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TMI-2: Lessons Learned by the U.S. Department of Energy

A Programmatic Perspective

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Idaho National Engineering Laboratory

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TMI-2 LESSONS LEARNED BY THE U.S. DEPARTMENT OF ENERGY—

A PROGRAMMATIC PERSPECTIVE

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TMI-2: LESSONS LEARNED BY THE U.S. DEPARTMENT OF ENERGY— A PROGRAMMATIC PERSPECTIVE

ABSTRACT

This report is a summary of the lessons learned by the U.S. Department of Energy during its decade-long participation in the research and accident cleanup project at Three Mile Island Nuclear Power Station Unit 2 near Harrisburg, Pennsylvania. It is based on a review of a wide range of project documents and interviews with personnel from the many organizations involved. The lessons are organized into major subjects with a brief background section to orient the reader to that subject. The subjects are divided into sub-topics, each with a brief discussion and a series of lessons learned. The lessons are very brief and each is preceded with a keyword phrase to highlight its specific topic. References are given so that the details of the subject and the lesson can be further investigated.

ACKNOWLEDGEMENTS

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SUMMARY

In the ten years since the Three Mile Island accident, millions of man-hours and approximately a billion dollars have been spent on plant cleanup. The U.S. Department of Energy (DOE) has been involved in many aspects of the TMI-2 research and recovery program. Its goal has been to advance nuclear reactor safety by transferring the knowledge gained from TMI-2 to the worldwide nuclear community. This report is a summary of the lessons—both technical and administrative—learned by 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
- Project Management and Administration.

The decontamination lessons focus on the specific equipment used at TMI-2 and on general observations (surveying techniques, preventing recontamination, training, etc.). Observations on radionuclide penetration into concrete are also presented. The lessons on robotics and remote technology are divided into program development lessons (teamwork, available funding sources, reliability, training, etc.) and specific equipment lessons (preventing vehicle damage, minimizing contamination, maintenance tips, etc.). TMI-2 developments in the areas of special dosimetry, respiratory protection, radionuclide measurements, worker training, and heat stress are discussed under worker protection. Among the most important TMI-2 lessons are those discussed under radioactive wastes and fuel debris. These lessons address volume reduction techniques, performance of ion exchange media, control of combustible gases, waste disposal techniques, and a variety of lessons related to radioactive material shipments. Reactor defueling lessons include prevention of recriticality, underwater disassembly techniques, specialized data acquisition tooling, molten material formation, and various techniques to expedite removal of damaged fuel. The accident analysis lessons address radionuclide behavior, steam explosions, reactor vessel damage, and the performance of instruments and electrical equipment during the accident. The final section on project management and administration includes lessons on corporate organization, data acquisition and research, public affairs, and effective documentation.

The goal of TMI-2: Lessons Learned by the U.S. Department of Energy—A Programmatic Perspective is to provide a source of ideas, techniques, and approaches for those working in the nuclear industry, as well as others involved in large-scale, multi-disciplinary technical projects.

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1. INTRODUCTION

Plant cleanup of the Three Mile Island Nuclear Power Station near Harrisburg (PA) has taken over ten years. Approximately a billion dollars will have been spent by the time the project is completed. Since the first days of the accident, the nuclear industry has learned many lessons from the accident investigation and research. The knowledge gained over the past decade has influenced all aspects of the industry. A partial list includes:

- A complete refocusing of reactor safety research worldwide;
- Fundamental changes in the way reactors are regulated;
- Mandatory new equipment to help prevent accidents;
- New training requirements for reactor operators;
- New knowledge of the mechanisms of high temperature fuel damage;
- Innovative techniques for plant decontamination;
- Unique tools for defueling and sample acquisition;
- New equipment and procedures for measuring radioactivity;
- Improved techniques for processing radioactive wastes;
- Major improvements to the computer codes used to predict reactor behavior during an accident; and
- Innovations in transporting reactor fuel and wastes.

Following the accident, the U.S. Department of Energy (DOE) was given the charter by Congress to participate in the cleanup program, learn from the accident, transfer the knowledge gained to the nuclear industry, and sponsor original research into reactor safety issues. Other organizations participated in this effort including GPU Nuclear (operator of TMI-2), the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, the Edison Electric Institute, the Commonwealth of Pennsylvania, numerous contractors, and a number of foreign countries.

This report is one attempt to summarize many of the lessons learned at TMI-2 . No one report could adequately condense all that has been learned. The lessons focus only on those aspects of TMI-2 research and recovery in which the DOE was involved directly. This report is intended as a resource for managers, engineers, and technologists within the nuclear industry, or those faced with other large, formidable, technical projects. Accordingly, while some lessons are quite specific, others are much more general. Perhaps some lessons will call readers' attention to techniques, ideas, and approaches that can be applied to their unique situations.

This report is organized into major subjects, each of which is in turn divided into a few specific sub-topics. A brief background section explains the subject in relation to TMI-2. Brief discussion sections provide additional explanations of the sub-topics. A series of lessons learned is then presented for each sub-topic. A brief title (in bold type) precedes each lesson. This format makes it easy for the reader to scan through the lessons and locate those of interest. Complete references for subjects and lessons are located at the ends of each section.

Many lessons may have applications beyond nuclear reactor safety. While the knowledge gained from TMI-2 has been of immeasurable help to the nuclear power industry throughout the world, much of this knowledge could benefit other large-scale technical projects. It is with the goal of technology transfer in mind that the DOE prepared this report.

2. DECONTAMINATION

2.1 Background

During the TMI-2 accident, fuel rods ruptured and mixed fission products and core debris escaped with the coolant water, steam, and hydrogen out of the reactor pressure vessel through the stuck-open pilot operated relief valve on the pressurizer. The coolant collected in the reactor coolant drain tank until the rupture disk on the tank burst, discharging contaminated water and steam into the basement of the reactor containment building. The discharge continued for about two hours until the pressurizer block valve was closed, releasing an estimated 265,000 gallons of water. Contamination also entered the auxiliary and fuel handling building (AFHB) of TMI-2 as tanks and sumps overflowed and airborne contamination entered the ventilation systems. The result was unprecedented contamination for a commercial reactor, both in extent and radionuclide composition .

Approximately eight hours after the start of the accident, the hydrogen that had accumulated in the containment building ignited, actuating the containment spray system. The spray system operated for more than five minutes, discharging almost 17,000 gallons of water which eventually found its way to the basement sump. During the next two years, the amount of water in the basement gradually increased because of continued leakage from both the reactor coolant system and the reactor building air cooling assembly. Those systems leaked about 180,000 gallons each. In total, more than 640,000 gallons of water, containing about one-half of the core inventory of Cs^{137} and large amounts of other radionuclides, collected in the reactor building basement.

Examination and decontamination of other areas of the facility (including the AFHB) began immediately after the accident, although general contamination levels remained elevated for a long time. High airborne radioactivity, high surface contamination, and the volume of contaminated water 8-1/2 feet deep in the basement made the reactor containment building completely inaccessible after the accident. It remains so till this day. The first entry into the reactor building did not occur until sixteen months later, following venting of radioactive gases, video camera inspection of the building condition, and analyses of the containment building air and basement water samples. Several years of extensive decontamination efforts were required to reduce the radiation fields to levels that allowed worker access for repair of equipment, decontamination, and defueling. (Reference: 2.1, 2.2, 2.3)

2.2 Gross Decontamination

2.2.1 Discussion

A Containment Assessment Task Force was established about a month after the accident. Its objectives were to evaluate the environment of the reactor building, determining if personnel entry was feasible, and develop plans for the plant cleanup and reactor defueling. The data acquisition efforts and the later venting of the radioactive gases from the containment paved the way for the first manned entries. The entries made possible a thorough examination of the level of contamination. That evaluation indicated that a large-scale effort to decontaminate the floors of the reactor building would reduce dose rates by factors of 10 to 100.

This extensive effort, referred to as the gross decontamination task, began in March 1982. Various decontamination techniques were tested on different surfaces and components within the building . Low pressure water (about 2,000 psi) was used to flush the polar crane, D-rings, missile shields, refueling canal, refueling bridge, and other pieces of equipment. Selected floors and surfaces were cleaned with high pressure water (up to 10,000 psi), mechanical scrubbers, concrete scabblers, chemical additives, and strippable coatings. The gross decontamination task was a significant step in the recovery program because it:

- Systematically evaluated the safety, effectiveness, and efficiency of various decontamination techniques and equipment;
- Determined the personnel and equipment resources required;
- Significantly reduced contamination on many surfaces in the reactor building; and
- Acquired data essential to planning further decontamination. (Reference: 2.4, 2.9)

2.2.2 Lessons Learned

Recontamination Concerns

Recontamination was an annoyance 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, and splashing and overspray onto adjacent surfaces contributed to the problem. Once surfaces were decontaminated and nearby unconfined sources of water eliminated, step-off pads and barriers were quickly implemented to reduce the opportunity for recontamination. (Reference: 2.5)

Frequent Surveying Important

Frequent surveying of the areas decontaminated was essential to tracking the progress made in reducing contamination and identifying recontamination sources. Though difficult, monitoring surface contamination levels during the decontamination efforts (by surveying surfaces during brief interruptions of the operation) improved the effectiveness of decontamination. (Reference: 2.5)

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. (Reference: 2.5)

No Water Temperature Effect

Surface decontamination effectiveness was not significantly altered by flushing water temperature despite other studies indicating hot water to be superior. (Reference: 2.5)

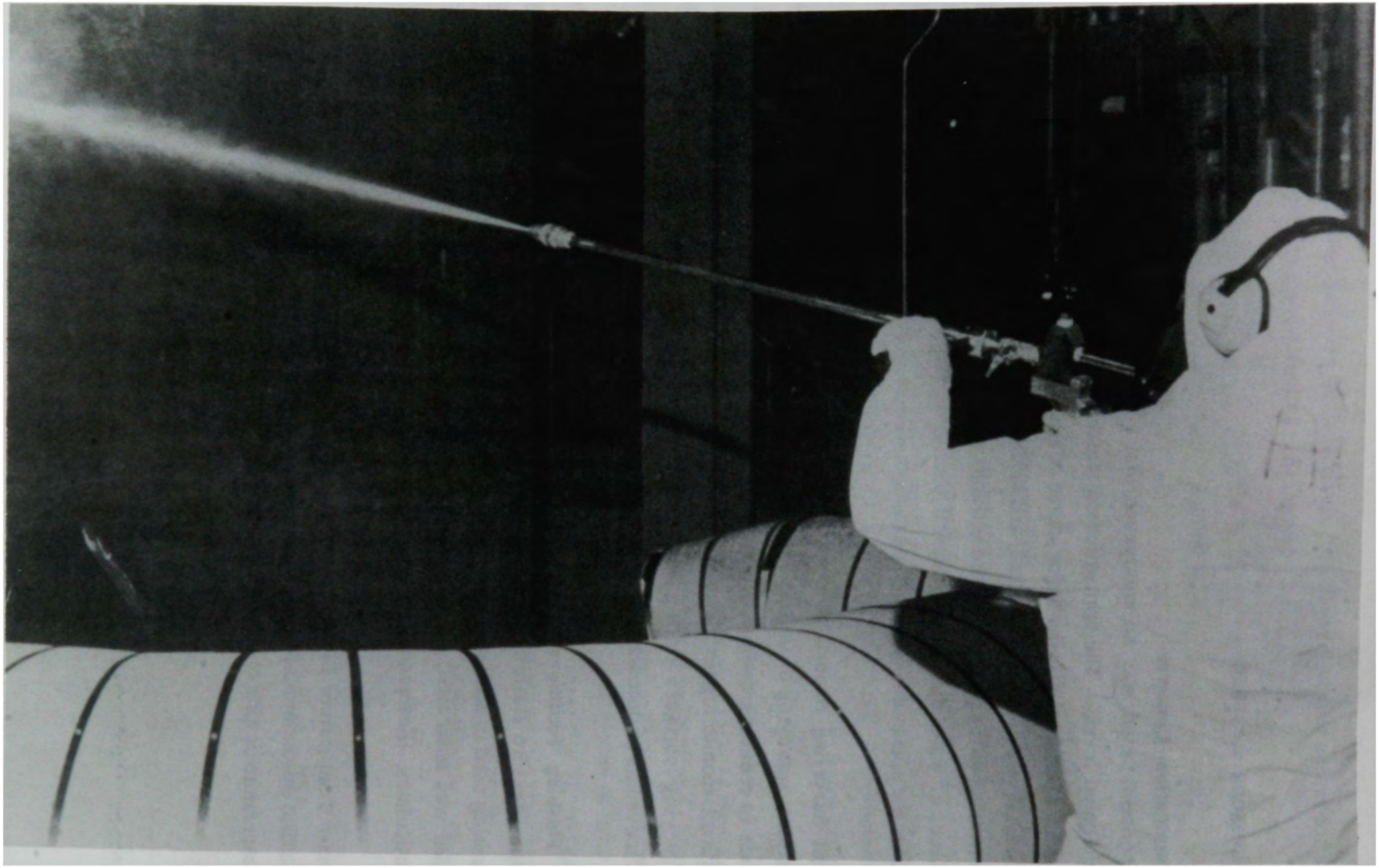


Figure 1. High-pressure spray system in use in the TMI-2 reactor building.

2.3 Decontamination Techniques and Agents

2.3.1 Discussion

Gross decontamination tested a variety of techniques in the TMI-2 reactor building, but the principal technique used was water spray systems. Much free water from the spray systems drained to various sumps and into the basement of the reactor building . Since various processing systems (mainly ion exchange resins and zeolites) were installed to filter radionuclides present in the accident-generated water, the spray systems that could have been used for decontamination were limited. For example, certain chemical additives that might have improved the decontamination efficiency of the sprays would have damaged the water processing equipment.

The water spray systems were capable of delivering water at temperatures up to 180°F, pressures up to 10,000 psi, and at flow rates up to 25 gpm. The hydrolaser, a high pressure spray probe, was used on the floors and walls. It was most effective at flow rates of 7 to 12 gpm. Low pressure sprays were used mainly to flush equipment, though they also were used to remove loose surface debris on floors. Though capable of operating up to 2,000 psi, the low pressure systems were generally used at 400 to 700 psi and at flow rates of 20 to 25 gpm.

One very effective decontamination device utilized a combination steam supply system and vacuum system, with a self-contained waste collection container. That device decontaminated painted and uncoated concrete, ductwork, diamond deck plate, lead brick, Herculite penetration covers, piping and conduit cable trays, and drain covers. The equipment applied steam at approximately 200 psi and 350° F to contaminated surfaces and then vacuumed the non-adherent contaminants freed from the surface by the steam.

Strippable coatings were used on contaminants fixed on painted surfaces, lodged in concrete pores and cracks, and on some pieces of equipment. A self-stripping coating was used at TMI-2. As the coating dried, it cracked and peeled away from the surface; it was then swept up or vacuumed.

Another effective method of decontaminating coated and bare concrete surfaces was mechanical scabbling. Scabblers used pneumatically operated reciprocating pistons equipped with tungsten carbide bits to pulverize the concrete surface. Scabblers using one, three, or five pistons were tested on concrete areas of varying size and configuration. To prevent airborne contamination, a vacuum system with a high efficiency particulate air (HEPA) filter was attached. (Reference: 2.5, 2.6, 2.7, 2.8, 2.11)

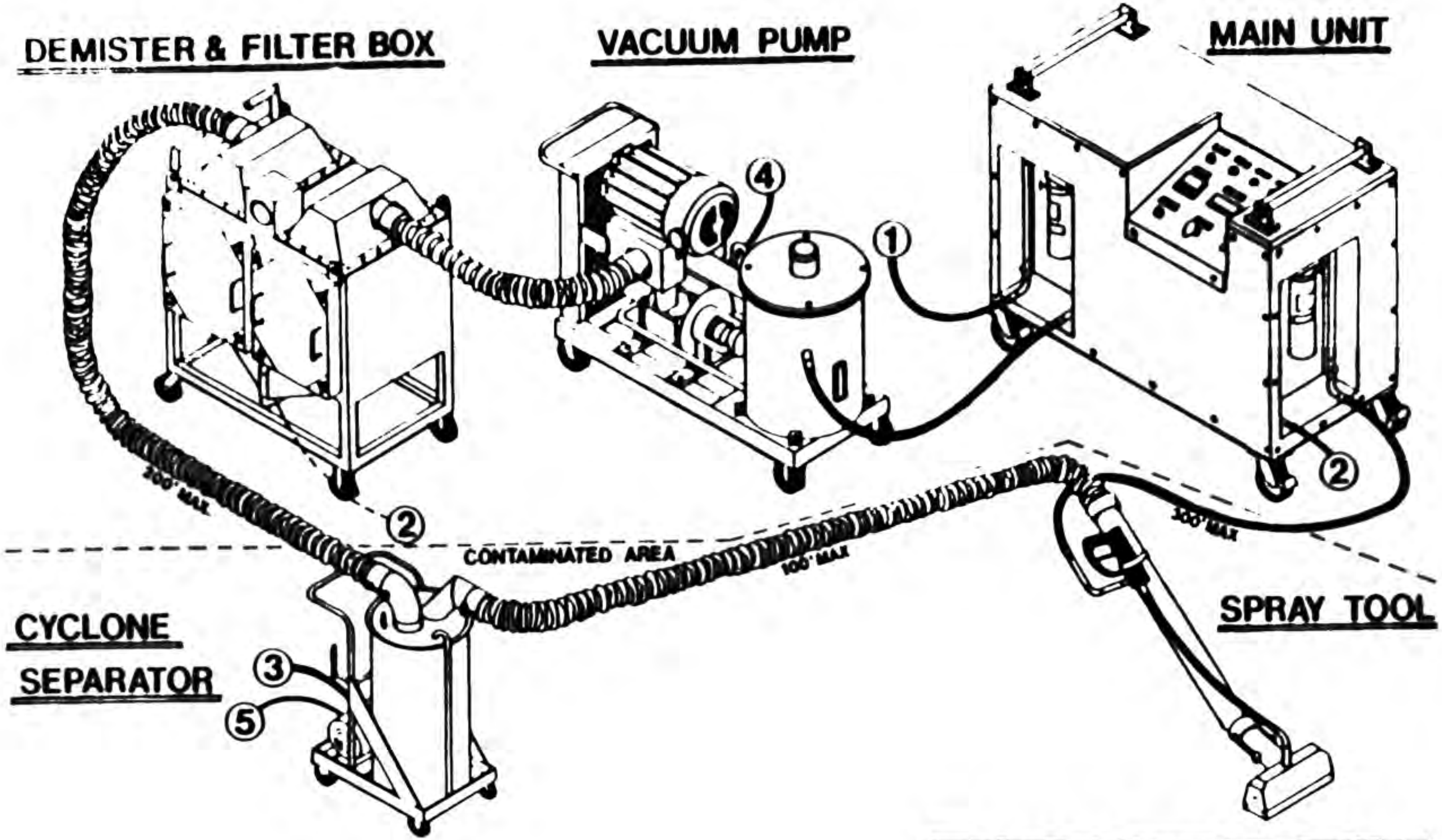
2.3.2 Lessons Learned

Chemical Additives for Decontamination

Many chemical additives are available to improve the performance of decontamination systems. Most could not be used at TMI-2 because of the potential for damage to the water cleanup systems. Detergents and phosphoric acid were evaluated, however they were found to have limited effect and were not widely used. When considering decontamination chemicals, their effects on stainless steel and other materials within the nuclear steam supply system must be evaluated carefully. (Reference: 2.5, 2.7)

Steam/Vacuum System Performance

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 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 such as Herculite, which were drawn into the vacuum inlet. (Reference: 2.11)



SYSTEM REQUIREMENTS	
1	WATER INPUT
2	RESERVOIR AND CONDENSATE
3	CONTAMINATED WATER OUTPUT
4	480v. 3ph.
5	110v. 1ph.

Figure 2. Combination steam/vacuum system used at TMI-2.

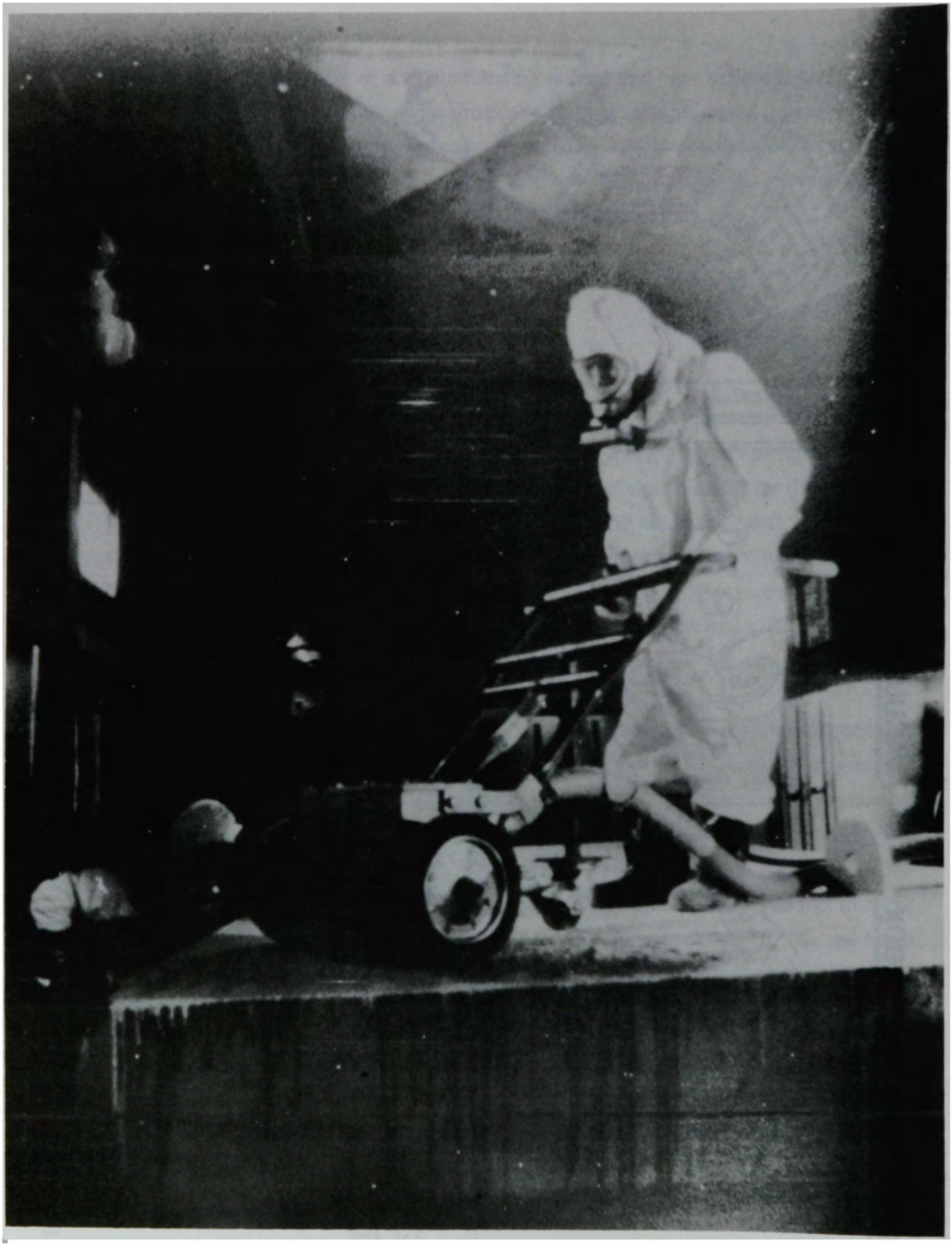


Figure 3. Manually operated scabbler used in TMI-2 reactor building.

Removal of Strippable Coatings

At TMI-2, strippable coatings (e.g., synthetic polymers applied by spraying or manual applicator) used on large floor areas were removed manually by cutting, peeling, and rolling the material up to contain the contamination. A 55-gallon waste disposal drum will accommodate the refuse from 2,000 to 2,500 ft.^{2} of coated surface. Successful application and removal of strippable coatings were dependent on operator experience. Dedicating a trained group of workers was cost effective.

Workers at TMI-2 did have some difficulty in removing coatings from highly porous surfaces. A cheesecloth base was tested to determine if it increased the tensile strength and body of the coating to make removal easier. The base did make the coating come off more completely, but was unnecessary for most applications. Self-stripping coatings are useful in high radiation areas because the coating can be applied and removed by remote vehicles. (Reference: 2.5, 2.6, 2.7)

Recontamination Protection

Strippable coating used after initial decontamination by water spraying adsorbed residual loose debris. The coating also protected against recontamination. (Reference: 2.6)

Versatile Vacuum System

A high efficiency vacuum collection system was designed to attach to a variety of devices, including manual scabblers. The system eliminated 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. (Reference: 2.10)

Remote Scabbler

A remotely operated scabbler was designed for use at TMI-2, although it was developed too late to be used. The device has been successfully tested in other decontamination applications. The scabbler can be operated from 50 feet away. It cuts a path 18 inches wide and can decontaminate concrete surfaces at rates of 400 ft^2 per hour, about three times faster than manual scabbling. A self-contained vacuum system equipped with a HEPA filter eliminated dusting. (Reference: 2.6, 2.10)

Figure 4. TMI-2 worker removing strippable coating from concrete floor.

Figure 5. Remotely operated scabbler designed for use at TMI-2.

2.4 Radioactivity Penetration into Concrete and Its Removal by Leaching

2.4.1 Discussion

After the accident, the contaminated water that pooled in the basement of the reactor building was pumped out, processed through ion exchange media, and stored in holding tanks. Residual radioactivity from the accident water contaminated the coated and uncoated concrete of the floors and walls and penetrated to various depths. A proposed decontamination method was reflooding the basement with clean water, and leaching the contaminants from the concrete. Because high radiation fields in the basement prohibited personnel entry, a remote sampling program was implemented to acquire data. Core samples of the floors and walls were collected and tested to determine the distribution and quantity of radionuclides in the three types of concrete found in the basement, and the rate at which leaching removed radioactivity from the various types of concrete.

Samples of the different types of reactor building basement concrete were leach tested. The samples included coated 5,000 psi concrete, uncoated 3,000 psi, and block wall. Side surfaces of all samples and bottom surfaces of the 3,000 and 5,000 psi concrete were sealed with paraffin. Thus, all leaching from each core sample occurred through the surface(s) that had been originally exposed to the accident water. The samples were immersed in a leach solution that simulated reactor coolant containing 5,000 ppm boron and 1,500 ppm sodium, at a pH of 7.6. Each test lasted 125 days; the immersion solution was replaced every 33.3 days to measure variations in leach-rate. At the conclusion of the test, samples were analyzed destructively for cesium and strontium. (Reference: 2.12, 2.13, 2.14)

2.4.2 Lessons Learned

Effect of Concrete Coatings

Coating concrete surfaces does not significantly reduce the maximum penetration depth of radionuclides absorbed from spills. However, coating does reduce the quantity of radionuclides absorbed by one to two orders of magnitude, and decreases the rate of radionuclide penetration. Thus, protection of concrete surfaces with epoxy coatings makes cleanup from a radioactive liquid spill much easier. (Reference: 2.13)

Radionuclide Penetration into Concrete

For the high strength concretes (3,000 and 5,000 psi), radionuclide penetration was limited to ~1.0 cm., with ~90% of the activity located in the first 0.5 cm. (Reference: 2.13)

Radionuclide Absorption into Concrete Block

The concrete block absorbed large quantities of activity from aqueous solutions; radionuclides penetrated deep into its structure. Concrete block should not be used in areas subject to waterborne contamination. (Reference: 2.13, 2.14)

Radionuclide Leaching from Concrete

Cesium and strontium can be leached from all types of concrete. (Reference: 2.14)

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3. ROBOTICS AND REMOTE TECHNOLOGY

3.1 Background

Contamination in parts of the TMI-2 containment building and auxiliary and fuel handling building (AFHB) following the accident presented access and radiation exposure problems to which remote technology provided the best solution. In the early stages of cleanup, conventional decontamination techniques were used to gain initial access to important areas like the AFHB. The basement of the reactor building however, was so contaminated that all activities—characterization, sample acquisition, and decontamination—were conducted using remote technology. Since high radiation fields also remained in other areas, requiring periodic surveillance, it was clear that remote vehicles could be used to eliminate some personnel radiation exposure.

In 1980, a remote technology project team examined robotic applications at TMI-2 and identified two categories of equipment needed for cleanup operations: (1) remotely operated transporters; and (2) fixed position remotely operated tools. Implementation of a robotics program began in earnest in 1981. None of the commercially available robot vehicles completely suited the TMI-2 requirements; therefore, the first robots used were modified commercial models. Early practical experience was also gained using robotic vehicles loaned to the TMI-2 project by DOE. It was not until 1984 that the first robotic equipment custom-designed for TMI-2 surveillance, characterization, sample acquisition, and decontamination was delivered and deployed. Several series of robotic vehicles were developed, each with attachments providing tools for specific tasks. Those vehicles were both versatile and productive, and proved useful in many different tasks, including video camera inspections, radiation monitoring, sediment sampling, acquisition of concrete samples by coring, high pressure water flushing, concrete scabbling and scarification, and debris pickup and removal.

In addition to the remote vehicles, a number of fixed-position, remotely operated tools was developed for work inside the reactor vessel. The tools included a plasma arc cutting system to remove the stainless steel core support assembly, and several manipulator arms for handling damaged fuel and structural components. (Reference: 3.1, 3.2, 3.3, 3.4, 3.5, 3.9, 3.11, 3.12)

3.2 Robotics Program Development

3.2.1 Discussion

An extensive remote technology program evolved at TMI-2. The program included the development of robotic vehicles and fixed-position robotic tools, and included loaned equipment, modified commercial equipment, and custom-designed devices. The robots were developed by various organizations and supported by funding and engineering services from utilities, government agencies, research organizations, foreign nuclear organizations, and universities.

The TMI-2 program was the most extensive remote technology program yet undertaken by a utility. As a result, many issues were identified and illuminated during the course of the program, including selection of tasks for remote technology, detailed description and characterization of tasks, assembly of a multi-disciplinary planning team on robotics, developing functional and operational requirements for each robot, design considerations for each robot, cost-benefit analysis of using robotics vs. workers, training and qualification program for operation of each robot, and the potential impact of remote technology on plant licensing and regulation. (Reference: 3.2)

3.2.2 Lessons Learned

Developing a Robotics Team

Crucial to success in using remote technology at TMI-2 was the establishment of a dedicated and multi-disciplinary robotics team. Team members included managers, engineers, technicians, end-users, craftsmen, and laborers from various departments of GPU Nuclear. Among the departments and disciplines represented were mechanical, electrical, instrumentation and controls, industrial safety, quality assurance, radiological controls, and decontamination. Each member contributed an important perspective to planning, task selection, approval, design of equipment, worker acceptance, development of procedures, performance evaluation, and plant licensing implications. (Reference: 3.2)

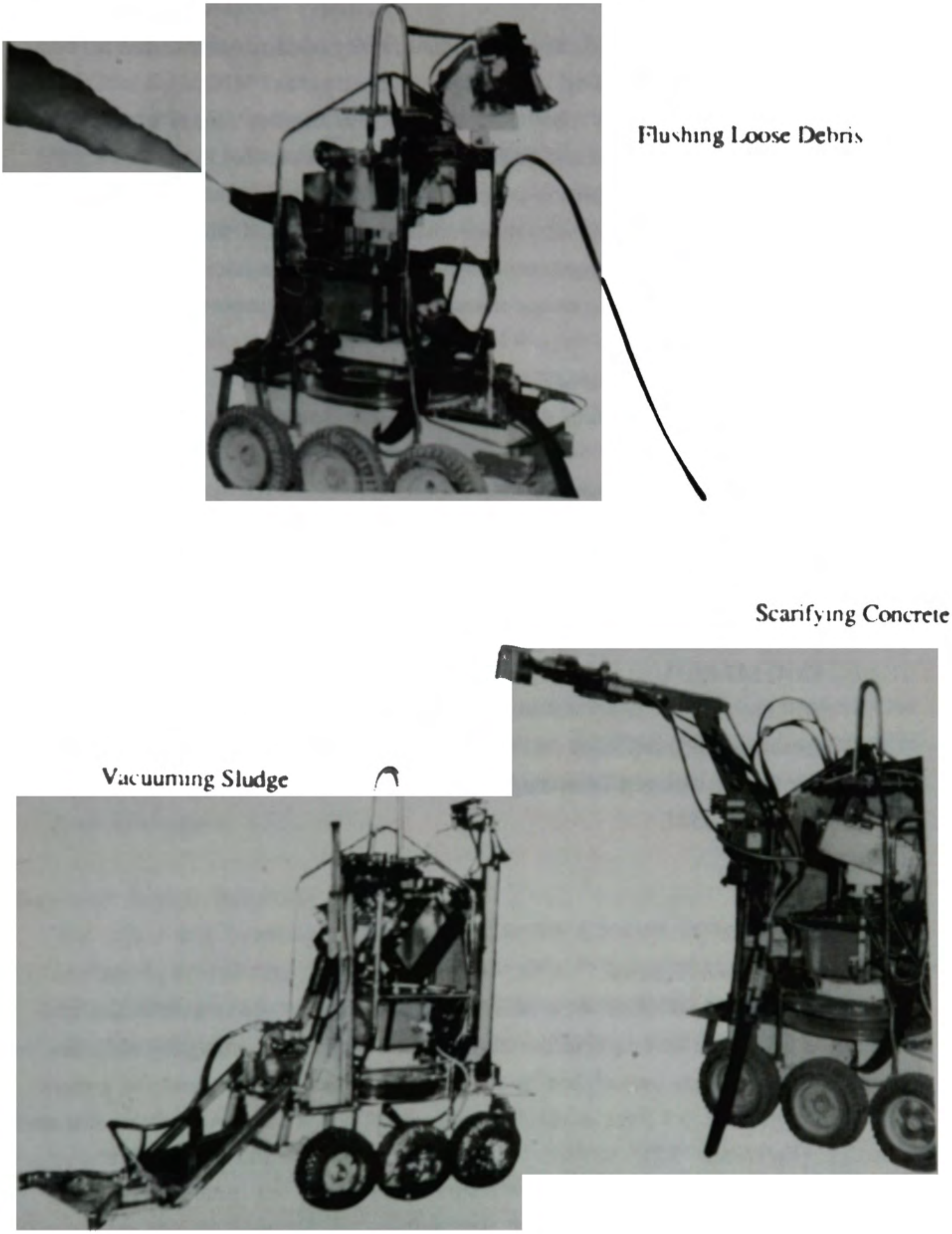

Figure 6. The TMI-2 Remote Reconnaissance Vehicle (RRV) at work

Program Funding Sources

During the course of the TMI-2 robotics program, many options materialized for cost sharing and supplemental funding. The unique applications at TMI-2, the visibility of the program, and the relative robotics inexperience of utilities caused a variety of organizations to offer financial and engineering support. Costs for implementing the robotics research and development program were minimized by exploring outside funding options. Industry, robotics manufacturers, federal and state governments, research organizations, remote equipment manufacturers, and educational institutions all had an interest in participating in unique remote technology programs. (Reference: 3.2)

Remote Vehicle Support Organizations

Among the organizations providing guidance to the utility on remote technology systems and uses were:

Utility-Manufacturer Robotics Users Group
(201) 430-6646

Electric Power Research Institute
Maintenance Equipment Applications Center
(704) 547-6100

American Nuclear Society
Remote Systems and Technology Division
(803) 725-3527.

(Reference: 3.2)

Tethered vs. Untethered Vehicles

At TMI-2, tethered vehicles were selected despite reduced maneuverability and limitations caused by the length of the tether and the problem of entangling obstacles. Those drawbacks were outweighed by the unlimited operation time and the greater vehicle strength and tool force available from external power sources versus on-board batteries. (Reference: 3.2)

Supplemental Cameras on Vehicles

To help operators orient the vehicle within its environment, experience gained at TMI-2 indicated that one or more survey cameras viewing both the vehicle and the general area would be useful. An on-board camera viewing the vehicle's tether reel system, and a vehicle operator responsible for tether management, were essential. Safe operation of the manipulator arm required camera observation not only of the tool attachment, but also motions of the elbow and shoulder. (Reference: 3.7, 3.10)

Licensing Implications of Remote Vehicle Use

10 CFR 50.59 mandates that any alteration of the plant configuration as outlined in the final safety analysis report (FSAR) requires a safety analysis be written and submitted to the Nuclear Regulatory Commission. The impact on GPU Nuclear's operating license by the use of remote controlled equipment was evaluated and it was determined that robotic equipment itself did not alter the FSAR, because the equipment was in the same category as other maintenance equipment. Licensing impact could result, however, if the specific task performed by the robot altered the plant configuration or if permanently installed remote equipment was being proposed. (Reference: 3.2)

Vehicle Lifting Considerations

If a robot vehicle is lifted over a safety related area or component, design factors for the lifting point may need increasing. For example, the TMI-2 remote reconnaissance vehicle's lifting attachments were designed with a safety factor five times greater than the load. (Reference: 3.7)

Improved Vehicle Reliability

The safety and financial consequences of losing a remote device made reliability important. Accordingly, special attention was given to redundant vision systems, tether management procedures, radio signal interference with remote devices, and tracking component failure rates to eliminate design flaws. (Reference: 3.10)

Important Operator Skills

Individuals possessing certain skills were found superior in operating remote vehicles. Testing, screening, and training were used to identify operators with the ability to correlate the position of the manipulator with the target object, good hand-eye coordination, the ability to interpret surroundings through the perspective of a video

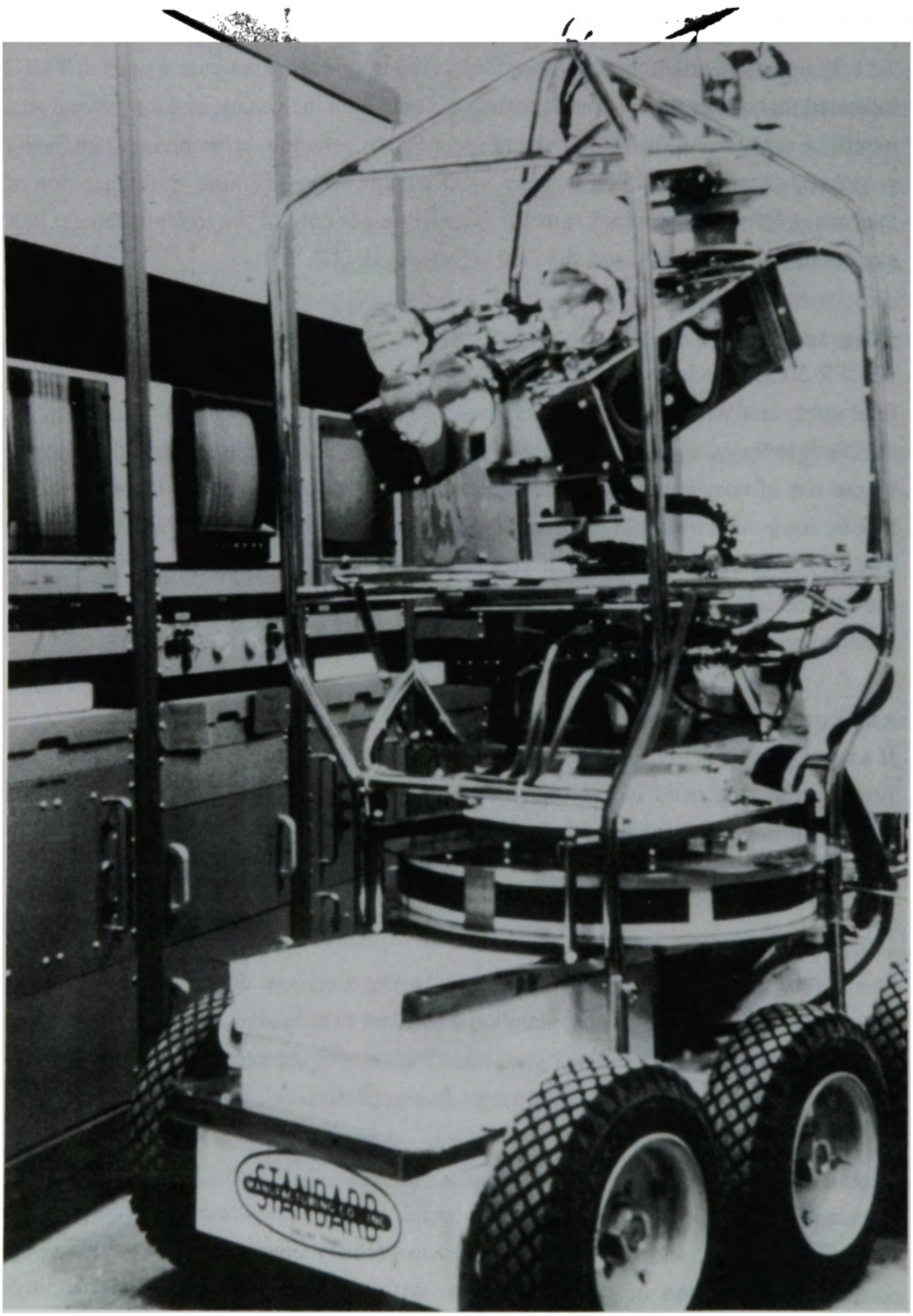

Figure 7. Multiple camera systems on the TMI-2 RRV.

camera, the ability to integrate multiple camera images of the work area and the vehicle, and focused concentration. (Reference: 3.1, 3.2)

Duplicate Robots May Be Cost Effective

The cost of repeatedly decontaminating a remote vehicle so that it can be used for operator training can exceed the value of a duplicate unit. Accordingly, for remote devices designed for a variety of tasks, procuring two units may be advantageous. At TMI-2, a duplicate of the remote reconnaissance vehicle (RRV) was available to mock-up tasks, develop procedures, train operators, and "trouble shoot" problems. The extra vehicle eliminated the time, expense, and radiation exposure that would have been required had only one device been available. (Reference: 3.1, 3.8)

Accurate Mockups Important

The use of realistic mockups was a critical part of robotic task training at TMI-2 , and was considered crucial to both mission accomplishment and safety. Effective mockups simulated not only the specific task performed, but also the complete working envelope (obstacles, barriers, boundaries, etc.) in which the vehicle operated. (Reference: 3.1, 3.2)

Demonstrating Success

An effective robotics program must demonstrate successful applications thereby convincing plant operations and management personnel that remote devices are useful and productive tools. At TMI-2, acceptance of robotics was accomplished by starting with simple tasks, gradually increasing difficulty and complexity, and then adopting a rigorous, formal training program to ensure both operator and equipment capability. (Reference: 3.2)

Vehicle Decontamination Support

Special remote vehicle decontamination equipment was used at TMI-2. The equipment included a high pressure water flush ring, a remote vehicle transporter box, a special enclosed room for performing maintenance operations on the contaminated vehicle, and a shield cage and shield blankets for storing the difficult-to-decontaminate vehicle tether. (Reference: 3.2)

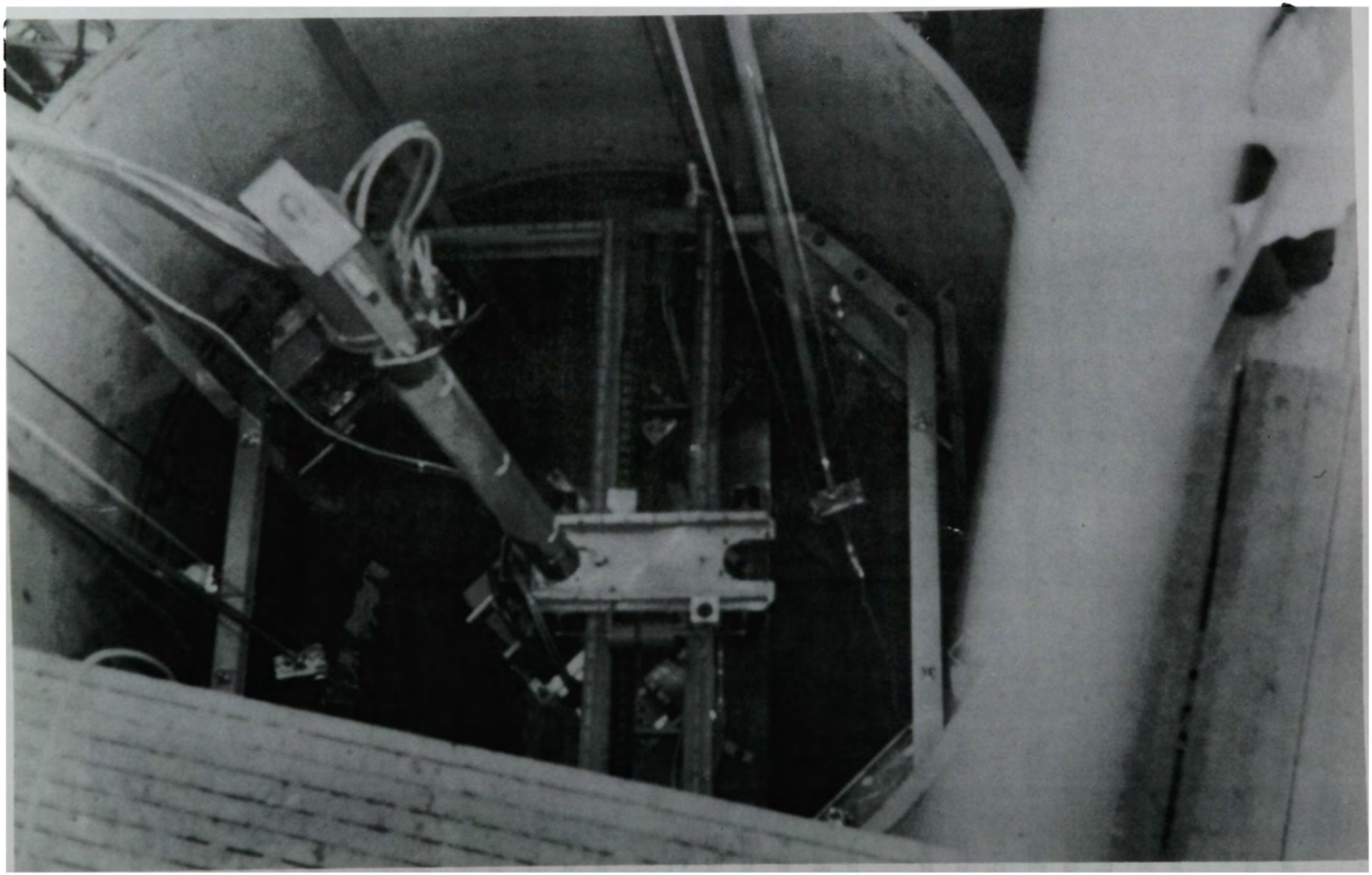

Figure 8. Reactor vessel mockup used for testing the automated plasma arc cutting system.

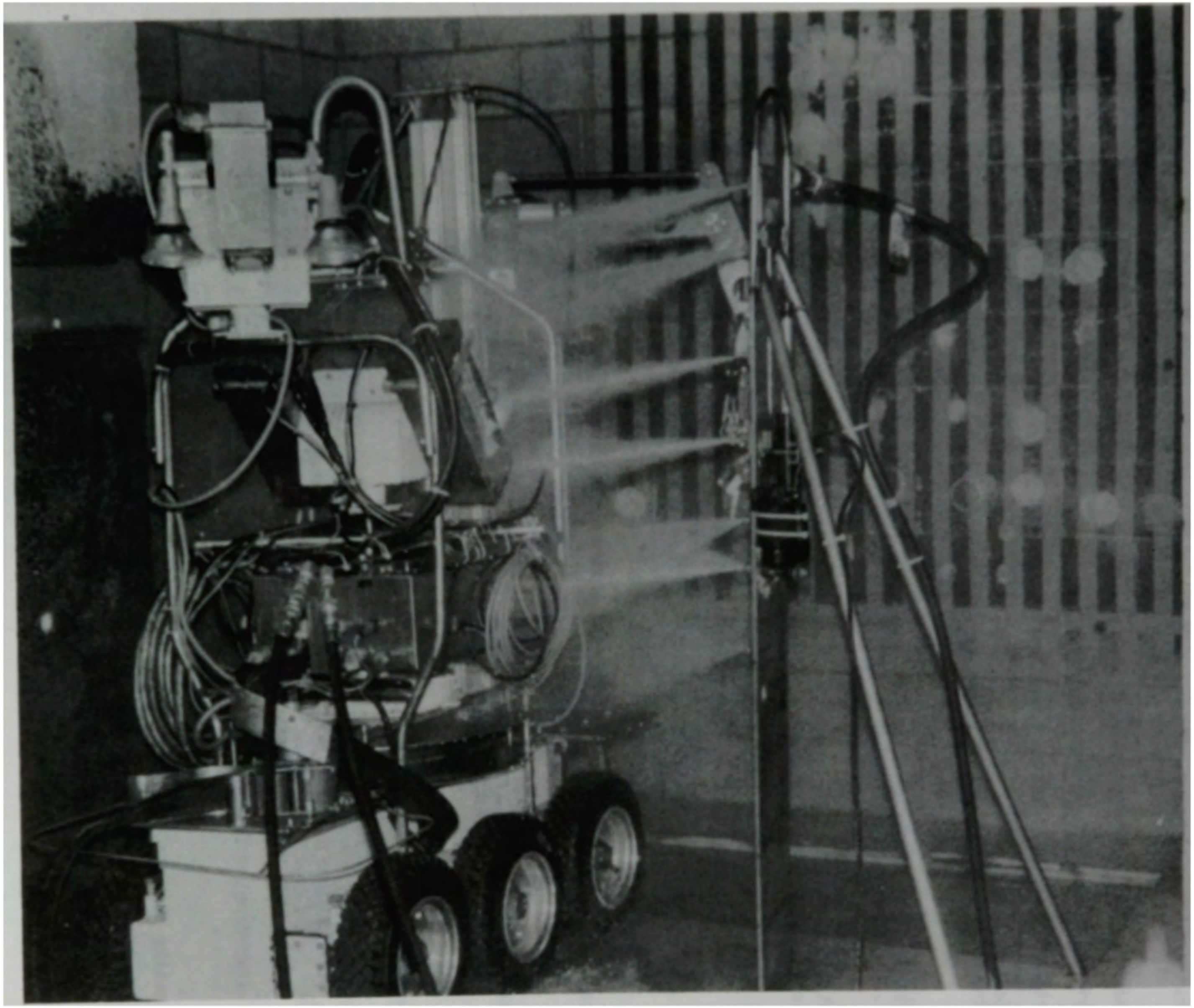

Figure 9. The RRV being decontaminated using the flush ring.

3.3 Robotics Equipment Maintenance and Operations

3.3.1 Discussion

Because the TMI-2 robotics program investigated, tested, and operated a large number of remote devices, many practical operational lessons were learned. Unlike the previous section which addressed program development issues, this section focuses on specific lessons and "tricks-of-the-trade" gleaned from thousands of hours of robot testing, personnel training, and robot deployment.

3.3.2 Lessons Learned

Reducing Vehicle Contamination

Robots should be easy to decontaminate or designed with replaceable parts. At TMI-2, special measures to minimize contamination included the design and use of environmentally sealed components, elimination of crevices and other contamination traps, use of temporary barriers (such as duct tape or Herculite to cover seams), electropolishing metal finishes for easier decontamination, use of strippable coatings, and design of the system to withstand flushing with high pressure water . In addition, inexpensive and readily available components were sometimes used and replaced when they failed or could no longer be maintained. (Reference: 3.10)

Avoiding Arm Damage

Operators of remote vehicles working from video camera monitors found it was easy to lose track of the exact position of the manipulator arm of the vehicle. To prevent damage to the arm, as well as nearby components, the arm was either programmed for specific operations or restricted in motion by limit switches. (Reference: 3.2)

Tracking Remote Vehicle Failures

At TMI-2, a team of maintenance technicians was responsible for tracking failure rates of components of the robot vehicle, so that the vehicle could be redesigned to eliminate failure-prone components. A computer-based tracking system of the component failures generated data on expected service life. These data were important to developing the spare parts inventory of the vehicle. Those efforts substantially increased vehicle reliability and reduced vehicle maintenance requirements. (Reference: 3.1)

Configuration Control Essential

Effective troubleshooting was promoted by scrupulous attention to configuration control on prints, drawings, and equipment documents, especially when duplicate remote devices were used for work and training. (Reference: 3.1)

Vehicle Maintenance Tips

The following important maintenance tips resulted from the TMI-2 robotics experience.

- Component replacement was easier if simple access panels were used and panel attachments were made with hex-head instead of Allen head bolts.
- To facilitate removal and repair, selected electrical leads were attached with bolt-together connectors instead of the usual crimp splice.
- Cork gaskets, standard on some components, were replaced with neoprene for better performance.
- Electrical noise on video monitors was eliminated by replacing the commercial dimmers on the video camera lights with "Variac" variable transformers.
- Ammeters were installed to monitor drive motor operation and as an aid to troubleshooting.
- Quick disconnect connectors were installed on components subject to routine replacement or repair, such as video cameras.
- Selected switches on the operator's consoles were changed to a foot operated switch for comfort. (Reference: 3.6)

Vehicle Operator Mistakes

Operators of remote vehicles at TMI-2 found that their operating proficiency suffered and mental mistakes increased after approximately three hours of working at the video camera consoles. (Reference: 3.2)

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4. WORKER PROTECTION

4.1 Background

The discharge of radioactive material and products of the disintegrated reactor core from the TMI-2 primary coolant system resulted in severe contamination and radiologically hazardous conditions within the containment building and auxiliary and fuel handling buildings (AFHB). Access to the AFHB was required to achieve safe shutdown; continued access to the buildings was necessary to maintain safe shutdown, and permit cleanup, defueling, and maintenance work. The radioactive contamination and resulting high radiation fields were removed or lowered to acceptable limits to enable workers to proceed with the cleanup.

The health physics program at TMI-2 was inadequate for dealing with the high amount of contamination that existed after the accident. Since the potential existed for severe overexposures, the development, implementation, and effective management of a new radiation protection program became a priority task. New approaches were needed in a number of basic worker protection areas, including protective clothing, respiratory protection, dosimetry, radiation field characterization, and exposure tracking systems. Another worker protection issue—heat stress—surfaced later in the cleanup during extended work periods in the high ambient temperature containment building.

An enormous amount of knowledge and practical experience has been gained at TMI-2 in providing effective radiation protection for workers operating in high contamination areas, high radiation fields, and high heat environments. One measure of the effectiveness of the radiation protection program at TMI-2 is the cumulative radiation exposure for the cleanup. Shortly after the accident, the NRC estimated that 2,000-8,000 person-rem would be required. In 1983 the NRC revised that number upward to 13,000-46,000 person-rem. As of December 31, 1989, with the cleanup about 99% complete, the cumulative dose was 6,180 person-rem. (Reference: 4.3, 4.5, 4.6)

4.2 Radiological Protection

4.2.1 Discussion

Post-accident radiological conditions at TMI-2 were substantially different from those normally encountered at commercial operating nuclear plants due to the magnitude of contamination and the specific mix of the radionuclide contamination. At TMI-2, massive fuel failure caused the release of mixed fission products to the coolant. Hundreds of thousands of gallons of highly contaminated water escaped the reactor's primary coolant system through the burst rupture disk of the reactor coolant drain tank. Most of it collected in the basement of the reactor building, but contamination spread throughout the reactor building and into parts of the AFHB. Radiation surveys made shortly after the accident showed general area radiation readings ranging from 150 to 500 mrems per hour in the fuel handling building and 50 to 5,000 mrems per hour in the auxiliary building. Hot spots were measured in the auxiliary building ranging up to 125 R per hour in the access area, and exceeding 1,000 R per hour in some cubicles. The high-energy beta component was up to one hundred times the gamma component. Sixteen months after the accident, average radiation readings in the reactor building during the first entries showed 500 mrem per hour on the entry elevation and 250 mrem per hour on the next higher elevation. Typical hot spot radiation measurements were 2-5 R per hour at floor drains, 18 R per hour at the open stairwell at the top of the basement (which was filled with contaminated water). The highest measurement, obtained remotely, was 40-45 R per hour about six feet from the surface of the basement water.

Of unique concern at TMI-2 was unusually high-energy beta contamination due to Sr/Y^{90}. Typically, betas at operating plants are low-energy, so protective clothing provides sufficient shielding. Since the high-energy beta emitter present at TMI-2 was rarely encountered in nuclear power plants, the monitoring equipment needed to measure it was not available at the time of the accident. After several incidents of skin exposures exceeding regulatory limits, it became clear that special equipment and procedures would be required.

Considerable research was needed to establish protection criteria for workers and develop monitoring equipment. New tools, techniques, and procedures in radiation protection have evolved from the experience at TMI-2 that are applicable to the industry in general. (Reference: 4.1, 4.2, 4.3, 4.7, 4.8)

4.2.2 Lessons Learned

Dosimetry for High Energy Beta Particles

Dosimetry analysis of workers entering the highly contaminated areas at TMI-2 revealed unexpectedly high readings resulting from beta radiation falsely elevating the measured penetrating (gamma) dose. The problem of mixed beta-gamma fields encountered at TMI-2, in combination with the two element dosimeter that was in use, meant the actual dose to either skin or deep organs could not be determined accurately. Dosimetric studies showed that the problem of measuring the penetrating radiation in a mixed beta-gamma field could be overcome by using a thicker filter over the penetrating chip. However, beta inaccuracies were not affected by this modification and actual dose to the skin could not be determined. New beta dosimetry techniques were required at TMI-2.

Multi-element dosimeters were developed and tested under programs sponsored by DOE at several national laboratories. The thinnest element in these multi-element dosimeters allowed essentially 100% beta transmission; the thickest element allowed only gamma rays to pass through. Using known beta sources, the dosimeters were calibrated to determine the beta energy spectrum, the beta to gamma ratio, and the appropriate algorithms for personnel dose evaluation. Although the dosimeters were not engineered to the point suitable for high volume, automated processing, they did prove valuable for beta spectrum characterization. (Reference: 4.1, 4.2, 4.5, 4.11)

Respiratory Protection

There were numerous areas of high airborne activity within the plant following the accident. In the first days after the accident, there was a major problem providing sufficient self-contained breathing apparatus (SCBA), SCBA cylinders, and adequate air-charging capacity. The location of the high pressure air compressor (HPAC) used to charge the SCBA became a prime concern; nearby contamination could be drawn into the HPAC. Therefore, a HPAC was positioned on the back of a flatbed truck for mobility. For low capacity operations, an alternative to a mobile HPAC was a bench-mounted 100 psi input air compressor capable of filling SCBA to over 2,000 psi.

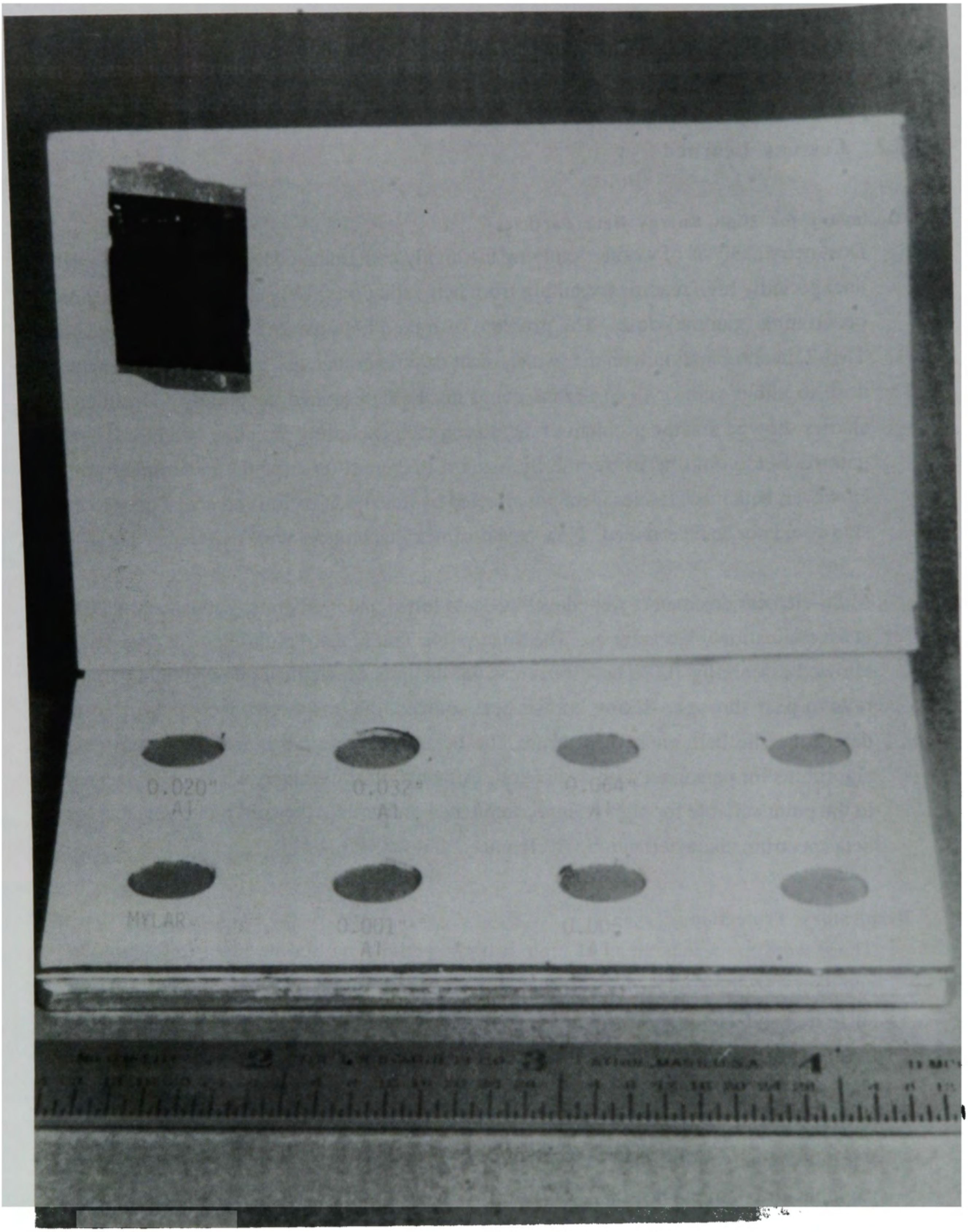

Figure 10. Multi-element beta dosimeter developed for TMI-2.

Self-contained respirators limited workers stay times to 20 minutes. Negative pressure respirators were not used extensively because of the low protection factor and the limited time a worker could tolerate them. The powered air purifying respirator (PAPR), commercially available at the time of the accident, but not generally used in the nuclear industry, was modified for use at TMI-2. The PAPR is a battery-operated respirator that draws ambient air through a filter and blows it into the facepiece, providing positive pressure to prevent in-leakage. Added advantages are the elimination of dead air space in the facepiece and less lens fogging. For those workers who could not pass a respirator fit test or could not wear a tight fitting mask, a new type of respirator—termed the "Breezer"—was developed. The Breezer is a powered air purifying hood that fits over the head. It has the same high protection factor as the PAPR but is loose fitting on the face. This respirator is now available for industry use because of the research and development done at TMI-2. (Reference: 4.5, 4.9)

Detector Modifications for Improved Contamination Characterization

In a radiation field that results from a large number of sources, minimizing workers exposures requires that the major source contributors to personnel dose be identified and treated. At TMI-2, a fast sorting measurement technique was developed to initially prioritize surfaces for exposure reduction and rapidly evaluate the effectiveness of a decontamination effort. Development of this quick sort method required addressing existing instrument limitations and providing modifications that narrowed the angle of resolution for a radiation detector so "hot spots" could be located in a high radiation background.

Cleanup personnel initially used an unmodified Eberline HP 220A detector in the TMI-2 reactor building to determine where to locate shielding. The angular response of the HP-220-A probe approaches 2π steradians and allows toward-away type measurements. Sources distributed over 4π steradians are hard to define with this system. Angular differentiation was improved to $\sim\pi/2$ steradians by redesigning the probe shield. The change allowed unambiguous six-direction measurements (up, down, front, rear, right, left) with practically no angular overlap or exclusion.

Another exposure rate survey problem was essentially opposite to that described above; i.e., too much directionality in survey instrumentation. This problem stemmed from the need to do exposure rate surveys in areas with both high beta and gamma sources. Area

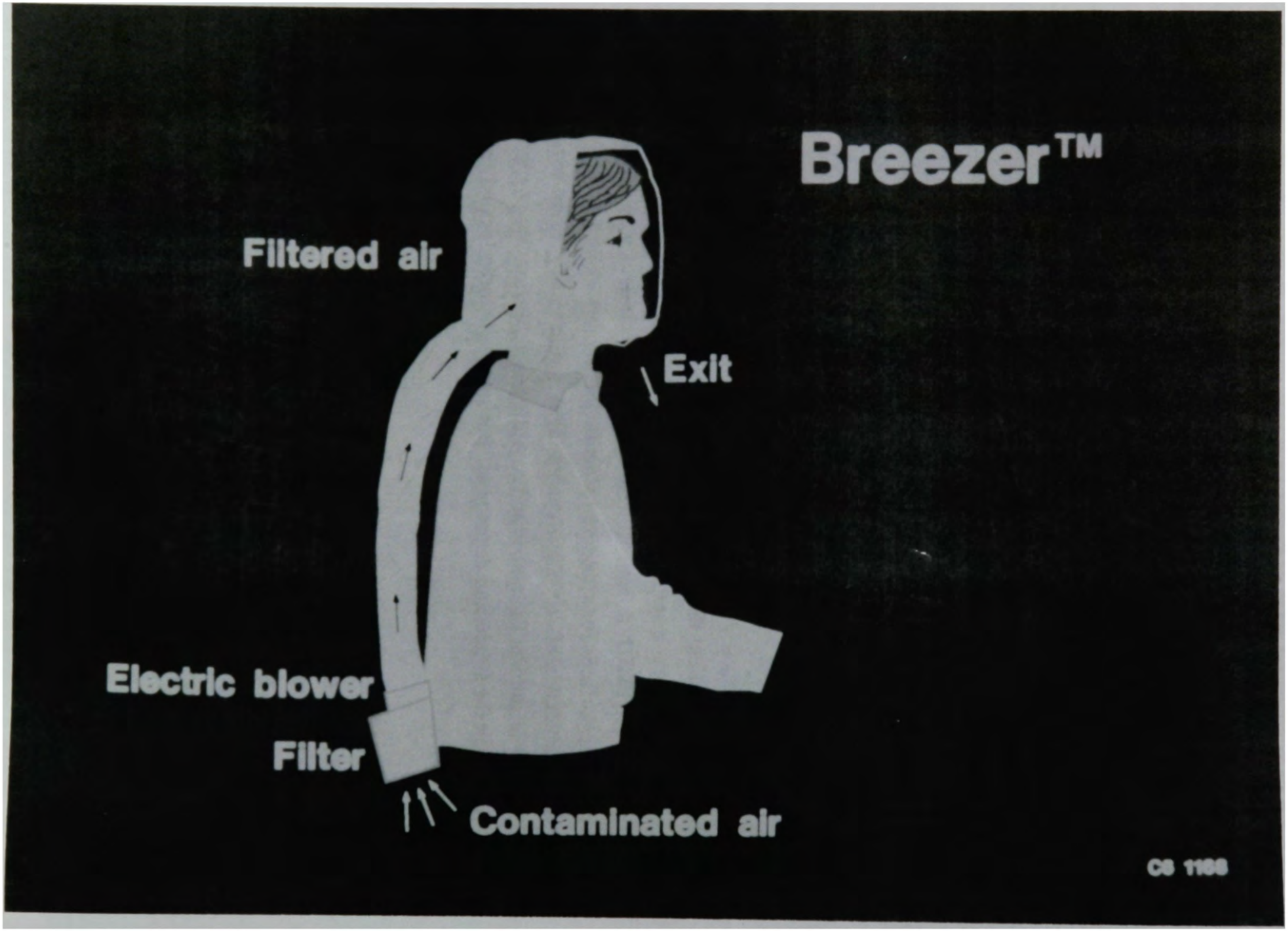

Figure 11. Powered air purifying hood respirator ("Breezer").

surveys were being made with Eberline RO7 digital ion chambers. The RO7 is essentially omnidirectional in response to gamma rays, but because of the metal housing around the detector, is directional in response to beta radiation. Only beta particles entering through the front end of the tubular RO7 probe strike the ion chamber and are detected. This was a concern at TMI-2 because much of the beta contamination was from Sr/Y^{90}, which has an energetic, penetrating beta particle. Thus a worker entering an area of mixed beta-gamma contamination and using the RO7 instrument could underestimate his exposure. The solution to this problem was to modify the RO7 to make it beta omnidirectional. This was done by replacing the flat mylar beta window over the ion chamber with a thin hemispherical acrylic window, which effectively extended the ion chamber volume. Pointing the modified probe in two opposite directions showed beta-gamma general area exposure rates. (Reference: 4.2)

Innovations in Radionuclide Measurements

Gamma spectrometry was widely used at TMI-2 to identify specific isotopes and measure quantity. Many measurements required positioning the spectrometer at valves, pipes, and other components in tight and difficult-to-reach locations. The large, heavily shielded spectrometers commonly available could not be used in many of these locations. Accordingly, a compact and lightweight model, using a sodium iodide (NaI) crystal detector and interchangeable tungsten shielding, was designed and tested. This spectrometer, which weighed about 70 pounds in its most common configuration, was easily transported. The shielding pieces could be interchanged to vary the collimator size and shielding amount. Although more accurate spectrometers were available, the NaI spectrometer was widely used for screening measurements because of its portability.

The dispersal of fuel material within the TMI-2 primary coolant system required that techniques be available to accurately measure special nuclear material (SNM). Neutron interrogation, using an antimony-beryllium (Sb-Be) source and a shielded, helium gas-filled neutron proportional counter, was used to assay SNM in selected reactor system components. The Sb-Be source produces low-energy interrogating neutrons that impinge upon the fuel and induce fission reactions in the fissile material. Some of the neutrons returning from the surrounding fuel debris are detected by the He^4 counter, which differentiates the high-energy induced fission neutrons from the low-energy source neutrons. (Reference: 4.2, 4.3, 4.10, 4.15)

Skin Dose from Hot Particles

The release of reactor coolant containing finely divided fuel debris caused discrete radioactive particles ("hot particles") to be a problem at some locations within the plant. The VARSKIN computer code and other published methods of assessing skin dose were designed to calculate a dose to the basal cell skin layer from contamination in contact with the skin surface. No provisions were built into the codes to accommodate special situations, such as moustache contamination, where the particle was elevated from the skin. To estimate the actual dose in these circumstances, the dose calculated by VARSKIN for the location directly beneath the particle in contact, was attenuated using the inverse square law. Subsequent comparison with first principal equations revealed the technique yielded close, yet conservative, results. (Reference: 4.13, 4.14)

Dedicated Dressing Facility

The TMI-2 cleanup required working in highly contaminated areas. To properly prepare workers for contaminated environments and to reduce incidents of skin contamination, a dedicated dressing facility, known as the personnel access facility (PAF), was established. The PAF staff helped workers correctly don their protective clothing. 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 (tools, radio equipment, etc.). The PAF also served as a staging area for personnel awaiting authorization to enter the reactor 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. (Reference: 4.3, 4.8, 4.12)

Video Cameras

The innovative use of video technology at nuclear plants was pioneered at TMI-2. A broad range of cameras and support equipment were employed in numerous applications, including worker surveillance to ensure safety, robot vision systems, and in-vessel inspections of the damaged reactor core. Innovations in camera deployment techniques, maintenance, modifications, and support equipment have helped minimize worker exposure and reduce cleanup costs. Video cameras for task management have been particularly important. A communications center supported the work teams performing cleanup tasks inside the reactor building. The support staff was in radio and video contact with each work team. Multiple video cameras controlled from the

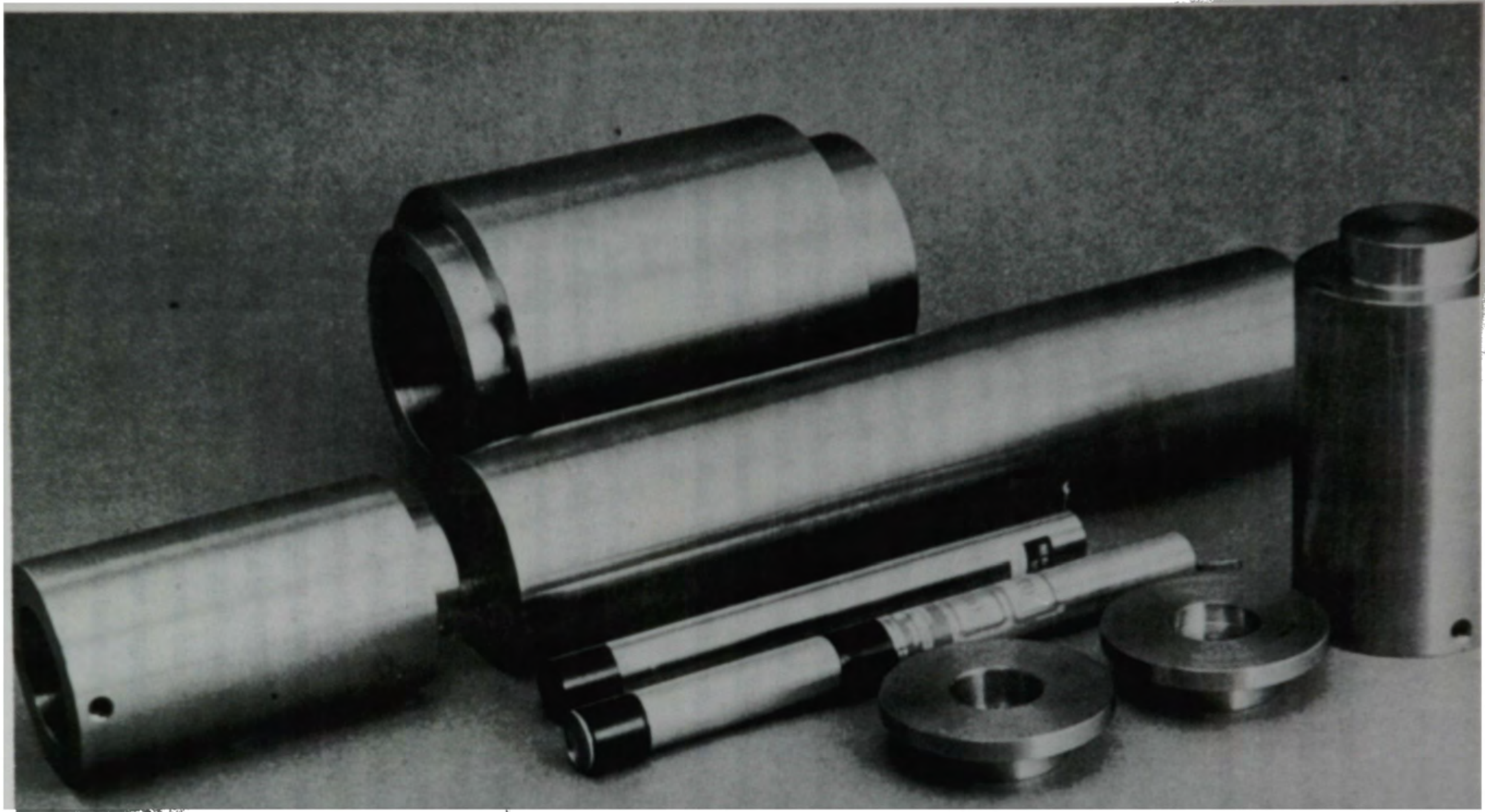

Figure 12. Portable sodium iodide detector.

communications center permitted work progress to be tracked, provided safety oversight, and allowed technical support from experts outside the radiation zone. The video cameras have been important tools for acquiring data, increasing productivity, and reducing radiation exposure. (Reference: 4.16)

Microcomputer-Aided Decision Analysis

Engineers and managers, particularly in the TMI-2 radiation protection group, benefited from microcomputer-aided decision analysis. They developed spreadsheet programs for analyses involving many variables, such as operational feasibility, cost, material, time required, licensing considerations, health and safety, occupational radiation exposure, and other schedule constraints. MICROSHIELD, a commercial program developed in part because of difficulty in applying mainframe shielding programs to TMI-2 problems, was particularly valuable in deriving optimum shielding configurations for simple geometries. Another software program developed at TMI-2 calculated the rate of hydrogen gas generation in waste packages. A third program classified radioactive wastes by category to facilitate processing, handling, and packaging decisions. All of these software programs are available to the nuclear industry. (Reference: 4.2, 4.4)

Realistic Radiation Protection Training

As part of the training to become qualified radiation workers, TMI-2 employees participated in a four-to-five person enhanced practical factors class that used realistic mock-ups and environments. The class was briefed on the proper procedures to suit-up, enter a radiation area, unsuit, frisk for contamination, and close-out the task. The students were then taken to a mock-up area and given a radiation work permit (RWP) describing the simulated radiation fields, the required protective clothing, and the task to be performed. Working through the simulated task gave students experience in job planning, teamwork, reading and understanding RWPs, interpreting radiation area survey maps, donning and removing protective clothing, proper use of radiation detection equipment, proper handling of radioactive components, good housekeeping practices in radiation areas, and proper radiation frisking techniques. The instructor often altered the area posting signs, sounded an evacuation alarm, or made other changes to determine if the team responded correctly. TMI-2 cleanup workers have received radiation exposures comparable to or less than those received by operating plant workers, despite the significantly higher radiation fields and contamination levels. The realism of the worker training was considered to be an important contributor to that record. (Reference: 4.2, 4.4)

4.3 Heat Stress Management

4.3.1 Discussion

Because of the high contamination during the initial stages of the cleanup and defueling effort, TMI-2 workers were required to wear many layers of protective clothing, including impermeable plastic suits. Those layers of protective clothing imposed a significant heat stress burden during hot weather when the building temperature was in excess of 90°F. Generally, workers could tolerate only an hour in that environment. To prevent serious injury and maintain reasonable productivity, an effective heat stress management program was required. The personal cooling devices and garments developed at TMI-2 have found widespread application in the industry. (Reference: 4.4, 4.5, 4.8)

4.3.2 Lessons Learned

Vortex Cooling Suit

Body cooling devices produce a flow of cool air to the skin which removes body heat through convection and increased sweat evaporation. The most common body cooling device is the Vortex tube. Vortex body cooling suits were tested at TMI-2 in May, 1981, in a small-scale decontamination experiment. The cooling effect produced by the Vortex tube successfully protected workers from heat stress. However, there were several logistical and operational problems that hindered extensive use of these devices. The part of the Vortex tube outside the protective clothing became contaminated with radioactive material and could not be readily decontaminated. In addition, a large volume of service air was required to operate several workers simultaneously on Vortex suits. Finally, worker mobility was restricted by the umbilical hoses supplying air to the suits. Those problems limited the use of Vortex suits at TMI-2. (Reference: 4.4, 4.5, 4.8, 4.17)

Ice Vests

Body cooling garments were considered after encountering problems with the Vortex tubes. Three types of body cooling garments were investigated: the Cool Vest™ and the Cool Head™ (which use circulating water tubes in the garment to remove body heat), and the frozen water garment. At TMI-2, the first two garments were found to be difficult to decontaminate, expensive, and their pumps required regular maintenance. Greater success was achieved with simple, easy to maintain frozen water garments. The frozen water garment, or ice vest, is a tight-fitting vest worn under protective clothing. It has 60 small pockets to hold ice packets with a total capacity of ~8 lbs of ice. The ice serves as a heat sink for metabolic heat produced by the body; the heat dissipates as the ice melts. While the heat sink provided by the ice packets is limited, workers in the high heat environment wearing the garments doubled their stay times. Prepared garments and additional ice packets were kept in a freezer in the worker dress-out area. Ice packets were regularly replaced since they often would break in use. The garments were laundered with other uncontaminated protective clothing. Ice vest use was carefully planned because substantial melting occurred if there were delays between the dress up period and entry into the work area. Work times also were monitored because once the ice melted the garment's weight added 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 the ice packets were so cold that worker frost bite was a danger. (Reference: 4.4, 4.5, 4.8, 4.17)

Figure 13. Ice vest (left) and vortex tube cool suit used at TMI-2.

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5. MANAGING RADIOACTIVE WASTES AND FUEL DEBRIS

5.1 Background

The TMI-2 accident and cleanup generated a variety of radioactive wastes requiring collection, treatment, storage, transportation, and disposal. Large quantities of liquid waste (mainly contaminated water) and solid waste (fuel debris) were produced by the accident. The subsequent decontamination tasks also resulted in substantial quantities of contaminated water, as well as organic resins and inorganic zeolites produced from the water processing systems. Both the quantities and types of wastes were unique within the commercial nuclear power industry. Never before had a utility faced the prospect of dealing with millions of gallons of contaminated water, approximately 150 tons of fuel debris, and—in a few cases—wastes that did not fit into established waste classification and disposal categories. The large extent of fuel failure meant that the isotopic composition, the concentration of transuranic elements, and the high beta-to-gamma ratio of the TMI-2 wastes were never before encountered in commercial nuclear power plants. Also unprecedented was the extent of facility decontamination required and, therefore, the quantity of wastes generated by these activities.

Advanced technologies were needed for handling, processing, and disposing of some of the TMI-2 radioactive wastes, including the large volume of liquid and reactor core debris. Consequently, DOE committed funds for research and development in managing these wastes, as part of the TMI-2 Information and Examination Program. In 1981, the NRC and DOE signed a Memorandum of Understanding, delineating each party's role in dealing with abnormal wastes (wastes not meeting the criteria for classification as A, B, C, or TRU). The subsequent handling, packaging and transporting of wastes from TMI-2, as well as successful disposal of most forms, demonstrated the government's role in the development of new waste disposal technologies, and the transfer of those technologies to the commercial industry. (Reference: 5.1, 5.3)

5.2 Waste Treatment Technology

5.2.1 Discussion

Most new developments in waste treatment resulted from the need to deal with the large quantity of contaminated water generated by the accident. The reactor building contained approximately 640,000 gallons, the reactor coolant system about 96,000 gallons, and the auxiliary and fuel handling building (AFHB) about 570,000 gallons. Later decontamination activities and other tasks added to this water inventory, so that the final volume of water requiring treatment was over 2,000,000 gallons. This water was highly radioactive; the reactor building water, for example, contained about 160 µCi / ml of fission product activity (mainly Cs^{137}).

Two special water treatment systems were developed to remove contamination from the water and put the activity in a form suitable for disposal. The EPICOR-II system was produced for the AFHB water (which was lower in activity) and the submerged demineralizer system (SDS) for the reactor building water. The EPICOR-II system used organic ion exchange resins (most had a top layer of inorganic zeolites) to process the water, while SDS used inorganic zeolites (aluminosilicates).

Design of the EPICOR-II system began a few weeks after the accident and was operating by October 1979. The resins were contained in tanks (called liners) four feet in diameter by four feet high. Strontium and cesium were removed by filtration and ion exchange. Each liner could process about 17,000 gallons of water at an average rate of 10 gallons a minute. After processing, the condition of the water was well within guidelines for release under Environmental Protection Agency regulations, but—because of public objections to release—it was stored in tanks on the island. The spent resin liners were also stored in a shielded facility on the island. The EPICOR-II system produced 72 liners while removing approximately 55,000 curies from the AFHB water. In 1981, 22 of the liners were disposed of as commercial low-level radioactive waste. The 50 highest activity liners were retrieved from storage at TMI and transported to DOE's Idaho National Engineering Laboratory (INEL) for analysis, storage, and disposal research.

The SDS was conceived in the summer of 1979 and designed, fabricated, and installed on an accelerated basis over the next two years. Major support was provided by the TMI-2 Waste Management Advisory Group, a group of technical experts assembled by DOE. Like EPICOR-II, the SDS was a series of tanks containing ion exchange media. But in this case they were smaller and loaded with inorganic zeolites, selected because of their high capacity for cesium adsorption and their long-term stability under high-radiation conditions. The inorganic zeolite could be loaded to more than 20,000 curies per cubic foot, while the EPICOR-II resins could only accommodate about 40 curies per cubic foot. SDS produced a decontamination factor in excess of 30,000 for cesium and 250 for strontium.

In a series of water processing campaigns, the SDS system was used to decontaminate the reactor building basement water, the reactor coolant system water, and (using a backflush and elution technique) the demineralizers in the reactor makeup and purification system. A total of 19 stainless steel SDS vessels resulted, some loaded with up to about 113,000 curies of radioactivity. The DOE accepted these vessels from GPU Nuclear for a research program to (1) prove the feasibility of vitrifying the zeolites; and (2) demonstrate long-term retrievable disposal in special concrete overpacks. Transportation of these SDS vessels was a major accomplishment because of the high curie loadings and the concern over internal gas generation. Transportation was done in a special cask procured by the DOE.

TMI-2 generated some wastes—termed "abnormal wastes"—that were impossible to dispose of under NRC regulations because they (1) had a curie content greater than disposal limits; (2) were in a form that precluded disposal; or (3) had a transuranic element content that exceeded burial limits. In some instances, special processes were developed to convert the wastes into a disposable form. Other wastes were accepted by DOE for waste disposal research or long-term storage. (Reference: 5.1, 5.2, 5.3, 5.12, 5.15)

5.2.2 Lessons Learned

Volume Reduction

The EPICOR-II system reduced the volume of radioactive waste by a factor of approximately 20, from about 570,000 gallons of liquid (76,000 cubic feet) to about

3,600 cubic feet (the total volume of the 72 liners). The SDS reduced the volume of radioactive waste by a factor of 500 over conventional waste processing systems. (Reference: 5.4)

Ion Exchange Media Not Significantly Degraded by Radiation

The TMI-2 EPICOR-II resin liners were loaded to as much as 2,000 curies (primarily Cs^{137}). DOE research suggested that loadings up to about 1,300 curies produced no significant deterioration, only some media surface cracking and spalling, over a short time period. A low ion content in liquid samples indicated that no significant amounts of either corrosion products or ion exchange media degradation products were present in the liners' residual liquid. The liquid sample had a pH of 5.3, which would not be expected to present a corrosion hazard to the liner steel. The radiochemical analysis revealed no significant release of radionuclides from the resin matrix. As a result of this work, the EPICOR-II liners are estimated to have a minimum life of 50 years. Recent research indicates that the damage threshold for the organic resins is about 10^8 rads. Dose to the organic resins can also be reduced by placing a thin layer of inorganic zeolite on top of the resin bed. The water entering the liner will pass through the zeolite first, depositing some of its radionuclides in the more radiation tolerant inorganic material. (Reference: 5.5, 5.6)

Resin Transfer System

A novel vacuum sluicing technique was developed to transfer difficult-to-handle resins. The technique was successfully used at a DOE facility to remove the ion exchange media from two EPICOR-II prefilters used in research programs. (Reference: 5.6)

Selection of Ion Exchange Media

Zeolites permit higher specific activity waste loadings—without radiation-induced damage than organic ion exchange resins. (Organic resins are most commonly used by the commercial light water reactor industry.) Zeolites are hydrated silicates of aluminum and can contain sodium or calcium or both. The sodium zeolites demonstrate superior selectivity for Cs^+ and Sr^{++}. Na^+, commonly found in solution in contaminated power plant water, competes actively for resin or zeolite adsorption sites with Cs^+ and Sr^{++} Sodium zeolites, by reducing the adsorption of Na^+, reduce the required number of ion exchange vessels. This lowers operation and disposal costs. (Reference: 5.15)

Cellulose Filter Deterioration

Pre- and post-filters were used in the SDS. Cellulose cartridge filters were found to release radioactive filtrate during the cartridge dewatering process. Sand filters, composed of various grain sizes, replaced the cellulose filters. The sand filters also meet disposal requirements since, unlike cartridge filters, they are considered a uniform waste form. (Reference: 5.15)

Vitrifying Ion Exchange Resins

Tests were conducted as part of the DOE research program to determine the feasibility of converting spent zeolites into a more stable waste form. The ion exchange media (which contain silicates) from three TMI-2 SDS liners were mixed with other glass-forming chemicals. The mixture was fed into a canister in a furnace and heated to approximately 1050°C. When the mixture cooled, the canister became the container for the final waste product, a glass column that was a stable form for the zeolites. (Reference: 5.12)

Conversion of Waste to Disposable Form

Nuclear power plants routinely dispose of ion exchange resins from plant demineralizers as low-level waste. However, the TMI-2 demineralizer resins were loaded with such high concentrations of radioactivity that they could not be disposed of in the normal manner. In addition, the resins were not designed for such high loadings and some degradation of the media occurred. The cost of long-term storage of the resins by DOE was so high that a process was developed to elute the radioactivity (primarily cesium) from the resins, capture the cesium on SDS zeolites, and render the demineralizer resins suitable for disposal as low-level waste. This successfully demonstrated the ability to convert waste that could not meet established classification criteria into waste that was suitable for disposal. (Reference: 5.1)

5.3 Control of Combustible Gases in Wastes

5.3.1 Discussion

Generation of flammable gases inside sealed radioactive waste containers is a potential hazard, and NRC regulations limit the quantity of such gases allowed to accumulate. Two reactions contribute to gas generation: (1) the reaction between metals and water, which oxidizes the metal and releases hydrogen gas; and (2) long-term exposure of water and organic materials to ionizing radiation (radiolysis). Because many TMI-2 wastes—particularly SDS zeolites and canisters of fuel debris—were loaded with high concentrations of radioactivity, the latter reaction was a potential source of flammable gaseous mixtures (oxygen plus hydrogen).

Radiolytic gas generation in highly loaded SDS vessels was calculated to be significant. Measurements of gas buildup confirmed that this could be a problem during storage and transportation. A DOE research program developed a number of techniques to deal with the problem. To reduce buildup of flammable gas during transport and storage, the vessels were drained and vacuum pumped to remove free water. A catalyst was added to each vessel to recombine the hydrogen and oxygen as it was generated. A pressure relief system, consisting of a burst diaphragm and micropore graphite filter, was also added to each vessel to prevent uncontrolled, long-term buildup of nonrecombinable gas mixtures. (A net hydrogen buildup can occur due to oxygen scavenging by various chemical reactions, such as the formation of CO and CO_2 from oxidation of organic materials trapped within the zeolites.) (Reference: 5.13, 5.14)

5.3.2 Lessons Learned

Remote Removal of Combustible Gases

A unique gas sampler was designed to remotely remove vent plugs from TMI-2 ion exchange resin containers, sample the gas content, vent the container, purge the container with inert gas, and reinstall the vent plugs. The remote operation was safe, saved significant exposure to personnel, eliminated combustible gas hazards, and allowed the containers to be transported safely. The gas generation data became the basis for a computer-assisted method of calculating combustible gas generation rates and safe storage and transportation periods. This calculational method, based on isotopic content and curie loadings, has been successfully applied to a variety of power plant wastes. (Reference: 5.7, 5.8, 5.9, 5.10)

Calculations for Determining Gas Generation Rates

Gas generation data in TMI-2 waste containers became the basis for a computer-assisted method for calculating rates of generation of combustible gases in a variety of wet radioactive wastes. The NRC reviewed the technical basis for the method and approved use of the calculations as an alternative to direct measurement for demonstrating compliance with their regulations. The Electric Power Research Institute, with the support of DOE, developed a training program to provide instruction on use of the computer program, its technical basis, and how to obtain NRC approval for plant-specific programs. Calculating combustible gas concentrations is now an acceptable means of determining quantities of gas in sealed radioactive containers. This calculational technique has reduced costs and personnel radiation exposures for waste generators by eliminating some radioactive waste handling. (Reference: 5.13, 5.22)

Generic Solutions To Gas Generation Problems

TMI-2 experience with containers of ion exchange resins showed that when the quantity of waste containers is large, and when the containers and their contents are similar, generic solutions to gas generation problems can be both safe and cost effective. TMI-2 was faced with either measuring gas generation rates in each container, or analyzing curie content and then calculating gas generation rates for each container. Instead, it was decided to vent and inert each container and then install a hydrogen-oxygen recombiner in each. This approach proved less expensive than a specific evaluation of each container, even though the requirements for the generic solution (extent of venting, capacity of recombiner) had to be designed for the worst case container. (Reference: 5.14)

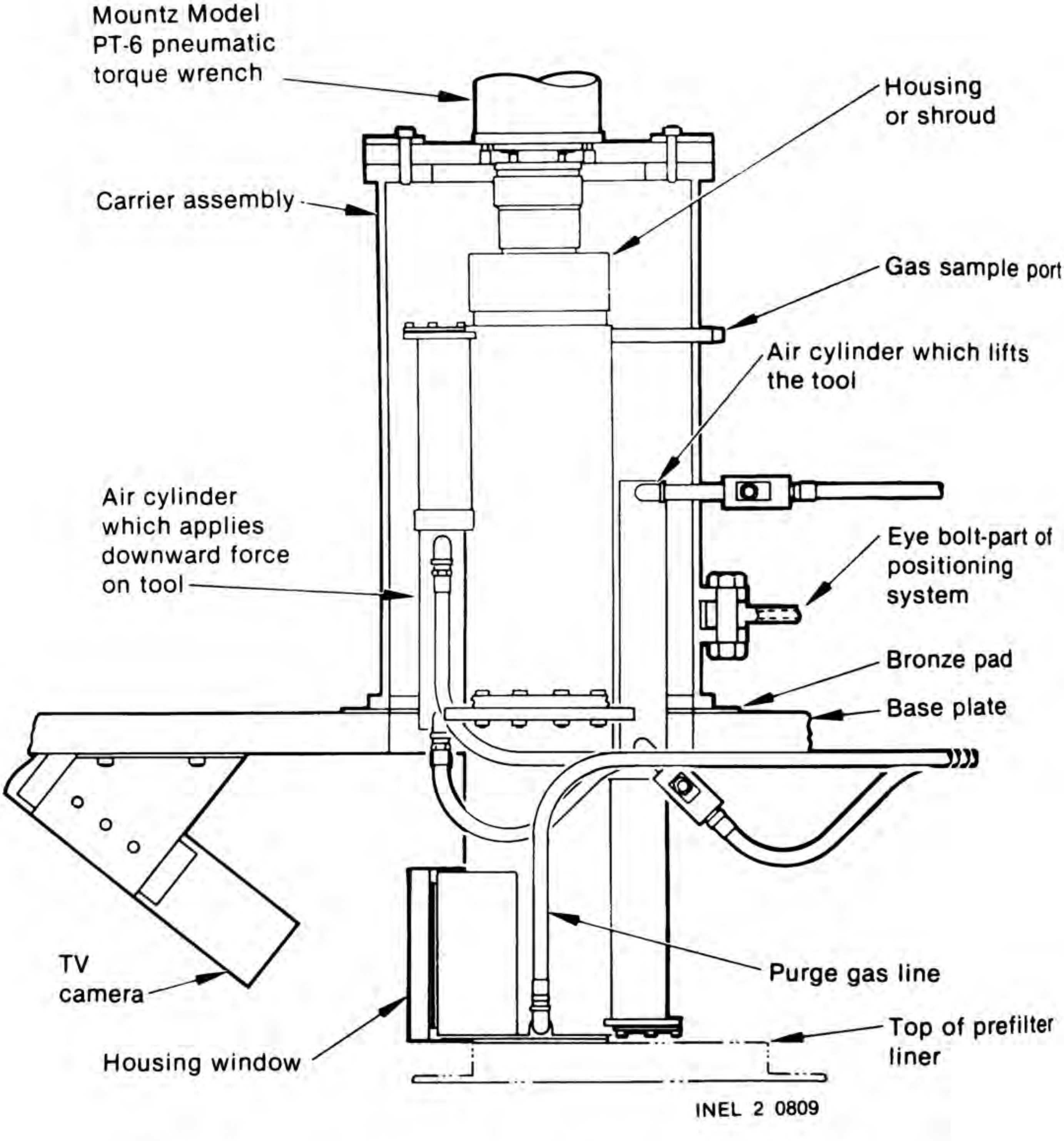

Figure 14. Cross-sectional view of tool used to vent the ion exchange resin canisters

Catalysts for Hydrogen Control in Wet Radioactive Wastes

Catalyst beds were used in the TMI-2 core debris canisters to recombine radiolytic hydrogen and oxygen and prevent buildup of combustible mixtures of gases. The catalyst bed was designed with porous metal filters at each end to contain the particles while allowing gases to flow to and through the catalyst. Testing revealed that a mixture of 80% Engelhard-D and 20% Atomic Energy of Canada Limited (AECL) catalysts performed better than either catalyst separately. The AECL catalyst will recombine hydrogen and oxygen even when wet. The heat generated by the catalysis will then cause the more efficient Engelhard catalyst to function. Various additives and contaminants to which the catalysts might be exposed had little effect on performance. A wet-proof, platinum-on-silica catalyst was subsequently tested and found more effective than the silicone-coated catalyst used in the TMI-2 canisters. (Reference: 5.11, 5.14, 5.23)

5.4 Waste Packaging, Transportation, and Disposal

5.4.1 Discussion

DOE, in conjunction with the utility and a large number of contractors, conducted several major transport campaigns for the TMI-2 accident-generated wastes. These included:

- The shipment of the EPICOR-II prefilters from TMI-2 to a DOE facility;
- The transport of EPICOR-II prefilters in high-integrity containers from a DOE facility to a commercial disposal facility in Washington state;
- The transport of SDS vessels to a DOE facility for research and disposal;
- The shipment of the fuel debris to a DOE facility for research and storage.

These campaigns led to a variety of innovations in waste packaging, transportation, and disposal. In addition, the campaigns received considerable attention from the public and from public officials, resulting in a number of important communications lessons.

DOE research produced the first steel reinforced concrete high integrity container (HIC) to be licensed and used for low level waste disposal in the U.S. The HICs were designed to have a burial life of at least 300 years. Forty-six of the TMI-2 EPICOR-II liners, previously transported to INEL, were placed in the new HICs and processed for commercial disposal as

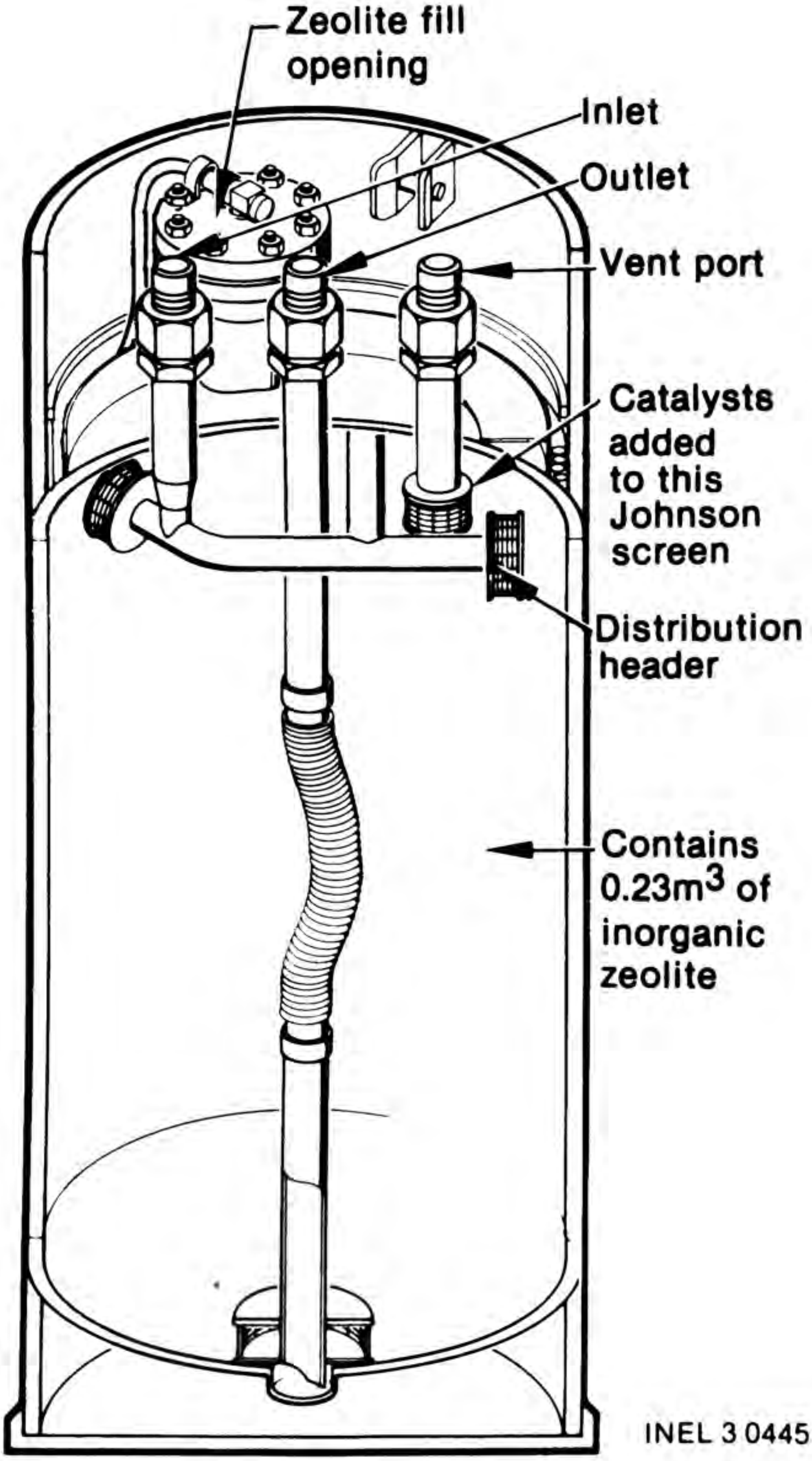

Figure 15. Cutaway view of SDS liner showing screens to which catalysts were added.

Class C waste. The remaining four liners are being used in research and will be disposed of at a DOE facility.

The packaging, transportation, and storage of the TMI-2 fuel debris represented one of the most rigorous radioactive material handling campaigns ever conducted. In March 1984, the DOE and GPU Nuclear signed an agreement providing for transportation, storage, and disposal services for the TMI-2 core. Special stainless steel canisters were developed to contain the loose debris. The canisters were placed inside newly designed and fabricated rail casks for off-site transportation. Each cask holds seven canisters and meets all regulations for double containment of plutonium-bearing materials. The transportation campaign (about 98% complete as of January 1990) will ship about 343 canisters in about 49 individual cask shipments over a period of about 4 years (22 rail shipments of one to three casks each). (Reference: 5.12)

5.4.2 Lessons Learned

Unique HIC Design

Several novel features were designed into the TMI-2 resin disposal HIC. The lid contained a passive venting mechanism that prevented water vapor ingress yet allowed release of hydrogen and oxygen gases generated as a result of radiolysis within the container, thus preventing internal pressurization during disposal. Instead of using bolts or mechanical fasteners, the container lid was sealed in place with epoxy. The HIC and seal withstood drop tests; radiation exposure tests indicated that the epoxy withstood 10^9 R without degradation. The epoxy seal minimized radiation exposure to workers during lid installation because it did not require hands-on installation. (Reference: 5.16, 5.17, 5.18)

Large Shipments Possible With Proper Preparation

Some of the SDS vessels shipped from TMI-2 contained up to 113,000 curies of radioactivity. These shipments of ion exchange media were the most radioactive ever shipped in the U.S. DOE demonstrated that, with proper preparation and attention to safety, shipments of this magnitude could be accomplished without incident. (Reference: 5.1)

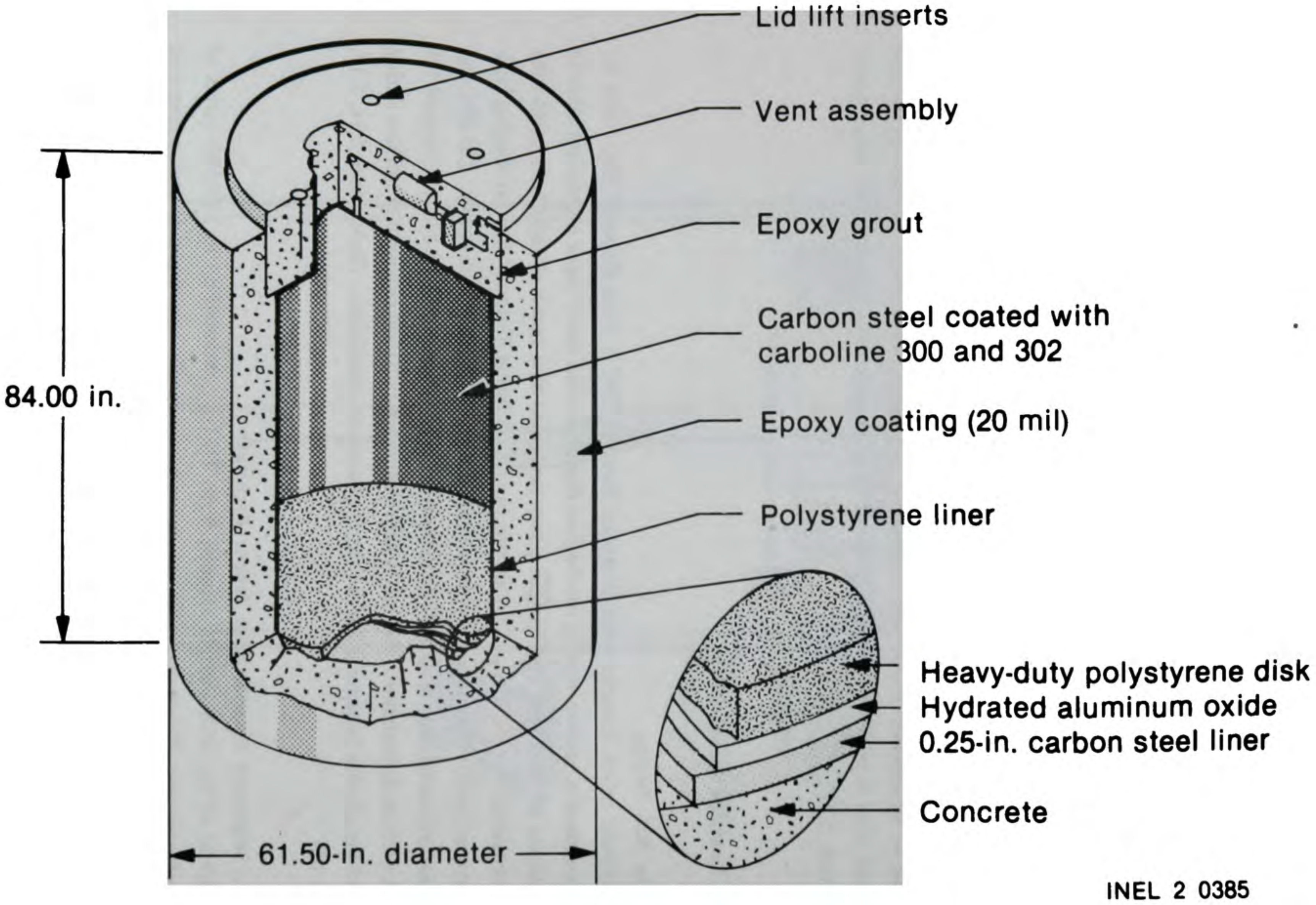

Figure 16. High integrity containers used for disposal of TMI-2 wastes.

Working Team Relationships

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. Special efforts by DOE and its contractors were responsible for this progress; similar steps may be applicable to other programs. Among the important contributions to this effort were the working team relationships authorized by DOE and the specific tasks performed by the team members. A TMI-2 Core Shipping Technical Working Team—representing all of the organizations involved—met monthly. Careful attention was paid to regulatory requirements to ensure that the cask design met or exceeded requirements. A major effort was undertaken to perform safety analyses, select a qualified vendor, and perform engineering coordination and vendor QA through an on-site team. (Reference: 5.19)

Conducting Tests Beyond Requirements Aids in Licensing

Although computer modeling and analysis of certain structural design features of the TMI-2 cask system would have been adequate, DOE conducted drop tests of a 1/4 scale model of the cask and full-scale model of the fuel debris canister to verify performance during simulated accidents. Although component fabrication was expensive and the testing costly, some estimates suggest that as much as a year was saved in acquiring certification. If correct, this indicates that the tests clearly saved substantial funds. 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. (Reference: 5.19)

Integrated Equipment Tests Prove Invaluable

DOE procured two new rail shipping casks, railcars, and some of the cask support equipment. GPU Nuclear procured cask loading and facility interface equipment. DOE arranged for an integrated test of all of these components at one of its facilities. This integrated test provided opportunity for worker training, verification of equipment fitup, procedure preparation, and other coordination tasks. The integrated test is credited with eliminating startup problems and delays at TMI-2. (Reference: 5.19, 5.20)

The Potential for Conflicting Regulations

Potential sources of conflict developed early in the TMI-2 program because of differences in regulations and quality assurance (QA) practices followed by the utility, DOE, and NRC. For example, though many projects were research related, NRC regulations (which govern nuclear utilities) generally superseded those of DOE when working with the utility. When fabricating research equipment, DOE's QA requirements were generally followed. However, when the equipment was brought to TMI-2, the equipment was generally operated under the utility's QA requirements. 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 regulations. (Reference: 5.19)

Documenting NEPA Compliance

There was public concern over the lack of an Environmental Impact Statement (EIS) specific to transporting the TMI-2 core debris. The environmental aspects of TMI-2 core debris transport had been discussed in various safety documents, in the EIS for the TMI-2 cleanup, and in relation to other studies of the environmental impacts of shipping spent fuel. But, in retrospect, the program's compliance with the National Environmental Policy Act (NEPA) was insufficiently addressed with the public prior to the start of shipping. An early step in any such large and complicated program should be documentation that either explains NEPA compliance or invokes exclusion based on existing environmental documentation. (Reference: 5.19)

Public Perception of Routing Transportation

Assuring the safe transportation of radioactive material is primarily a function of container design. The intrinsic safety of radioactive shipments has been demonstrated historically and concluded in a number of studies. Containers such as the TMI-2 fuel debris shipping cask were designed to withstand all credible accidents, including impact, drop, fire, and sabotage. The route over which the cask traveled is a decision that had only a small effect on the postulated consequences of an accident, nonetheless, the route was a major concern of the public. The Department of Transportation has regulations for transporting "highway route controlled quantities" of radioactive materials [49 CFR Part 177.825(b)], but has no equivalent regulation for rail transportation. A large number of factors entered into railroad route selection, including quality of track, population along the route, carrier accident rates, transit time, number of carrier or switching changes, etc. DOE conducted a very thorough route selection process for the TMI-2 shipments based on considerations similar in importance to highway routing.

Figure 17. Map of shipment route of TMI-2 wastes to Idaho National Engineering Laboratory.

The route selected involved ten states, two carriers, a few metropolitan areas, and a total track length of about 2,400 miles. Despite the lengthy process to select the safest route, repeated concerns were raised by citizens and public officials throughout the campaign. As a result of the TMI-2 experience and other departmental evaluations, DOE is reviewing policies on route selection to determine if improvements or better documentation is needed. (Reference: 5.19, 5.24)

Importance of Pre-Notification

DOE adopted a stringent pre-notification policy for shipments of TMI-2 fuel debris to the DOE research and storage facility. There were extensive briefings of state and local officials for several months preceding the first shipment. These informed public officials then responded to questions from their constituents, avoiding many problems of public misunderstanding. DOE has also issued revised orders, based in part on TMI-2 experience, regarding pre-notification of states. This policy requires the shipper to notify the governor, or his designee, in writing, seven days before any movement of nuclear fuel through his state. This is done either by registered letter or special messenger. While prenotification is a straightforward requirement, the practical aspects of compliance is important for the states involved. Continual effort is required to ensure records (names, telephone numbers, addresses, messenger instructions, etc.) are current and procedures are in place to verify notification. A single mistake in the notification chain can delay the entire shipment. (Reference: 5.1, 5.21, 5.24, 5.25)

Addressing Problems En Route

In controversial transportation programs such as the TMI-2 fuel shipments, some problems, jurisdictional disputes, and delays can be expected. To minimize the impact on the TMI-2 campaign, a dedicated transport officer provided constant attention during operations, and DOE-trained contract personnel accompanied about one-half of the shipments. In addition, complete documentation was available aboard the train, including detailed information on the contents of the shipments, copies of approved safety documents, and copies of the shipment notification forms sent to each state. As a result, most TMI-2 shipments proceeded without serious delays once underway. (Reference: 5.25)

Design Simple and Easily Maintained Equipment

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. To avoid difficulties, keep equipment simple and where practical, capable of manual operation. (Reference: 5.25)

Rail Cask Improvements that Decreased Maintenance/Increased Efficiency

The NuPac 125-B rail cask and its railcar required a formal inspection/maintenance program. Review of the maintenance records identified both routine tasks that were excessively time-consuming and certain repairs that occurred repeatedly. Further analysis indicated that these activities could be eliminated, reduced in frequency, or made more efficient by subtle equipment hardware enhancements or modifications to maintenance procedures. Improvements such as the following significantly increased maintenance operations efficiency.

- using welded instead of epoxied joints in the aluminum honeycomb internal impact limiter, thus eliminating the need for constant repair;
- inserting a small diameter tube through the center of each lower impact limiter to pump residual water from the cavity, instead of removing the impact limiter, thereby reducing maintenance time;
- using uncoated stainless steel cables as lanyards instead of vinyl-coated steel aircraft cables corrected the problem that was causing the lanyard loop to open;
- adding tapered lead-in collars around each bolt hole alleviated the time-consuming process encountered in installing attachment bolts for the overpacks;
- revising procedures to greatly extend the useful wheel life of the railcars as a result of early identification of excess wheel wear.

These were examples of what at first appeared to be routine maintenance turning out to be equipment modification needs. It is important to regularly examine maintenance records in order to identify tasks that may be able to be eliminated or minimized by equipment modifications. (Reference: 5.26)

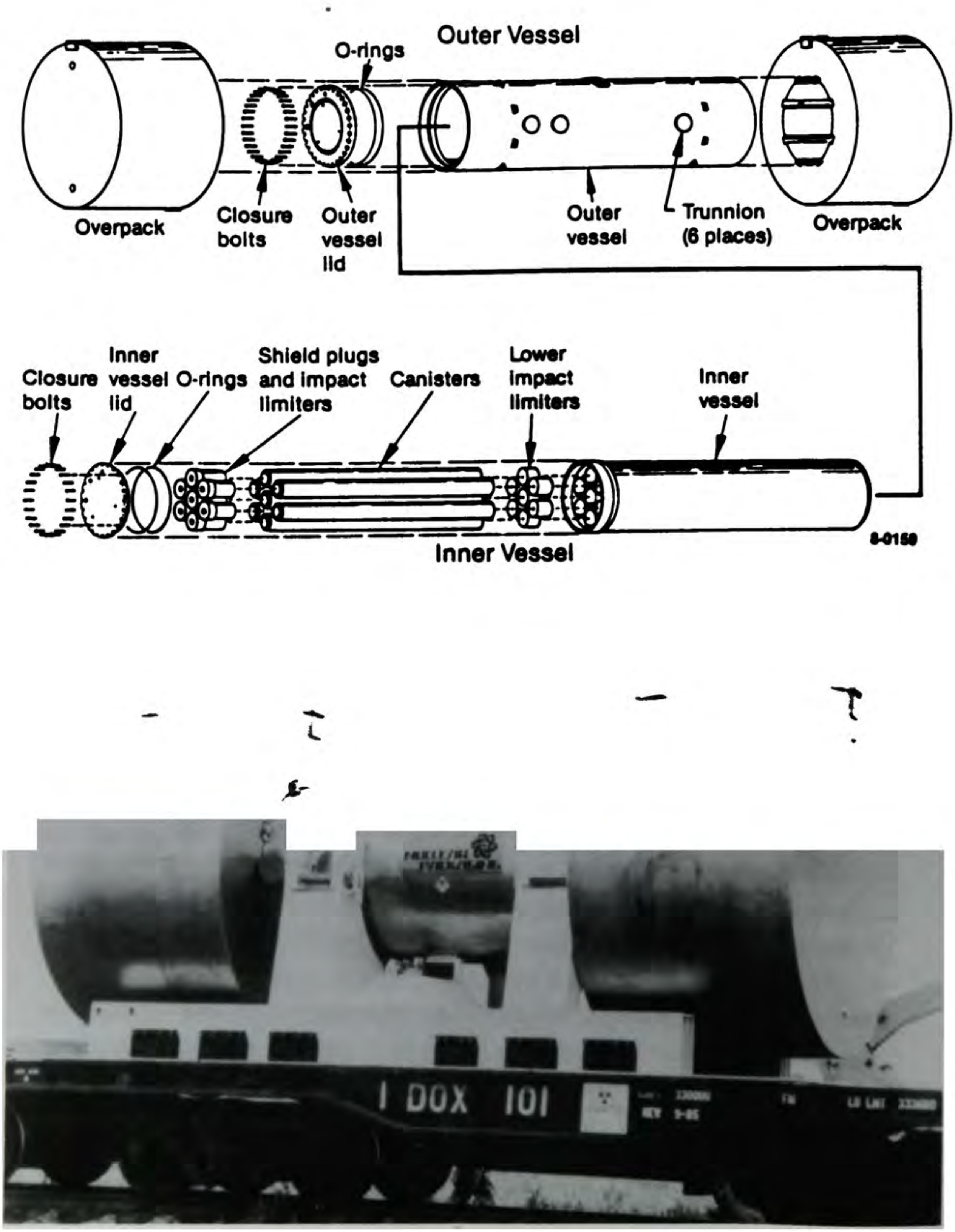

Figure 18. Exploded view of NuPac-125B rail cask and photo of cask on railcar.

Maintenance Program Highlights for Rail Casks

Inspection and maintenance activities were established for the three NuPac 125-B rail casks and their railcars. Minimum maintenance requirements for the rail casks were described in the Safety Analysis Report for the package and issued by the Nuclear Regulatory Commission as a condition of licensing; maintenance of the railcar was satisfied by requirements of the Association of American Railroads. Inspection and maintenance activities were performed by several organizations (i.e. GPU Nuclear, EG&G Idaho, and Union Pacific Railroad).

- Decontamination of the casks after each shipment was a time-consuming operation but was effective in: (a) preventing the buildup of contamination in casks and canister loading equipment; (b) minimizing the spread of contamination at both TMI and INEL; and (c) keeping exposures to operating personnel as low as reasonably achievable. Loading operations at the cask were accomplished with only smocks, gloves, and shoe covers worn as protective clothing.
- TMI experience has shown the helium leak testing procedure to be an effective and timely test method for use in routine operations. It yielded conclusive results and could be accomplished in the same or less time than the less sensitive and qualitative pressure rise test method. This was not intuitively obvious when first considering methods for testing seal integrity.
- Union Pacific Railroad dedicated an experienced, senior maintenance crew to inspect, maintain, and repair the railcars enabling all activities to be accomplished in one day during a single shift.

Positive maintenance is not enough for transport systems as complex as that used for moving core debris from TMI to INEL. Detailed maintenance planning for, and rigorous maintenance of equipment saves time and money over the long term and contributes immeasurably to an enhanced public perception that DOE is concerned foremost with ensuring public and environmental safety. (Reference: 5.26)

Attention to Procedural Quality Overcomes Constraints of Tight Schedule

To produce the NuPac 125-B rail cask in the shortest amount of time for the least amount of money meant the production goal was to build the NuPac 125-B right the first time. Addressing quality timely and adequately kept it from becoming a major issue. When possible, before work was started or, prior to its completion, records were reviewed to verify that personnel writing and performing procedures for various processes or examinations (e.g., welding, nondestructive examinations, helium leak testing) were qualified and certified. All activities related to fabrication and certification of the cask were monitored and records of those activities were audited. Working documents (any engineering/technical documents which convey instructions to those who fabricate, inspect, or test hardware including shop drawings and travelers) received detailed technical review. Whenever those documents differed from contract drawings the inconsistency was resolved thus identifying and correcting mistakes and oversights before they resulted in actual hardware deficiencies. (Reference: 5.20)

Early Detection/Correction/Prevention of Quality Nonconformances
Stepped-up in-process inspection and nondestructive examination of components beyond established requirements added cost but paid big dividends in detecting and correcting problems early and saving time. Although there were cost trade-offs, additional informational tests and inspections were beneficial because the earlier deviations were identified, the easier they were to fix. (Reference: 5.20)

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6. REACTOR DEFUELING AND RELATED OPERATIONS

6.1 Background

Virtually the entire TMI-2 reactor core, approximately 150 tons of uranium dioxide, zircaloy, and stainless steel, was damaged by the accident. Of the approximately 37,000 fuel rods in the core, all but about 7,000 shattered. Peak core temperatures of about 5000° F caused melting of about 50% of the core materials. Many tons of molten debris relocated within the reactor vessel, and a large quantity of this slag-like debris melted through the heavy steel support plates around and beneath the core, and resolidified on the lower head of the vessel. (See additional discussion of the accident sequence in Section 7, Accident Analysis.) The magnitude of the defueling task is illustrated by the post-accident condition of the TMI-2 core, shown in Figure 19. Defueling required more than 4 years of effort, including hundreds of workers and millions of engineering and operations man-hours.

It is important to remember that the detailed description of core damage shown in Figure 19 evolved over about five years. It is a product of accident analysis, specialized data acquisition tasks, and direct observation of damage structures revealed during the defueling itself. Thus, when defueling began in October, 1985, many details of the core condition were unknown. To accommodate unexpected conditions, the defueling approach had to be flexible. Though a variety of defueling techniques were investigated—including shredding the core debris *in situ* for easier handling and totally automated remote defueling—a straightforward manual approach was finally selected. (Reference: 6.1)

6.2 Defueling-Related Operations

6.2.1 Discussion

Numerous tasks were required in the early stages of the TMI-2 cleanup to stabilize plant conditions, including special decay heat removal systems, water sampling systems, and a number of special instrumentation and control systems. The lessons learned from some of these tasks are discussed elsewhere in this report. This section is limited to those tasks

TMI-2 Core End-State Configuration

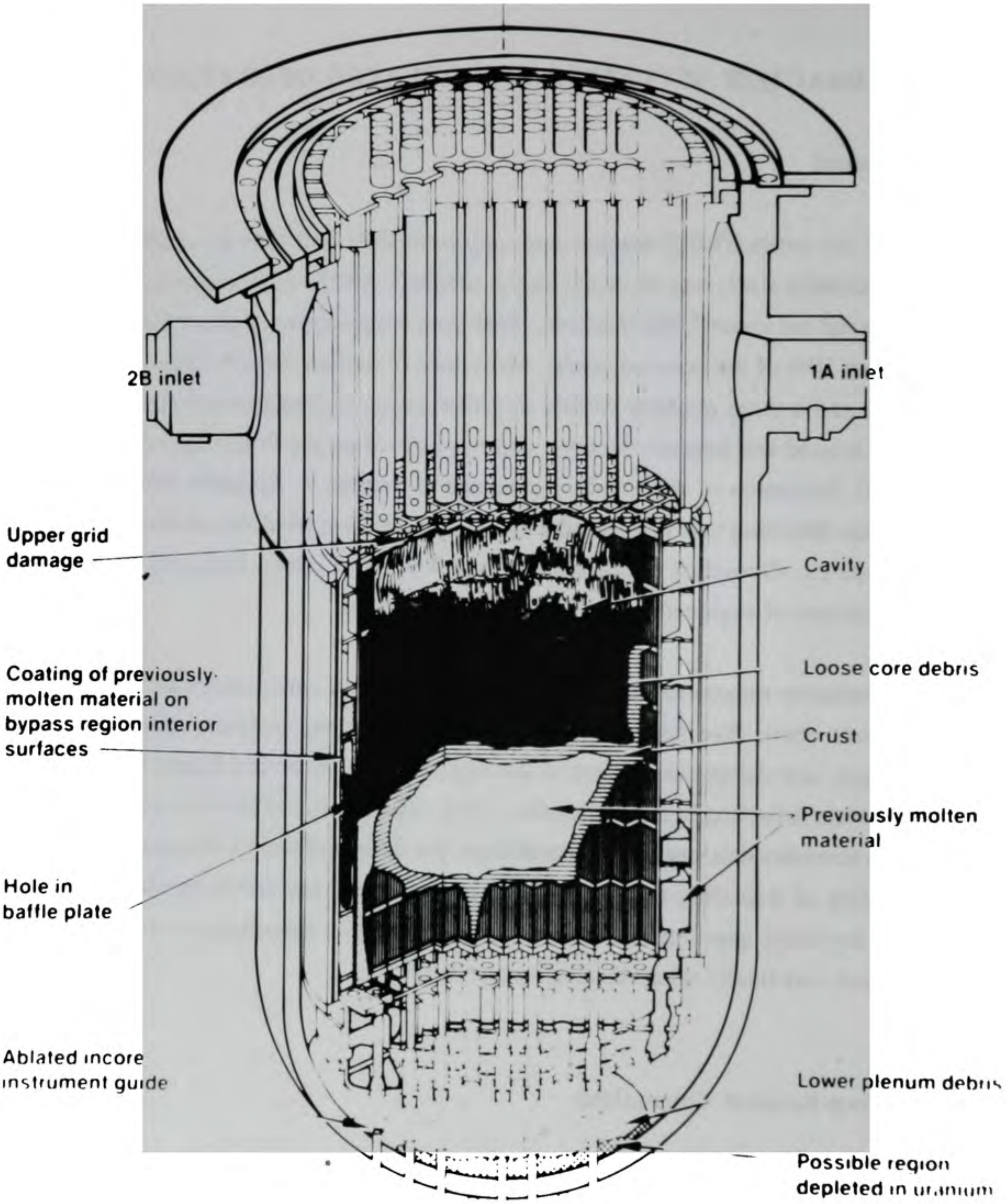

Figure 19. Post accident condition of the TMI-2 core.

specifically required to gain access to the damaged core for defueling. These include, preventing accidental criticality, opening the primary coolant system, reactor head removal, upper reactor internals removal, and lower core support assembly removal.

While various analyses showed that recriticality was unlikely, the lack of precise knowledge about core configuration and the extreme danger from an accidental criticality dictated that core reactivity had to be controlled. The addition of soluble chemical poison was chosen as the best method to ensure the core remained subcritical during all possible post-accident configurations.

A variety of concerns were expressed over the opening of the pressurized primary coolant system. The lowering of the water level, the loss of the nitrogen gas over-pressure, and the diffusion of oxygen (from the air) into the system were evaluated to assess their impact on criticality safety (by altering the amount of dissolved boron in the coolant), radioactive krypton gas release, hydrogen generation, pyrophoric reactions, and worker radiation exposure.

The procedure for removing the reactor pressure vessel head was generally the same as that used during routine refueling. However, some additional steps were needed to assess damage to the head, determine the extent of radioactivity plated out on the underside of the head because of the accident, and to provide adequate shielding of the head while in its storage position.

The upper core support assembly, commonly referred to as the plenum assembly, is a large, stainless steel structure located immediately above the reactor core. The plenum assembly provides support and alignment for the 69 control rod clusters that enter the core from the top. Plenum assembly removal was a concern because of the potential for high radiation levels, remnant fuel assemblies fused to the underside of the assembly, and assembly distortion making removal difficult.

The stainless steel lower core support assembly (LCSA) consists of the grid into which the bottoms of the fuel assemblies engage, and a series of massive steel plates and forgings that provide a variety of support and coolant flow control functions. After the original core volume was defueled, the LCSA had to be cut apart to gain access to the roughly 20 tons of fuel debris that had relocated below the LCSA onto the reactor vessel's lower head. (Reference: 6.2)

6.2.2 Lessons Learned

Boric Acid for Criticality Control

Six elements (B,Cd, Gd, Li, Sm, and Eu) were studied for addition to the coolant system to maintain k_{eff} below 0.95. Boron (as boric acid) was found to have a variety of advantages, including:

- lower cost;
- minimum impact on water cleanup systems;
- no serious materials compatibility problems; and
- could be added using existing chemical addition equipment.

Dissolved boron levels of 5,500 ppm were found to be adequate to maintain the core 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 primary coolant system. (Reference: 6.3)

No Pyrophoric Reactions

Finely divided metallic Zircaloy is pyrophoric. Even though evidence showed that most of the Zircaloy had been oxidized by the accident, the fact that the Zircaloy cladding had fragmented caused some people to express concern over a pyrophoric reaction (and a consequent large metal fire) if core debris was exposed to air. Analytical studies were done and samples of fine core debris 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 prior to head lift (thereby uncovering fine debris resting on the top of the plenum) and air allowed into the system, no pyrophoric reactions occurred. During the entire reactor defueling operations, including sawing and plasma arc cutting of core materials, no pyrophoric reactions were observed. (Reference: 6.4)

Air Exposure Increases Radioactivity

Exposing the reactor coolant to air caused an increase in the dissolved oxygen content of the water. The higher oxygen content increased the solubility of some fission product-bearing species in the coolant, causing the radioactivity in the coolant to increase. The increases were greater than expected and some additional shielding had to be installed to maintain worker radiation exposure as low as reasonably achievable. (Reference: 6.5)

Minimizing Airborne Contamination

Removal of the reactor head required the water level be lowered to just below the top of the 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. As a result, airborne contamination was not a problem. (Reference: 6.6)

Verifying Dimensional Data

Because of the possibility of damage or distortion due to high accident temperatures, extensive planning went into the plenum assembly removal operation. Special measurements revealed some variations between the plenum assembly dimensions and the dimensions indicated on the design drawings. Though difficult, time-consuming, and adding to radiation exposure, the measurements prevented even greater delays and possible rework of specially fabricated components. For critical tasks, even as-built drawings require verification. (Reference: 6.7)

LCSA Removal by Plasma Arc Cutting

A broad range of techniques were evaluated to cut apart and remove the massive stainless steel lower core support assembly (LCSA) in order to access the debris on the reactor bottom. Analysis ruled out some techniques, 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 (ACES) was designed and installed to perform the task. The LCSA was cut into about 50 pieces; disassembly required about one year. Though actual cutting was quick, productivity was hampered by equipment failures, torch failures, and control system redesign. Fuel debris adhering to the LCSA plates made cutting difficult. (Reference: 6.8)

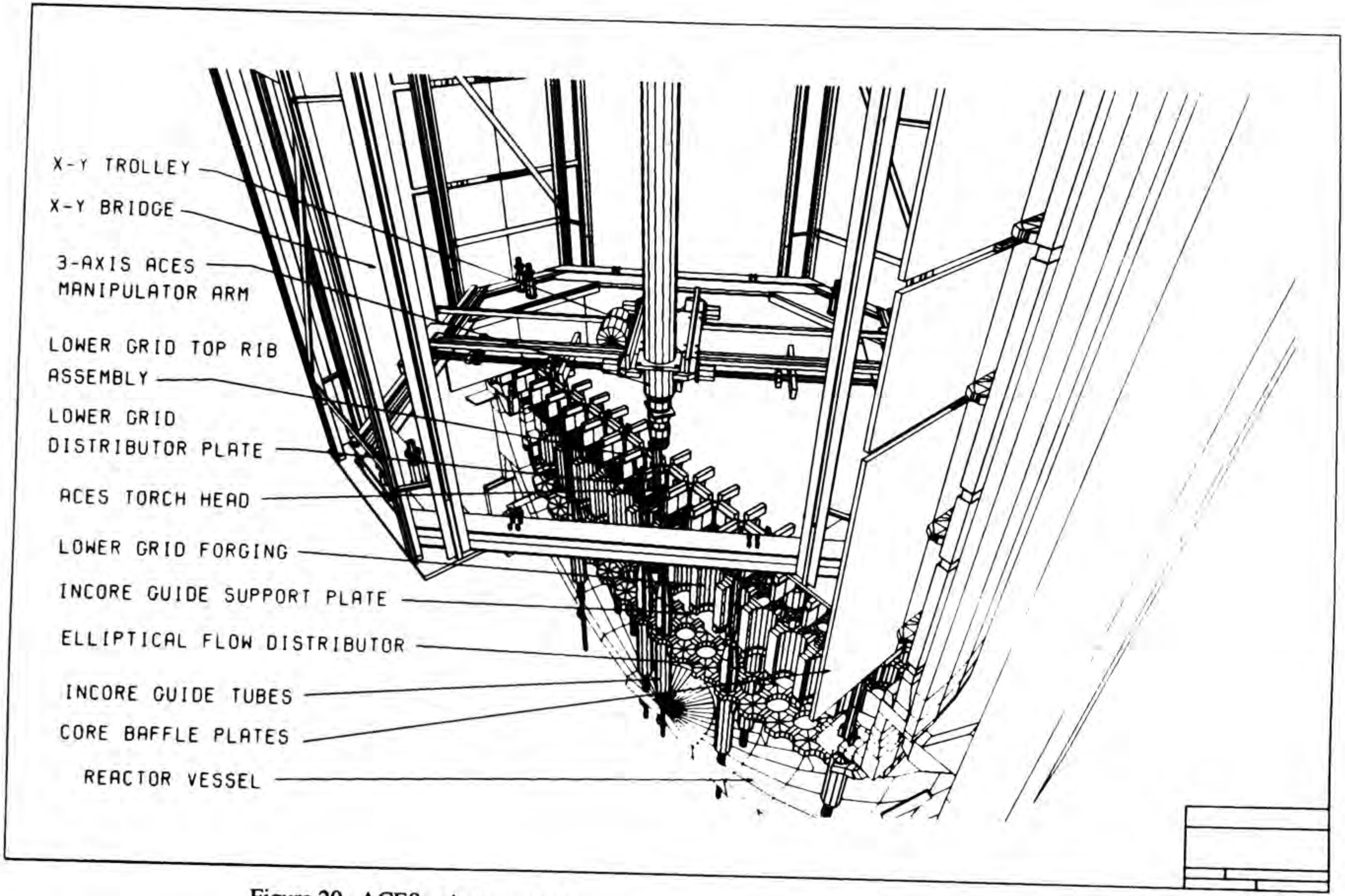

Figure 20. ACES—Automated plasma arc cutting equipment system schematic.

6.3 Reactor Defueling

6.3.1 Discussion

At TMI-2, the defuelers worked on a shielded work platform located immediately above the water-filled reactor vessel. Using long handled tools, some manual (grapples, buckets, scoops, etc.) and some power-assisted (saws, cutters, pincers, vacuum hoses, etc.), they loaded debris into canisters. The debris handling and loading process was aided by fixed position and movable underwater TV cameras. The defuelers had to deal with a broad range of core debris, including largely intact fuel assemblies, gravel-like debris, cladding pieces, broken fuel rods, large masses of fused debris, and rock-like pieces of once-molten slag. After the canisters (located in a carousel underneath the work platform) were filled, they were moved via a shielded transfer bell out of the vessel and into the normal fuel transfer canal used for reactor refueling. From that point, the canisters were handled the same as intact fuel assemblies would be during routine refueling. They were placed on their side and moved on a transfer mechanism into the fuel handling building and then into the fuel storage pool. The fuel debris canisters were loaded into rail casks and transported to a DOE facility, as described in Section 5. The overall defueling concept is shown schematically in Figure 22. (Reference: 6.2)

6.3.2 Lessons Learned

Microbial Growth

Only a few months after defueling started, water clarity began to deteriorate. TV camera visibility was rapidly lost and defueling 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 vessel. It took more than a year to completely restore clarity and visibility. Studies revealed that small amounts of hydraulic fluid from the defueling tools leaked into the reactor coolant and provided the organic food source for the microorganisms. This was aided by the correct water temperature and light from the underwater TV camera lights. Ultimately, hydrogen peroxide was used to kill the growth and prevent recurrence. (Reference: 6.9)

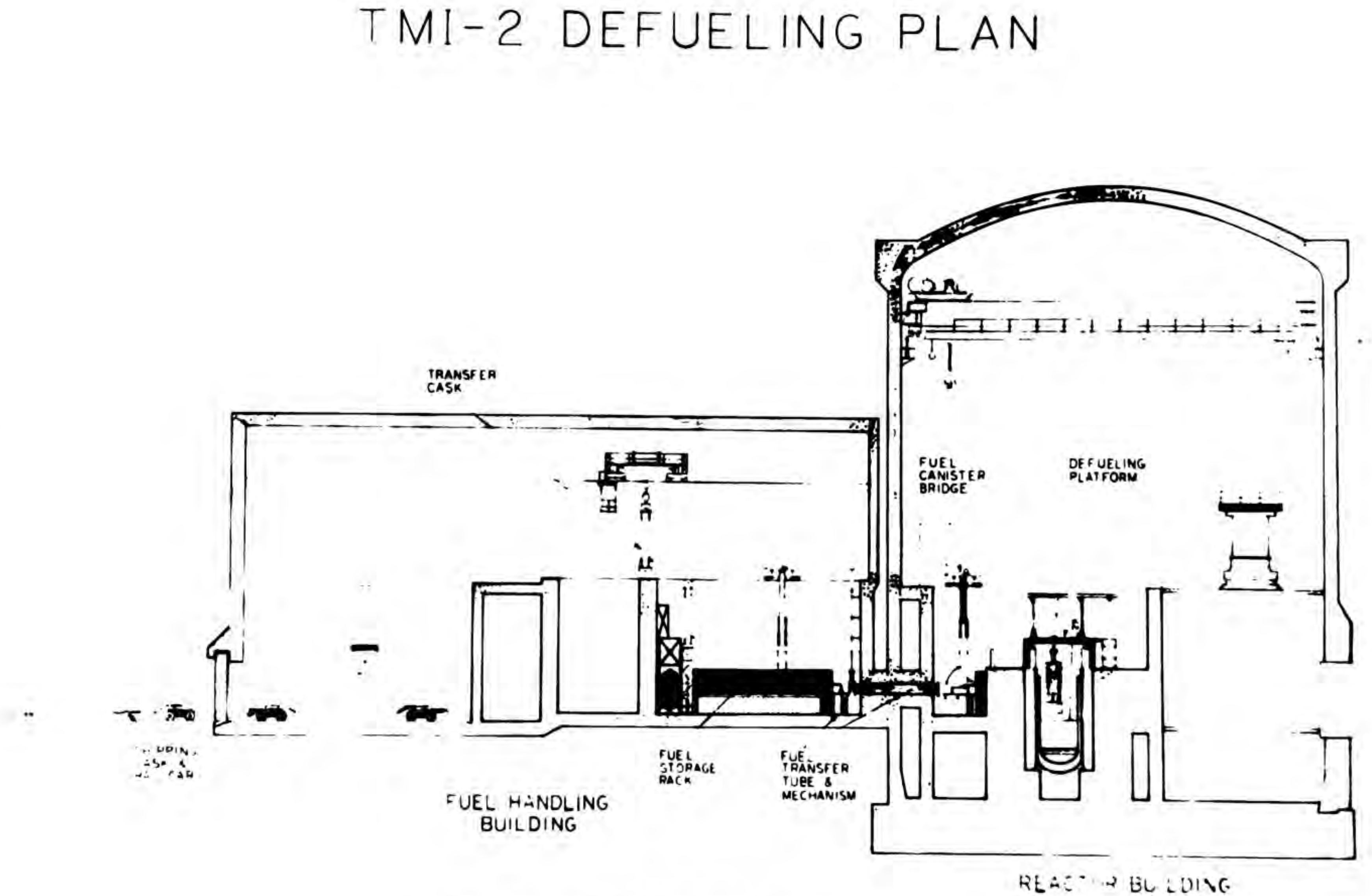

Figure 21. TMI-2 defueling schematic.

"Blind" Defueling

Though the microbial growth virtually halted defueling for about nine months, defueling actually progressed fairly rapidly during the early stages of reduced visibility. Once the defuelers realized the visibility problem would remain for some time, they began to develop techniques for working in these conditions. The rubble bed had been cleared of large pieces of material before visibility was lost, leaving several feet of loose, granular debris. Using a clamshell-like tool and working blind, the defuelers were able to scoop up the gravel, position it over the known location of the debris canister, and dump the material into the canister. They even developed a canister funnel to collect more of the material. Thousands of pounds of granular material were removed in this manner during periods of almost no visibility. (Reference: 6.10)

Molten Material Formation

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. The molten core material solidified into a heterogeneous, funnel-shaped disk over a meter thick in the center and weighing many tons. Heavy-duty defueling tools (impact chisels and wedges) were unable to break apart the monolith. A specialized drilling apparatus was finally used to pulverize the material. Analysts had not predicted the extent to which the molten material would form into a large monolith within the core, nor had the material's resistance to fracture been understood. (Reference: 6.1)

Coordination Center Support

The defueling efforts taking place on the work platform above the core were monitored from a coordination center established in the nearby turbine building. Support staff could observe the work teams via closed circuit TV cameras mounted in the reactor building, whose pan, tilt, and zoom controls were remotely operated from the coordination center. TV monitors in the coordination center also displayed images from the in-vessel TV cameras used by the defueling teams. In addition, the coordination center was in radio communication with each member of the defueling team. The center could record the video and audio for archive records of the operations, analysis of the footage, worker training, etc. Support could be given to the defuelers (e.g., special data, engineering expertise, procedure changes, suggestions for solving problems, ALARA advice, etc.) via communication from the coordination center rather than by sending additional workers into the reactor building. This concept of remote coordination proved to work extremely well; it helped increase productivity and minimize radiation exposure. (Reference: 6.11)

Figure 22. TMI-2 Coordination Center.

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7. ACCIDENT ANALYSIS

7.1 Background

The TMI-2 accident consisted of the following sequence of events. Maintenance tasks had produced a series of circumstances that caused the pumps supplying the cooling water to the steam generators to trip. Backup pumps started automatically but no cooling water reached the steam generators because valves in the pump lines had been improperly left closed following a recent system test. With no cooling water flowing through the steam generators, the reactor—operating at 98% power—could not dump its heat load. The reactor coolant heated up and expanded, causing the water level in the pressurizer to rise and the system pressure to increase. As designed, the pressure increase caused the reactor to scram and also caused a valve at the top of the pressurizer to open to relieve the system pressure. Nine seconds had elapsed since the initiating event.

When the reactor system pressure fell to a certain value, the pressurizer relief valve was supposed to close and the system pressure stabilize. Even though the closure signal was sent to the valve, the valve failed to close. However, the plant operators believed the stuck open valve was closed. Their instrumentation told them the closure signal was sent, but not that the valve failed to respond. With the pressurizer valve open, the system pressure continued to fall and reactor coolant water flowed out of the primary system. As the pressure fell, water in the primary system flashed to steam and the resultant voids caused the water level in the pressurizer to rise due to expansion. The rising pressurizer level alarmed the operators because it seemed to indicate that the pressurizer was filling with water and the steam pocket normally at the top of the pressurizer (which is critical to controlling the reactor system pressure) was disappearing. As the system pressure fell below a certain set point, a safety system—the high pressure injection system—activated and began pumping additional cooling water into the reactor. Concerned that the additional water would overfill the system, the operators throttled the valve to reduce the water flow into the reactor. In reality, the reactor was losing water through the stuck open valve, and was not in danger of overfilling as their instrumentation indicated. Though water inventory in the reactor system was dangerously low and there was a lot of steam in the piping system, the reactor coolant pumps were circulating enough of the water / steam mixture to keep the fuel temperatures near normal. At this point, less than five minutes had elapsed since the accident began. (Reference: 7.1)

7.2 Core Damage Scenario Analysis

7.2.1 Discussion

At 100 minutes into the accident, excessive vibration caused the operators to shut down the remaining reactor coolant pumps to prevent damage. With no forced circulation, the steam and water separated and soon the water level fell enough to expose the tops of the fuel assemblies. At about 140 minutes fuel failures began. By about 170 minutes the rapid oxidation of the Zircaloy cladding generated so much heat that Zircaloy melting began. Brief operation of one pump at 174 minutes sent a large quantity of water into the vessel, causing the now hot and oxidized cladding to shatter. The tops of the fuel assemblies collapsed into a rubble bed but the brief cooling was not enough to prevent continued heat up and melting beneath the rubble. A large molten zone formed in the center of the core, held in place by a resolidified crust acting like a crucible. Cooling water flow resumed at about 200 minutes but cooling was slow because the water and steam could not easily penetrate the crust and heavy damage. At 224 minutes the crust broke and an estimated 20 tons of molten material fell as slag-like debris onto the bottom head of the reactor vessel. Continued introduction of water created a coolable configuration and terminated the accident about 300 minutes after it began.

It has taken many years of analysis to understand the events occurring within the TMI-2 reactor vessel during the accident. Though certain aspects of the event sequence remain unclear, the available data suggest some important reactor safety lessons. (Reference: 7.1)

7.2.2 Lessons Learned

Vessel Remained Intact

The TMI-2 core damage experience indicates that existing reactors are remarkably rugged and capable of withstanding accident events that—while considered in their design—were never expected to occur. The reactor vessel in particular, though damaged, was capable of withstanding extremely high core temperatures and the impact of many tons of molten core material. (Reference: 7.2)

Radionuclide Retention

Though large quantities of radioactive fission products were released from the damaged and melted fuel, very little radioactivity was released to the environment. In addition to specific safety systems designed to prevent release, a number of natural processes occur within the reactor vessel to contain radioactivity within the primary system. These include, chemical reaction with steam, dissolution in the coolant, reactions between fission products and among fission products and other core materials, and plate out on high surface area structures within the reactor. (Reference: 7.4)

Retention of Volatile Species

Volatile fission products, in particular iodine and cesium, were retained inside once-molten fuel debris to an unexpected extent. Though the amounts of these species in debris samples varied widely (depending upon location in the core and melt composition) retention in some samples was on the order of 30% for both species. Since estimates of the off-site radiation exposure during a severe accident depend heavily on the release of these species, consequence models should be revised to include this phenomenon. (Reference: 7.3)

Steam Explosions

There is disagreement as to the likelihood of a steam explosion inside the reactor vessel during a severe accident, due to large quantities of molten core material falling rapidly into water. Such explosions have been hypothesized to fracture the reactor vessel and release the molten core material. While not precluding steam explosions under other accident conditions, one did not occur at TMI-2. Despite the rapid relocation of about 20 tons of molten core material into water that occurred when the crust supporting the melt failed. (Reference: 7.2)

Recriticality

The TMI-2 control rods failed relatively early during the core damage sequence due to melting of the silver, indium, and cadmium control alloy and the subsequent failure of the stainless steel tubes containing the alloy. Nonetheless, there was no recriticality. While concern over accidental criticality is warranted because of the extreme danger and the positive actions taken to preclude it were appropriate (see Section 6.1.2), accidental criticality appears to have been unlikely because of the loss of a regular core geometry and the heterogeneous mixing of fuel and other core materials. (Reference: 7.5)

Small Coolant Flow Adequate

Analysis of the TMI-2 core damage scenario showed that at about the time the fuel began to be uncovered, as little as 200 gpm of subcooled water flowing through the core would have been enough to remove the decay heat and prevent core damage. This is an extremely small fraction of the total pumping capacity of the reactor coolant system and well within the capacity of even one of the safety systems. Maintaining even a small amount of water flow during an accident will probably preclude major core damage. (Reference: 7.6)

7.3 General Analysis of the Accident

7.3.1 Discussion

The TMI-2 accident provided an opportunity to evaluate a variety of instrumentation and electrical equipment for the effects of exposure to severe accident conditions including steam, water spray, radiation, and hydrogen burn (including the resultant high pressure). The examination of this equipment over a several year period also provided information on long term effects of the exposure to moisture from continuing decontamination efforts and to the high radiation background. The DOE Instrumentation and Electrical Program was established to evaluate the ability of the instrumentation and electrical components to meet design criteria and to survive the accident environment. Although the primary thrust was the evaluation of survivability and performance, the program revealed many weaknesses in the design, installation, maintenance and testing of both safety-related and balance-of-plant equipment. Generally, safety-related equipment performed well, although failures were noted in pressure transmitters and motor-operated valves located in the flooded basement. (Reference: 7.8)

7.3.2 Lessons Learned

Equipment Failures Due to Moisture Intrusion

Most equipment failures occurred within the first 24 hours after the accident and were predominantly a result of corrosion due to moisture intrusion. Class 1E and safety-related equipment were generally more resistant to moisture than nonqualified equipment. Moisture intrusion generally occurred at the electrical penetration to the device due to faulty or inadequate seals and may have occurred eventually even without the accident. Additional failures were observed when the equipment was mounted incorrectly, for example with the vent positioned where it could collect water. Where a reliable seal existed at the cable entry into the equipment housing, the internals were generally not corroded and the instrumentation or electrical equipment was operable. Particular care should be taken with conduit and junction box seals, equipment drains and vents, and the sealing of connector backshells to protect against moisture intrusion. (Reference: 7.8)

Pressure Transmitters

Testing proved that radiation had little effect on operation of the pressure transmitters during and following the accident. Failure of some transmitters resulted from moisture inside the transmitter housing. Two possible sources of the moisture were:

- Water from the reactor building spray system, or condensation from the humidity in the building on the cables or on the ends of the conduits.
- Humidity in the building, combined with the lack of adequate ventilation in some of the conduit, caused condensation on the inner walls of the conduits that drained into the transmitter housings.

DOE's investigation has shown that the transmitters are capable of surviving a loss-of-coolant accident, but proper installation of the conduit, junction boxes, and cabling is essential for protecting the transmitters from moisture intrusion. Unless a seal around electrical leads as they exit the transmitter housings is an integral part of the unit, verification of water resistance after installation is not possible. (Reference: 7.7)

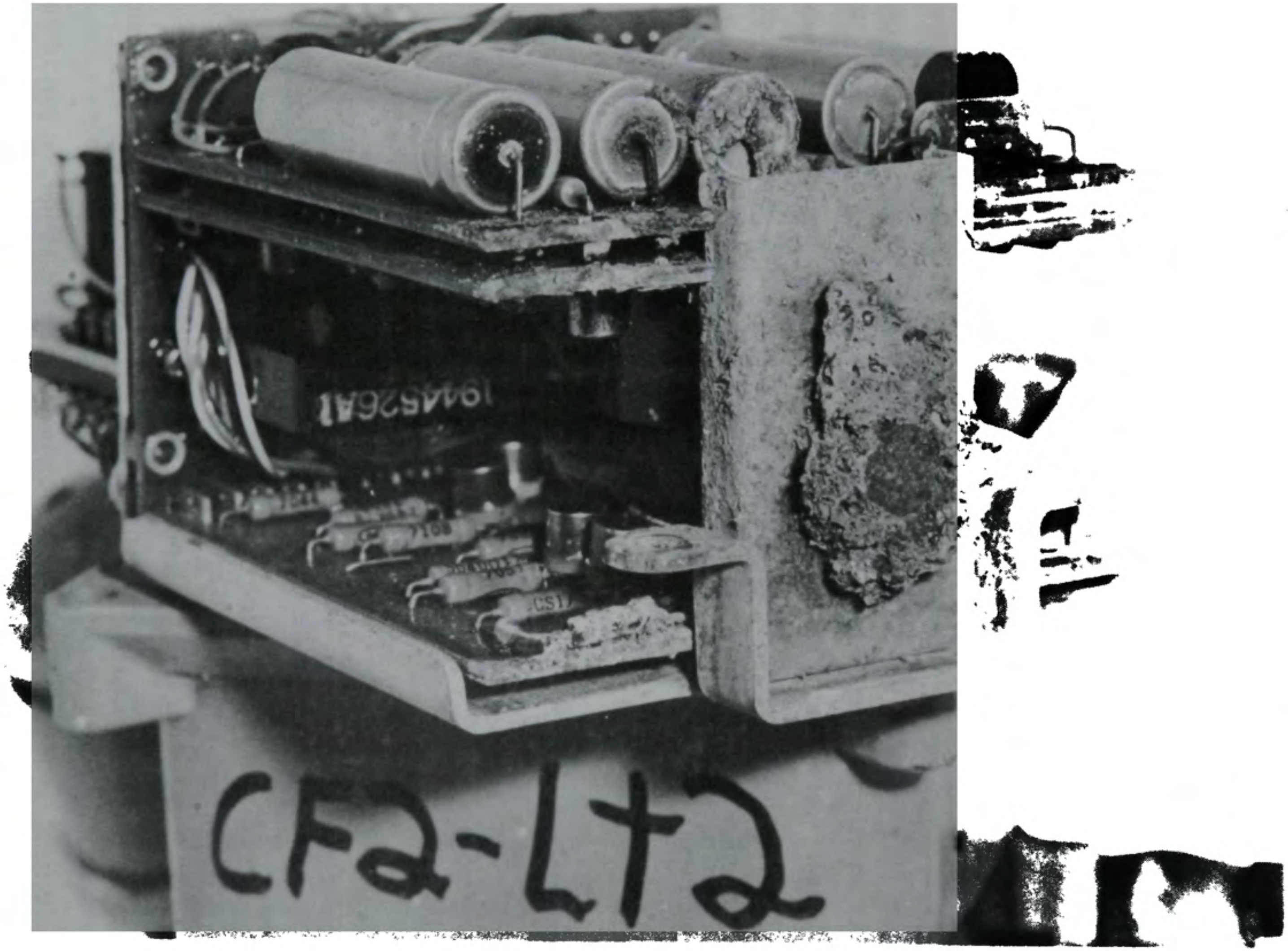

Figure 23. Instrument damage due to moisture intrusion.

Electrical Circuit Characterization and Diagnostic System

Electrical shorts and degraded circuits are difficult to detect and locate, particularly if they occur in penetrations such as those through the walls of a reactor containment building. The Electrical Circuit Characterization and Diagnostic (ECCAD) System was designed to distinguish small differences in the electrical characteristics of circuits and to identify anomalies. This computer-controlled measurement system can detect impending electrical failures, thereby improving electrical maintenance and increasing reliability. Although developed for DOE by EG&G Idaho for use at TMI-2, ECCAD technology is being tested at other plants and ECCAD-like diagnostic systems are likely to become standard maintenance equipment at most electric utilities. (Reference: 7.8)

Metal Oxide Semiconductor Transistor Degradation

Metal oxide semiconductors (MOS) transistors or MOS-integrated circuits should not be used in any application where radiation exposure is possible. Most MOS devices are abnormally radiation-sensitive and degrade dramatically at reasonably low doses. (Reference: 7.7)

Military Grade or Better Components Recommended for Electronics Packages

Military grade components undergo rigorous inspection and testing procedures and have a much improved reliability over standard commercial grade components. Commercial grade components such as electrolytic capacitors, plastic-encapsulated transistors, and reed switches are not suited for use in important equipment, particularly where severe environments are possible. Mil Std 883 Class B components should be used for these applications. (Reference: 7.7)

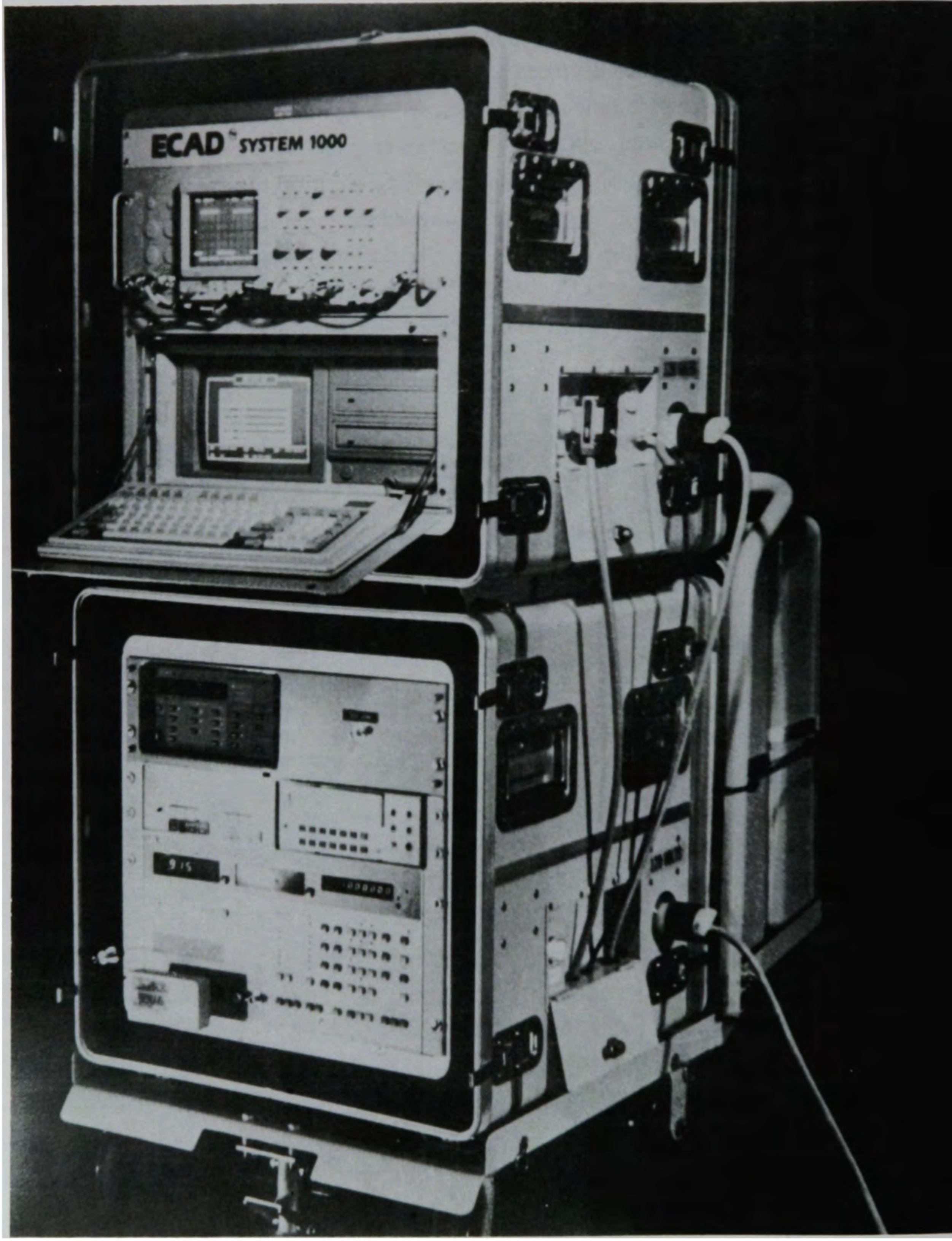

Figure 24. ECCAD system.

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8. PROJECT MANAGEMENT AND ADMINISTRATION

8.1 Background

Many of the lessons presented in previous sections of this report have been very specific, dealing, for example, with specialized robotics, decontamination techniques, or core damage events. This section assembles some of the more general lessons, lessons applicable to other large-scale technical projects having high public visibility. While TMI-2 was a unique event, some of its attributes have been and will be present in other projects. These include:

- Widespread public, political, and media awareness;
- Technically complex, with some elements never before done;
- Perceived to be more dangerous than it really is;
- Government agency involvement in many aspects;
- So large and complex that multiple organizations (public and private) are involved;
- Extremely expensive;
- Participation by international organizations;
- Widespread implications for the industries affected.

Because so much of the success and so many of the complications of large-scale technical projects depend upon many individuals and organizations, TMI-2's project management and administration lessons are particularly important.

8.2 Project Management

8.2.1 Discussion

The organization put in place to conduct the TMI-2 cleanup was dramatically different than that normally encountered at a nuclear power plant. Because TMI-2 represented a major financial burden with large technical uncertainties, the fundamental structure of the operating utility was changed. A separate legal entity was created to focus resources on the two TMI reactors and limit the impact of TMI-2 on the company's other generating facilities. Completely separate organizations were created to operate TMI-1 and cleanup TMI-2. The

TMI-2 staff had to be increased substantially and augmented by new technical disciplines. Outside companies were hired to assume architect engineering and construction responsibilities and provide decontamination expertise and manpower. As discussed in the Introduction, mutual agreement was reached to allow participation by a wide range of federal, state, and nuclear industry organizations. Because of the valuable research opportunities, foreign countries participated in some aspects of the cleanup. The responsible organization, GPU Nuclear, had to create a management structure that accommodated all participants. (Reference: 8.1)

8.2.2 Lessons Learned

Thoroughly Integrated Organizations

GPU Nuclear 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. Integration occurred at all levels, with GPU Nuclear workers reporting to Bechtel managers and vice-versa. The organization hierarchy remained flexible. A GPU manager who left the organization might be replaced by a Bechtel employee, depending on whom 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 the contractor, Catalytic Corporation, that provided much of the union manpower for the cleanup activities. The integration was not achieved to the same degree within all parts of the organization. Nor were jurisdictional and organizational disputes eliminated. Nonetheless, for the companies involved (including a large number of small subcontractors not mentioned above), there was a general lack of corporate posturing and oneupmanship. (Reference: 8.1)

Recognition of the Importance of Data Acquisition

Because of 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 plant operations staff objected to the delays resulting from research tasks. There were numerous instances, however, where data acquired for research purposes turned out to be important to the cleanup operations. Data acquisition became such an important part of the overall program that a group was created within the TMI-2 organization to support DOE's data acquisition needs and acquire and interpret its own data specifically to benefit the cleanup program. Competition for resources would never completely eliminate disagreements over the value of data acquisition tasks. Nonetheless, there was general recognition that the cleanup, and the condition of the damaged core in particular, held so many potential surprises that data acquisition was an important part of each step in the program. (Reference: 8.2)

Separation of Operations and Research

Throughout the TMI-2 cleanup, the primary responsibility for conducting research has been with the DOE (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 the research program. While GPU Nuclear's staff was essential to assisting 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. GPU Nuclear's management was focused on the accident cleanup. 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, GPU Nuclear allowed DOE contractor personnel access to the TMI-2 facilities and permitted, in special instances, these people to perform research and data acquisition tasks. This clear demarcation of responsibilities and the creation of on-site organizations for coordination and cooperation, allowed plant cleanup and research to proceed efficiently and to complement each other. (Reference: 8.8)

8.3 Public Affairs

8.3.1 Discussion

It is generally acknowledged that the utility, federal agencies, and state agencies dealt poorly with the public and the news media during the TMI-2 accident. Information was withheld, poorly presented, and uncoordinated, causing confusion and apprehension. Over time, community relations and information dissemination vastly improved. However, there was such widespread public and media attention during the entire TMI-2 cleanup process, that new public affairs lessons were continuously being learned. The following lessons stem from the DOE's experience. GPU Nuclear's communications and public affairs lessons are even more extensive. They are summarized in Reference 8.3 and 8.5.

8.3.2 Lessons Learned

Public Involvement

The public's lack of understanding of nuclear issues and skepticism over official pronouncements was a continuing problem at TMI-2. To help combat this, the DOE developed a program of public participation whereby representatives of 12 nearby communities, selected by town officials and citizens, were given training in the basics of radiation. They were then given radiation monitoring equipment and taught how to calibrate and operate it. Radiation monitoring sites were established and the citizen groups made regular measurements of airborne activity to complement the measurements made by the utility and government agencies. The results were made available to the press and were compared with other available data. Skepticism over radiation releases declined. (Reference: 8.4)

General Observations

Numerous general observations pertaining to communications and public affairs have been noted during the course of DOE's TMI-2 program.

- Work closely with state officials to develop good communications and work relations. They are among the most knowledgeable of outside parties and can provide valuable support in communicating with local officials and citizens.
- Certain local officials are often the important decision-makers and opinion leaders. Effort should be made to identify and communicate with these people.
- Provide timely responses to inquiries.
- Videotapes, scale models, and information packets are cost-effective ways to transmit information to officials and the public.
- Establish a single point of contact—a public affairs professional—to handle press and public inquiries. Provide some basic technical training for this individual and provide technical staff with good communications ability to handle detailed technical questions.

- Formally review public affairs performance and community interest on a regular basis to identify areas for improvement.
- Delay shipments of radioactive waste to avoid conflicts with elections.
- Press interest in the technical aspects of the program may mean that scientists and engineers will be queried on their work (e.g. at technical society meetings). Special training in dealing with the press may be appropriate for selected individuals. (Reference: 8.3, 8.5)

8.4 Documentation

8.4.1 Discussion

The wealth of information stemming from the TMI-2 cleanup and research programs has been disseminated throughout the world. The DOE recognized early that among its more important responsibilities was the collection and publication of this unique information. Accordingly, a wide variety of technology transfer vehicles were used, including scientific meetings, technical journals, technical reports, videotapes, workshops, and scale models. This effort culminated in a TMI-2 international topical meeting sponsored by the American Nuclear Society.

8.4.2 Lessons Learned

Target the Utility Audience

The documentation of the DOE research was largely done by and written for the national laboratory audience. There were many research lessons, however, for nuclear utilities. The utility audience required a completely different documentation approach. Technical detail and background was less important than specific direction on the practical aspects of implementing the lesson. Generally, reports for the utility audience should be concise and stress the cost, performance, or productivity improvement that can be expected. (Reference: 8.9)

Consolidated Reporting

Many DOE research reports were published as GEND documents, even though the work was done by a variety of organizations that had their own technical documentation systems. (GEND being the acronym for the principal participants in the TMI-2 research program: GPU Nuclear, Electric Power Research Institute, Nuclear Regulatory Commission, and Department of Energy.) The GEND reports came to be recognized as an important definitive source of TMI-2 data. This system allowed multiple organizations to publish TMI-2 information in a standard format. (Reference: 8.6)

Internal Documentation

Much of the TMI-2 research data were not only valuable to the nuclear industry, but were important to the cleanup effort itself. This information had to be distilled and packaged differently so that it was useful to the TMI-2 operations staff. GPU Nuclear developed a concise, flexible format called a "Technical Bulletin" that was widely disseminated within the cleanup organization. Engineers preparing these bulletins extracted the research data most relevant to the cleanup and summarized the data for the operations audience. This allowed DOE's research efforts to be of direct and immediate benefit to the cleanup program. (Reference: 8.10)

Videotape Documentation

Videotape became an important medium for documenting many aspects of the TMI-2 program, particularly the damage to the reactor core and the progress of the defueling. However, the massive quantity of videotape meant that significant resources had to be applied to managing the information. This included high-speed equipment to review and analyze the raw footage, tape copying equipment, a video library to catalogue the footage, and personnel dedicated to maintaining the equipment and the library. Because of widespread interest in the footage, procedures had to be developed to authorize its release. The videotapes were used for many applications, including, press releases, public meetings, corporate management briefings, briefings of government officials, employee information, technical analysis, industry publicity, to complement oral presentations at scientific meetings, and worker training. (Reference: 8.11)

The TMI-2 Data Base

The DOE established a microcomputer data base that eventually indexed about 20,000 documents on the TMI-2 research and cleanup programs. The data bank was designed to be easily accessed by researchers throughout the country. The data bank was widely used by the program documentation staff to identify and retrieve documents. However, despite being easy to use, its on-line capability was not widely used by the nuclear industry. It was not a cost-effective way to disseminate information to the nuclear community. Periodic reviews of the data bank contents, particularly in the early stages of development, were important to assuring that the most useful documents were being included. These reviews must include both technical and documentation support staff. (Reference: 8.7)

8.5 References

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