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Instrumentation Performance During the TMI-2 Accident

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Joy L. Rempe
Darrell L. Knudson

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Joy L. Rempe, *Senior Member, IEEE,* and Darrell L. Knudson

Abstract— **The accident at the Three Mile Island Unit 2 (TMI-2) reactor provided a unique opportunity to evaluate sensors exposed to severe accident conditions. Conditions associated with the release of coolant and the hydrogen burn that occurred during this accident exposed instrumentation to harsh conditions, including direct radiation, radioactive contamination, and high humidity with elevated temperatures and pressures. As part of a program initiated by the Department of Energy Office of Nuclear Energy (DOE-NE), a review was completed to gain insights from prior TMI-2 sensor survivability and data qualification efforts. This new effort focused upon a set of sensors that provided critical data to TMI-2 operators for assessing the condition of the plant and the effects of mitigating actions taken by these operators. In addition, the effort considered sensors providing data required for subsequent accident simulations.**

Over 100 references related to instrumentation performance and post-accident evaluations of TMI-2 sensors and measurements were reviewed. Insights gained from this review are summarized within this paper. As noted within this paper, several techniques were invoked in the TMI-2 post-accident program to evaluate sensor survivability status and data qualification, including comparisons with data from other sensors, analytical calculations, laboratory testing, and comparisons with sensors subjected to similar conditions in large-scale integral tests and with sensors that were similar in design but more easily removed from the TMI-2 plant for evaluations. Conclusions from this review provide important insights related to sensor survivability and enhancement options for improving sensor performance. In addition, this paper provides recommendations related to sensor survivability and the data evaluation process that could be implemented in upcoming Fukushima Daiichi recovery efforts.

***Index Terms*—Three Mile Island Unit 2, Accident Instrumentation**

I. Introduction

The accidents at the Three Mile Island Unit 2 (TMI-2) and Fukushima Daiichi Units 1, 2, and 3 nuclear power plants demonstrate the critical importance of accurate, relevant, and timely information on the status of reactor systems during a severe accident. Conditions associated with the loss of coolant and the hydrogen burn that occurred during the TMI-2 accident exposed Pressurized Water Reactor (PWR) instrumentation to harsh conditions, including direct radiation, radioactive contamination, and high humidity with elevated temperatures and pressures. The TMI-2 accident also highlighted the critical importance of understanding and focusing on the key elements of system status information in an environment where operators may be overwhelmed with superfluous and sometimes conflicting data and yet have to make urgent decisions. While progress in these areas has been made since TMI-2, the accident at Fukushima suggests that there is still a need for additional improvement, in particular with respect to gaining insights related to sensors exposed to Boiling Water Reactor (BWR) severe accident conditions.

In preparation for addressing this need, a review was recently completed to gain insights from TMI-2 sensor survivability and data qualification efforts[1]. Over 100 references related to instrumentation performance and post-accident evaluations of TMI-2 sensors and measurements were reviewed. As reported in this paper, post-accident evaluations of instrumentation components and data provided significant insights related to what types of conditions (e.g., temperatures, pressures, dose levels, etc.) were experienced by TMI-2 sensors, what failures occurred, and what types of enhancements were needed to ensure that operators have better access in the future to the data required to diagnose and mitigate unanticipated events.

II. Background

Numerous insights were gained from the TMI-2 post-accident evaluations. Although there is still some debate about certain aspects of the TMI-2 accident[2,3], insights obtained from post-accident evaluations and enhanced simulation models provided a basis for improving plant design features, operator training, and accident mitigation strategies [4,5].

A. Plant Design

The TMI-2 power plant contained a PWR designed and manufactured by Babcock & Wilcox, Inc. (B&W). The core housed 177 fuel assemblies, corresponding to 93.1 metric tonnes of fuel. Core reactivity was controlled with control rod assemblies containing silver-indium-cadmium alloy and boron dissolved in the coolant. Reactivity was also controlled with burnable poison rod assemblies during the first fuel cycle. As shown in Fig. 1, the Reactor Coolant System (RCS) consisted of the reactor vessel, two vertical once-through steam generators, four shaft-sealed reactor coolant pumps, an electrically heated pressurizer, and interconnecting piping. The system was arranged into two heat transport loops, each with two pumps and a steam generator (often designated as the A and B loops).

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J. L. Rempe* and D. L. Knudson are with the Idaho National Laboratory, P.O. Box 1625, MS 3840, Idaho Falls, ID, 83415, USA *(phone: 208-526-2897; fax: 208-526-2930; e-mail: Joy.Rempe@inl.gov).

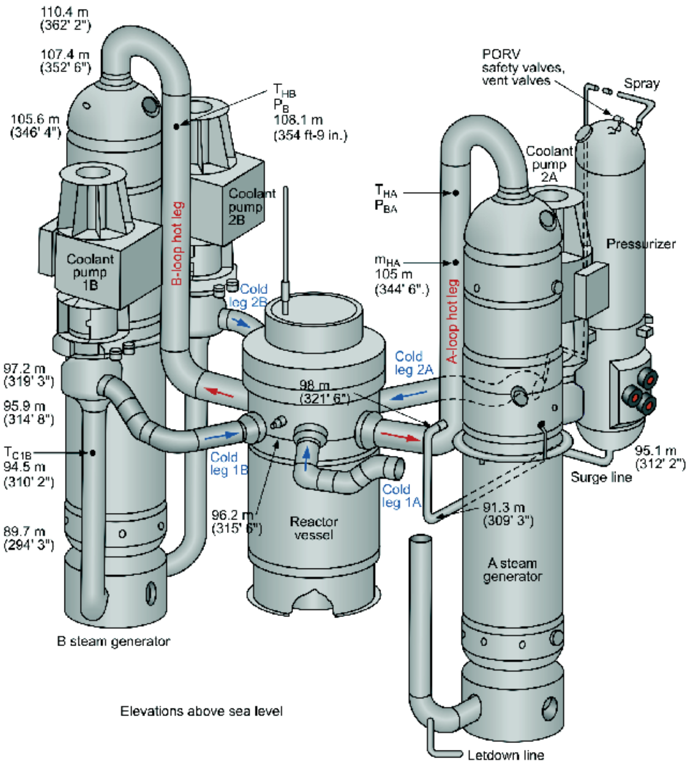

Fig. 1. TMI-2 primary system layout.

B. Accident Synopsis

The TMI-2 accident was initiated on March 28, 1979, by a shutdown of secondary feedwater flow due to condensate booster pump and feedwater pump trips that occurred when the plant staff was trying to unclog a pipe leading from the condenser demineralizers. Best estimates for plant data and events during the accident, as obtained from various post-accident evaluation programs [5], are depicted in Fig. 2. As described in [1], significant events occurring during the initial stages of the accident included turbine isolation (defined as time zero in Fig. 2), reactor trip (when reactor pressure reached 16.3 MPa at 10 seconds after turbine trip), RCS heat up and pressurization. The Pilot Operated Relief Valve (PORV) opened to relieve RCS pressure, but failed to close when RCS pressure decreased. This was incorrectly interpreted by the reactor operators as indicating that the RCS was nearly full of water; when in fact, the RCS was continually losing its water inventory. Emergency core cooling was reduced by the operators, and the coolant void fraction increased due to coolant loss through the PORV and decay heat generation in the fuel. The steam fraction in the primary system piping increased to such an extent that RCS pumps were tripped by the operators to prevent permanent damage from pump cavitation after 100 minutes.

As described in [1], instrumentation response suggests that core uncovery began between 114 and 120 minutes and that the vessel liquid level had dropped to the core midplane by approximately 140 minutes. Insufficient decay heat removal associated with core uncovery is estimated to have led to upper regions of the core heating to temperatures that caused the cladding to overheat, balloon, and rupture. When operators finally realized that the PORV was failed in the open position, they closed the pressurizer block valve upstream of the PORV. In-core self-powered neutron detector (SPND) output and RCS pressure data (see Fig. 2) indicate that core temperatures continued to increase between 150 and 165 minutes. Zircaloy-steam exothermic reactions were initiated, producing large amounts of hydrogen and dramatically increasing the core heatup rate. When Zircaloy melting temperatures were exceeded, molten Zircaloy and some liquefied fuel relocated to lower core regions, solidifying near the coolant interface. This continued until 174 minutes, when a dense agglomeration of degraded core material formed in the lower regions of the core, which blocked core flow.

At 174 minutes, one of the reactor coolant pumps in the B-loop was turned on for approximately 19 minutes. This coolant injection into the vessel rapidly repressurized the RCS. At 200 minutes, the high pressure injection system was operated for 17 minutes, and the reactor vessel was refilled with water by approximately 207 minutes. Although the core was estimated to have been covered with coolant, analyses suggest that little coolant was able to penetrate into core regions with agglomerated debris and that these materials continued to heat up. Between 224 and 226 minutes after reactor scram, plant instrumentation (RCS pressure increases, Source Range Monitors (SRMs) count rate increases, cold leg temperature increases, and in-core SPND signal increases) indicated that the outer crust (resolidified molten material) surrounding the relocated core material failed; and molten core material relocated to the lower plenum. Increases in SRM count rates (see Fig. 2) suggest that small quantities of molten debris may have continued to relocate to the lower head between 230 and 930 minutes, although peak count rates are considerably lower than values during the 224 to 226 minute relocation time period. At 930 minutes, one A-loop primary coolant pump was restarted, re-establishing heat removal from the vessel.

C. Post Accident Insights

Post-accident insights related to what occurred at TMI-2 event were not available until at least a decade after the event and required an integrated process that included post-accident videos, examinations of samples of core debris and vessel structures, instrumentation data, calculations with 'best-estimate' severe accident analysis tools, separate effects laboratory tests, and in some cases, data from large integral tests. This process is schematically shown in Fig. 3. Analyses to interpret and integrate these information sources were crucial, since insufficient data were available from any single source to uniquely define a consistent understanding about the TMI-2 accident scenario. Example insights highlighted in [3] include:

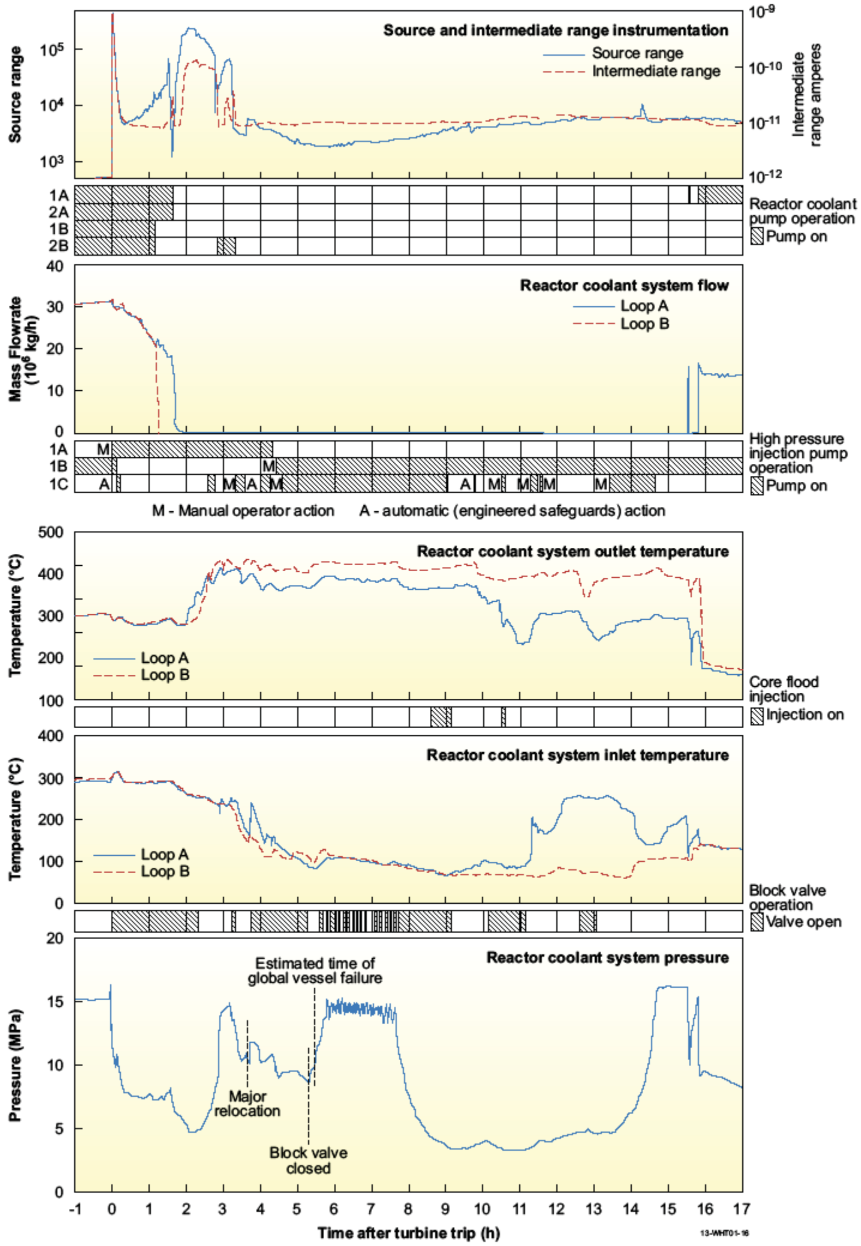

Fig. 2. TMI-2 data.

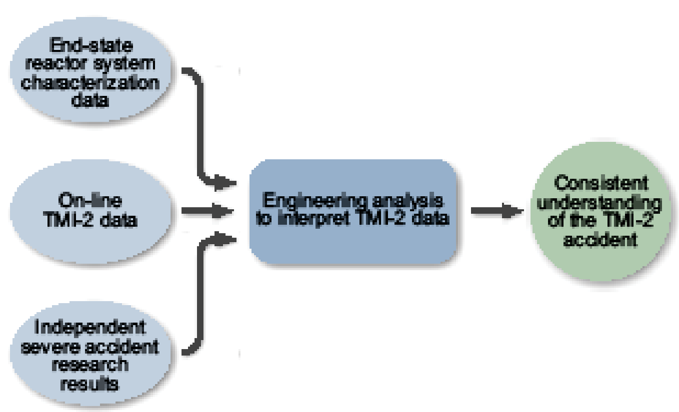

Fig. 3. Integrated process used to develop TMI-2 post-accident insights.

- All TMI-2 fuel assemblies were damaged. Large regions of the core exceeded the melting temperature of the cladding (~1900 °C). Significant fuel liquefaction by melted Zircaloy and some fuel melting occurred (corresponding to peak temperatures of at least 2800 °C).
- Approximately 20% of liquefied core materials escaped from the core as a liquid phase and solidified in the core bypass region, the Core Support Assembly (CSA) region, and the vessel lower head region.
- Based on the end-state core and CSA configuration and supporting analysis of core heatup, it is believed that the crust (or resolidified molten material) surrounding the relocated core material failed near the top of the molten core region in the southeast quadrant of the reactor vessel.

Limited damage to the CSA occurred as core material flowed to the lower plenum. Fig. 4 illustrates the currently-postulated final state of materials within the TMI-2 vessel based on integrated Fig. 3 evaluations.

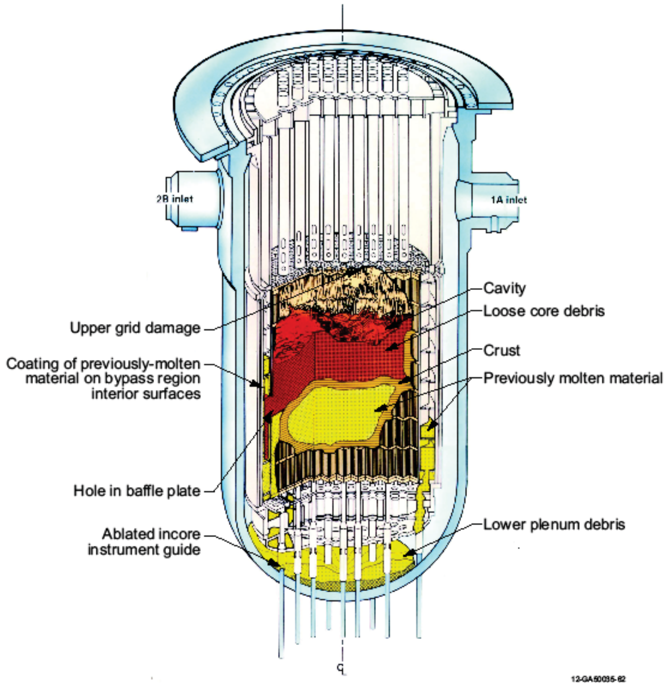

Fig. 4. Postulated final state of materials within the TMI-2 vessel.[5]

- Metallurgical examinations of the vessel steel samples in conjunction with visual observations suggest that an elliptical region of the vessel, approximately 0.8 m by 1.0 m, reached peak temperatures of 1100 °C during the accident (see Fig. 5). At locations away from this "hot spot", there is no evidence to indicate that vessel steel temperatures exceeded 727 °C.

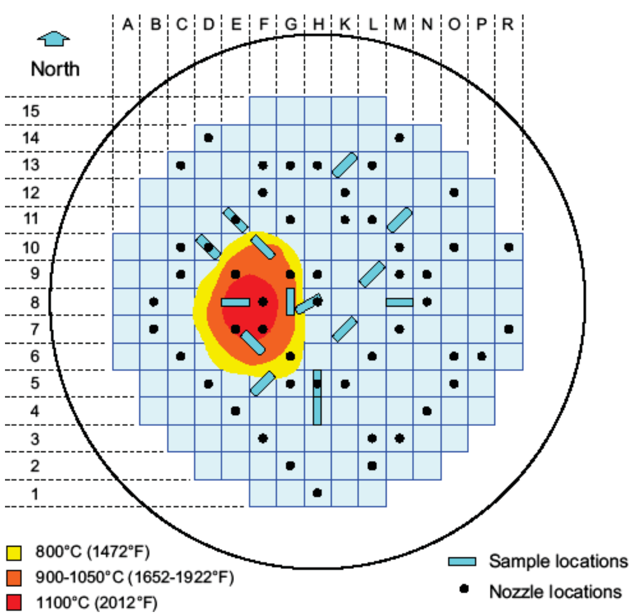

Fig. 5. Location of TMI-2 lower head vessel steel samples and "hot spot"[5].

- Instrumentation nozzle damage (see Fig. 6) was caused by molten core material relocating to the lower head. The most severe damage was observed in nozzles located within the "hot spot" region of the vessel and was not related to the embedded debris height (e.g., nozzle L6 was submerged in debris, but remained undamaged).

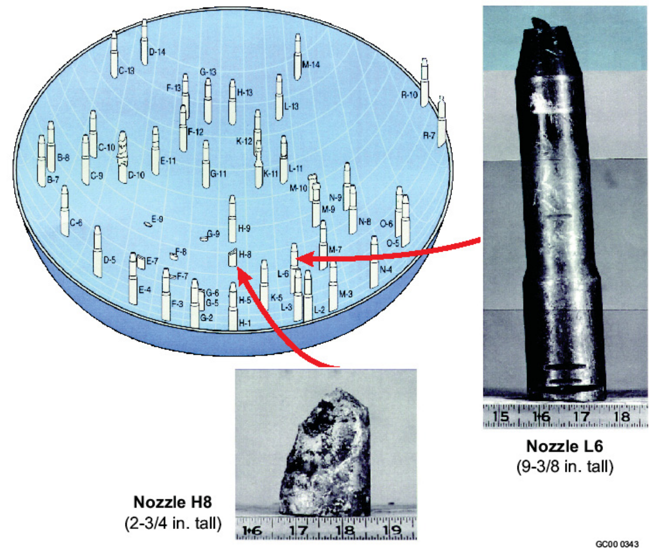

Fig. 6. End-state of nozzles on the TMI-2 vessel lower head.[5]

III. TMI-2 Sensor Evaluations

Detailed TMI-2 sensor evaluations were conducted to gain confidence about instrumentation data which provided a basis for assessing and improving severe accident simulation models and to assess the ability of sensors to provide operators much needed information to assess the status of the plant and the effect of mitigating actions.

A. *Qualified Database for Accident Simulation*

An important aspect of the TMI-2 Accident Evaluation Program (AEP) was to provide a qualified data base for an analysis of the TMI-2 Accident, known as the "TMI-2 Analysis Exercise." This analysis exercise was completed to assess the accuracy of available data and modeling tools, which were developed using small-scale experiments, when they were applied to a full scale PWR. A qualified database and a data qualification process were established for this analysis exercise. Prior to being entered into the database, the data and estimated uncertainties were reviewed by a Data Integrity Review Committee (DIRC). Understanding gained from the TMI-2 Accident Exercise was ultimately applied toward improving phenomenological models related to the chemical and materials interactions that occurred in the TMI-2 core and resolving applicable severe accident and source term issues. Hence, the analysis exercise contributed toward establishing a sound technical basis for post-TMI-2 regulatory actions.

B. *Sensor Selection*

Sensors allowed approximately 3000 measurements to be made at TMI-2. Earlier programs focused on data required by

TMI-2 operators to assess the condition of the reactor and containment and the effects of mitigating actions taken by these operators. In addition, these prior efforts focused upon sensors providing data required for subsequent accident simulations. Prior efforts to evaluate data from TMI-2 sensors included careful integration of instrumentation data, analysis relying on basic engineering principals, operator information, laboratory evaluations, comparisons with accident simulation results and large integral test data, and post-accident inspection. The current review focused upon the set of sensors deemed most important by post-TMI-2 DIRC and instrumentation evaluation programs. Table I[1] lists the RCS and containment sensors evaluated in the current review.

TABLE I
TMI-2 SENSORS REVIEWED

Parameter	Sensor	Function	Post Accident Status
RCS			
Core Exit Temperature	Type K Thermocouples (TCs)	Primary: core exit temperature; Secondary: liquid level	Failed due to high temperatures, steam, and moisture ingress following sheath degradation; Virtual junction formation occurred in many of these thermocouples.
Cold Leg Temperature	Platinum Resistance Temperature Detectors (RTDs)	Primary: Inlet temperature	Operating; some cabling and connector damage may have allowed moisture to degrade insulation; extension cable shorting may have occurred
Hot Leg Temperature	Platinum RTDs	Primary: Outlet temperature Secondary: Insights on RCS pressure	Operating; some cabling and connector damage may have allowed moisture to degrade insulation; extension cable shorting may have occurred
Reactor Coolant Pressure	Pressure transmitters	Primary: RCS pressure	Operational, but RCS pressure primarily below 11.7 MPa - gauge.
Flux - In-Core Measurements	Self-Powered Neutron Detectors (SPNDs) on In-Core Instrumentation Assemblies and Moveable In-Core Detection System	Primary: Neutron flux Secondary: Insights on temperature and liquid level	Most damaged due to high temperatures, steam, and moisture ingress causing sheath degradation.
Flux - Ex-Core Measurements	Source Range Monitors (SRMs)	Primary: Neutron flux Secondary: Qualitative insights on core liquid level	Operational
	Intermediate Range Monitors (IRMs)		Operational, but large uncertainty. Power levels at lower end of operating range.
	Power Range Monitors (PRM)		Power levels at lower end of operating range.
Pressurizer Liquid Level	Differential Pressure Transmitter	Primary: Pressurizer liquid level	Operational
Steam Generator Water Level	Differential Pressure Transmitter	Primary: SG water level	Operational, but full range transmitter installed incorrectly.
Loose Parts Monitoring	Accelerometer and charge converters	Primary: Presence of loose parts	Charge converter degraded due to gamma radiation
Hot Leg Mass Flowrate	Mass flowmeter	Primary: Mass flowrate	Operational; required corrections for depressurization and voiding
Containment			
Building Pressure	Pressure Transmitter	Primary: Pressure; Secondary: timing of hydrogen burn	Operational
Building Temperature	Platinum RTDs	Primary: Temperature	Operational, although possible degradation due to moisture; Data points too far apart to be useful during hydrogen burn.
Core Flood Tank Pressure Monitor	Pressure transmitter sealed in stainless steel casing	Primary: Core Flood Tank Pressure	Operational
Core Flood Tank Water Level Monitor	Transmitter with linear variable differential transformer (LVDT) and bellows	Primary: Water Level	Three of the four units experienced seal failures allowing severe corrosion
Building Radiation Levels	Area Radiation Monitors Most: Geiger-Muller (G-M) tube gamma detectors Dome Monitor: Ion chamber	Primary: radiation monitor; Secondary: Timing of fuel failure and fission product release	Failed due to high temperatures, pressure wave associated with hydrogen burn, high radiation levels, and moisture.

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IV. Insights

As indicated in Table I, sensor failures were primarily associated with the combination of moisture, high temperatures, pressures, and radiation. Specific insights gained from the TMI-2 sensor and data evaluations include:

- The simultaneous increase in SRM count rate, RCS pressure, and cold leg temperatures, provided confidence about the timing of a major relocation of materials from the reactor core to the lower head (see Fig. 7).

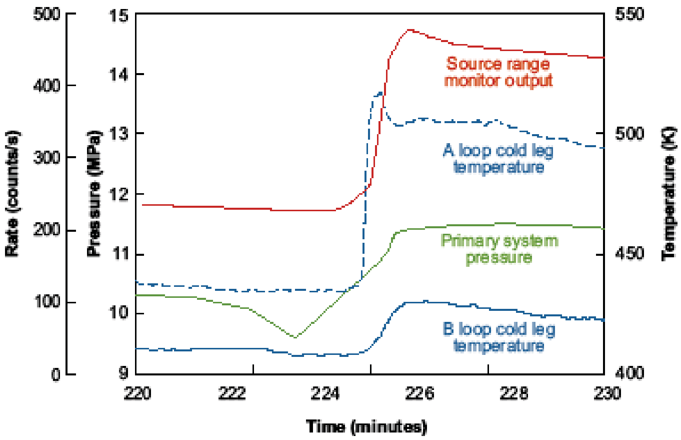

Fig. 7. Overlay of SRM count rate, RCS pressure measurements, and cold leg temperatures.

- Peak values for containment building temperature would not have been obtained without considering data from other sensors such as the containment building pressure transmitters. Calculations assuming peak containment pressures (see Fig. 8) yielded peak containment temperatures of 650 °C, which are much higher than the measured 93 °C peak temperature data (Fig. 9). Recognizing that the TMI-2 containment temperature data had a limited sampling rate, experts qualified the containment pressure and a modified set of containment temperature data.

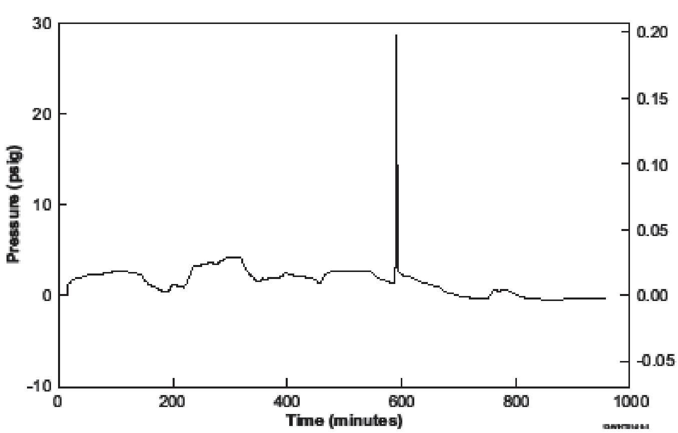

Fig. 8. Containment building pressure.

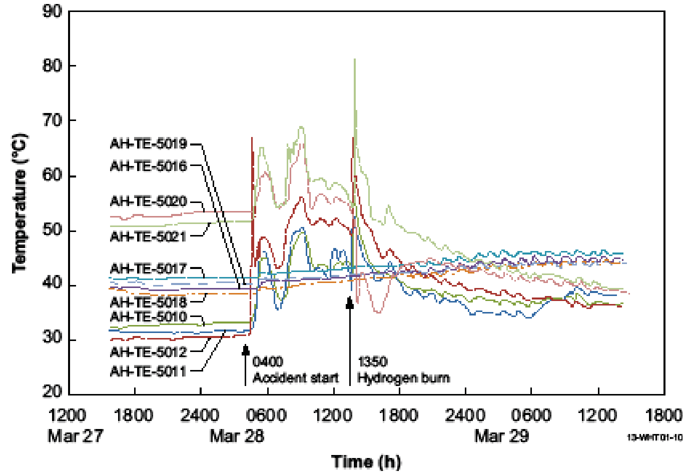

Fig. 9. Reactor building temperatures at selected locations.

- Data unavailability was often due to computational limits, such as storage memory, inadequate paper or ink, insufficient sampling rates, and 'preset' limits associated with anticipated operating ranges (rather than sensor operating limits as illustrated by the RCS pressure data shown in Fig. 10). A wider range of limits and enhanced computational capabilities, with easy-to-read graphical displays, could alleviate such issues, as occurred with TMI-2 building resistance temperature detector (RTD) temperature and steam generator reference pressure transmitter sampling.

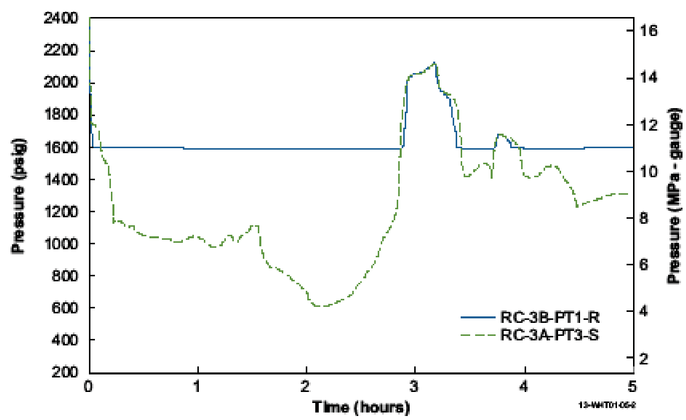

Fig. 10. RCS pressures at selected locations.

- Data unavailability was often due to sensor range limitations that were focused on assumed normal operating conditions. For example, sensors with ranges that encompassed unanticipated accident conditions (e.g., at saturated conditions with steam voids present in a PWR) could have provided operators much needed information.
- Data unavailability was also attributed to inadequate status indicators. For example, the inability of the operators to detect that the PORV failed to close could have been rectified by the use of additional indicators and sensors. In this case, indicators were only available to

show that the solenoid coil was energized (nothing about the status of the valve position). Since the TMI-2 accident, the US Nuclear Regulatory Commission (NRC) required that licensees make design changes so that positive indication of valve position is available in the control room. However, sensors could also have been included to measure the drain tank water level, which would have provided the operators information that the drain tank relief valve was open. A thorough investigation of other such situations could help alleviate similar occurrences in the future.

- Failures in sensors located within the vessel were often due to a combination of high temperatures and moisture ingress following sheath failure. In some cases, vibrations, moisture, and/or radiation exposure led to failures of sensors. Clearly, it is important to have sensors with operating envelopes that are extended to consider more likely accident conditions.

- Failures were often related to transmission component exposure, rather than sensor exposure. For example, cabling and connectors located outside the RCS were subjected to higher than anticipated temperatures, moisture levels, and radiation levels. It was speculated that most of the moisture intrusion problems would have occurred eventually in the plant without the accident. However, better positioning and enhanced components and/or shielding could alleviate such limitations.

- Qualitative insights can be obtained by considering sensor response for alternate applications, e.g., ex-core source-range detector signals provide insights about RCS water levels, in-core SPNDs provide insights about RCS temperature and water levels. However, such interpretations often require detailed analyses and assumptions related to the status of the core, the RCS and containment (as evidenced from efforts to interpret SRM data in Fig. 11).

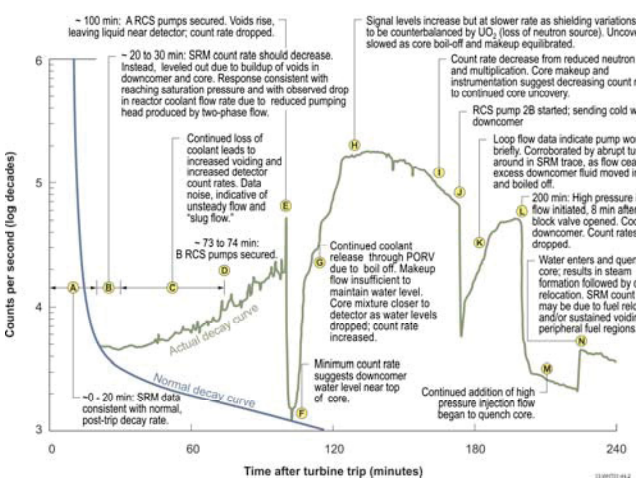

Fig. 11. TMI-2 SRM response during the first 4 hours of the accident.

- No functional damage to the nuclear plant instrumentation or electrical components from thermal effects of the hydrogen burn could be identified. One Geiger-Mueller tube was determined to have failed at the time of the hydrogen burn, but its failure was deemed to be shock-related, possibly caused by the pressure wave associated with the hydrogen burn.

- Evaluations emphasized the need to consider anticipated applications and more extensive inspection and maintenance programs for instrumentation and related systems. For example, data unavailability or high uncertainties could have been alleviated by the use of better installation and testing procedures with increased calibration checks. Such actions could have alleviated issues observed in dome monitor and RTD components.

- Post-accident evaluations emphasized the need for more accurate containment radiation measurements. Identified Dome Monitor failures and data uncertainties (see Fig. 12) led to several recommendations for design improvements, such as better seals that are periodically leak tested, the use of moisture and radiation resistant components and cabling, and relocating electronics outside the containment so that the lead shield could be removed.

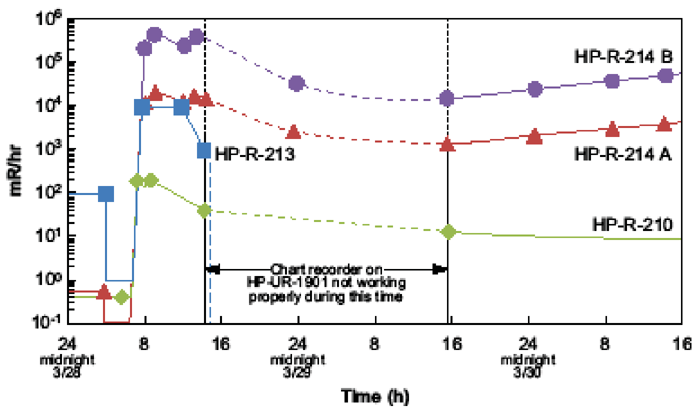

Fig. 12. Containment radiation monitor response (Two curves are provided for HP-R-214 to reflect upper and lower bounds associated with uncertainties in recording scale).

- Post-accident extraction and examinations are needed to confirm insights from some evaluations. For example, inspections of components from the loose parts monitor system found that they had degraded due to radiation exposure; whereas, data suggested that sensors were still operational.

- Careful evaluations of sensor data led to unexpected detection of instrumentation errors. For example, comparison of steam generator (SG) water level data led to the conclusion that the full range transmitter was incorrectly installed because readings were observed to be erroneously low when the SG was steaming.

- Surrogate testing of similar sensors and components that were more easily accessible and not required for plant safety monitoring, such as core drain tank water level and pressure measuring system components, allow insights related to instrumentation degradation to be obtained without adversely impacting systems essential to maintaining the TMI-2 plant in a safe condition.

Evaluations emphasized the need for 'applications analyses' to determine possible environments during which the devices must function (or not fail). These “environments” are not limited to just temperature, pressure, humidity (or steam), submersion (flooding), radiation, and vibration (both operational and seismic). They should also include the availability of power sources and the characteristics of supporting services such as instrument air, cooling water, lubrication (allowable contamination levels, moisture), calibration, and preventive maintenance. Such factors are often overlooked details of applications engineering that affect both equipment reliability and the interpretation of information received, as demonstrated at TMI-2.

Evaluations found that TMI-2 instrument and electrical equipment degradation was often due to moisture ingress and corrosion. Water and vapor intrusion into the equipment housings caused erratic readings and ultimate failure. The TMI-2 post-accident environment was more humid than normal plant conditions, but the number of paths for moisture intrusion, the number of instrument failures, and the extent of corrosion found have generic implications for long-term equipment operability and maintenance practices at operating plants. These findings are reinforced by the fact that TMI-2 had just begun power operation. Seals had not undergone any significant aging, and there was limited human activity regarding disassembly of connectors or potential damage to conduit, connectors, or housing seals. In operating plants, routine maintenance activities will repeatedly disturb and challenge these seals.

It is also worth noting how the US regulatory response was informed by TMI-2 instrumentation evaluations [6]. As noted above, the US NRC initially required that licensees make design changes so that positive indication of valve position is available in the control room [7]. In addition, prescriptive requirements for more robust instrumentation and computational and power sources to support this instrumentation were implemented. As more insights related to sensor performance became available, additional requirements related to anticipated accident environments were implemented [8]. Although current requirements [9] are less prescriptive, they still require that licensees be aware of what data are needed and the conditions that sensors must withstand. Nevertheless, current regulatory guidance for instrumentation has not included a comprehensive evaluation of the instrumentation required for severe accident conditions. It is possible that this situation may change as the US NRC addresses the Near Term Task Force Actions that they identified be taken after the events at Fukushima [10].

V. Summary

In summary, a comprehensive set of instrumentation evaluations, that included careful integration of available data, analysis relying on basic engineering principals, operator information, laboratory evaluations, comparisons with accident simulation results and large integral tests, and post-accident inspection, was required for researchers to qualify sensor data for TMI-2 accident simulations. Knowledge gained from these evaluations offered important lessons for the industry with respect to sensor survivability, the need for additional and/or enhanced sensors and indicators, and the identification of unanticipated failure modes for sensors when exposed to extreme accident conditions. The events at Fukushima Daiichi Units 1, 2, and 3 offer the nuclear industry the opportunity to reap BWR-specific benefits.

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Acknowledgement

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