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# Managing Nuclear Reactor Accidents: Issues Raised by Three Mile Island

Hamilton, G.W.

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# MANAGING NUCLEAR REACTOR ACCIDENTS: ISSUES RAISED BY THREE MILE ISLAND

Gary W. Hamilton

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

THE AUTHOR

G.W. HAMILTON participated in the 1979 IIASA Junior Scientist Summer Program and is currently in the process of completing his J.D. and M.P.A. degrees at the Lyndon B. Johnson School of Public Affairs, University of Texas at Austin, USA.

## PREFACE

This paper provides a descriptive account of significant events in the accident at the Three Mile Island nuclear power plant in March, 1979. It is based upon documents collected as background materials for the IIASA workshop: Procedural and Organizational Measures for Accident Management: Nuclear Reactors. In additon to the references listed, information was supplied by John Lathrop, who conducted interviews with government and industry officials involved in the crisis.

There have been several reports from several sources describing the accident at Three Mile Island. This report distinguishes itself by presenting a summary of those aspects of the accident especially relevant to the development of improvements in procedural and organizational measures for accident preparedness and management.

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# MANAGING NUCLEAR REACTOR ACCIDENTS: ISSUES RAISED BY THREE MILE ISLAND

Gary W. Hamilton

## I. INTRODUCTION

Nuclear power plant safety has become the focus of increasing public concern in virtually every nation involved in a nuclear program. While the safety of the entire nuclear fuel cycle is being questioned, a major controversy in recent months has arisen over the risks associated with operating nuclear power plants near major population centers. The recent accident at Three Mile Island has intensified the debate over both the probability and the consequences of a major accident at a nuclear facility.

Using Three Mile Island (TMI) as a case study, this paper begins with a short chronological description of the accident, followed by a discussion of the several categories of failures which compounded to exacerbate the accident's severity. Attention is then given to the various actors and the circumstances under which they made decisions to mitigate the crisis. Although the next accident involving a nuclear reactor will probably not occur in the same manner as TMI, the specifics of the TMI experience may be used to identify issues which may surface again in future efforts to manage accidents involving nuclear reactors.

## II. THE ACCIDENT AT THREE MILE ISLAND UNIT II

### A. Chronological Summary

The information in this section is compiled from the report of the investigation into TMI by the Nuclear Regulatory Commission Office of Inspection and Enforcement [13], and the analysis of TMI by the Nuclear Safety Analysis Center [18].

At approximately 4 a.m. on March 28, 1979, the second unit of the Three Mile Island nuclear power plant (TMI II) experienced a malfunction in its secondary (non-nuclear) cooling system which triggered a series of events leading to significant damage to the reactor core. In the first 13 seconds, the sequence of events was generally normal for an anticipated feedwater transient and the plant response was as expected. However, subsequent events--combinations of operator errors, design errors and mechanical failures--contributed in varying degrees to heightening the accident's severity.

The loss of secondary coolant began with a malfunction which caused the condensate pump to shut off. This resulted in the automatic tripping of both secondary feed pumps which in turn led to a turbine trip on high pressure. Shortly after the turbine trip, the auxiliary feedwater system began operation but was unable to provide secondary coolant because the flow paths were blocked by closed valves. As the rate of heat removal declined in the secondary loop, the pressure in the primary loop rose to 2255 psi and the pilot operated relief valve (PORV) opened to vent excess pressure (t=4 sec.). When the pressure in the primary loop reached 2355 psi (t=9 sec.), the reactor tripped (scrammed), thereby terminating the nuclear reaction and reducing the heat generated to decay heat alone.

Approximately 9 seconds after the PORV began venting pressure in the primary loop, the reactor pressure was reduced to 2205 psi. At this point the valve should have closed but failed to do so (t=13 sec.). This was the first abnormal occurrence in the plant's response to the accident sequence. For the next two hours the reactor coolant vented through the stuck valve into the drain tank. Meanwhile, in response to what was believed to be normal transient behavior, the operators began injecting water into the primary loop.

As reactor pressure decreased to a pre-set level (1640 psi), the plant's high pressure injection (HPI) emergency core cooling system (ECCS) was automatically initiated and began to inject cold water into the reactor (t=2 min.). Within a few seconds the drain tank pressure increased to the point where a small amount of coolant was released through a relief valve and began to collect in the reactor building sump (t=3 min. 14 sec.). This continued until the accumulation of reactor coolant in the drain tank caused the rupture disk to blow (t=14 min. 50 sec.), thereby allowing approximately 32,000 gallons of radioactive water to spill from the drain tank in the first 100 minutes of the accident.

With the rapid and continuing depressurization of the system, steam voids formed, causing the pressurizer water level to cease to directly reflect the actual reactor coolant inventory. Yet the operators did not realize that voids were forming, and concentrated on keeping the pressurizer water level within the bounds stressed in their training. As a result, when the pressurizer water level reached 90 per cent (t=4 min. 40 sec.), with reactor pressure at 1400 psi, the operators turned off one of the ECCS pumps and throttled down the second pump.

As the water from the reactor coolant drain tank accumulated in the reactor building sump, the pressure in the containment building rose approximately 2 psi. However, the isolation of the containment building, which would have occurred automatically with an increase of 4 psi, had not yet been initiated. Therefore, when the reactor building sump pumps were automatically activated in response to the rising water level, they discharged the radioactive water into tanks in the auxiliary building (t=7 min. 30 sec.). These tanks soon filled and overflowed onto the floor of the building.

For the remainder of the first hour the operators worked to stabilize the reactor but were handicapped because the pressurizer level readings did not directly reflect the reactor coolant inventory. Primary coolant continued to vent through the stuck relief valve and steam voids in the primary system prevented the normal flow of coolant. With the system parameters in saturated conditions, the indicated flow decreased and the operators noticed vibration in the reactor coolant pumps. Because the vibration was believed to be an indication of pump cavitation, they shut off two of the four primary reactor coolant pumps to avoid damaging them (t=1 hr. 13 min.). The remaining two pumps were soon turned off for similar reasons (t=1 hr. 41 min.).

The operators were attempting to cool the core with natural circulation but steam voids prevented them from achieving the desired circulation. As a result, the temperature in the primary loop hot leg increased rapidly and within fifteen minutes went off the scale at approximately 620 degrees F, while the temperature in the cold leg continued to decrease. The large temperature differential continued for approximately the next 8 hours. During this time the severe damage to the reactor core is believed to have occurred. Inadequate cooling caused the fuel temperature to increase to the point where the zircalloy fuel cladding reacted with the hot steam to produce hydrogen gas. This gas was released into the primary cooling system and was ultimately vented through the failed PORV into the containment building. When the operator discovered the stuck relief valve and isolated it by closing a block valve in series with it (t=2 hrs. 18 min.), the release of steam and water ceased and the primary system was sealed for the first time in over two hours. The system pressure then increased and was regulated by intermittently opening and closing the block valve.

A short time later the reactor containment building radiation monitors indicated that there was a potential for off-site releases of radiation (t=2 hrs. 45 min.). Therefore, a site emergency was declared (t=2 hrs. 50 min.). For the next thirteen hours the operators attempted to restore primary cooling but were unable to do so because of hydrogen gas and steam voids present in the system. At approximately 10 hrs, a 28 psi pressure spike was registered. This is believed to have resulted from an explosion of hydrogen in the containment building.

At about 8 p.m., 16 hours after the initiation of the accident, the operators successfully restarted one of the primary reactor cooling pumps. The core inlet and exit coolant temperatures then began to indicate a cooling trend. The reactor pressure stabilized and heat was transferred through one steam generator to the main condenser. Forced circulation of the primary coolant was maintained until April 27, 1979, when the primary reactor coolant pump was shut down and the plant was placed in a natural circulation mode with heat removal taking place through the the steam generator.

B. Major Factors Compounding Accident Severity

Human Error

Perhaps the most obvious example of human error was the failure to open the valves on the auxiliary feedwater system. The valves were closed during a required plant safety system surveillance procedure two days before the accident and either were not reopened, despite a checklist provision for such an action, or were inadvertently closed later. If the valves were left closed after the surveillance procedure, the situation could have gone unnoticed for days because each shift change required a status review but not a checklist of key systems. Furthermore, the situation was not readily apparent to operators in the control room because the lights on the control board were color-keyed with "red" indicating that a valve was in the "open" position and "green" indicating that a valve was in the "closed" position. One of the indicators may have also been obscured by maintenance tags hanging down from another system. While this example of human error is quite disturbing because of its implications for human performance concerning reactor safety, it did not in fact substantially exacerbate the accident.

Another error was the interpretation of high readings from the pressurizer indicator to mean that there was an adequate inventory of reactor coolant. Operator training and experience had emphasized the necessity of maintaining a steam vapor space in the pressurizer. However, the operators apparently did not realize that the continued depressurization could lead to the formation of steam voids in regions of the system other than the pressurizer and that under these conditions the pressurizer level reading could be misleading. Assuming the level indication to mean that the core was flooded, the operators throttled the HPI/ECCS system.

Finally, when the operators turned off the main coolant pumps to avoid damaging them, they initiated a series of events which greatly increased the scope of the damage to the rest of the reactor. The severe undercooling of the reactor core caused the reaction between the fuel cladding and the primary coolant. The resulting hydrogen gas released into the primary system hampered efforts to bring the reactor into a cold shutdown state.

## Mechanical Failures

A mechanical failure--the malfunction of the condensate feedwater pump in the secondary loop--was the initiating event of the Three Mile Island accident. But by far the most serious mechanical failure was the pressurizer relief valve which failed to close once the pressure in the primary loop had been sufficiently reduced. The stuck valve provided a path for the reactor's radioactive coolant to escape. This in turn led to the high pressurizer level on low coolant inventory, which led the operators to the incorrect conclusion that the core was covered with coolant.

## Design Errors

There are several features peculiar to B&W designs which are particularly sensitive to transient conditions originating in the secondary system. Some of these features were identified by Harold Denton in testimony before the House Subcommittee on Energy Research and Production [1]; (1) design of the steam generators to operate with relatively small liquid volumes in the secondary side, (2) the lack of direct initiation of reactor trip upon the occurrence of off-normal conditions in the feedwater system, (3) reliance on an integrated control system (ICS) to automatically regulate feedwater flow, (4) actuation before reactor trip of a pilot operated relief valve on the primary system pressurizer (which may aggravate the event if the valve sticks open), and (5) a low steam generator elevation (relative to the reactor vessel) which provides a smaller driving head for natural circulation. In addition, the proper functioning of the pressurizer valve is essential to the safe operation of pressurized water (PWR) plants because the water level in the core is typically not measured directly but is inferred from the water level in the pressurizer. Thus, a valve stuck in the open position allows the pressurizer to fill with escaping coolant, thereby giving an erroneous indication of coolant level to the operator in the control room.

Because of these specific features Denton concluded, "The B&W design relies more than other PWR designs on the reliability and performance characteristics of the auxiliary feedwater system, the integrated control system, and the emergency core cooling system (ECCS) performance to recover from certain anticipated transients, such as loss of off-site power and loss of normal feedwater. This in turn requires greater operator knowledge and skill to safely manage the plant controls during such anticipated transients [1]."

In addition, automatic isolation of the containment building is designed to take place with pressure increases of 4 psi. Yet the unexpected failure mode at TMI II produced a need for containment isolation with a pressure increase of only 2 psi. Radioactive water discharged from the relief valve was pumped out of the unisolated containment building once the transfer pumps were automatically initiated by the rising water level. This unintentional release of radioactive water ultimately was one of the principal sources of off-site releases of radioactivity.

## III. PRINCIPAL ACTORS IN CRISIS MANAGEMENT

### A. Federal

The federal agencies supporting the State of Pennsylvania during the Three Mile Island crisis were: Federal Disaster Assistance Agency, Defense Civil Preparedness Agency, Federal Preparedness Agency, Department of Defense (Army and Air Force), Health Education and Welfare, Nuclear Regulatory Commission (NRC), Federal Highway Administration, Department of Energy (DOE), Environmental Protection Agency, Department of Agriculture, Treasury, Internal Revenue Service, Veterans' Administration, Federal Aviation Administration, Housing and Urban Development, General Services Administration, Post Office. Additional support was offered by national organizations such as the Red Cross, the Salvation Army, the AFL/CIO, and the Council of Church Organizations. Approximately 250 federal personnel were eventually on hand at the plant site. Of those present about 75 were from the NRC and approximately 100 were from DOE.

Although not directly in the line of authority, the Department of Energy played a major role in coordinating the activities of several of the other agencies. A major DOE activity was coordination of the various radiation monitoring efforts. DOE Radiological Assistance Teams (RAT) and Nuclear Emergency Survey Teams (NEST) assumed most of the responsibility for radiation monitoring once the NRC had determined that the State of Pennsylvania did not have sufficient equipment to properly monitor off-site radiation levels. Monitoring and support equipment was provided under the Interagency Radiological Assistance Plan (IRAP).

At the time of the accident at TMI II, the Federal Emergency Management Agency (FEMA) was being organized. This agency will eventually combine the emergency response resources of the Fire Administration, the Insurance Administration, the Defense Civil Preparedness Agency, the Federal Disaster Assistance Agency (part of Housing and Urban Development), and the Federal Preparedness Agency.

B. State

Two major state agencies were involved at Three Mile Island. The Pennsylvania Emergency Management Agency (PEMA), at the time of the accident, was in the process of expanding its authority from "preparedness and response" to include "accident prevention, mitigation and recovery." The Bureau of Radiation Protection, part of the Department of Environmental Resources, had major responsibilities concerning planning for and responding to the crisis.

Civil defense in Pennsylvania is administrated at the county level with the state operating in the role of a coordinator. Because of the frequent need to respond to all types of emergencies, PEMA has established an Emergency Operations Center (EOC). The Center serves as a coordinating point for representatives of the emergency response teams of various state agencies. Representatives reporting to the EOC have prior permission from their respective secretaries to commit department and agency resources as necessary. The organizations involved in the EOC are: the Governor's Emergency Council, the National Guard, the Department of Agriculture, the Pennsylvania State Police, the Pennsylvania Department of Transportation, the Department of Public Welfare, the Department of Health, the General Services Administration, the Public Utilities Commission, and the Department of Education. For policy guidance concerning state emergency management, there is a council consisting of the Governor, the Lieutenant Governor, the secretaries of various state agencies, and four state legislators.

C. Operator/Licensee

The operator/licensee of the Three Mile Island plant is Metropolitan Edison Company, a subsidiary of General Public Utilities, Inc. In addition to the resources of the federal, state, and licensee groups involved, technical expertise and other assistance during the accident was provided by the manufacturer, Babcock & Wilcox, and by various organizations with an interest and expertise in nuclear energy, including the Atomic Industrial Forum, the Electric Power Research Institute, and the Edison Electric Institute. Observers from other nations were also on hand throughout the crisis, although they provided no direct assistance.

## IV. PRINCIPLES ESTABLISHED BEFORE THREE MILE ISLAND

### A. Control of Facilities

Nuclear generating facilities are subject to some of the most stringent regulatory guidelines imposed on any industry. The exact extent to which violations of established operating regulations contributed to and exacerbated the TMI accident is still a matter of dispute and of an ongoing investigation by a number of government agencies and by various Congressional review groups. A preliminary report issued by the NRC Office of Inspection and Enforcement in August, 1979, has identified 35 apparent violations of government regulations at the plant [13]. Nineteen of these violations have been listed as "potential items of noncompliance" in operating the facility and 16 of the items deal with radiation hazards. The charges vary in severity from failure to properly log events to violations involving the closure of emergency feedwater valves. Six major areas in which inadequacies were listed were: equipment performance, accident analysis, operator training and performance, equipment and system design, information flow, and implementation of emergency planning.

### B. Radiation Guidelines

Radiation guidelines for nuclear facilities are defined in terms of Protective Action Guidelines (PAGs) [14]. PAGs were originally introduced to assist public health and other government authorities in establishing levels of radiation hazard which would constitute a basis for initiating emergency protective actions or countermeasures. PAGs are definable for all radiation pathways which might lead to human exposure and are expressed in units of radiation dose (REM) representing trigger or initiation levels which warrant predetermined actions to protect the public health. Plume exposure PAGs for the most important countermeasures are 5 REM whole body and 25 REM thyroid. For milk ingestion, the correspondng PAGs are 30 REM thyroid to an individual and 10 REM thyroid for a suitable sample of the population--usually calculated on the basis of an infant's thyroid. While PAGs are to be used as tools for emergency response planning, they only represent countermeasure trigger levels--not acceptable dose levels.

### C. Emergency Response Plans

As early as 1962 the federal government recognized the need to have contingency plans for dealing with emergencies arising from the operation of nuclear generating facilities.

One of the earliest regulations in this area, 10 CFR (Code of Federal Regulations) Part 100 (1962) stated that a capability for taking protective actions to safeguard the general public in the event of a serious accident should be established for the Low Population Zone (LPZ), the region in the immediate vicinity of a nuclear power plant site. In 1970 the Atomic Energy Commission issued explicit requirements for plans to deal with emergencies in nuclear facilities. Yet, in accordance with the provisions of the Atomic Energy Act of 1954, the requirements were not directed at the state and local governments. Rather, they applied to applicants for licenses to operate nuclear facilities.

Neither the NRC nor the other Federal agencies presently have statutory authority to require state and local governments to establish emergency planning for coping with accidents arising from nuclear facilities. The NRC can require only the licensee to develop such emergency response plans. The approval of a licensee's plan, however, is contingent upon the establishment of a working relationship between the licensee and the local authorities to provide early warning to the public and upon the implementation of appropriate protective measures in the event of a nuclear accident.

The NRC recommended planning basis [14] suggests the establishment of "Emergency Planning Zones" (EPZs) about each nuclear facility. These zones are to be defined for both the short term "plume exposure pathway" and for the longer term "ingestion exposure pathways." Within an EPZ, appropriate emergency responses are to be determined to assure that "effective actions can be taken to protect the public in the event of an accident" involving a nuclear facility located within the boundaries of the zone. Plans should take into account the nature of the population groups, the environmental conditions, the plant conditions, and the time available to respond. The NRC, however, places bounds on the measures which officials are expected to employ in carrying out this emergency planning. For example, "no participation by the general public in test exercises of emergency plans" is recommended [14].

Under 10 CFR Part 100 (Siting Criteria) an applicant for a nuclear power plant construction permit must use population distributions to designate an exclusion area, a low population zone (LPZ) and a population center. The exclusion area must be of a size such that an individual at any point on its boundary would not receive a radiation dose of 25 REM to the whole body or 300 REM to the thyroid for two hours immediately following a "design basis" accident involving fission product release. The LPZ must be of such a size that an individual located at any point on its boundary would not receive a radiation dose of 25 REM to the whole body or 300 REM to the thyroid during a 30 day period of exposure to a radioactive cloud. Dose guidelines are not prescribed for the population center, although it is tacitly assumed that doses for this area would be lower than those for the LPZ.

## V. INFORMATION DURING CRISIS

The most fundamental information problem was suffered by the control room operators who were trying to maintain control of the crippled reactor. Instruments which were not designed to provide accurate readings under crisis mode operation failed to give information in the formats and quantities needed to make sound decisions. This fundamental information problem was inherited by the management personnel and public officials trying to make decisions to safeguard the public. The problem was compounded further by difficulties with communications. Phone lines in and out of the plant and control room were clogged to the point that sometimes communications were effectively at a standstill.

Confidence in the ability of the licensee to provide accurate information was eroded early in the crisis. In a report issued on the morning of the accident the company claimed: "There have been no recordings of any significant levels of radiation and none are expected outside the plant [19]." Yet a Pennsylvania Department of Environmental Resources helicopter flying over the plant shortly after the statement was issued reported detecting a small release of radiation into the environment. By the afternoon of March 28th, Lieutenant Governor William Scranton III suggested that he might not be getting accurate information from the plant officials. At a press conference he told a group of reporters: "This situation is more complex than the Company first led us to believe. Metropolitan Edison has been giving you and us conflicting information [19]."

With several company personnel acting simultaneously as spokesmen, it was almost impossible to coordinate information, even within the same organization. Nuances of differences between the various spokesmen gave the media opportunity to highlight discrepencies, thereby contributing to the atmosphere of confusion. For example, at times there was disagreement among the various parties about whether a release of radiation was unexpected or was part of a planned operation to control the plant. Therefore, on Friday, the 30th, it was decided that Metropolitan Edison would cease issuing statements regarding the status of the plant and that the NRC personnel at the plant site, not those in Washington, would serve as the official source of technical information. Meanwhile, the Governor's Office would serve as the official source of information regarding the possibility of an evacuation [10].

## VI. DECISIONS MADE IN RESPONSE TO THREE MILE ISLAND

In the initial moments of the accident sequence, the operators responded to what they believed to be a normal feedwater transient. Yet after nearly three hours of unsuccessful attempts to regain control of the plant, there was an indication of a potential for an off-site release of radiation. Therefore, the supervisor was required to notify off-site authorities.

At approximately 7:02 a.m. on the morning of the 28th of March, the Watch Officer of the Pennsylvania Emergency Management Agency received the first call from the Three Mile Island Plant Supervisor indicating that there was a site emergency, a condition which might lead to an on-site evacuation. By 7:35 a.m. PEMA had received notice of a general emergency, one which might involve the general public. The State's first response was to notify its Department of Environmental Resources, Bureau of Radiation Protection (BRP). Then all of the counties within a five mile radius of the plant were informed of the situation. By 7:45 a.m. Governor Thornburg had been notified of the crisis [10].

Readings taken by the BRP on Wednesday the 28th and Thursday the 29th indicated no need for any protective action to be taken by the public. During this time conflicting reports on the condition at Three Mile Island were being issued so the State did little more than ensure that its 5 mile evacuation plan was up to date and maintain a ready posture to implement any necessary protective action. Three crisis headquarters were established to coordinate information and to serve as clearinghouses for statements regarding the situation at the plant. The On-Site Crisis Headquarters at Three Mile Island was the headquarters for the NRC and for all technical activities which were taking place. The Governor's Office was the central headquarters for the State and the coordinating headquarters for state activities. Everything which had to do with health problems or evacuation decisions came out of the Governor's Office and was coordinated through the third center, the Evacuation Headquarters. In addition, a Rumor Center was set up in Harrisburg and in three of the six counties involved in the crisis operation. Each of these rumor centers established toll-free telephone lines so the public could call in for information about the crisis situation and possible evacuation announcements [10].

On Thursday the 29th a large non-condensing void was identified in the reactor vessel that threatened to uncover the reactor core. The void was determined to be composed of hydrogen which had been liberated in the reaction between the fuel cladding and hot steam. Plant operators wanted to compress the void but NRC officials advised against this action for fear that the void contained an explosive mixture. It was later determined that the mixture could not contain any free oxygen and hence posed no threat of explosion. Thus the operators were free to shrink the void.

The role the NRC assumed during efforts to deal with the hydrogen bubble is illustrative of the stance maintained throughout the crisis. Although the Commission has the authority to order the utility if the public safety is at stake, officials insist that they never actually took command at Three Mile Island. However, NRC officials maintained very close contact with plant personnel and offered advice freely whenever operators were "looking for good ideas." In effect, the NRC was in control of the activities at the site, although they never took complete command.

At 8:40 a.m. on the morning of Friday, March 30th, another general emergency message was received from Three Mile Island due to high radiation readings at a height of 600 feet above the stack. The Pennsylvania EOC was immediately activated and representatives were on hand in less than 30 minutes. At about 9:15 a.m., senior personnel at NRC headquarters in Bethesda, Maryland, issued a recommendation that people should be evacuated to a distance of 10 miles from the plant site [10]. Prior to this time no mention had been made of the need to plan evacuations to a distance of 10 miles. Needless to say, planning problems were compounded by the increased scope of the proposed evacuation. Within a radius of 5 miles of the plant there were 3 counties containing approximately 25,000 people but no hospitals or nursing homes. Within a radius of 10 miles, however, there were 4 counties with approximately 136,000 people, 3 hospitals, and many nursing homes [10].

By the time the evacuation recommendation had been received from the NRC, the BRP had determined that the emmissions had been halted, so they recommended against an evacuation. Therefore, the Governor did not recommend an evacuation but suggested that all people within a 10 mile radius of the plant should remain indoors until further notice. Then about noon of the 30th, the Governor recommended that pregnant women and preschool children be evacuated to 5 miles and that all schools within that radius be closed.

In the afternoon of Friday, the 30th, Harold Denton arrived at TMI, and later that evening recommended considering evacuation plans for a distance of 20 miles from the plant [10]. This greatly increased the resources needed by the civil defense authorities. For an evacuation to 5 or 10 miles, the counties involved could have taken care of their own people. But plans for the 20 mile evacuation would involve 30 counties, approximately 650,000 people, and 9 hospitals. Additional hosts would be needed in adjacent counties and the EOC would have to be involved in the planning processes. Furthermore, the time required to effect the evacuations would be much longer. It was estimated that 3 hours would be required for the 5 mile evacuation plan, 7 hours for the 10 mile evacuation, and 10 hours for the 20 mile evacuation [10]. All of these times, however, depended upon the fulfillment of several unmet needs. By Saturday, the 31st, all of PEMA's needs had been identified and requests for aid were submitted to the federal government. President Carter agreed to provide federal aid even though a state of emergency had not been declared.

The next few days were spent refining preparations and writing out plans for an evacuation which never occurred.

Nevertheless, many of the residents left of their own volition. The "selective evacuation" of the 5 mile radius involved only pregnant women and pre-school age children, yet it is estimated that up to 50 per cent of the general population evacuated of their own accord and approximately one-third of those in the 20 mile radius also left voluntarily [10].

## VII. CONCLUSIONS

### A. Human Error

Human error is virtually impossible to quantify and equally difficult to eliminate. Yet many of the "human" errors must be considered in the context of several related factors. The auxiliary valves were closed due to a human error. But the closed valves may have gone unnoticed for days of normal operation because there was no checklist procedure to doublecheck this system. Therefore, a procedural shortcoming must also be identified. The fact that the situation was not readily apparent in the control room suggests that basic control room design was also a contributing factor. Therefore, human factors aspects of control room design and other man-machine interface problems also played a role in this "human" error.

Similar complicating factors were involved in the operator's interpretation of the high pressurizer level to mean that the core was flooded. The design of Babcock and Wilcox pressurizers, in conjunction with training and experience regarding the retention of a steam vapor space in the pressurizer, led the operators to prematurely terminate HPI flow. Thus design features and operator training contributed to this "human" error.

Finally, testimony indicates that the operators may have been required by their standard procedures to turn off the main coolant pumps to avoid damaging them [12]. Though this may at first seem to be "human error," it might in retrospect be most correctly termed "procedural error."

### B. Mechanical Failure

Perhaps the most significant lesson learned from the mechanical failures at TMI II is that a serious accident can result from relatively minor mechanical mishaps. Previous analytical attention has focused on the largest, most catastrophic, but least probable accident scenarios. Thus the TMI II accident, which began with a relatively minor mechanical failure, has shown that more attention needs to be given to small-break LOCAs.

Mechanical failure, like human error, can never be completely eliminated, but it too can be minimized through careful reviews of chronic failure patterns. In testimony before the Senate on April 30, 1979, Harold Denton noted that Babcock & Wilcox reactors had experienced problems with faulty relief valves about 150 times before the incident at TMI II. A faulty relief valve had also been noted at in the licensee event report for an incident at the Davis-Besse plant in 1977 when 11,000 gallons of radioactive water escaped through a faulty relief valve into the reactor containment building. Yet this same mechanical component survived to plague operators at TMI II.

## C. Design Errors

General attention needs to be given to reactor designs which can be placed in a relatively passive mode even though instruments and major mechanical components have been severely degraded by an accident and subsequent events. The attempt to place the TMI II plant in the natural circulation state clearly illustrates the need for such designs. Furthermore, operators should be able to achieve this state with minimal instrumentation.

Plant design should also allow operators to assess equipment status and environmental conditions in areas where high radiation levels prohibit entry by plant personnel. Primary needs include the ability to extract samples of pressurized coolant in order to determine levels of dissolved gases, the measurement of radiation levels in areas where primary coolant may leak, and the measurement of water levels in containment.

## D. Mitigation and Management

Confusion in the early hours of the crisis clearly illustrated the need to establish a very limited number of credible sources of information. The decision to channel all technical information through the NRC personnel at the site and the decision to coordinate all evacuation information through the Governor's Office eventually accomplished this goal, but only after over 48 hours of sparse and often inaccurate information.

Another lesson learned is that the decision center should be moved to the site as soon as possible. A case in point was the recommendation from NRC headquarters to evacuate when information at the site indicated that there was no need for such an action. Harold Denton himself later said, "I guess I've learned that emergencies can only be managed by people on the site. They can't be managed back in Washington [9]."

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