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Nuclear Reactor Safety Research Since Three Mile Island

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Summary. The Three Mile Island nuclear power plant accident has resulted in redirection of reactor safety research priorities. The small release to the environment of radioactive iodine—13 to 17 curies in a total radioactivity release of 2.4 million to 13 million curies—has led to a new emphasis on the physical chemistry of fission product behavior in accidents; the fact that the nuclear core was severely damaged but did not melt down has opened a new accident regime—that of the degraded core; the role of the operators in the progression and severity of the accident has shifted emphasis from equipment reliability to human reliability. As research progresses in these areas, the technical base for regulation and risk analysis will change substantially.

The accident at Unit 2 of the Three Mile Island nuclear power plant (TMI-2) on 28 March 1979 will shape the course of commercial nuclear power for at least a decade. The accident began as a common operational upset following a minor failure in the feedwater system. The small pressure relief valve in the primary system stuck open, causing a loss of coolant and slow depressurization of the reactor. Misoperation and lack of proper diagnosis and corrective action over a period of hours led to continued loss of coolant and subsequent severe core damage. This was followed by mismanagement of the accident by most of the parties involved and vibrant media coverage. There are several excellent chronicles of the accident (*1–3*), and I will not describe the details here.

The process of analyzing the implications of the TMI accident for reactor safety and for planning future work began immediately after the accident and included the official investigations (*1*, *2*), special meetings, and symposia. One of the more thorough documents is the task action plan (*4*) of the U.S. Nuclear Regulatory Commission (NRC). Each document includes a long list of problems and proposed improvements. Since the proposed improvements were developed in hurried reaction to a complex accident, there is an overall lack of implementation strategy. This has resulted in quick implementation of some improvements and postponement of others, with debate over the degree of safety improvement afforded by any or all of the measures.

With regard to reactor safety research, the TMI accident raised several key technical issues and aroused a resolve to substantially improve reactor safety. In this article I concentrate on three aspects of the TMI accident that have broad implications for safety research and licensing and represent substantial departures from the situation prior to TMI.

1) In the course of the accident, 2.4 million to 13 million curies of the radioactive noble gases xenon and krypton were released to the environment, but only about 13 to 17 curies of radioactive iodine were released (*5*). This retention of radioiodine is in itself significant, but, more important, it brings attention to a lack of understanding of the radiological source terms, especially with regard to the chemical forms of the radionuclides released from the core and the phenomena determining movement of the released radioactive material in the reactor systems and buildings.

2) Once core damage began from loss of coolant and heat removal, the damage progressed slowly and was arrested when the coolant level was restored. This left the reactor with a severely damaged core still in place. About half of the volatile and semivolatile radioactive fission products were released from the core, and a large amount of hydrogen was produced during the core damage. This, in effect, defined a new class of accidents—degraded core accidents—which had been substantially overlooked because of emphasis on large-break loss-of-coolant accidents (LOCA's). In most studies it was assumed that LOCA's would terminate before core damage if the emergency core cooling system worked or would proceed to core meltdown if it did not.

3) The accident was initiated by a minor valve malfunction of a type that is anticipated and is correctable by operator action. The subsequent progression to a severe accident was due to a complex operations failure involving inadequate instrumentation and several operating errors or deficiencies.

I will briefly review the course of recent studies of these three aspects of the TMI accident and indicate their effects on reactor safety research and development. I believe that the new directions of research resulting from the TMI-2 accident will have substantial long-term effects on nuclear power. Although regulatory, economic, and social implications will have greater short-term effects, these will eventually give way to substantive changes in the underlying technical base resulting from the new research directions.

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Radioactive Source Term

The unexpected behavior of radioiodine in the TMI accident was first brought to my attention on 3 April 1979, when Jim Eldridge and Steve Hamley of Oak Ridge National Laboratory (ORNL) returned from the accident site. They were the second ORNL radiation monitoring team to arrive at TMI and were assigned to off-site monitoring. Finding very little off-site radiation to monitor and a large number of monitoring teams at work, they returned to Oak Ridge and reported that in their measurements they found no radioactive iodine in the environment.

Radioiodine is an important concern in a severe reactor accident because it is sufficiently volatile to escape a failed reactor containment easily and, unlike xenon and krypton, it enters the life cycle through grasses, then concentrates in milk-producing animals, and is further concentrated in the thyroid after ingestion by man.

There were conflicting reports in the newspapers about the release of radioiodine from TMI-2 for several weeks after the accident. However, the report by Auxier *et al.* (*5*) for the Kemeny Commission is a complete and credible account. This report shows that the off-site radiation dose was due to the release of radioactive noble gas and was sufficiently small that less than one additional cancer should be expected in the affected population in which over 300,000 similar cancers will occur from natural incidence. Radioactive iodine levels were so low that they did not contribute significantly in the health effects assessment. Iodine in the environment is monitored through milk, air, and water samples. The best data were obtained for milk samples, as the potential measurement sensitivity for radioiodine in cow's milk is about 1 picocurie per liter. Only 8 percent of the milk samples analyzed gave positive results; that is, iodine was detected in the samples. In the press reporting shortly after the accident, negative results were ignored, and the reports of measurements were not reported in context with the instrument sensitivity. In the study by Auxier *et al.*, they accepted only positive results, which biased the analysis somewhat on the high side, and they concluded that 13 to 17 curies of radioiodine had been released, giving an insignificant exposure to the population.

Following the TMI accident experts on iodine stated that they were not surprised at the low off-site release and that they had argued against the overconservative iodine assumptions used in reactor accident analysis. For example, in the regulatory guidelines it is assumed that in a design basis accident 25 percent of the equilibrium core inventory of radioiodine would be released from the core into the containment and that 91 percent would be molecular iodine, 5 percent particulates, and 4 percent organic iodides.

In the Reactor Safety Study (*6*), a simple mechanistic model is used to estimate fission product release from fuel and retention in the primary coolant system and containment. This model assumes that iodine in the fuel is molecular iodine, that iodine is released and transported like the noble gases (except that iodine plate-out and its removal by containment sprays were considered), and that organic iodides amount to about 0.6 percent of the initial inventory. In the summary for accidents involving the core, the maximum ratio of noble gases to iodine released to the environment is given as 375 for the category of containment concrete base melt-through. The ratio is 20 for the category involving a failure to isolate containment, which is more similar to the TMI case. The actual ratio of noble gases to iodine at TMI was greater than 1.4×10^5. The low release of iodine was due to its retention, which is significantly underestimated in conservative analyses, and the fact that the containment was sealed except for the release of small quantities of liquids and gases through the auxiliary building. The low release of iodine was identified in the Kemeny Commission investigation as an important finding requiring further investigation.

In the TMI accident the fission products were released from the fuel at very high temperatures, perhaps 2000°C, but when transported to cooler zones they came in contact with sufficient water that almost all the iodine dissolved in the water, greatly reducing the amount that was airborne and available for leakage to the environment. The reactor conditions were as follows. Severe core damage began about 2 hours into the accident. The relief valve on the pressurizer was stuck open, the block valve downstream from the relief valve was not yet closed, and the high-pressure emergency cooling water had been turned off. The high-pressure charging pump was operating at a very reduced flow, the letdown line was operating and transferring water from the primary system to auxiliary building tanks, and the last main recirculating pump had just been turned off because of vibration. The coolant level in the core was about at its midplane. The noble gas fission products xenon and krypton were released through the pressurizer relief valve and quench tank into the containment. They were also transported in solution through the letdown line to the auxiliary building, where they evolved from solution in the gas storage tanks.

The iodine presumably was released as CsI and may have condensed on cooler surfaces and formed aerosol particles, but predominantly it dissolved in the water and was transferred to the auxiliary building through the letdown line. Overloading of the auxiliary building systems resulted in gas releases and in some leakage of water, which spilled onto the floor. Although iodine was volatilized from this spillage, the very low release is attributed to the initial retention in the liquid and the subsequent small quantity of spillage onto the floor. Later in the accident, the emergency coolant was restarted and the primary coolant system contents were flushed into the containment sump. This would have dissolved and retained any of the CsI deposited in the primary system. The low amount of iodine vaporized prior to the leakage onto the floor is explained by the aqueous chemistry, and essentially the same behavior would occur whether the iodine was released as CsI or I_2.

William R. Stratton of Los Alamos National Laboratory and David O. Campbell and Anthony P. Malinauskas of ORNL studied the iodine release for the Kemeny Commission and afterward pursued the study personally and brought the issue to the attention of the Nuclear Regulatory Commission. The NRC with several contractor laboratories conducted an assessment of the state of the art for fission product release with special attention to iodine (*7*). This report indicates that much more research is needed in order to obtain realistic estimates of fission product behavior in reactor accidents.

The best explanation of the low release of iodine at TMI is that the iodine was retained in the available water in the containment and in auxiliary building tanks. The noble gases were almost completely in the gas phase and thereby partly released to the environment. The processes for iodine retention in water are complex, involving chemical reactions and partitioning between vapor and liquid phases. The recent finding that radioactive iodine is released from the fuel at least partly in the form of CsI may be important in understanding the retention at TMI (*8, 9*).

For the TMI water chemistry and in a

closed container such as the auxiliary building tanks or the containment, the liquid-to-vapor partition coefficient for an equilibrium solution of iodine would be greater than 10^6. Gas transfers or leaks from the container would release very little iodine. Radioactive iodine solutions in a closed container will, over a period of time, produce another vapor species, methyl iodide (CH_3I), presumably by reaction of the I_2 vapor with methane produced from radiolytic decomposition of organic materials, such as paint, oils, and grease, on the container surface.

On the basis of discussions with experts who worked on iodine control after the accident, I believe that little of the iodine released from TMI came from the cover gas over the iodine solutions in the containment and auxiliary building tanks. Although the processes have not been identified, experience shows that when a dilute, iodine-bearing solution is accidentally spilled onto a floor in a chemical process building, a substantial amount of the iodine is evolved (*10*). In this case, the chemistry involves a large surface area, a thin liquid film, a variety of organic and inorganic contaminants on the floor surface, and the process of drying. It is not surprising that the volatile species CH_3I, I_2, and HOI are produced. For example, on 2 April 1979 the iodine species collected on the TMI auxiliary building exhaust filter were 28 percent CH_3I, 19 percent HOI, 26 percent I_2, and 27 percent iodine particulates. At TMI there was substantial spillage from overloaded tanks in the auxiliary building, but most, if not all, of this occurred before fission products were released from the core. Perhaps the largest iodine release resulted from small leaks (cubic centimeters per hour) from the letdown system seals and other small leaks after the core damage occurred.

The iodine investigation is leading the way to a program for improving the understanding of the radiological source term in accidents, especially the role of physical chemistry. An improved understanding is crucial to the development of a comprehensive accident management technology. The studies performed recently have shown that insufficient information exists to revise the source term assumptions now used in licensing. The results and studies of the TMI accident have shown that the present source term assumptions are inadequate and have indicated the areas needing the most attention—fission product chemistry and aerosol behavior. The NRC is undertaking a substantial research program in these areas.

Degraded Core Accidents

The TMI accident may be credited with starting the concern over degraded core accidents. As a working definition, a degraded core is one that has been sufficiently damaged to release fission products well in excess of an amount released by normal operating leaks but not sufficiently damaged to lose its overall geometric arrangement. This accident regime was almost totally ignored in the LOCA-dominated pre-TMI safety technology for light-water reactors (LWR's). The progression of a core melt and the possibilities of an arrested melt have been researched in the fast breeder reactor programs in the United States and abroad and in some LWR programs abroad.

Postulated accidents that include total core meltdown require widespread incapacitation of the reactor systems, such as a large break of coolant piping with a simultaneous failure of the emergency core cooling system, a disabling of all systems due to an earthquake far above the design level, a total loss of normal and emergency electrical power for a long period, or a rupture of the main pressure vessel below the core level.

Before TMI there were no plans for management and operation of a reactor facility after severe core damage. Since the TMI experience, there has been increased attention to accident sequences in which core heatup progresses slowly and core damage is arrested prior to total melt by restoration of the coolant level. Some of the issues related to degraded core accidents are:

1) What design changes or equipment modifications should be made to mitigate and control such accidents?

2) What operator training, procedures, aids, and so on are needed?

3) What off-site response resources should be developed to assist after a degraded core accident?

4) What siting and public emergency planning changes are needed?

The NRC has issued an advance notice of rulemaking on degraded cores that deals with a number of specific issues identified from the TMI experience (*11*). The nuclear industry has formed a cooperative program called Industry Degraded Core Rulemaking (IDCOR), under which they plan to perform the necessary analyses and develop a technical basis for degraded core rulemaking. The NRC rulemaking may be scheduled for 1983, and this will allow time for the IDCOR program to be completed as well as for additional progress in NRC research programs.

The NRC rulemaking call includes the following issues: hydrogen management, high-point vents in primary systems, protection of safety equipment, in-plant iodine instrumentation, sampling during and following an accident, leakage integrity outside containment, accident monitoring instrumentation, detection of inadequate core cooling, and training to mitigate degraded core accidents.

Hydrogen. One of the most dramatic aspects of the TMI accident was the massive evolution of hydrogen and the subsequent related problems. In ordinary operation, a pressurized water reactor is operated with a slight excess of hydrogen in the coolant to suppress the radiolytic production of free oxygen. In the TMI accident, however, the core temperatures were sufficiently high that hydrogen was produced by the oxidation of zirconium in steam:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

The rate of this reaction increases rapidly with temperature and is important above 1100°C, producing heat at a rate comparable to the radioactive decay heat. At TMI, approximately 450 kilograms of hydrogen were produced. The urgent concern of 30 March to 1 April 1979 was due to an inaccurate estimate by NRC that the hydrogen trapped in the primary coolant system might become explosive because of radiolytic production of oxygen. In fact, excess hydrogen is expected to suppress oxygen production as it does in ordinary operation.

The principal problem related to hydrogen at TMI in the first week after the accident was that noncondensable hydrogen dissolved in the primary coolant limited operation to relatively high pressures. If the pressure had been lowered, the dissolved hydrogen would have evolved and caused a bubble, which might have impeded circulation. As a consequence, the hydrogen was slowly released to the containment through the letdown system and the pressurizer power-operated relief valve, and then it was removed from the containment atmosphere by a catalytic converter.

When the core damage occurred on 28 March hydrogen released through the pressurizer into the containment produced a sudden burn, which was revealed by both a pressure spike and a reduction of the containment oxygen. The oxygen data and analysis of the pressure pulse indicate that 270 kilograms of hydrogen were burned (*2*). A recent visual examination of the containment did not show significant damage from the burn. Thin-walled steel drums were indented from the pressure pulse and many, but not all, flammable objects showed flame damage.

Hydrogen control is a central problem in the planned degraded core rulemaking. In the proceedings to license the Sequoyah I plant, the NRC attempted an ad hoc ruling that the Sequoyah containment should withstand a hydrogen burn at least as large as that at TMI. After many calculations, the Tennessee Valley Authority (TVA) stated that the containment would withstand three times the design pressure of 12 pounds per square inch and would survive a burn equal to the TMI burn, but with little margin. TVA therefore incorporated glow plug igniters to burn off hydrogen and thereby preclude a large burn. Other means being considered for hydrogen control are filling containments with inert nitrogen, using carbon dioxide or Halon burn suppressants, or using water fog. Although all of these may be effective methods, each has undesirable side effects. Research and design should disclose the best alternative for each application.

Severe accident phenomenology. Our understanding of severe core damage accidents is characterized by large uncertainties regarding the heat removal from a damaged core, the progression and phenomenology of meltdown, meltthrough of the vessel, the behavior of melt on the concrete floor, the energetics of rapid steam production, and the effects of the transport of radioactivity to normally nonradioactive systems. Experimentation to resolve these uncertainties is difficult, primarily because the phenomenon can be produced only in full scale by an actual reactor; accidents have a large degree of variability in initiation, progression, and arrest; and the high cost argues against experimenting with full-scale reactor meltdown. Since the TMI accident, the NRC, the Department of Energy, and the nuclear industry have revitalized work in this area and are focusing on best-estimate analyses of severe accidents and medium-scale experiments on separate effects to establish a technology base for the important physical phenomena.

Man and Machine

The TMI accident forcefully brought to our attention the point that the operators do interact with machines and that they may introduce additional faults by errors of omission or commission. This is not to say that the operators' role in safety was previously ignored, but rather that the priority of operations relative to equipment failures was much increased by the TMI accident. Since TMI, there have been significant incidents involving anomalous operations at Oyster Creek (*12*), Arkansas Nuclear One (*13*), Crystal River (*14*), Indian Point (*15*), and Sequoyah (*16*).

The response by the industry and the NRC to the increased concern about operational safety has been substantial. Industry has cooperatively formed the Institute for Nuclear Power Operations (INPO), with headquarters in Atlanta, Georgia. Its role is to set standards for nuclear power plant management and operation, to audit and enforce those standards, and to admit reactor plants to an insurance pool as the reward for an accredited operation. The NRC is giving greater emphasis to research on operator performance, human factors, and operational aids. The regulatory and enforcement arms of NRC have tightened their requirements, including requirements for larger operating crews, more difficult examinations for licensed operators, improved procedures, and so on. All these new activities deal with the reactor systems and operational and management institutions as they exist. Although changes are being made in areas of perceived weakness, there is no method of systematic analysis to determine whether the changes will result in improved operational reliability or safety. I strongly support most of the short-term efforts, but I believe that long-range improvement requires a systematic approach that incorporates both the machine and operations in sufficient detail for objective assessment of modifications.

Operator models and experimental data. Preliminary work is being done on the development of an operational system model (*17*). This model is purely qualitative, but it does help identify subsystems such as the maintenance or auxiliary operators, reactor operators, procedures, and communication channels and is a first step toward a functional model. When a quantitative model is developed that encompasses the operators and the operational systems (hardware and software), it may be possible to determine how changes in procedures, crew configurations, controls, instrumentation, and so on would affect the overall operational reliability and failure modes. Until such models exist, we must rely on subjective professional judgment. Even though we may regard that judgment as sufficient, it must be assumed to be fragmentary and subject to biases.

The creation of models is dependent on an experimental data base and a well-controlled means for experimental verification. Just before the TMI accident, Botts and Haas (*18*) began to obtain data to quantitatively determine the operator response time, which is the elapsed time from the indication of a malfunction to the execution of the correct action. In their initial work, Botts and Haas concluded that analysis of actual operating events after the fact would not provide a sufficient data base. They followed this work with the development of a program that includes (i) operator response experiments, using the full-scale simulator for the Sequoyah plant, and (ii) acquisition of detailed information on actual operating events at a number of reactors with which to calibrate the simulator data. This work is in progress with two subcontractors: General Physics Corporation, which is performing the simulator experiments, and Memphis State University, which is performing the analysis of operating reactor events. Also included in this program is the development of techniques and tools to be used across a broad range of problems in the following areas: procedures testing, task analysis verification, operating crew configuration and assignments, instrumentation and control changes, effects of operational aids, effects of automation, and identification of operating errors.

Computerized operational aids and automation. While there is general agreement that it is advantageous to have well-trained and qualified operators, good procedures, and effective instrumentation and controls, there is substantially less agreement on the use of computers for control. Advocates of manual control state that a nuclear reactor plant should be a simple, stable, and "forgiving" plant that does not need computer control; that computer software is too complex and unreliable; and that a computer isolates an operator from the reactor so that the operator is unprepared to take over in accident situations. Advocates of computer control state that computers are more reliable than humans, that the unreliability of computers can be minimized by straightforward analysis and design, that the TMI accident and the large majority of other operating failures would be easily corrected with computer control, and that the successful application of computer control in other fields such as commercial aviation demonstrates the use of computers to improve both risk and reliability.

Nuclear power reactors now incorporate automatic control of the reactivity control rods for small power maneuvers to maintain a set power level or to follow modest load changes. Also, the emergency systems for shutdown of the fission chain reaction, emergency coolant injection, containment isolation and spray operation, emergency feedwater, auxiliary electrical generators, and so on are automatically actuated, but for the most part they are manually controlled.

There is no published information indicating any substantial effort in plant design simplification and automation. However, many computerized aids are being developed to inform the operator of the operational status of the plant through data assimilation, data reduction, trend determination, and so on. A development that will be suitable for early implementation is the Safety Parameter Display System (SPDS), which is being studied by the Nuclear Safety Analysis Center of the Electric Power Research Institute (EPRI) (*19*). The SPDS will bring together information on key safety parameters and display the information on color video monitors with wide rangeability. The display will show trends as well as current values. Selected parameters will supply information on five safety functions: primary coolant inventory, core heat removal, secondary heat removal, reactivity control, and containment integrity. Although the SPDS may use microprocessors, it will not be a high-level, computer-based operational aid, in that no analysis or diagnostics will be performed. SPDS systems will be available this year.

The next step in domestic development of computer-based operational aids is the Disturbance Analysis and Surveillance System (DASS), which is jointly funded by EPRI and the Department of Energy. Work is being managed by Sandia National Laboratories and has been contracted to two design teams, one headed by Westinghouse and one by Babcock and Wilcox, who are developing conceptual designs and evaluating technical feasibility. The purpose of DASS is twofold: to provide a high-level computer analysis of all the nuclear power plant data as obtained from the process computer and, through suitable models, to diagnose operational upsets and advise the operator.

A European equivalent of DASS is considerably more advanced due to its long-term development at the Halden Project in Norway, funded by multinational sources. Based on the Halden work, the STAR system for disturbance analysis has been developed jointly by the Gesellschaft für Reaktorsicherheit with the Institut für Atomenergie, the Kraftwerk Union, and the Bayernwerk electric utility and has been installed at the Grafenrheinfeld reactor (*20*). The STAR and DASS systems are similar in scope. Their diagnostic capabilities are provided by cause-consequence models, which are essentially preanalyzed accident sequences. When the computer matches a disturbance to a sequence, it can then advise on corrective action.

The SPDS, DASS, and STAR systems do not provide any simplification or automation of the reactor systems. They are add-on information processors and, in fact, they add more complexity. The operators cannot control the reactor by using these systems; instead, they gain the computer-digested information or diagnostic assistance, and then they operate the reactor from the usual control boards. The true safety significance of these systems is somewhat questionable, and the extent to which elaborate computer assistance should be added as a backfit to existing control rooms is also questionable. Nevertheless, the TMI accident has underscored the need for improved operation, and the computerized operational aids may be the best intermediate step toward operational simplification and automation. I restate my concern that in order to effectively design and verify real system improvements a method is needed for self-consistent analysis of the total operational system, including operators, procedures, and so on, as well as hardware.

Conclusion

In this article I have discussed three areas in which long-term developments and technological changes are expected to result from the TMI accident. In each of these important areas—the radioactive source term, degraded core accidents, and man-machine interaction—several years will pass before the technology matures. I do not believe that the existence of these issues means that the present generation of reactors, both operating and under construction, offers undue risk. I do believe that the issues require resolution through well-paced investigations, avoiding the pitfalls of either a crash effort that looks only for short-term payoffs or a prolonged effort with vacillating support. This research may identify desirable backfit changes for present reactors, and these could be made well before the midway point in their collective operating lifetime. The research will also contribute significantly toward the design of a new generation of reactors of greater simplicity and safety that may replace the present reactors as they are phased out in the period from 2000 to 2020.

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