.

- ***Dose Reduction Techniques***. The decontamination and dose reduction efforts focused on tasks to minimize cumulative worker exposures through the end of the cleanup. Areas most frequently accessed by many workers were given the highest priority. Dose reduction solutions included: (●) keeping inner and outer personnel airlock doors open (with NRC approval) to reduce time to stage equipment and materials; (●) changing entry and transit routes to new ones through lower dose fields; (●) restaging the tool storage cabinet to a lower dose area; (●) removing trash and welding machines; (●) eluting and removing the submerged demineralizer system resin test column; (●) flushing areas and equipment, such as air coolers, loss-of-coolant-accident (LOCA) ducts, the seal table, D-ring interiors and equipment surfaces, the enclosed stairwell, and the elevator shaft; (●) decontaminating the seal table, reactor vessel head service structure, and walls of the refueling canal; (●) applying shielding, as necessary, to air coolers, the seal table, core flood tank discharge lines, hatch covers, LOCA ducts, the head service structure, the open stairwell, polar crane components, and cable trays; and (●) conducting extensive scabbling operations on concrete surfaces. [352, 353]

- ***Use of Video Technology***. The TMI-2 cleanup effort pioneered the use of video camera technology for surveillance and inspection in nuclear power plants.

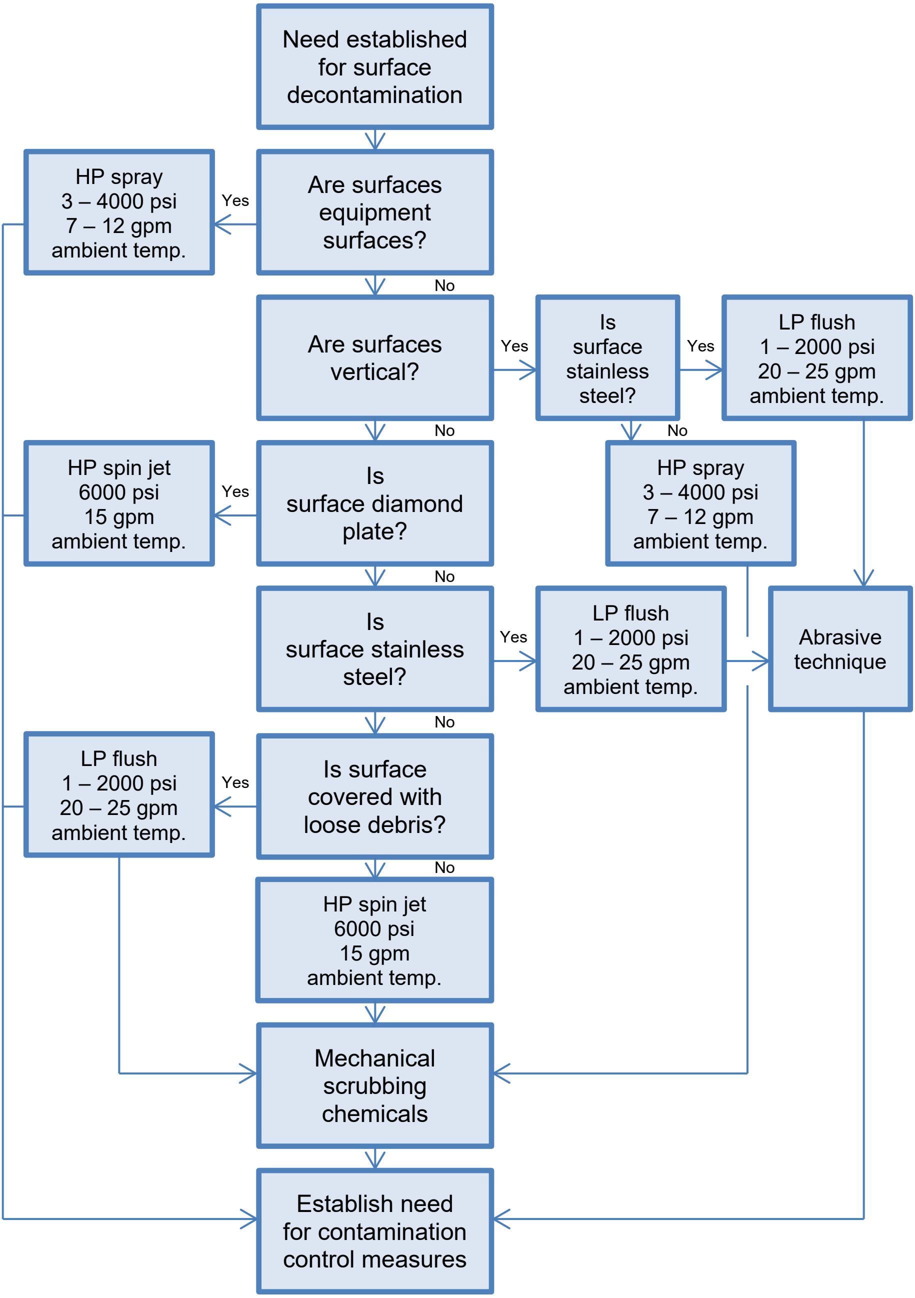
The remote coordination center, located in the TMI-2 turbine building, used many cameras to survey 75 percent of the containment building with remote pan, tilt, and zoom capabilities. The cameras proved extremely valuable to task management and personnel safety by allowing supervisory work guidance without the supervisor being in the area. This resulted in significant personnel dose savings in the early years when radiation levels were considerably higher before decontamination and dose reduction planning took effect. (354)

- ***Use of Computer-Aided Design Models***. An effort was undertaken to create a three-dimensional (3-D) computer-aided design model of in-containment systems and structures from the design drawings. This was the early days for such modeling. The value was that viewing the 3-D displays served to better understand the positions of structures, systems, and components within the containment building. For example, the 3-D model showed the existence in the containment building basement of two previously unknown small lubricating oil tanks for the main coolant pumps.

- ***Equipment and Materials Control***. The amount of materials and equipment brought into contaminated areas was controlled to prevent interference with work and unnecessary contamination. Every effort should be made to use the shielding already available in the containment building. Although shielding lowered the initial person-rem-per-dollar cost, the overall cost increased when workers eventually returned to clean up a shielded area. (355, 356)

- ***Piping Access***. The limited number of piping system access points, such as high-point vent or low-point drain valves, resulted in additional time spent in radiation areas to remove the valve internals or "rig" an opening in a pipe. (357)

Lead shielding around the enclosed stairwell at the 305-foot elevation (entry level) inside the containment building.



(Abbreviations: gallons per minute---gpm; high pressure---HP; low pressure---LP; pounds per inch---psi; temperature---temp)

Decontamination logic diagram based on results of the gross decontamination experiment in March 1982. (481.15)

6.3 Decontamination Methods and Agents

The decontamination logic diagram summarizes the conclusions on decontamination effectiveness and efficiency from the gross decontamination experiment. Table 5 is the TMI-2 decontamination method reference table. Other experiences are summarized below.

- ***Water Flushing Techniques***. High-pressure flushing was generally as effective as both low- and high-pressure flushing used in sequence. However, if the surface debris was loose, the low-pressure flush was used first because it was more controllable and less likely to disperse particulates. Experience from the gross decontamination experiment revealed the following insights: (●) Hydrolance operations were limited to 3,000 pounds per square inch (psi) during the gross decontamination experiment because of the inability of workers to maintain their footing while spraying. However, large workmen (in the 250- to 270-pound range) could satisfactorily spray with 6,000 to 7,000 psi. (●) High flow rates with high pressures caused problems on horizontal surfaces because of the inability of operators to properly direct the water to a drain and the attendant mist that recontaminated cleaned surfaces. (●) The lances, as shipped from the supplier, were deemed too short by the site safety office because of the potential for the lance operators to shoot their foot during high-pressure flushing. The short-tip lances were replaced with longer tip lances. (●) High-pressure spray activity with the lance and water floor scrubber caused contamination of other surfaces. Thus, the experiment report concluded that procedures should provide for an adequate flush after high-pressure activity and that the pressures should be sufficiently constrained to reduce contamination overspray and debris splatter. [358, 359, 360]

- ***No Water Temperature Effect***. Surface decontamination effectiveness was not significantly altered by the flushing water temperature, despite other studies

Decontamination using a high-pressure hydrolance.

indicating hot water to be superior. [361, 362]

- ***Scabbling.*** Scabbling was an aggressive decontamination technique that roughened concrete surfaces and removed surface coatings with toothed pistons or a rotating drum. Testing conducted in 1984 evaluated the effectiveness of removing the surface coating from areas on the upper 347-foot elevation (operating level) in the containment building using a scabbler machine. The scabbling operation was performed in two passes, each pass removing approximately 1/16-inch from the surface. Radiation measurements showed approximate dose rate reductions of 50–60 percent gamma and 80–98 percent beta. The resultant surface was suitable for application of epoxy, polymer, or similar finishes. The scabbler was modified to include a vacuum shroud connected to a high-efficiency particulate air-filtered vacuum system for collecting contaminated dust. Approximately 930 cubic meters of the containment floor coatings were removed, and the cleaned floors were recoated. [363]

- ***Remote Scabbler***. A remotely operated scabbler was designed for use at TMI-2, although it was developed too late to be used. The device was successfully tested in other decontamination applications. The scabbler could be operated from 50 feet away. It could cut a path 18 inches wide and could decontaminate concrete surfaces at a rate of 400 square feet per hour, about three times faster than manual scabbling. A self-contained vacuum system equipped with a high-efficiency particulate air filter eliminated dusting. [364, 365]

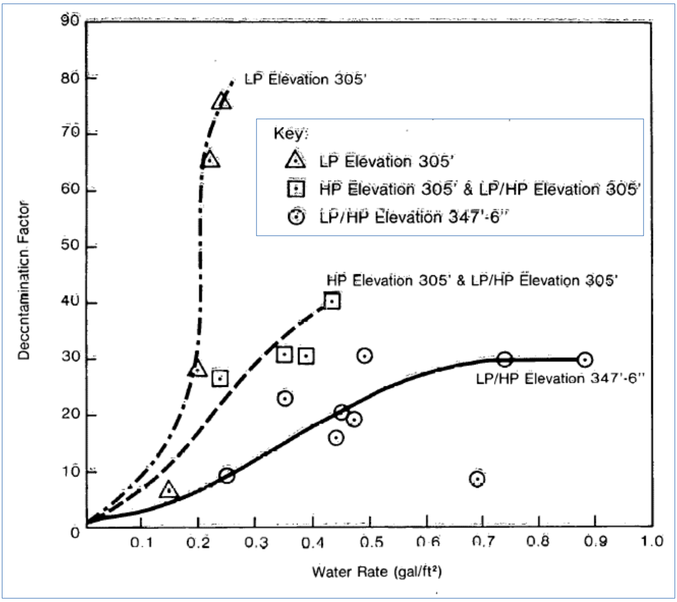
- ***Vacuum System***. A high-efficiency vacuum collection system was designed to attach to a variety of devices, including manual scabblers. The system removed residual loose debris on the cleaned surface. Operators did not contact the contaminated material because the design of the system permitted the exchange of full waste drums with empty ones while the vacuum system was operating. [366]

Underside of a typical hand-pushed scabbler machine with vacuum used to roughen concrete surfaces and remove contamination in the surface coatings or embedded deep into the concrete surface.

- ***Steam/Vacuum System Performance***. A modified commercial steam/vacuum system was effective in decontaminating overhead areas and cable trays, which contained too many complex surfaces to clean effectively using flushes or hand wiping. The steam supply and vacuum removal system was an integrated unit that collected water and contaminants simultaneously. This type of system required fewer operators than separate water flush and vacuum systems and reduced the potential for the spread of contamination. Recontamination was reduced by collecting water and filtering it to remove radionuclides before it was reused. The powerful vacuum capability of the combined unit allowed the decontamination tool to be located as far as 175 feet from the steam supply and collection systems. Thus, only the decontamination tool and hoses were in the contamination zone. One problem encountered with this system was blockage by sheet materials that were drawn into the vacuum inlet. [367, 368, 369]

- ***Chemical Additives for Decontamination***. [370, 371, 372, 373] Chemical decontamination agents, such as phosphoric acid foam, sulfamic acid gel, and citric acid complexes, were evaluated at TMI-2 to improve the performance of decontamination systems. Small-scale use of specific chemicals was subject to evaluation, and chemicals were controlled, used, and disposed of in accordance with appropriate procedures and applicable Federal, State, and local regulations.

  - *Advantage*. The biggest advantage of the use of chemical treatments was that they could be used in those areas where flushing or abrasive techniques could not be used, such as external surfaces of pipes and tanks and system internals.



Plot of decontamination factor (based on contact measurements) verses water rate. (481.15)

- *Disadvantages*. The disadvantages of chemical treatments included the following: (●) Techniques and reagents needed to be compatible with reactor coolant system component materials to avoid excessive degradation of such components. (●) A relatively large volume of chemical had to be applied to an expansive surface area or intricate piping system to provide coverage at the optimum concentration. (●) Chemical waste had to be treated and processed for disposal in a manner that followed regulations.

• ***Recontamination Protection***. The strippable coating that was used after initial decontamination by water spraying adsorbed residual loose debris. The coating also protected against recontamination of the underlying surface. [374, 375]

• ***Strippable Coatings***. [376, 377, 378] The strippable coating was a synthetic polymer compound that was used to remove oxides and radioactive contamination from oxidized ferrous and nonferrous surfaces and from nonporous surfaces. Experiences from the use of strippable coatings included the following:

- *Coating Application*. The coating was applied by an airless spray gun, allowed to dry, and then removed manually by cutting, peeling, and rolling the material up to contain the contamination. A 55-gallon waste disposal drum accommodated the refuse from 2,000 to 2,500 square feet of coated surface. Successful application and removal of strippable coatings were dependent on operator experience. Thus, dedicating a trained group of workers would be cost effective.

- *Coating Removal*. Workers at TMI-2 had some difficulty in removing coatings from highly porous surfaces. A cheesecloth base was tested to determine the tensile strength and body of the coating to make removal easier. The base did make the coating come off more completely, but it was unnecessary for most applications. The self-stripping coating could not be removed easily; too much effort was spent removing the coating manually. However, self-stripping coatings were useful in high radiation areas because the coating could be applied and removed by remote vehicles.

- *Coating Effectiveness*. The copolymer coating produced decontamination factors of up to 245. Based on experimental data on carbon steel, the surface condition after using the copolymer coating for oxide removal was comparable to that achieved by commercial blast cleaning. The rate of application was comparable to that of high-pressure flushing with vacuuming to pick up water. The application and removal times for the strippable coating were also comparable to the high-pressure flush with vacuuming. Low-pressure flushing plus strippable coating produced substantial reductions and decontamination factors in area readings, contact readings, and smearable contamination results.

- *Recontamination Protection*. The strippable coating that was used after initial decontamination by water spraying adsorbed residual loose debris. The coating also protected against recontamination of the underlying surface.

- ***Vertical vs. Horizontal Surfaces***. The decontamination of vertical surfaces proceeded somewhat differently from that of horizontal surfaces. Vertical surfaces generally did not have debris embedded in their surfaces as floors did. Beyond that, decontamination factors observed on vertical surfaces were also higher than those observed on some horizontal surfaces. Experience showed that water volume per unit area required for run off was considerably less than that for horizontal surfaces. Additionally, as a vertical surface was flushed from top to bottom, the buildup of water flowing down the surface increased the volume per surface area and was effective in the elution of solubles and the transport of particulates. Such elution and transport were not so readily achieved on horizontal surfaces. [379]

- ***Use of Containment Building Spray***. The use of the containment emergency spray system to spray down large volumes of water, detergents, chemicals, or steam on the structures, systems, and components inside the containment building was not pursued. This approach was not necessary, mainly because lower than predicted radiation fields were found in the containment building as the result of 2 years of dripping condensation (rain) caused by high humidity. The effectiveness was uncertain, and the spray would have generated a large volume of waste (1,500 gallons per minute pump flow rate). In addition, the spray down could cause damage to important equipment and instrumentation. [380]

- ***Use of Remote Control Equipment (Robotics)***. An important experience in the decontamination area was the use of robotics. Starting with simple commercial devices and borrowed DOE robots, TMI-2 developed unique robots designed for specialized accident recovery tasks. These tasks included radiation measurements; video camera inspections; data acquisition; sediment sample acquisition;

Strippable coating used to decontaminate floor surfaces. (481.15)

high-pressure water flushing; acquisition of concrete core samples; concrete scabbling and scarification; sludge vacuuming; and debris pickup and removal. Remote-controlled robotic vehicles and supporting control equipment were used extensively to perform work in extremely high radiation areas, including the containment building basement, the makeup demineralizer room in the auxiliary building, and the reactor coolant pump seal injection valve room in the fuel handling building. Robotics research at TMI-2 produced innovations in robot design, deployment, and operator training. [381, 382]

The use of robots at TMI-2 did not require any special NRC licensing reviews; however, activities in which robots were used, like most recovery and cleanup activities, required safety evaluations for NRC review and approval. [383]

- ***Robot Maintenance***. Based on experience, it was reported that robotic designs should be considered for reducing the contamination of internal parts. The design should also provide for easy maintenance by workers wearing anticontamination clothing with multiple sets of rubber gloves and respiratory protection. [384]

6.4 Radioactive Contamination Penetration

Radioactive contaminants that penetrated surfaces inside the containment building included concrete floor coatings (paint), basement walls, and cinder blocks (elevator shaft, stairwell). Contamination in the cork seam of expansion joints was discovered in the control and service building clean areas (adjacent to the fuel handling building).

- ***Concrete Coatings (Upper Levels)***. Protective coatings over concrete surfaces provided significant protection against radionuclide penetration. Analysis of concrete core samples from the entry and operating levels (305-foot and 347-foot elevations, respectively) inside the containment building in 1984 indicated that most of the radionuclides released from the reactor coolant system into the containment building environment were trapped in the concrete's surface coating. Cesium generally was confined to within a few millimeters of the top surface of the coating layer. However, at floor locations that had coatings damaged before the accident, cesium penetrated the subsurface concrete to a depth of several centimeters. A breach or partial breach in the coating layer combined with long-term pooling of contaminated water at the location of the damage was thought to be the cause of this phenomenon. The outward spread of subsurface contamination at such locations appeared to have been confined to the near vicinity of the site of the damage. The removal of the coating from the samples revealed that up to 99 percent of the total measured activity was removed with the coating. [385]

- ***Concrete Coatings (Basement)***. The quantity of radionuclide deposition in the containment building concrete was affected by the type and density of the concrete. Analysis of concrete core samples from containment building basement surfaces in 1987 indicated that much of the radionuclide content of the unpainted and painted concrete cores was deposited near the sample surface exposed to the accident water. Paint appeared to substantially restrict the uptake of fission products by the concrete. For the high-strength concretes (3,000 and 5,000 pounds per square inch), radionuclide penetration was limited to about 1.0 centimeters, with about 90 percent of the activity located in the first 0.5 centimeter. The data suggested that the average penetration into the unpainted concrete was slow (approximately 0.1 centimeter per month) during the approximately 9-month exposure to accident water and that much of the activity was probably deposited in the first day after the material was submerged in accident water. (386)

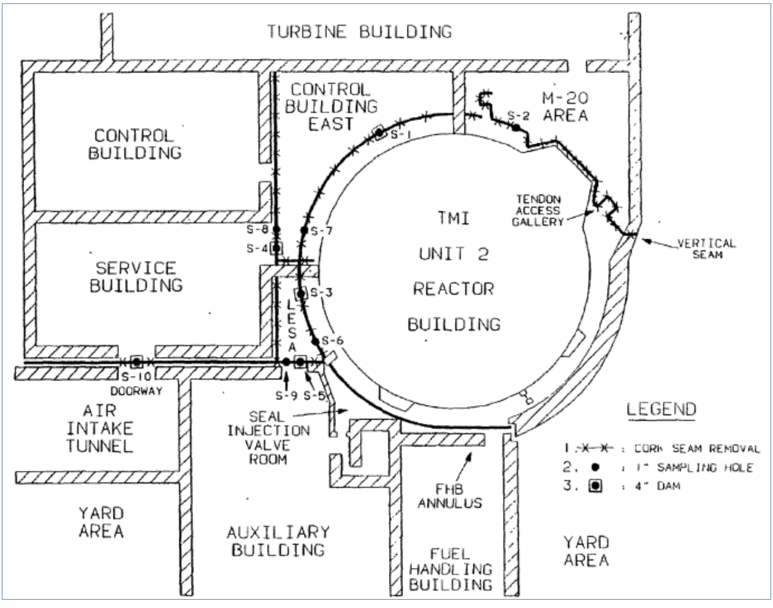
- ***Cinder Block Absorption***. Cinder blocks were used in the containment building as walls for the elevator shaft and one of two stairwells; these blocks were only coated to 1.68 meters (5.5 feet) above the basement floor. The concrete block was considerably more porous that the other concrete structures, and significant amounts of cesium-137 were transported through the block. Radiation levels in the porous concrete block were the highest in the basement area, exceeding 1,000 roentgen per hour, and were a major obstacle to basement cleanup. The blocks were only submerged in coolant for a period of about 10 months; however, capillary action in the concrete tended to carry water into the concrete some distance above the surface of the free-standing water level. (387)

- ***Leaching Tests***. Tests determined the leachability of the radionuclides absorbed into the concrete. The tests included three core concrete samples from the containment building basement and an in situ leaching test of concrete blocks surrounding the elevator shaft. Although the tests proved the potential of leaching as a decontamination method, other programmatic considerations ruled against reflooding the basement, such as schedule, water processing concerns, and an emphasis on defueling rather than decontamination. (388)

  - *Concrete Core Samples*. The results of 4-month leach tests of concrete core samples from the containment building basement showed that the concrete could be leached of cesium and strontium. These results suggested that leaching could be an alternative to the mechanical removal of surface-deposited or absorbed radionuclides, or both, from concrete surfaces that had been submerged in reactor coolant for a period of time. Leaching cesium and strontium from containment building surfaces was significant, as up to 93 percent of the strontium and up to 78 percent of the cesium could be removed by leaching over the 4-month period. Also, the data suggested that longer leach periods with fresh coolant would desorb, or leach, additional quantities of fission products from the concrete. The leach rate for the basement block wall core sample was lower than that for the 3,000-pounds per square inch (psi) concrete wall because of the lower diffusion length for isotopes through the 3,000-psi concrete. (389)

  - *Concrete Block Test*. The licensee conducted an in situ leaching test to reduce the radiation levels from the concrete block walls surrounding the elevator in the containment building. The walls were porous, hollow concrete block. This test consisted of injecting a high volume of water under low pressure into penetrations in the block wall to maintain a water level as high as possible within the block wall. The fill-and-leach operation reduced radionuclide content by 33 percent in the treated areas and removed 1,200 curies of cesium-137, or approximately 7.1 percent of the total block wall radioactivity. (390)

- ***Floor Expansion Joint Contamination***. In late 1980, contamination in the cork seam of expansion joints was first discovered during a routine radiation survey in the control and service building area (adjacent to the auxiliary and fuel handling building). The seam was a cork-filled construction joint located between major structures to accommodate differential expansion between building structures and to attenuate vibration and wave motions during a seismic event. During the period following the accident, the cork seam located in the auxiliary and fuel handling building seal injection valve room was saturated with reactor coolant water due to leaking valves. Initial decontamination attempts were not successful. Over the years, the radioactive material had spread along the joint into noncontaminated areas inside the plant. However, the radioactive contamination was prevented from entering the ground water table by a water stop barrier imbedded in the floor. Modifications were made to the cork seam to allow periodic monitoring of the water levels in the joint, to permit periodic water removal, and to prevent water and contamination migration within the cork-filled joint. (391)



Contamination in the cork seam of expansion joints. Modifications were made to the cork seam to allow periodic monitoring of the water levels in the joint, to permit periodic water removal, and to prevent water and contamination migration within the cork-filled joint. (481.16)

6.5 Recontamination

Recontamination of previously decontaminated areas was caused by splashing, overspray, and drainage from decontamination efforts in adjacent areas. Airborne transport of contamination was also a significant problem.

- ***Recontamination Concerns***. Recontamination was a concern that kept dose rates from being reduced to anticipated levels. The contaminated waste water from the low- and high-pressure flushing operations was the major source of recontamination. The large volume of water produced was difficult to control splashing and overspray onto adjacent surfaces contributed to the problem. Once surfaces were decontaminated and nearby unconfined sources of water were eliminated, stepoff pads and barriers were quickly implemented to reduce the opportunity for recontamination. In late 1988, most of the remaining plant decontamination was postponed until the completion of defueling due to the recontamination of some previously cleaned areas. This also focused project resources on the highest priority work; only decontamination that directly supported defueling was performed. (392, 393, 394)

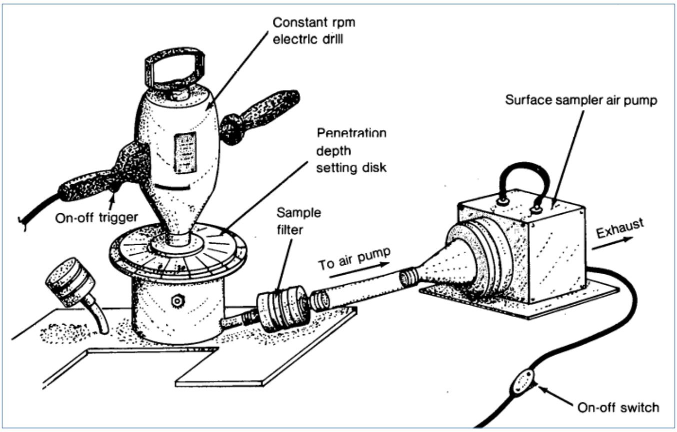
- ***Contamination Control***. The results of the gross decontamination experiment and actual experience provided the following insights: (●) Sequencing of decontamination activities to take into consideration gravity flow and location did not prevent recontamination. (●) Personnel traffic from the air lock to various areas of the containment building caused recontamination of surfaces where there was a significant difference in contamination levels between areas traveled. (●) Adequate controls to isolate clean areas from contaminated areas reduced recontamination. (●) High-pressure spray activity with the lance and water floor scrubber caused contamination of other surfaces. (●) A sufficient amount of time should be spent with the decontamination crews in training on the recontamination problem (i.e., how to recognize it and the corrective actions to be taken during decontamination activities). (●) Work procedures should consider recontamination of areas being decontaminated. (●) Moving equipment and large tools through contaminated areas to support decontamination efforts at higher elevations required protection, or the equipment had to be cleaned before it was placed on clean surfaces. This was especially true if the hoist area was where a great quantity of debris had been dumped or flushed and not cleaned.

- ***Contaminant Migration in Coatings***. Conventional decontamination methods were only partially successful because of recontamination caused by contaminants embedded in the epoxy system's primer coat layers migrating to the surface. For some areas, the recontaminations were so frequent that floors were scrubbed mechanically and wet-vacuumed as often as three times per week. An alternate solution was to remove the coatings. (395)

- ***Airborne Recontamination***. Significant recontamination problems in the containment building were largely due to the airborne transport of contamination from highly contaminated surfaces. One major source of recontamination of floor surfaces was airborne contaminants primarily originating in the building air handling systems. This source was identified by tests that measured the contamination levels above and under a plastic plate placed over a cleaned test area for 24 hours. Another source of contaminants was friable, powdery film or boric acid crystals caused by the use of borated water for flushing building surfaces. This source was associated with the airborne activity concentrations measured on personnel samplers. This activity was caused by resuspension due to personnel movement. To reduce airborne transport, the containment building air cooler fans were reduced to two fans running at slow speed, unneeded ducts were closed, and some top-to-bottom ducts and air coolers were flushed. (396, 397)

- ***Misting System***. Removal of the reactor vessel head required that the water level be lowered to just below the top of the internal plenum assembly. The finely divided debris that had settled onto the top of the plenum assembly was thought to have the potential to become airborne, particularly when the water film left on the top surface evaporated. Accordingly, a misting system was installed to wet the exposed plenum surface to reduce airborne contamination. (398, 399)

- ***Minimized Welding***. Welding inside the containment building was avoided to minimize airborne contamination. (400)



A drill-vacuum system was developed by the INEL to collect the surface deposition samples. The sample sequence consisted of (a) setting up the drill-vacuum system at the sample location; (b) vacuuming an small area about 40 cm2 into a filter; (c) changing the filter and boring a 1/2-inch-diameter hole with a flat nose bit while continually vacuuming all debris from the bored hole; and (d) moving the drill-vacuum equipment a short distance away and repeating the sequence for the deeper hole. Several samples of varying depth were collected at each location to aid in determining the extent of contamination. An ion chamber instrument provided beta and gamma readings at same locations as surface samples. (481.15)

Table 5. TMI-2 decontamination method reference table. [401]

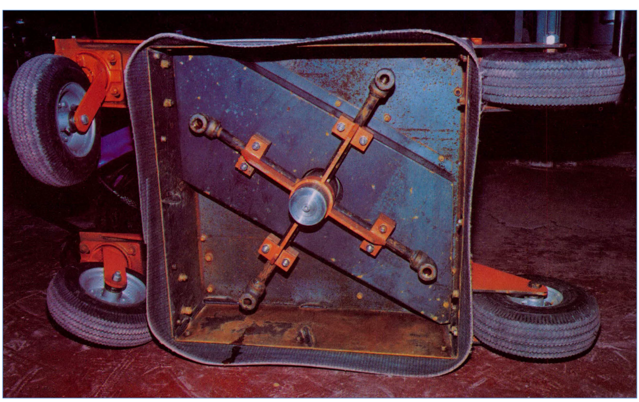
Method	Description	Benefits	Disadvantages
Low-Pressure Flushing	Flush wand using <1,000 pounds per square inch (psi), high volume of water	Approx. 1,000 square foot per hour (sqft/hr); large areas quickly flushed; easily controlled	Large volume of waste generated; unable to remove more tightly adherent contamination
High-Pressure Flushing	Flush wand using 10,000 psi, low volume of water	200 sqft/hr; removed oxide layers; most effective flushing treatment	Not easily controlled; personnel safety concern; can rapidly spread contamination
Multiplaner Flushing	Two- or three-dimensional multijet sprays using low pressure and high volume of water for gross flushing	360 degrees, four-pie coverage of target/cubicle; effective volume dose reduction	Large volume of waste generated; usually unable to remove more tightly adherent contamination
Reflooding	Leaching of contaminants from concrete through water resaturation	Total leaching possible; however, several years of processing would be required	Very expensive to reflood expansive areas; high volume of waste water generated
Fill and Leach	Block wall leaching from inside out via low pressure and high volume of injected water	Reduced radionuclide content 33 percent in tested areas; method performed remotely	Cost/benefit marginal; high volume of waste water generated
Simple Tools	Mop and bucket, towel wipes, scrub brushes	Inexpensive tools; little training needed; smearable contamination directly reduced	Sometimes person-rem intensive; extra worker care must be taken
Dry/Wet Vacuuming	Basic industrial wet and dry vacuum with high-efficiency particulate air filters	Effective in collecting loose debris on a small scale; easily operated equipment	Dry-vacuum could increase airborne levels; vacuuming is not for large-scale decontamination
Mechanical Scrubbing	Basic industrial floor scrubbers with abrasive pads	100-150 sqft/hr; excellent results on painted concrete, more tightly adherent contamination	Splatter from rotary pads; operator fatigue

Table 5. TMI-2 decontamination method reference table. (Continued)

Method	Description	Benefits	Disadvantages
Hydro-Scabbling	Concrete surface removal using ultra-high-pressure water, 10,000 to 40,000 psi; manual or remote operations	Could easily remove surface concrete from walls and floors	Manual operations are dangerous w/ultrahigh pressures; need subsequent processes to pick up and dispose of waste and to smooth surfaces prior to refinishing
Hydro-Scarifying	Concrete surface removal using ultra-high-pressure water, 10,000 to 40,000 psi; manual or remote operations	20–40 sqft/hr; demonstrated excellent vertical surface capability	Manual operations are dangerous w/ultrahigh pressures; need subsequent processes to pick up and dispose of waste and to smooth surfaces prior to refinishing
Scabbling	Concrete surface removal by pneumatically driven, toothed pistons	400 sqft/hr; remotely operated; 1/16-inch depth of surface removed per pass; little or no airborne	Manual operation quickly fatigues operators; poor vertical surface capability
Scarifying	Concrete surface removal using rotary, drum-housed blades	100 sqft/hr achievable; radiation levels effectively reduced in conjunction with scrub and vacuum	Increases airborne activity; many passes to remove; leaves unfinished surface
Steam Vacuuming	Enhanced steam cleaner with high-efficiency vacuum	Decontamination factor >10; easily operated up to 175 feet from the base unit; little system residue	Some surfaces could clog the vacuum inlet
Dry Abrasive Blasting	Particles of steel, sand, glass, etc. entrained in air or water, driven at high velocities to blast surfaces clean; internal vacuum reclaims particles	Slow but effective; leaves smooth surface ready for protective coatings	Difficult to reclaim blasting media
Liquid Abrasive Blasting	Particles of steel, sand, glass, etc. entrained in air or water, driven at high velocities to blast surfaces clean; internal vacuum reclaims particles	Known to have good decontamination factors on relatively small-scale projects	Relatively expensive process with many operational constraints
Flex Hone/Mole Nozzle	Pipe snakes with rotary brush and high-pressure heads enter and scrub pipes of various sizes	Inner-pipe oxide layers were removed; a polishing effect was observed; easily operated	Relatively slow production rates

Table 5. TMI-2 decontamination method reference table. (Continued)

Method	Description	Benefits	Disadvantages
Strippable Coating	Organic coatings containing chemicals that bond to and remove surface contaminants; strippable requires manual removal; self-stripping blisters and peels by itself	1,000 sqft/hr applied, 775 sqft/hr removed; reduced loose contamination level; prevented recontamination	Organic-based materials pose waste disposal concerns
Self-Stripping Coating		Saved worker resources by self-strip; effectively reduced surface contamination levels	Sometimes "self" strip was not complete with certain coatings
Chemical Foams	Expanding foam mixed with cleaning solution increasing coverage and contact time	Increased residence time of chemical decontaminants on target surfaces, especially verticals	Waste disposal concerns; interference with water processing systems
Reagents/ Detergents	Surfactants and chelating surface cleaning agents usually applied with water spray	Proved to be more effective than plain water; increased scrubbing effectiveness	



High pressure spin jet floor cleaner with pressures up to 10,000 psig at a cost of $54,000 (1983 dollars). The water seals on the rotating nozzles developed leaks probably caused by operation of the nozzle rotational motor without water flow provided to the seal. (481.15)

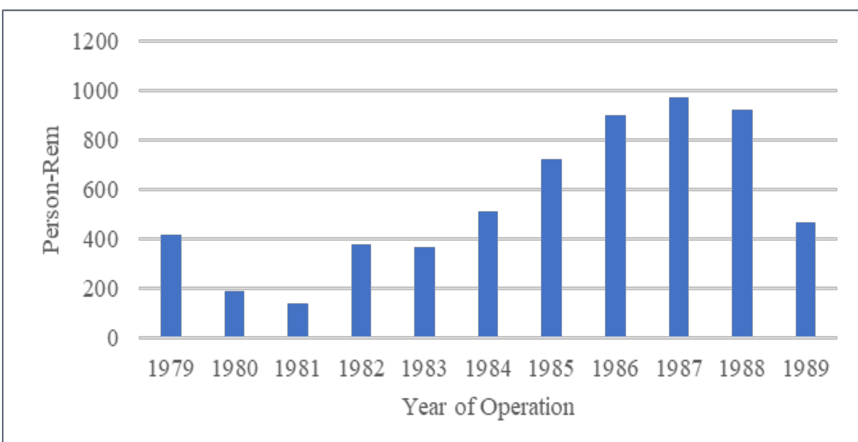
Figure on Next Page. An attempt was made on May 20, 1980 to enter the containment building prior to the purging of radioactive krypton gas. However, the initial entry was delayed until after the purging because of a malfunction of the inner door to the building's personnel airlock. (This photograph maybe the actual attempt or a training exercise.)

7 PERSONNEL PROTECTION

The extensive contamination and the concern for worker protection during decontamination activities prompted a variety of innovations, including new surface cleaning techniques and new radiation survey equipment to quantify contamination levels; improvements in protective clothing; techniques for reducing worker heat stress; and improvements in beta dosimetry. In prescribing protective clothing in the hostile environment, the focus was on the overall risk to the worker, [402] including heat stress, visual and hearing acuity, and cardiopulmonary stress. One measure of TMI-2 success in personnel protection was the radiation exposure record. Even though decontamination had been an ongoing effort throughout virtually the entire decade-long cleanup, total worker exposure was less than half of the revised estimates of Supplement 1 to the TMI-2 PEIS. [403]

7.1 Dose Exposure Control

- ***Cumulative Worker Exposure Over 10 Years***. Although worker activities at TMI-2 had been quite different from those at operating power plants, the cumulative doses at TMI-2 since the accident had been lower than the average doses experienced at operating reactors. By the end of 1989, the collective dose to all workers was 6,180 person-rem. This was comparable to the collective occupational radiation exposure of 2,000 to 8,000 person-rem [404] estimated in the original TMI-2 PEIS. The revised estimates from Supplement 1 of the PEIS [405] were between 13,000 and 46,000 person-rem. The cumulative occupational dose for defueling and defueling support activities was much less, below 2,000 person-rem. The exposure rate to defueling workers averaged less than 10 millirem per hour. [406]



Annual personnel cumulative dose during 1979 to August 31, 1989. Cleanup was considered completed in January 1990. During the last 5 months defueling of the core former region behind the baffle plates was started and completed, lower reactor vessel head airlift/vacuum was completed, and ex-vessel defueling was completed. (481.17)

- ***ALARA Review Criteria***. The criteria used at TMI-2 to determine the need for an ALARA review for a task included: (●) any task anticipated to accumulate 5 person-rem or more of total exposure; (●) any task for which the dose or dose rate to the skin or the extremities, or both, might be limiting without special radiological controls; (●) any task in which the airborne concentration was expected to exceed the limits specified in 10 CFR Part 20, "Standards for Protection Against Radiation," Appendix B, "Annual Limits on Intake (ALIs) and Derived Air Concentrations (DACs) of Radionuclides for Occupational Exposure: Effluent Concentrations; Concentrations for Release to Sewerage," Table 1, "Occupational Values," by a factor of 1,000 times (i.e., respiratory protection of 1,000 times was inadequate); (●) any task that could release radioactive material directly to the environment; (●) work with highly contaminated systems or components, as identified by radiological engineering; and (●) reactor disassembly and defueling operations involving core alterations. (407)

Additional considerations for performing an ALARA review included evaluating the relative risks of radiation exposure verses physical safety hazards. For example, ALARA reviews were conducted where fall hazards were present and the restricted visibility and physiological stress when wearing respirators could increase the risk of falling. (408)

Worker standing next to radiation shielding of interlocking fiberglass columns filled with sand that was used to shield the enclosed stairwell and the reactor vessel head.

- ***ALARA Evaluations***. A typical ALARA evaluation at TMI-2 included the following steps: (1) Evaluate radiological conditions in each location of work to determine the sources and their relative percentages of contribution to the total area dose rate. (2) Evaluate the area work occupancy in terms of the total job hours and the schedule of work. (3) Determine applicable dose reduction methods (i.e., shielding or source removal). (4) Identify options and estimate the degree of reduction from each. (5) Calculate the net positive benefit derived from each combination of options. (6) Select options with the highest net positive benefit for prioritization and implementation. (409)

- ***External Exposure Control***. For jobs involving major, or significant, exposures, the following controls were required to reduce external exposure: (●) radiological controls incorporated in the design; (●) written instructions; (●) getting workers involved in the development of tools and procedures; (●) use of mock ups to practice and to test tools and work plans; (●) prejob briefings before beginning work; and (●) postjob debriefings for lessons learned. (410)

• ***Skin Dose from Hot Particles***. The release of reactor coolant containing finely divided fuel debris that generated discrete radioactive particles (or "hot particles") was a problem at some locations within the plant. Hot particles were small, sometimes microscopic, particles of contamination with relatively high specific activity. Hot particles at TMI-2 were primarily fuel fines from damaged fuel and activation particles originating mainly from the high-cobalt alloy used in valve seats. A computer code and other published methods of assessing skin dose were used to estimate doses from hot particle contamination. (411, 412)

• ***Control of Hot Particles***. To control hot particles during defueling operations, the containment building was arranged in a set of successive rings of increasing contamination with the defueling platform at the center. Disposable gloves and booties were staged at sticky stepoff pads. A layer of gloves and booties were removed when moving into a cleaner area. Sometimes a clean set of booties could be used to cover the dirty pair. (413) Additional precautions were taken to ensure that hot particles remained in the containment building, such as (●) frequent wipedowns of workers; (●) ventilation controls in the desuiting area; (●) increased frequency of personnel monitoring; and (●) automated personnel contamination measuring devices. These control mechanisms were very effective at limiting personnel exposure to hot particles. At TMI-2, no worker exceeded the licensee's administrative dose limit for the skin (50 millisievert/calendar quarter) as a result of hot particle exposure. (414)

A radiation work permit was required to access contaminated ceiling areas above the clean lower areas of the auxiliary building main corridors.

• ***Skin Protection***. During early containment building entries, workers entering the containment building wore two sets of cloth coveralls. Some workers who were entering areas of very high surface contamination also had an outer plastic suit over the two sets of cotton coveralls. The coveralls were commercially laundered and reused as was typical of most nuclear power plants. However, the radioactive contamination on the coveralls from TMI-2 proved more difficult to remove by laundering. Further, significant amounts and types of contamination on the coveralls from TMI-2 were not typical of other nuclear facilities. Despite efforts to try different methods to launder the clothing, some contamination remained "fixed" in the cloth material. The residual contamination did not present a significant skin dose to the worker so the continued used of the contaminated garments was considered acceptable. However, the number of skin contamination incidents continued to increase with the workload and contamination levels workers encountered. It was eventually determined that workers' physical exertion and perspiration contributed to contamination leeching out of the material of the inner set of coveralls and onto the skin. This leaching resulting in minor but numerous detectable skin contamination incidents. Consequently, it was decided that the inner set of laundered cloth coveralls should be replaced with a new, clean set of disposable, breathable paper coveralls. The clean layer of paper helped to prevent skin contaminations caused by cross contamination from the laundered cloth coveralls. [415]

TMI-2 workers who wore paper garments beneath their cloth coveralls reduced instances of skin contamination by 64 percent while working in the containment building. Skin contaminations were limited to those areas on the body not protected by the paper garments. In addition, paper garments were more comfortable than two sets of cloth coveralls. [416]

- ***Containment Atmosphere Dose Control***. As a result of the accident significant quantities of fission gases and volatile radionuclides, primarily radioiodine, were released into the enclosed containment building atmosphere from the damaged reactor core. Approximately 1 year after the accident, air samples of the containment building atmosphere showed that krypton-85 was the principal remaining radionuclide. Krypton-85 concentration was estimated to be $3.77 \times 10^{+10}$ becquerel/cubic meter. [417] To permit less restricted access to the containment building and to proceed toward decontamination of the TMI-2 facility, it was necessary to remove the krypton gas and to provide a suitable environment for workers. The purging began on June 28, 1980 and continued until the morning of July 11, 1980. [418] Removal of krypton-85 from the containment building atmosphere was estimated to reduce the radiation dose rate for workers by a factor of about 4. [419] The removal of 44,000 curies of radioactive krypton-85 gas from the containment's atmosphere allowed workers to begin to clean up the containment building, to maintain instruments and equipment, and to remove the damaged fuel from the reactor vessel. [420]

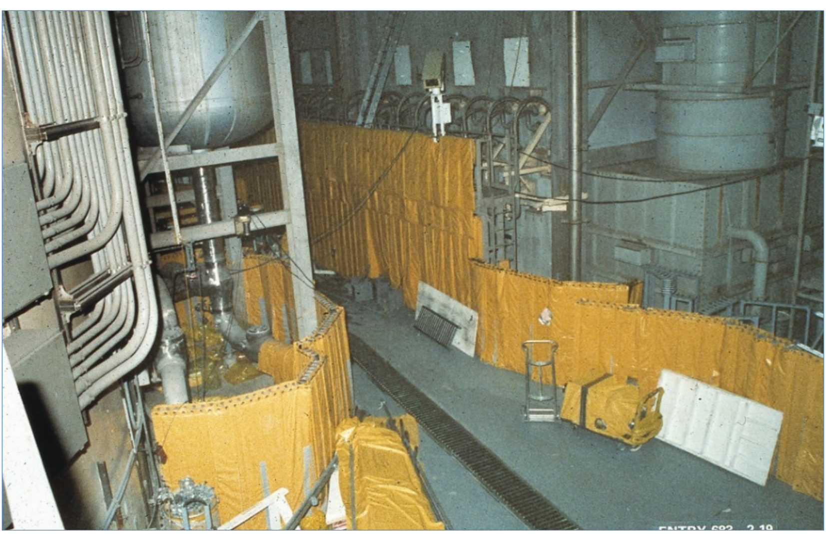
7.2 Worker Wellness Considerations

Considerations for worker safety and convenience included heat stress controls; psychological concerns; respiratory protection; whole body counting; and a dedicated dressing facility.

- ***Heat Stress Control***. Heat stress concerns are common at all nuclear power plants, but at TMI-2, workers wore more lavers of protective clothing, including respirators and plastic suits. The potential for heat stress became the limiting stay-time factor, especially during the summer months. Experience had shown that summer temperatures could reach between 79 and 89 degrees Fahrenheit in the containment building, thus limiting working time to 1.5 hours per crew. The licensee's industrial safety office, EPRI, and Pennsylvania State University developed a comprehensive heat stress control program consisting of employee training, administrative controls, and personal cooling devices. The most significant means for reducing heat stress was the installation of an air chiller unit inside the containment building.

- *Initial Program*. The licensee's initial program for reducing heat stress focused on three actions: (●) medical screening, (●) education of workers to recognize heat stress, and (●) controlling work times. Protective clothing requirements were sometimes reduced, when possible; however, the types of tasks required for cleanup did not allow much flexibility. Attempts to screen and partially acclimate workers using mockup simulations, or a standard exercise, were very time consuming and did little to improve the productivity of the cleanup effort. Administrative controls to control work times resulted in short time limits that hindered productivity and caused an accumulation of dose as more workers had to travel through areas of high radiation levels. [421] A computer program estimated a safe stay-time for a specific task in a specific work area. Estimates were based on work rate, air temperature, and insulating effects of protective clothing types. [422]

- *Ice Garments*. The frozen water garment, or ice vest, was a tight-fitting vest holding 8 pounds of ice packets worn under protective clothing. Although melt time was limited, workers in the high heat environment wearing the garments doubled their stay times. Field tests conducted at TMI-2 showed that the garments lowered body core temperature and heart rate. Prepared garments and additional ice packets were kept in a freezer in the worker dressout area. Experiences reported from the use of ice garments included the following: (●) About 5 to 10 percent of ice packets broke or leaked during each use and had to be replaced. (It was suggested that the use of a heavier



Lead blankets used to shield worker pathways. (Upper left: core flood tank; upper middle: containment building air chillers; right: plenum of air-cooling assembly.)

plastic could have prevented breakage.) (●) A more durable cotton twill material had a very long service life and cost substantially less than the original ripstop nylon garment. (●) Garments were difficult to decontaminate; those heavily contaminated had to be disposed. (●) To avoid cross contamination, garments were laundered separately from contaminated protective clothing. (●) Substantial ice melting occurred if there were delays between the dressup period and entry into the work area. (●) Melted ice added weight to the worker's heat stress burden. (●) Liquid nitrogen was used to quick-freeze the water packets to save time, but this practice was discontinued because the ice packets were so cold that frost bite was a safety concern. [423]

- *Air-Flow Cooling Garments*. Other commercially available body-cooling garment designs were considered, including those using circulating water tubes in the garment to remove body heat. These garments were found to be difficult to decontaminate and expensive, and their pumps required regular maintenance. The *vortex cooling suit*, which was tested at TMI-2, produces a flow of cool air to the skin that removes body heat through convection and increases sweat evaporation. The cooling effect produced by the vortex tube (a passive tube that separates a compressed gas into hot and cold streams) successfully protected workers from heat stress. However, problems limited the use of vortex suits at TMI-2 for the following reasons: (●) The part of the vortex tube outside the protective clothing could not be easily decontaminated. (●) A large volume of service air was required to simultaneously operate vortex suits for several workers. (●) Worker mobility was restricted by the umbilical hoses supplying air to the suits. [424]

- *New Air Chiller*. The installation of an additional air chiller to the containment building air handling system proved to be the most successful strategy for preventing heat stress. [425] The new chiller system reduced the temperature to 64 degrees F and permitted worker stay-times of 3 to 4 hours. This also limited the use of short frozen water garments to an exception-only basis. [426] However, air cooling resulted in some condensation when the humidity was high, thus creating additional, although not significant, contaminated water. [427]

- ***Psychological Concerns***. One reported issue that would have benefited from additional attention at TMI-2 was the emotional and psychological concerns of the cleanup workers. Management decisions often did not factor in workers' real concerns associated with the safety of their families, or "taking doses home." An example that was cited where management tried to overcome these concerns involved the licensee's requirement to reduce the use of respirators in areas of the containment building or during activities where airborne contamination was not a problem. From an ALARA perspective, working without respirators improves work efficiency, thus reducing time and dose. The licensee assembled survey data and technical expert assessments to show the workers that the air in the containment building was safe to breathe and within regulatory limits. Management and health physics technicians met with the workers to discuss their concerns and to try to put at rest their fears of incurring additional internal doses and taking contamination home. Building and maintaining trust among coworkers and confidence in the health physics department were the keys to easing the workers concerns. The cleanup required special attention to worker morale. [428]

- ***Respiratory Protection***. Of the numerous types of respirators used at TMI-2, the two most useful devices from the standpoint of worker comfort, productivity, and dose reduction were powered air purifying respirators (PAPRs) and supplied air hoods. The PAPRs were used almost exclusively for cleanup and recovery operations at TMI-2. Advantages of the PAPRs were that they limited dead airspace and lens fogging while providing a cooling effect on the face. Advantages of the supplied air hoods were that they were much more comfortable to wear and very useful in mitigating heat stress because the exhausted air was directed down the wearer's torso. [429]

For the bulk of the decontamination and defueling efforts PAPRs were used where worker mobility was required, such as maintenance and decontamination activities. Supplied air hoods were used where worker mobility was limited and where worker stay times were extended over several hours. [430]

Left: Typical defueling entry radiological control suit during dressing. The powered air purifier battery and pump pack as well as the dosimetry were attached at the waist. The plastic coat would be pulled up over the shoulders and the lower hood and taped in place. Right: Containment building entry and exit facility called the contamination control corridor, also known as "C Cube". (481.18)

- ***Dedicated Dressing Facility***. A dedicated dressing facility, known as the personnel access facility (PAF), prepared workers for highly contaminated environments and reduced incidents of skin contamination. The PAF staff helped workers put on their protective clothing correctly. In addition, they verified that the provisions of the radiation work permit were met, assured proper respirator fit, provided special dosimetry, and assembled any necessary support equipment (e.g., tools, radio equipment). The PAF also served as a staging area for personnel awaiting authorization from the remote coordination center to enter the containment building, thereby reducing queuing at the access control point. The PAF was an effective tool in managing the containment entry process, reducing worker skin contaminations, and improving productivity. [(431, 432, 433, 434)]

In order to minimize cross contamination from workers and equipment exiting the containment building, a contamination control corridor (CCC) was established within the PAF. In the CCC health physics technicians assisted in the removal of equipment and in undressing the workers. The CCC was very effective in reducing the risk of contamination spread beyond the radiologically controlled areas. [(435)]

- ***Whole-Body Counting***. The whole-body counter for the measurement of radioactivity within the human body was open for use whenever it was needed, which was approximately 20 hours per day, during operations to remove and store the reactor vessel head. For any large-scale operations after the reactor vessel head removal, it was recommended that the counter continue to be open for use, as needed, to support the remaining work. [(436)]

- ***TMI-2 Worker Registry***. In response to an April 1, 1979, memorandum from the Secretary of Health, Education, and Welfare, a cooperative effort between the NRC and the U.S. National Institute for Occupational Safety and Health established a registry of occupational exposure at TMI-2. This registry would facilitate future radiation epidemiological studies. [(437)]

In 1980, the NRC concluded that the preexisting dosimetry program supported by personnel and medical records was fully satisfactory for carrying out future studies. The licensee retained those essential elements of a work registry (i.e., personnel records, medical records, exposure history) of every radiation worker. The NRC recognized that work registry information would not be useful in distinguishing a causal-effect relationship between TMI-2 worker radiation exposures and future health effects. Individual worker doses at TMI-2 were subject to the same NRC limits as at any other licensed facility. Further, almost all worker exposures had been maintained administratively well below NRC limits. Within these limits, the statistical likelihood of any resulting health effects from occupational radiation exposure (i.e., cancer, generic defects in future generations) would be very small and would not be discernible from health effects from any other cause. [(438)]

Radiation Exposure Control Techniques

Work Planning

- Plan in advance
- Delete unnecessary work
- Determine expected radiation levels

Preparation of Work Procedures

- Plan access to/exit from work areas
- Provide for service lines (air, welding, ventilation, etc.)
- Provide appropriate communication (includes closed-circuit television)
- Remove sources of radiation
- Plan for installation of temporary shielding
- Decontaminate
- Minimize discomfort of workers
- Work in lowest radiation levels
- Perform as much work as practicable outside radiation areas
- State requirements for standard tools
- Consider special tools

Temporary Shielding

- Perform engineering load analysis in advance
- Control installation and removal by written procedure
- Inspect after installation
- Conduct periodic radiation surveys
- Minimize damage caused by heavy lead temporary shielding
- Balance radiation exposure received in installation against exposure to be saved by installation
- Shield components with abnormally high radiation level early in the maintenance period
- Shield travel routes
- Shield specific work locations
- Use full-scale models (mock-up) to plan temporary shieling design and installation
- Perform directional surveys to improve shielding design by locating radiation source

Rehearsing and Briefing

- Rehearse
- Use mock-up duplicating working conditions
- Use photographs
- Brief workers

Performing Work

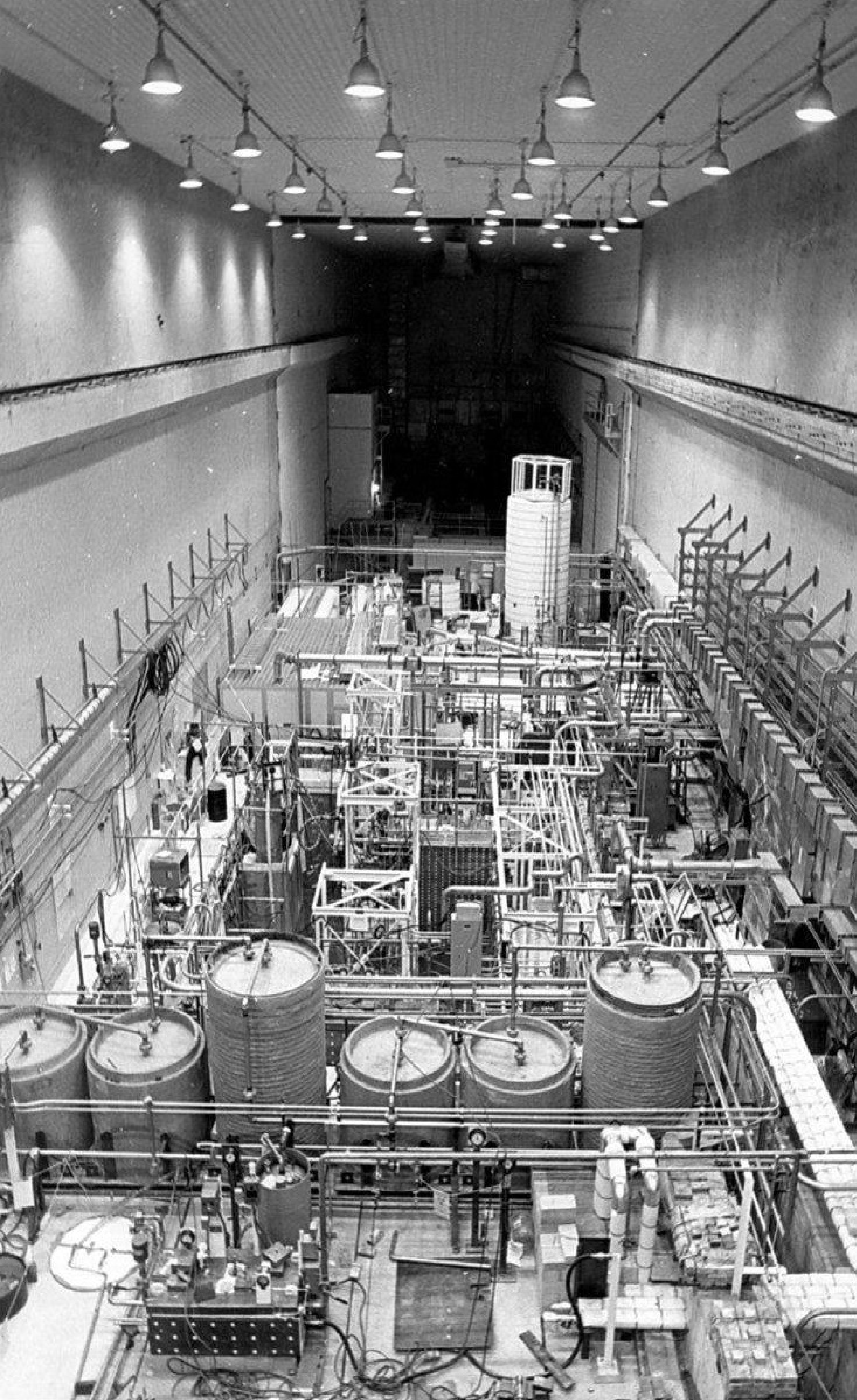
- Post radiation level
- Keep excess personnel out of radiation areas
- Minimize beta radiation exposure
- Supervisors and workers keep track of radiation exposure
- Evaluate use of fewer workers
- Reevaluate reducing radiation exposures

Optimization

- Compare benefits of exposure control activities with their costs in health terms to select the best combination of protective Measures

Considerations applied at TMI-2 for maintaining personnel radiation exposure ALARA during plant maintenance, repair and recovery. (481.19)

Figure on Next Page: The submerged demineralizer system in the spent fuel pool.



8 WASTE MANAGEMENT

The TMI-2 accident and subsequent cleanup presented challenges in terms of the management of various forms and concentrations of radioactive waste. The management of highly contaminated water, fuel debris, and related solid waste byproducts included various tasks, such as handling, processing, temporary onsite storage, transportation, and final disposal. Decontamination activities resulted in substantial quantities of contaminated water and organic resins and inorganic zeolites produced from water processing systems. Fuel debris that spread throughout the plant created unique radiological waste characteristics. Also, some waste did not fit into established regulatory waste classification categories for transportation and disposal, and the possible generation of flammable gases inside sealed radioactive waste containers was a potential hazard. [(439)]

Most radioactive trash and solid decontamination wastes were handled as at other nuclear power plants but on a much larger scale. TMI-2 generated approximately 6,000 cubic meters of radioactive waste (excluding fuel debris). About 98 percent was classified as low-level radioactive waste that could be commercially buried; the remaining 2 percent was disposed of by special arrangements with the DOE. Since TMI-2 was a newer plant, several unusual factors made waste management there much less difficult, such as limited quantities of fission and activation products (especially cobalt-60), two empty spent fuel pools, and an uncontaminated steam generator chemical cleaning building set up for water processing. [(440)]

A few of the many experiences from the management of liquid and solid wastes during the TMI-2 cleanup are presented below. Thorough discussions of these topics appear in EPRI-TR-100640 and the DOE report, “Historical Summary of the Fuel and Waste Handling and Disposition Activities of the TMI-2 Information and Examination Program (1980–1988),” issued October 1988 (EGG-2529).

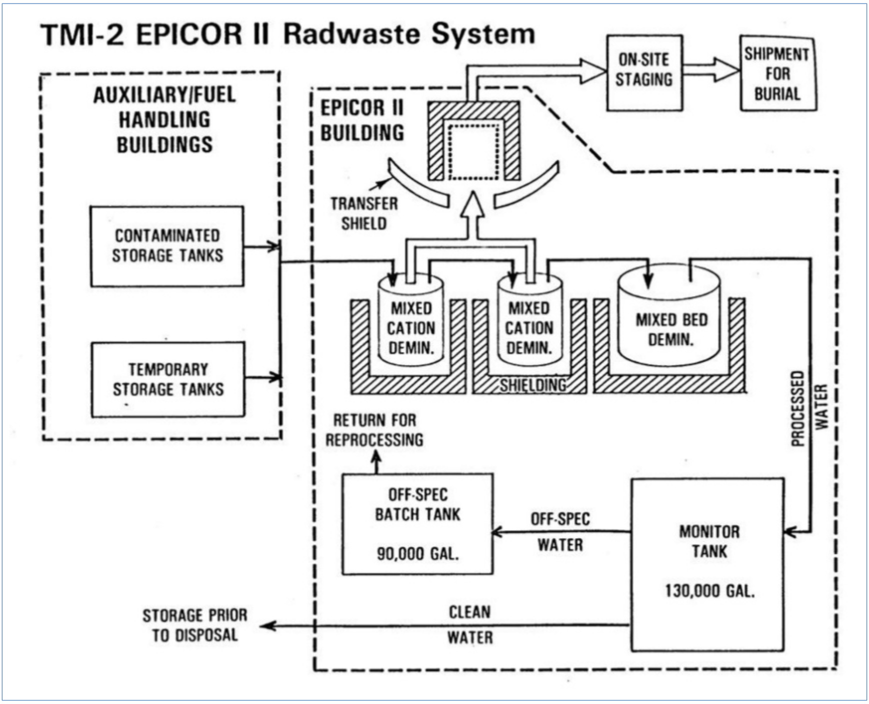
8.1 Liquid Waste

Over one million gallons of contaminated water existed in the plant shortly after the accident. The water ranged in concentration from less than 1 microcurie per milliliter to hundreds of microcuries per milliliter and existed in auxiliary building tanks and systems, the containment building basement, and the reactor coolant system. New water processing systems that were designed and installed to decontaminate the accident-generated water included the EPICOR II system, submerged demineralizer system, and defueling water cleanup system. The processed water disposal system removed residual contaminants from processed accident-generated water through a closed-closed evaporator. [(441)]

- ***Water Management***. [(442, 443)] Over the first few years, a major portion of the licensee’s resources were spent on water management. Before the accident, radioactive waste tanks were already 60 percent full of waste water from the TMI Unit 1 shutdown outage just before the accident. In addition, leakage from various operating systems in the auxiliary and fuel handling building added about 800 to 1,000 gallons per day. The water was initially distributed in the containment building basement, reactor coolant system, and auxiliary building sumps and tanks and over the lower elevation floor of the auxiliary building. The water, with the associated high radiation fields, prevented system maintenance and hindered cleanup work.

During the early weeks and months following the accident, plant operators transferred contaminated water between existing tanks. The existing plant systems were unable to process any of this water, which contained cesium-137 concentrations that were initially several terabecquerels per cubic meter. Railroad tank cars were considered for onsite storage of low-level radioactive waste water; however, they were never used to store contaminated or processed water. In July 1979, the fuel pool waste storage system (known as the "tank farm") was available with 110,000 gallons of storage capacity. In July 1981, two new processed water storage tanks were available (each with a capacity of 500,000 gallons).

- ***EPICOR I***. The EPICOR I system was installed at TMI before the accident to process low-activity, nonaccident-generated liquid waste water, mainly from the preaccident TMI Unit 1 outage. [(444)] In their policy statement of May 25, 1979, the NRC Commissioners permitted discharge of preaccident waste water decontaminated by the existing EPICOR I decontamination system and discharge



Simplified schematic of the EPICOR II process flowpath.

of industrial waste water (water slightly contaminated because of leakage from secondary plant service support systems) into the Susquehanna River, as consistent with the facility operating license and NRC regulations. However, restrictions were imposed on the allowed discharges of EPICOR I and industrial waste water. The statement required the NRC staff to prepare an environmental impact statement for public comment and NRC Commissioner approval before the discharge of other (accident) waste water and the operation of the EPICOR II system. [445]

- ***EPICOR II—Initial Cleanup Mode***. The existing plant water processing system lacked the capability to process accident-generated water, which contained cesium-137 concentrations initially ranging from 1 to over 100 microcuries per milliliter. The auxiliary building emergency liquid cleanup system (known as "EPICOR II") was designed and installed after the accident to clean up about 450,000 gallons of intermediate-level waste water from October 1979 to December 1980. This water was held in various storage tanks and sumps inside the auxiliary and fuel handling building. Consistent with the design objectives of simplicity and use of proven technology, the EPICOR II system employed a series of disposable ion exchangers, preloaded with organic and inorganic resin media selected specifically for the physical and radiochemical characteristics of the contaminated water. EPICOR II reduced the volume of radioactive waste by a factor of 10 over conventional waste processing systems. [446] The system was in the preexisting chemical cleaning building. [447] Problems were encountered during the initial mode of EPICOR II processing.

Prototype gas sampler installed on an EPICOR II liner. INEL designed and built the device to sample and vent the liners remotely and to add recombiner catalyst. (481.20)

- ***EPICOR II: Hydrogen Generation***. [448] An unexpected problem with the storage of spent EPICOR II liners that became programmatic at TMI and the U.S. nuclear industry was the discovery of gas generation inside heavily loaded (radioactive) demineralizer liners that used resin-based media for ion exchange. During preparations to ship a heavily loaded prefilter liner to the DOE's Battelle Columbus Laboratories for characterization, [449] a flash ignition of hydrogen occurred at the EPICOR II cask loading station in the TMI-2 waste packaging and handling facility. Hydrogen and oxygen gas generated by radiolytic decomposition of residual water in the liners became a safety concern during handling, transportation, and reception of the liners.

INEL designed and built a device to sample and vent the liners remotely and add recombiner catalyst. A remotely operated vent tool was devised to remove the vessel vent plug while maintaining a sealed environment around the storage module cell. The liners were purged of hydrogen gas, and the hydrogen gas generation rate was quantified before shipment to comply with U.S. Department of Transportation shipping regulations.

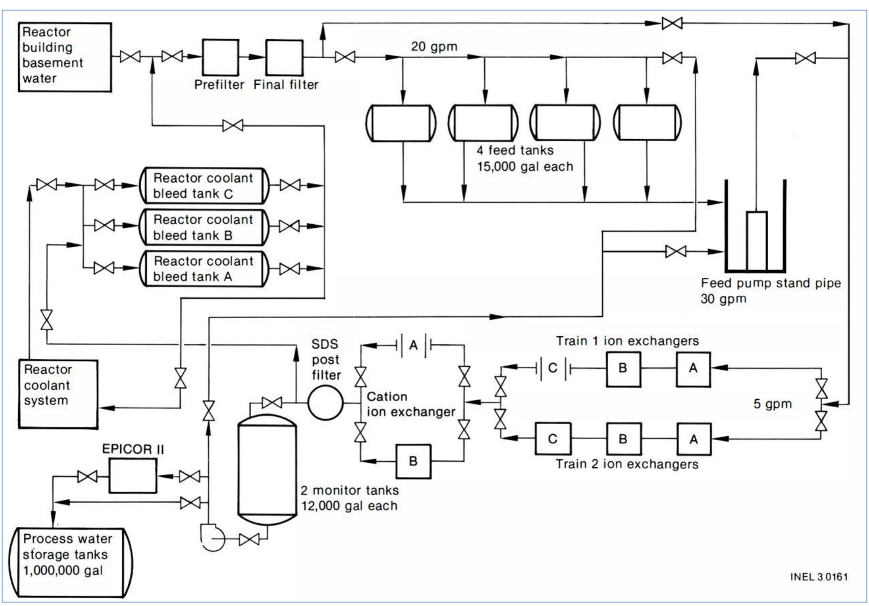
The DOE had studied the generation of hydrogen gas as a result of radiolysis of water before the TMI-2 accident; however, these studies were limited to high-level and transuranic wastes. The NRC sponsored later studies of hydrogen generation in EPICOR II vessels, which resulted in changes to the certification of shipping casks. In Information Notice 84-72, "Clarification of Conditions for Waste Shipments Subject to Hydrogen Gas Generation,"[(450)] issued September 1984, the NRC required plants to demonstrate, by tests or measurements, that combustible mixtures of gases were not present in radioactive waste shipments; otherwise, the waste was to be vented within 10 days of shipping. A task force, formed by the Edison Electric Institute to evaluate these NRC requirements, developed a calculational method to quantify hydrogen gas generation in sealed containers. EPRI then demonstrated this calculational method using a desktop computer at TMI-2, a method the NRC accepted.

- ***EPICOR II: Processing Problems***. Other problems encountered during EPICOR II processing included the following: (●) Repetition of problems encountered during EPICOR I operation. (Constant changing of the proprietary resin media allowed for very little preplanning of liner loading. Slow turnaround of chemistry and radiochemistry on samples did not allow the monitoring of liner corrosion breakthrough to be done in a timely fashion, requiring significant quantities of water to be reprocessed.) (●) Two loop seals in the line between the auxiliary building and the chemical cleaning building, where the EPICOR II system was housed, presented difficulties in initiating and maintaining flow to the EPICOR II system from the auxiliary building. (●) The installed automatic sampler never worked as designed. (●) The relatively high curie loadings of liners required special handling for transportation and disposal, including venting of combustible gases, overpacking with concrete high integrity containers, or providing additional intrusion protection in the burial trench. [(451)]

- ***Submerged Demineralizer System.*** The submerged demineralizer system (SDS) was located in the TMI-2 spent fuel pool (filled with processed water for shielding) to clean up high-level radioactive accident-generated waste water from the containment's basement, reactor coolant system, and reactor coolant bleed tanks. The very successful operation of EPICOR II established the confidence and experience that was to prove invaluable in dealing with the more highly contaminated water in the containment building basement. The SDS design started in the summer of 1979 and was designed and installed on an accelerated basis over the next 2 years. (452) The SDS design had a 2-year life expectancy, but it was operated for 7 years. (453)

Problems encountered during the operation of the SDS included the following: (•) Maintenance of valves and equipment in shielded manifolds and gloveboxes was difficult. (•) Maintenance of diaphragm valves in the leakage containment system required movements of highly radioactive vessels to permit underwater access by divers for repairs. (•) Postfilter cartridges were initially being plugged constantly by zeolite fines in the system effluent, which was most probably caused by insufficient flushing of the liners before use. (•) Early SDS vessels were designed with flow restricters, which were removed through modification. (•) Installed flow meters/totalizers were very erratic. (•) The lack of a sample point between the prefilter and the final filter required curie loading calculations on these liners, based on underwater dose rate surveys and computer models. (•) Tank farm eductors more than doubled the volume of water that they transferred. (•) The long-handled tools used to couple and decouple liners lacked the sensitivity required to ensure positive seating of quick disconnect fittings, which resulted in several leaks to the spent fuel pool. (454)

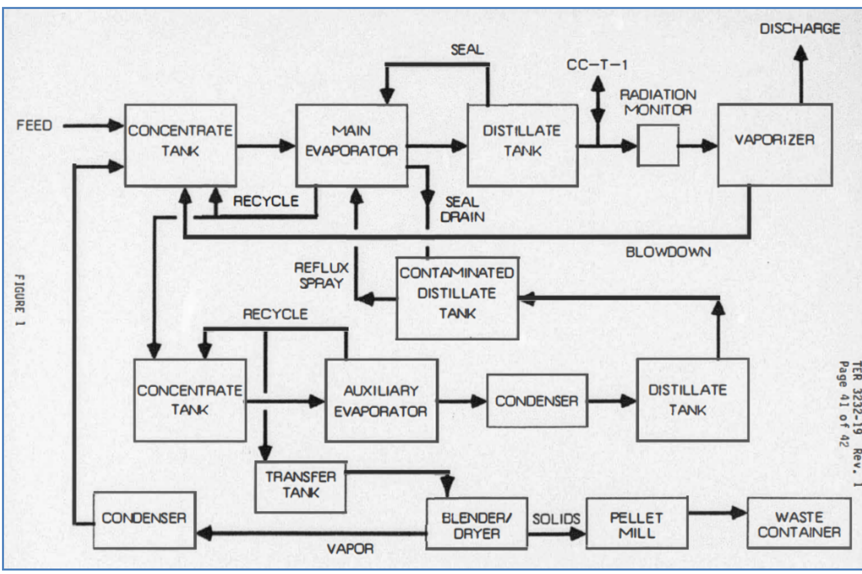
- ***EPICOR II—SDS Polishing and High-Integrity Container Polishing Modes***. EPICOR II removed residual radioactivity from submerged demineralizer system (SDS) effluents and processed miscellaneous wastes during a 6-year period. After the SDS was removed from operation in 1988, EPICOR II was the primary system to clean up the waste water mainly generated from building decontamination



Flowsheet for water processing through the submerged demineralizer system. (481.21) activities. The system configuration was the same as before; however, a high-integrity container (HIC) was placed in the first position to act as a roughing filter. EPICOR II processed water more than 14 years, beginning with the initial cleanup in October 1979.[455]

Problems encountered during these modes of operation of EPICOR II included: (•) Decreased cartridge postfilter life was caused by the lack of adequate prefiltration, allowing particulates to pass through ion exchangers. (•) Floating or swelling organic resins were responsible for some, but not all, of the erratic level indication and control problems. (•) The 10^8 rad integrated dose limit on the HIC lowered the allowable cesium-137 loading from 1,000 curies to 348 curies.[456]

- ***Defueling Water Cleanup System.*** The defueling water cleanup system (DWCS) removed organic carbon, soluble fission products, and particulate matter from the fuel transfer canal (FTC), spent fuel pool "A" (SFP-A), and the reactor vessel. The DWCS was two independent systems, one for cleaning up the FTC/SFP-A and the other dedicated to the reactor vessel. A temporary reactor vessel water filtration system was used until solutions could be incorporated in the DWCS to stop the microorganism growth and to remove the colloidal material.



The processed water disposal system consisted of the following: (1) a vapor recompression distillation unit (main evaporator) that distilled the processed water in a closed cycle and collects the purified distillate for subsequent release by vaporization; (2) an auxiliary evaporator that further concentrated the bottoms from the main evaporator; (3) a flash vaporizer unit that heated and vaporized the purified distillate from the main evaporator and released the vapor to the atmosphere in a controlled and monitored manner; (4) a waste dryer that further evaporated water from the concentrated waste and produced a dry solid; and (5) a packaging system that prepared the dry solid waste in containers acceptable !or shipment and for burial in a commercial low-level radioactive waste disposal site. (481.22)

The temporary system operated from February 1986 to May 1987, after which the improved DWCS took over the water filtration function. [457]

The problems experienced with the DWCS included the following: (●) Initial filter canister throughputs were less than 10 percent of expected levels due to fouling caused by organic colloids or biological growth in both the reactor vessel and the FTC/SFP-A. This problem was compounded by the presence of organically stabilized colloids and was solved in the reactor coolant system through modifications to the DWCS, providing coagulant and filter-aid (body feed) injection systems. However, success with the same modifications to the FTC/SFP-A portion of the DWCS was marginal. (●) The DWCS was plagued with hose failures and coupling leaks, many of which were caused through external damage resulting from improper handling of tools and equipment. Many coupling problems were caused by interference with inlet and outlet lines inside the reactor vessel and the rotation of the defueling work platform. (●) The inline nephelometers (turbidimeters) experienced ranging and fouling problems. [458]

- ***Improved Defueling Water Cleanup System (DWCS)***. The very fine particulates and suspended solids in the reactor coolant quickly plugged the DWCS filters. Diatomaceous earth (DE) was injected into the process stream to create a fine cake on the filter element surface in a filter canister. The DE was about 90 percent silicon dioxide. This cake collected the solids, thus protecting the metal filter material. Once the filter was no longer effective (indicated by high differential pressure), the process was secured, and the DE was knocked off the filter elements and collected on the bottom of the canister. A fresh coat of DE was applied, and the process was repeated until the canister was eventually filled with spent DE. Adding DE increased the service life from as short as 1 day to a month or longer. [459]

Processed water disposal system closed-cycle evaporator/vaporizer used to dispose of processed accident-generated water.

- ***Use of Accident-Generated Water***. The accident-generated water (AGW) was processed and recycled for decontamination to minimize the amount of fresh water likely to be contaminated. The NRC issued Supplement 2 of the TMI-2 PEIS after public comment in 1987. The processed AGW was stored on site in two 500,000 gallon tanks. A recycling system transferred the processed water into the containment building for decontamination activities. The processed water was also used as radiation shielding for both spent fuel pools in the fuel handling building and for the refueling canal in the reactor building. The 2.3 million gallons of processed AGW remained on site for about 10 years before it was evaporated and vaporized into the atmosphere over a 30-month period, starting in 1991, after the NRC granted its approval. This water contained 1,020 curies of tritium and 2.3 curies of all other contaminants. Other nonradioactive contaminants included 150 tons of boric acid and 11 tons of sodium peroxide. About 99.9 percent of the dissolved radioactive contaminants (other than tritium) contained in the evaporator influent were collected as dry solid waste. (460)

- ***Core Material Leaching***. In mid-1980, a reactor coolant sample was collected and analyzed to assess the extent of degradation of the reactor core and to provide long-term information concerning the continued leaching of radionuclides from the core material. At this time, the archived sample that was taken the day of the accident was divided into smaller portions, which were also analyzed. The results of these analyses indicated that radionuclide leaching from the core material was insignificant. The data were used to plan for reactor coolant system water processing by the SDS. (461)

8.2 Solid Wastes

Over 180,000 cubic feet of solid radioactive waste were generated and shipped during the cleanup period. Solid waste included spent EPICOR I and EPICOR II resin liners; spent submerged demineralizer system vessels; contaminated clothing, tools, and equipment; and decontamination materials. The DOE accepted about 3,000 cubic feet of certain wastes that exceeded commercial burial limits (called abnormal waste) for research and development of radioactive waste disposal technology, such as vitrification, hydrogen generation control, and the design and testing of high-integrity containers. (462) Fuel debris, including filter canisters from the defueling water cleanup system, was shipped to INEL for storage under unique agreements among the DOE, the NRC, and the licensee. (463)

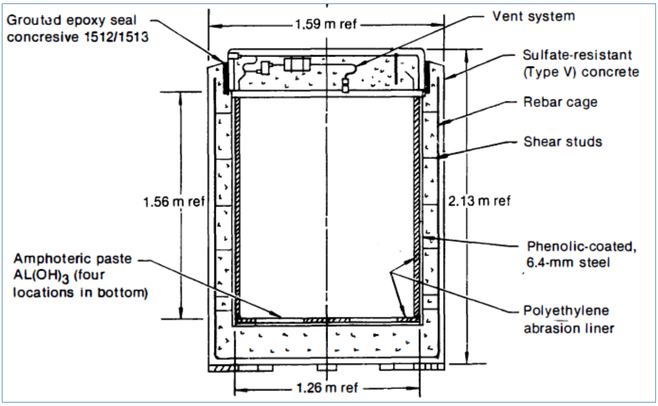
- ***High-Integrity Containers (HICs) to Dispose of EPICOR II Prefilter Liners***. The DOE designed and fabricated a special HIC to dispose of the original 45 highly loaded EPICOR II prefilter liners at the commercial low-level radioactive waste burial facility near Richland, WA. The HIC was an overpack (EPICOR II liner sealed inside the HIC) that would remain stable below ground for a minimum of 300 years (about 10 half-lives of predominant isotopes). The HIC consisted of a cylinder made of reinforced concrete and a permanently sealed lid. A vent system cast in the lid provided passive venting of the container. This HIC was restricted for use with only EPICOR II prefilter liners generated at

TMI-2. The State of Washington issued Certificate of Compliance No. WN-HIC-01 for this HIC on March 23, 1984. (464, 465)

- ***High-Integrity Containers (HICs) to Dispose of SDS Liners***. An attempt to qualify the design of the submerged demineralizer system (SDS) vessel as a burial container was unsuccessful because analysis indicated that pin-hole leaks in the stainless steel shell could not be ruled out within 300 years (10 half-lives of cesium-137) of burial. Therefore, the SDS vessels were buried inside polyethylene HICs. These poly HICs were permitted exclusively at the commercial low-level radioactive waste burial facility in Barnwell, SC. However, one problem existed with the use of the polyethylene HICs—some of the SDS liners exceeded 10^8 rads absorbed dose, which was the maximum authorized limit for these HICs. This problem was solved using a concrete liner inside the polyethylene overpack. With the concrete liner installed, the HIC was shielded from the SDS liner so that this absorbed dose limit was not exceeded over the required 300-year period. (466)

- ***Radiolytic Gas Generation***. Radiolytic gas generation in highly loaded submerged demineralizer system (SDS) vessels was calculated to be significant. Measurements of gas buildup confirmed that this could be a problem during storage and transportation, leading a DOE research program to develop several techniques to deal with it. To reduce buildup of flammable gas during transportation and storage, the vessels were drained and vacuum-pumped to remove free water. A catalytic recombiner system was developed, tested, and installed in SDS vessels that recombined the hydrogen and oxygen gases generated by radiolysis back into water, thereby eliminating gas generation. (467)

A pressure relief system, consisting of a burst diaphragm and micropore graphite filter, was also added to each SDS vessel to prevent the uncontrolled, long-term buildup of noncombustible gas mixtures. This addressed the possible net buildup of hydrogen due to oxygen scavenging by various chemical reactions, such as the formation of carbon monoxide and carbon dioxide from the oxidation of organic materials trapped within the zeolites. (468)



Design configuration of the HIC without an enclosed EPICOR II prefilter. (481.23)

- ***Solidification of EPICOR II resins***. The licensee pursued the solidification of EPICOR II resins in response to an NRC order; however, the value of such a complex, expensive, and non-ALARA operation was debated. As the regulatory and burial criteria were clarified (partly in response to this issue), alternative disposal methods became more appealing. The eventual agreement by the DOE to accept commercially nondisposable wastes from TMI-2 to research and develop high integrity containers satisfactorily resolved the issue without the need to solidify the resins at TMI-2. [(469)]

- ***Dry Waste Characterization***. Dry active waste at TMI-2 consisted of radiologically contaminated paper, plastic, rags, wood, and metal resulting from personnel access and work within contaminated areas of the plant. The dry active waste had high concentrations of fission products, with strontium-90 being the dominant isotope. The isotopic mix of the dry active waste from various points of generation throughout the plant was highly variable. To account for this variability, the dry active waste was categorized into distinct waste streams based on the ratio of cesium-137 to strontium-90, measured on contamination smears from various locations of the plant. Isotopic distributions, determined by gamma scans of the representative smears from these locations, were formulated for each waste stream. The transuranic and difficult-to-measure nuclides reportable under 10 CFR Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (i.e., technetium-99, carbon-14, nickel-63, iodine-129), were inferred from scaling factors [(j)] developed for the waste streams at TMI-2. A computer code developed a correlation between gamma radiation intensity and the isotopic distributions of each waste stream. Using this correlation, individual conversion factors for each waste stream were formulated based on various package sizes and waste densities. These dose-to-curie conversion factors determined the isotopic concentration of packaged dry active waste based on measured dose rates. [(470)]

- ***Incineration***. As an alternative to compacting lower activity solid waste, the project team investigated the use of an incinerator to reduce the volume. In 1981, the idea was studied (see GEND-021, "Controlled Air Incinerator Conceptual Design Study," [(471)] issued January 1982) and finally discarded because the volume of waste that could be incinerated was too small to justify the cost and technical difficulties. Regulatory uncertainties for air discharge permits were another factor in the decision to cease consideration. [(472, 473)]

8.3 Onsite Interim Waste Storage and Staging

Several onsite facilities were constructed for temporary storage of solid radioactive waste products from cleanup activities that were being readied for transportation.

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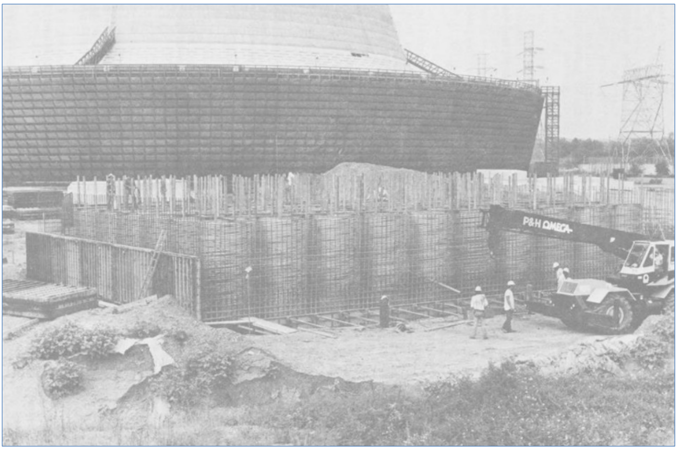
[j] Scaling factors were decay-corrected ratio correlations used to infer quantities of difficult-to-measure radionuclides from concentrations of tracer nuclides that are easily measured by gamma spectroscopy methods and routinely reported in sample results.

- ***Interim Waste Storage***. Waste disposal regulations established following the accident required considerable analysis and conditioning before waste shipment. This created a need to establish facilities or locations for the interim storage of waste to avoid impending delays in the decontamination of auxiliary and containment buildings. Interim waste storage was needed for the temporary storage of decontamination wastes. [474] Several temporary storage and staging facilities were constructed at TMI-2: (●) The *interim storage facility* was built in late 1979 to temporarily store EPICOR resin liners and filters until the construction of the solid waste staging facility was completed. (●) The *interim solid waste staging facility* (also known as the "car port") was opened in late 1982 and used to collect and temporarily store (stage) low-level solid waste packages from both Units 1 and 2. (●) The *solid waste staging facility* was used to collect and temporarily stage radioactive waste, such as dewatered resins, filters, and sludge, from both Units 1 and 2 before shipment. The first pad of 60 storage cells opened for use in early 1980. (●) The *waste handling and packaging facility* was used to process and package solid radioactive waste (see below). [475]

- ***Waste Handling and Packaging***. Completed in early 1987, the waste handling and packaging facility was a major support for the decontamination efforts. The facility processed and packaged solid radioactive waste, such as contaminated clothing, tools, and equipment. Processing of contaminated material consisted of compaction, size reduction, and decontamination for reuse at TMI-2. No radioactive waste was stored in this facility. [476] Sixty-nine percent of items were releasable after decontamination. [477]



Solid waste staging facility under construction.

Figure on Next Page: Model 125-B shipping cask loading tower. A fuel canister was lowered into the shipping cask (lower center) from the fuel transfer cask (not shown). The loading tower lowered the shipping cask to a horizontal position onto a skid that would be attached to the rail car.


3,100 LBS

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- ***American Nuclear Society (ANS).*** A special volume of the ANS *Nuclear Technology* journal includes 138 papers presented at the meeting held in Washington, DC, from October 30 to November 4, 1988. Volume 87 consists of four issues, each devoted to one of the specialized areas of technology covered during the meeting: Materials Behavior, Health Physics and Environmental Releases, Remote Technology and Engineering, and Decontamination and Waste Management. The papers in the proceedings may be purchased from the ANS Web site (http://www.ans.org/pubs/journals/nt/v_87).

- ***Electric Power Research Institute.*** EPRI staffed its TMI-2 site office from 1980 to 1992 with the purpose of transferring TMI-2 accident cleanup data and experience to member utilities and to provide technical support to the cleanup program. This technology transfer program involved EPRI, along with the licensee, the DOE, and the NRC. In the early stages, EPRI focused on research and development in support of decontamination and dose reduction. Towards the end of the cleanup, EPRI focused on all aspects of the cleanup program but placed the greatest emphasis on identifying developments and technologies that were applicable to operating plants.

EPRI sponsored the following series of reports to document every aspect of the decade-long cleanup at TMI-2. These reports are available to the public on its Web site (www.EPRI.com), except where noted:

- ***Contamination and Decontamination Experience with Protective Coatings at TMI-2***, EPRI Report NP-5206, 1987

  This report [478] documents the review of the TMI-2 experience with protective coatings, including the performance of protective coatings at TMI-2 before and after the accident. The report also documents the significant technical findings on coating behavior, including pertinent findings on the generic problems of coatings in contamination and decontamination procedures.

- ***Radiation Protection Management Programs at TMI-2: Noteworthy Practices and Accomplishments***, EPRI NP-5338, 1989

  This report presents an overview of the radiation protection tools and techniques that proved useful in the TMI-2 accident cleanup. It discusses protection training; exposure measurement; radiological engineering; and protection program management. Each discussion describes the challenge that confronted the cleanup effort, examines the tool or procedure that was designed to meet that challenge, and evaluates its effectiveness in contributing to dose reduction. This report is not available from EPRI's Web site.

- ***The Cleanup of Three Mile Island Unit 2, A Technical History: 1979 to 1990***, EPRI-NP-6931, 1990

  This report identifies the major questions and challenges that faced management, describes the influencing factors and the available options, and presents the final decisions and their consequences. This history of TMI-2 focuses on decisions related to seven major aspects of the cleanup: cleanup management; postaccident stabilization; personnel protection; data acquisition; radioactive waste management; decontamination; and defueling. A detailed chronology and extensive bibliography accompany the text.

- ***Decontamination Experience During the Cleanup of Three Mile Island Unit 2***, EPRI-NP-7157, 1990

  This report documents those lessons learned at TMI-2 in selecting and using various decontamination tools, products, and techniques to accomplish plant cleanup.

- ***TMI-2 Post-Accident Data Acquisition and Analysis Experience***, EPRI-NP-7156, 1992

  This report documents the data acquisition techniques used at TMI-2, describes the extent of damage and hazard conditions within the damaged plant, and provides a base of ideas and approaches for utilities that face an accident or other circumstances requiring special sampling and data acquisition techniques.

- ***TMI-2 Waste Management Experience***, EPRI-TR-100640, 1992

  This report provides comprehensive documentation on all the important aspects of the management of radioactive waste that resulted from the recovery and cleanup at TMI-2. In addition, this report provides a historical perspective to the recovery period by documenting the actual volumes of radioactive waste that were generated.

- ***Final TMI-2 Technology Transfer Progress Report***, EPRI-TR-100643, 1992

  This report discusses the technical accomplishments during the 1987–1992 period in the areas of decontamination; defueling; dose management; operations; radioactive waste management; reactor system characterization; robotics; and reactor damage assessment.

• ***International Atomic Energy Agency.*** IAEA publications provide technical guidance and recommendations for postaccident planning. The reports listed below, and others, are available to the public on its Web site (www.iaea.org):

- ***Recovery Operations in the Event of a Nuclear Accident or Radiological Emergency, Proceedings of a Symposium***, IAEA-STI/PUB/826, 1990

  This report [479] reviews the actual experience gained and lessons learned from recovery techniques and operations in response to serious accidents at nuclear facilities and accidents associated with radioactive materials, and to consider the development of emergency planning and preparedness resources.

- ***Catalogue of Methods, Tools and Techniques for Recovery from Fuel Damage Events***, IAEA-TECDOC-627, 1991

  This report provides information about possible methods and equipment to manage a nuclear fuel damage accident. The report serves as a reference catalogue of existing techniques. It draws primarily on work done at Chernobyl and TMI, but it also includes experience from minor fuel accidents and describes commercially available equipment that might be applicable.

- ***Management of Severely Damaged Nuclear Fuel and Related Waste***, IAEA-TRS-321, 1991

  This report [480] addresses onsite, postaccident management leading to a stable condition with respect to gaining control over damaged fuel, related waste, and radiological releases to the environment.

- ***Cleanup and Decommissioning of a Nuclear Reactor after a Severe Accident***, IAEA-TRS-346, 1992

  This report provides an overview of factors that are relevant to the identification of cleanup requirements and to the choice of a decommissioning option for a severely damaged nuclear power plant. A methodology is proposed to evaluate various options and to select an appropriate action in a particular accident situation.

- ***Experiences and Lessons Learned Worldwide in the Cleanup and Decommissioning of Nuclear Facilities in the Aftermath of Accidents***, IAEA-NW-T-2.7, 2014

  This report documents the review of experiences from IAEA Member States in the cleanup and decommissioning of nuclear facilities in the aftermath of an accident.

• ***U.S. Department of Energy***. The DOE documented lessons learned during its decade-long participation in the research and accident cleanup project at TMI-2. Reports are based on a review of a wide range of project documents and interviews with personnel from the many organizations involved:

- o ***TMI-2: Lessons Learned by the U.S. Department of Energy—A Programmatic Perspective***, DOE-ID-10276, 1990

  This report summarizes the lessons, both technical and administrative, learned by the DOE during its decade of involvement at TMI-2. It addresses a broad range of topics, including decontamination; robotics; radioactive waste management; reactor defueling; accident analysis; and project management and administration.

- o ***Historical Summary of the TMI-2 Core Debris Transportation Campaign***, DOE-ID-10400, 1993

  This report describes the TMI-2 core debris transportation campaign. Subjects include preparations for transport; loading at TMI-2; institutional issues; transport operations; receipt and storage at INEL; governmental inquiries and investigations; the exchange of information between the program and the public; and lessons learned.

- o ***Historical Summary of Fuel and Waste Handling and Disposition Activities of the TMI-2 Information and Examination Program (1980–1988)***, EGG-2529, 1988

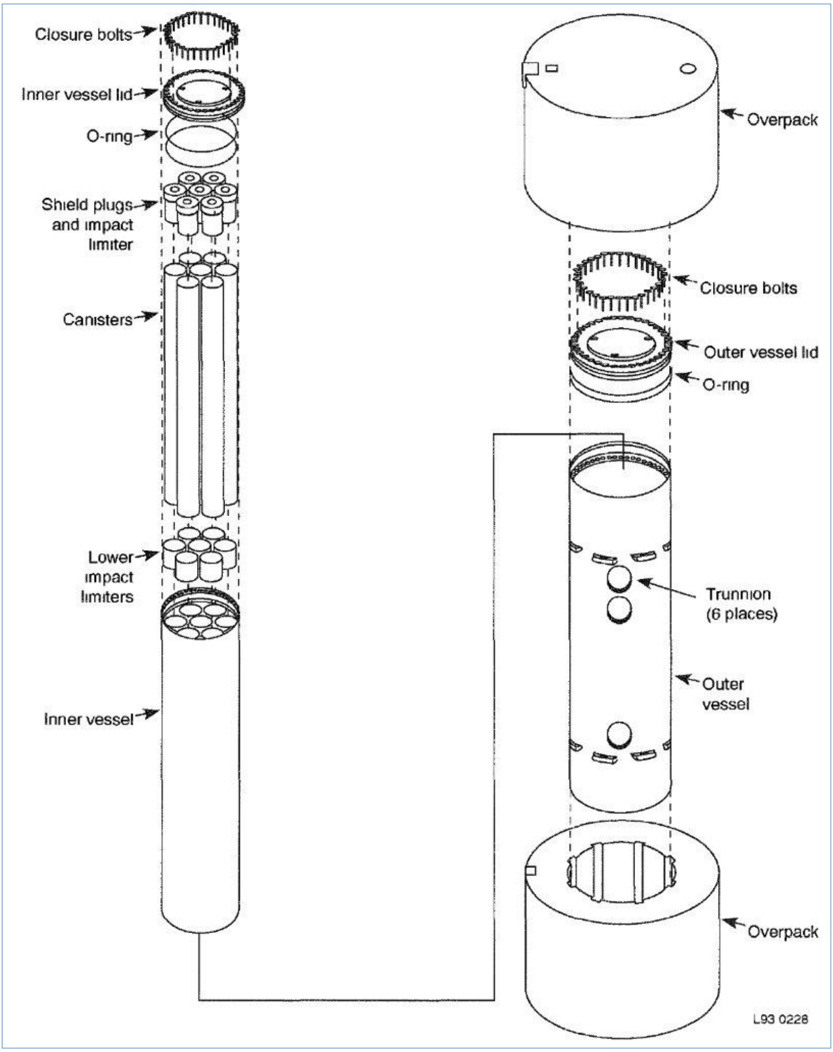
  This report provides an historical summary of the major activities conducted by the TMI-2 Information and Examination Program in managing fuel and special radioactive wastes resulting from the accident at TMI-2. The activities included the development and use of advanced handling, processing, and disposal technologies for those wastes.

- ***U.S. Nuclear Regulatory Commission***.

- o ***Three Mile Island Accident of 1979 Knowledge Management Digest: Recovery and Cleanup***, NUREG/KM-0001, Supplement1

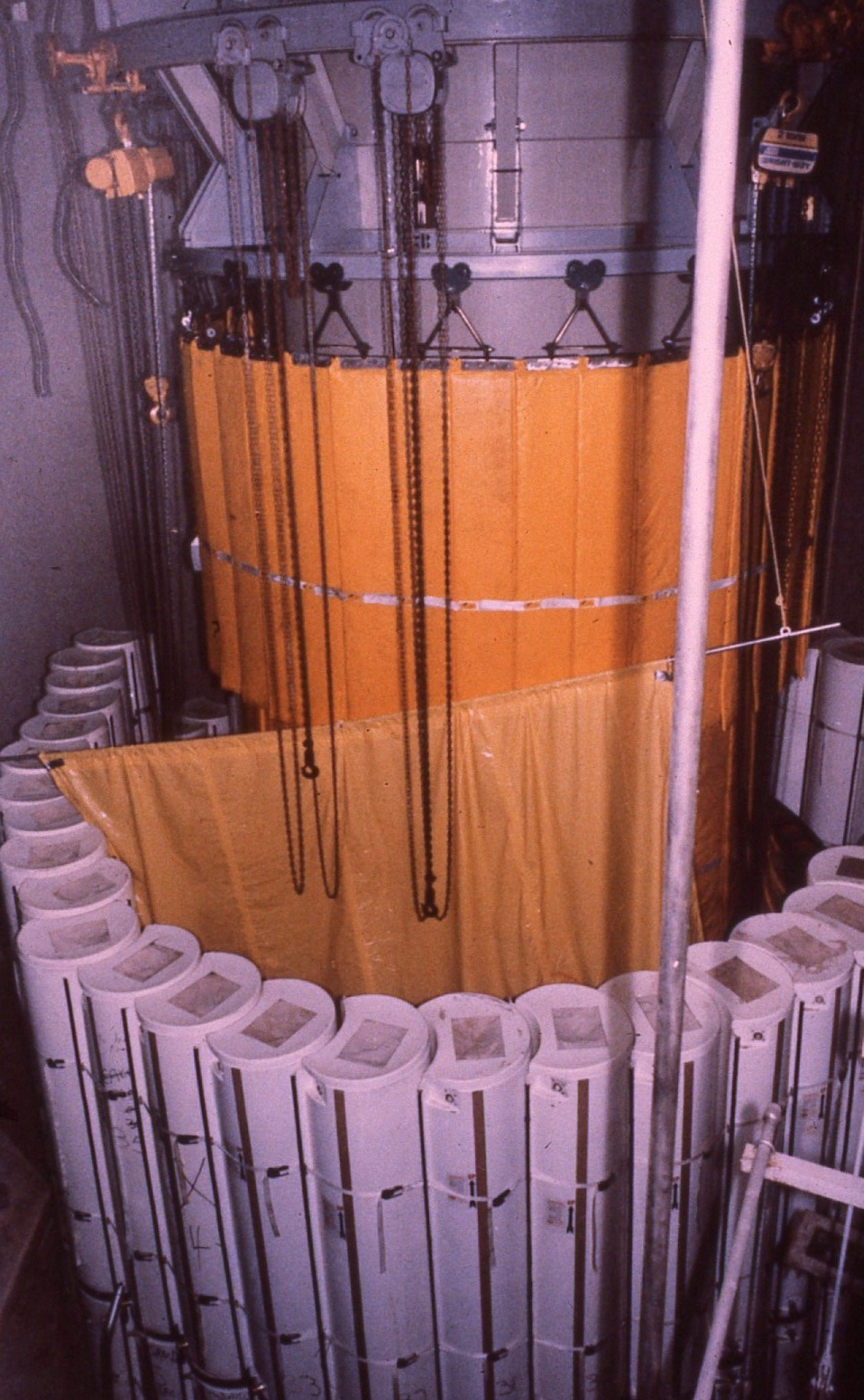
  The main objective of this supplement is to provide, in electronic format, the key historical documents that were issued during the recovery and cleanup efforts. The seven major aspects of the recovery and cleanup, as presented in EPRI-NP-6931, were used to organize the contents in this supplement into the following sections: management and oversight; plant stabilization; worker protection; data acquisition and analysis; radioactive waste management; decontamination; and defueling. It also includes an additional section on post-defueling activities. This supplement chronicles those activities that began a week following the accident and ended with the completion of disposal of accident-generated water and the entry into post-defueling monitored storage in 1993.

NUREG/KM-0001 and over 4,000 documents, photographs, and videos provided on the companion DVD set are available to the public from INL's Web site (https://tmi2kml.inl.gov). (481)



Model 125-B rail shipping cask. (481.24)

Figure on Next Page: Reactor vessel head (not shown) and service structure resting on its stand surrounded by shielding. Shown are white interlocking tubes filled with sand and yellow lead blankets. (Sand was found easier than water.)



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End notes embedded in figure captions are listed in the last endnote.

Many of the documents on the DVD are historical in nature and might contain information that is obsolete or superseded by current regulations and research results. The historical documents on the DVDs are for historical reference only and are not official NRC records. Please refer to the NRC's public Web site (http://www.nrc.gov) for current information on regulations, policy statements, regulatory guidelines, regulatory processes, and research results.

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11. ABSTRACT (200 words or less)

The objective of this report is to consolidate many of the experiences and lessons during the TMI-2 cleanup that had been recorded in numerous reports and papers. The experiences in this report focus on long-term plant stabilization, cleanup, and defueling. These experiences were based on an extensive review of a wide range of reports, presentations, and interviews with personnel formally from the key organizations involved in the cleanup.

Supplement 2 complements Supplement 1. The previous supplement provided summary descriptions of programs, activities, systems, and tools that were involved in the decade-long cleanup campaign of the damaged reactor core and severely contaminated equipment and buildings. In addition, the DVDs accompanying Supplement 1 contain most of the references cited in Supplement 2.

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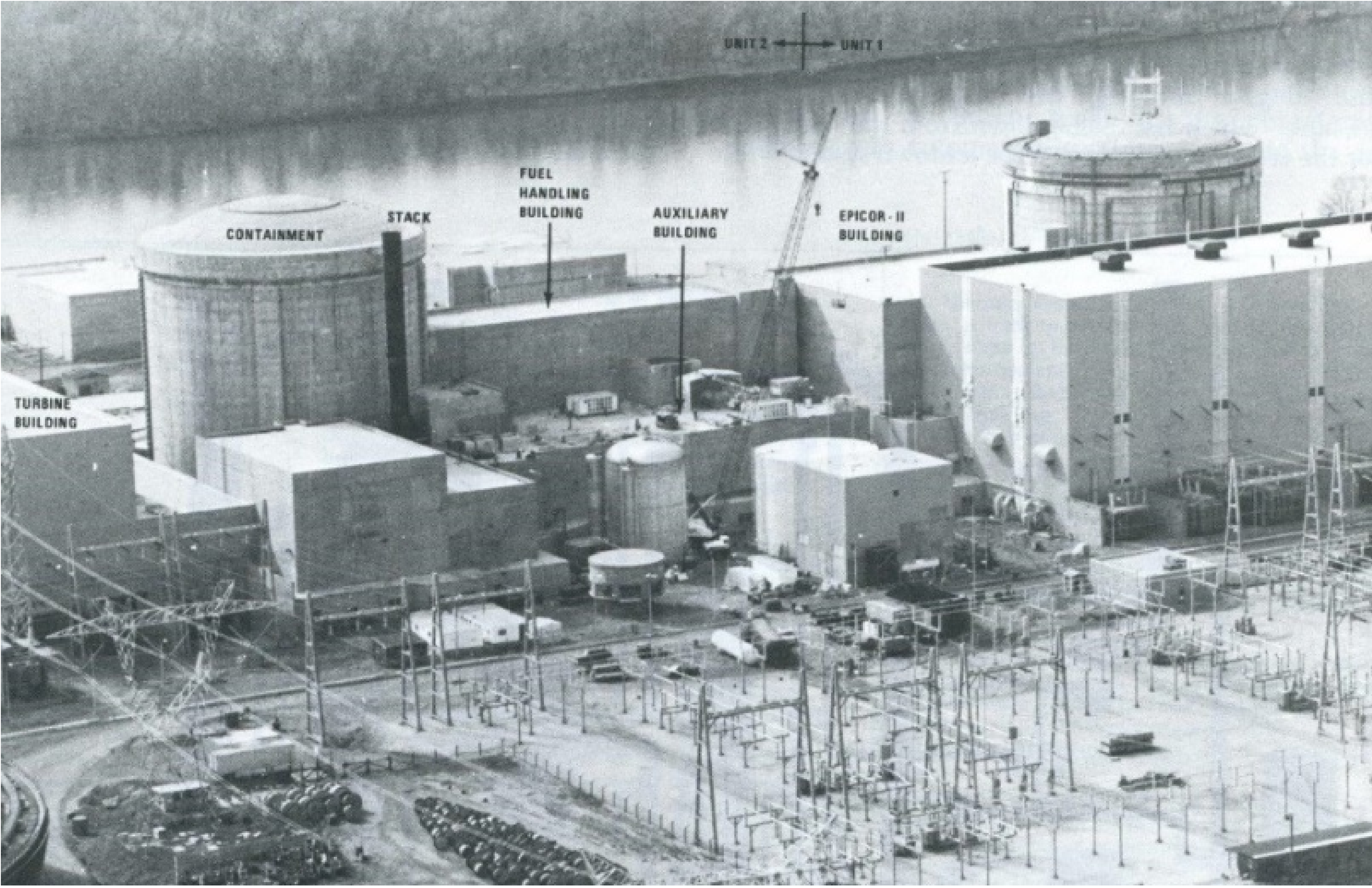
UNIT 2
UNIT 1
FUEL HANDLING BUILDING
STACK
CONTAINMENT
AUXILIARY BUILDING
EPICOR - II BUILDING
TURBINE BUILDING

CONVERSIONS

Radiation Dose

1 mrem (1 millirem, 10^{-3}) = *10 microsieverts (10 µSv, 10^{-5})

100 mrem = *1 millisievert (1 MSv)

1 rem = *10 mSv

100 rem = *1 Sv

Radioactive Concentration

27 picocuries (27 pCi, 2.7×10^{-11}) = *1 becquerel (1 Bq)

1 millicurie (1 mCi, 0.001) = *37 megabecquerels (37 MBq, 3.7×10^{7})

1 curie (1 Ci) = *37 gigabecquerels (37 GBq, 3.7×10^{10})

Radiation Absorbed Energy

1 roentgen = *0.877 rad = *0.00877 gray (Gy)

100 rad = *1 Gy

Length

1 inch (in.) = *2.54 centimeters (cm)

1 foot (ft) = 0.3048 meter (m)

Volume and Weight

1 gallon (gal) = 3.7854 liters (L)

1 pound (lb) = 0.4536 kilograms (kg)

1 ton (U.S.) = *2000 lb = 907.1847 kg

Pressure

1 pound per square inch (psi) = 6.8948 kilopascals (kPa)

1 atmosphere (atm) = *101.325 kPa

Temperature

Degrees Celsius (°C) = 5/9 × (°F - 32)

Degrees Fahrenheit (°F) = (9/5 × °C) + 32

* Exact conversion factor

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