Nuclear Power Safety:

Lessons From Three Mile Island and the Fukushima Reactor Accidents

ALEXANDER DEVOLPI

ABSTRACT

Of accidents that have involved nuclear-power reactors, all have ultimately delivered useful lessons about nuclear safety, reactor design, and radiation effects. Despite three major mishaps at nuclear-power reactors (in the United States, the former Soviet Union, and Japan), the accidents are noteworthy for very few, if any, public casualties. However, psychological trauma shocked the industrial world, and their occurrence has had expensive consequences in terms of radiation cleanup, power loss, decommissioning, and public apprehension. Now three Fukushima Daiichi reactors remain at risk of further internal damage. Irrespective of each deplorable accident, nuclear safety has duly improved, and important functional lessons have been derived.

Nevertheless, more could have been and could yet be implemented from the experiences, including added measures to diminish reoccurrences and consequences. In particular, a fundamental instrumentation shortcoming that contributed to the Pennsylvania Three Mile Island (TMI)-2 reactor meltdown was never fully addressed, and that omission might have indirectly hastened Fukushima reactor damage. Also yet to be implemented are some remedial measures and precautions forestalling the brutal hazards of further Fukushima fuel meltdown and subsequent reactor decommissioning.

This article (with supplementary sidebars) describes some overlooked autonomous nuclear instrumentation that can be installed to independently measure reactor water level and fissile fuel distribution — before, during, and after an accident.

MAJOR NUCLEAR REACTOR ACCIDENTS

Three accidents of significant consequence have occurred among civilian nuclear power reactors: TMI-2 in Pennsylvania (1979); Chernobyl in the former Soviet Union (1986); and Fukushima in Japan (2011).

Although these accidents resulted in devastation of the reactors, none caused provable injuries to members of the public. That judgment may startle many readers, but it is a demonstrably valid conclusion to draw from the various international technical assessments.

First of all, it's well-substantiated that neither the TMI nor Fukushima accidents have been responsible for any fatalities to date among the surrounding public. As for the Chernobyl nuclear-reactor destruction, it directly led to about three dozen deaths among operators and emergency workers, according to international Chernobyl Forum study reports that have tracked mortality data since the accident. With regard to potential fatalities induced by Chernobyl radiation fallout, no provable morbidity has been observed in the affected territories, even a quarter of a century later, contrary to dissenting predictions based on theoretical expectations. An international Chernobyl Forum report, 25 years after the accident, projected up to 4000 premature public fatalities, but there has been no actual post-mortem body count to validate that statistical estimate.

While (theoretically) a small percentage of thyroid cancers among juveniles might be attributable to the added radiation, it is surpassed by many more similar occurrences resulting from health-care deficiencies in the former Soviet Union. The Chernobyl Forum estimated about 15 radiation-induced thyroid-cancer fatalities, about one hundredth of the number of relevant juvenile deaths resulting from chronically poor medical treatment.

No matter what the actual incidence of human fatalities, considerable motivation exists to improve nuclear-reactor safety, at the very least because of financial impact, psychological trauma, and electrical capacity loss. Despite such long-standing incentives, some worthy engineering improvements have not been implemented for commercial reactors.

The TMI and Fukushima installations suffered accidental loss of water needed to remove residual heat from the reactor. This sudden coolant deficit resulted in serious damage to overheated nuclear fuel within the central (core) region.

I've had 40 years of technical education and experience in the nuclear field. My considered evaluation is that the disastrous TMI meltdown could have been averted if reactor operators had been aware that coolant in the nuclear core was below the level and density needed for heat removal.

Unanticipated conditions had degraded the TMI emergency cooling system, and existing conventional water-level indicators failed to function properly or meaningfully; thus, the amount and density of coolant water in the reactor vessel was not available to trained operators in the control room.

Had actual (insufficient) coolant conditions been known to the reactor operators, the entire TMI core meltdown would likely have been prevented.

And, as for the three Fukushima reactors, if the operators implemented (or had been able to implement) extraordinary emergency cooling measures sooner, they too might very well have forestalled or mitigated reactor-core damage.

The lead title of this paper was chosen deliberately to emphasize the safety of commercial nuclear power, thus alluding to the central function and necessity of water-transported heat, a role just as important as a controlled nuclear reaction.

Nevertheless, despite the occurrence of several major power-reactor accidents, no autonomous means of measuring water-coolant levels has been installed in commercial reactors.

Damaged reactors must be gradually and safely shepherded into a condition known as "cold shutdown" being disassembled and decommissioned. For TMI, the post-accident stage required about ten years. It involved substantial effort and cost, as well as the development of special decommissioning technologies. For the disabled Fukushima reactors — in order to better assist their harmless, systematic, and expeditious stabilization and dismantlement — it would be wise to anticipate and implement technical measures based on the TMI experience.

This article, and accompanying sidebars, contains my professional interpretation of some crucial events that led to core meltdowns at TMI and Fukushima.

CIRCUMSTANCES OF THE TMI REACTOR ACCIDENT

Two reactors were built in the 1970s on Three Mile Island in the Susquehanna River near Harrisburg, Pennsylvania. Both were of the pressurized-water type manufactured by the Babcock and Wilcox Company. In 1968 construction began on TMI-1, which commenced operation in 1974; it has now operated without incident for over 38 years. The second reactor suffered its ill-fated accident after just one year of operation.

The accident at TMI-2 was precipitated when a relatively minor malfunction in fluid flow caused its primary coolant temperature to rise. This in turn compelled the reactor to shut down automatically in about one second. A pressure-relief valve then failed to properly shut, but control-room instrumentation did not reveal that closure. As a result, coolant drained from the reactor core, and residual nuclear-decay heat was not removed at a sufficient rate.Worse yet, the reactor operators — erroneously believing at the time that there was too much water in the pressure vessel — turned off the emergency core-cooling system, and — after an hour or so of unrecognized overheating — they closed down the coolant pumps, further aggravating the situation.

During the accident sequence, operators and supervisors were unable to diagnose or respond properly to the unplanned automatic reactor shutdown. More specifically and more constraining, they did not have real-time knowledge of how much coolant water was in the reactor vessel, nor did they have any information about fluid density while the accident transpired. They had no actionable indication that coolant capacity was insufficient to relieve the dangerous overheating of reactor fuel.

Whereas instrumentation for monitoring and managing the fission-induced ***nuclear*** reaction functioned properly, the internal means to regulate water-transported ***power*** production failed, and no autonomous auxiliary indicators were available to alert operators of the impending disaster.

Evaluating the Accident

Major government and industry studies and evaluations ensued. Root causes of the TMI accident were ascribed largely to deficient control-room instrumentation and to inadequate emergency-response operator training. In addition, critical human factors and user-interface engineering problems were identified.

While unanticipated conditions did occur, some relevant conventional instrumentation inside the reactor failed to function. According to the World Nuclear Association, no direct information was available to the operators during evolution of the accident regarding the amount of water actually in the reactor vessel.

Lacking direct water instrumentation, control-room operators judged coolant solely by the pressurizer indicator, which advised that water level was apparently high. Thus, the operators assumed the core was properly covered with coolant, unaware that steam in the reactor vessel provided misleading pressure readings. This was a key contributor in their initial failure to recognize loss of coolant.

Had the operators known that water was being lost from the reactor vessel (and the core was going without coolant), the destructive part of the accident could have been avoided by correct remedial actions. As best as I can find, that conclusion never became actionable or even noticeable in subsequent commissioned reports or official follow-up dockets.

Aside from the traumatic accident event itself, the condition of the self-destroyed reactor remained for many years in a state of devastation and uncertainty. Nearly 10 years went by before it was confirmed that half the core fuel had melted and settled in the bottom of the pressure vessel.

What Lessons Were or Were Not Implemented?

Of the several comprehensive investigations that followed, the most influential was that conducted by the Kemeny Commission appointed by President Carter. It resulted in many recommendations, most of which were followed. For example, improvements were advised and implemented in procedural and analytical areas: operator training, emergency planning, dissemination of industry information, use of probabilistic safety assessment, and analysis of likely events.

Within the narrow purview of this article on major reactor mishaps, here's my own emphasis on relevant events that took place during the TMI accident:

> (1) Existing conventional reactor instruments failed to reveal the ongoing loss of coolant. Because internal water and pressure sensors were gradually destroyed in the course of the accident, they were unable to supply critical information for the grave situation that evolved.
>
> (2) Although there were some external instruments were on the reactor bridge structure outside the pressure vessel, those devices could not and did not help diagnose the loss-of-coolant evolution.

Notably absent from official post-TMI reports was a recommendation to implement autonomous external water-level instrumentation. Such specialized equipment, based fundamentally on nuclear rather than conventional sensor principles, would operate in such a manner as to be functionally and physically independent of other instruments and their power sources.

Whereas TMI operators had to infer the actual loss of coolant from an array of contradictory indicators, an instrument which directly measured reactor water level would have provided definitive information that reasonably might be expected to have prevented the reactor meltdown. This is what led me to applying 20 years of instrumentation experience toward devising and patenting a method for autonomous real-time detection of water level and density.

Had such an independent water-level diagnostic monitor been in operation, unambiguous loss-of-coolant data should have been available to reactor operators; therefore, subsequent core meltdown might very well have been averted. There would then have been clear indication that the water volume and density were actually being reduced rather than sustained during the accident sequence.

Although other measures to prevent or mitigate the same type of accident have since been taken in the 30 or more years after the TMI event, no operating nuclear reactors have been retrofitted with failure-resistant water-level instrumentation positioned external to the pressure vessel.

CIRCUMSTANCES OF THE FUKUSHIMA REACTOR ACCIDENTS

The extraordinary 11 March 2011 Tohoku earthquake of estimated 9.0 magnitude off the coast of Japan not only caused severe damage to populated areas, it also induced a tsunami that breached protective seawalls. Up to 20,000 residents are known to have died; 125,000 or more buildings were damaged or destroyed; and there were a multiplicity of secondary effects, such as nuclear-plant shutdowns and meltdown accidents near the earthquake epicenter. The unprecedented tsunami overwhelmed ocean-facing barriers at the Fukushima Daiichi nuclear-power station, thereby flooding subterranean backup power generators and pumps.

Although all Fukushima reactors had promptly shut down when the earthquake struck, the floods led to interruption in normal coolant-water recirculation. That was one of several nearly simultaneous consequences of the earthquake-induced electric-grid failure. Emergency electrical generators came on line for electronic controls and coolant systems, but backup electrical supply was insufficient for the reactor pumping systems. Moreover, reserve fuel for emergency generators was not intended to last more than about a day.

Some factors that caused internal reactor damage were similar to the accident at TMI in the sense that (1) the hot reactor core was suddenly deprived of sufficient water coolant, and (2) *ad-hoc* measures had to be undertaken to provide emergency cooling. At the Fukushima nuclear station, the contrived remedial measures, including injection of ocean water, were not sufficient to prevent partial or full core meltdown in the three reactors that had been in operation.

The Fukushima Dai-ichi nuclear power station is comprised of six separate boiling water reactors originally designed by General Electric and maintained by the owner-operator, Tokyo Electric Power Company (TEPCO). Combined electrical power for the station was 4.7 GWe. At the time of the quake, Reactor 4 had been de-fueled, while units 5 and 6 were in scheduled cold shutdown for planned maintenance. Before the earthquake, Units 1 to 3 were providing power at rated output.

After the earthquake, control rods were inserted, and the operating reactors (marked 1, 2, and 3 in Figure 3) automatically scrammed (closed down). When external electricity was lost, emergency diesel generators started up properly and many other instruments also functioned as designed.

About an hour later, the tsunami not only broke connection to the power grid, it also resulted in flooding of sub-grade rooms containing emergency generators. Consequently those generators stopped working and pumps that circulate coolant water in the reactor ceased to work, causing the reactors to start overheating. Operators were still engaged in prescribed post-shutdown procedures, such as controlling reactor pressure with limitations not to exceed an established cool-down rate. The flooding and earthquake damage greatly hindered external assistance.

Unanticipated site flooding resulted in impairment of electrical backup systems that would have sustained the Fukushima reactors during a safe, controlled shutdown. Flooding also lead to failure of secondary systems and to dramatically destructive explosions in three reactor buildings. Volatile gases had originated inside the reactors after zirconium fuel cladding reacted chemically with coolant water to produce a buildup of explosive hydrogen. In addition, radiation escaped reactor containment, polluting the land, sea, and air environment — although no known human casualties are known to have resulted, and it is not likely that any will occur.

Because of the tsunami, AC power sources (except for one emergency diesel generator) lost their functions, and motor-driven pumps and valves were inoperable. Numerous switch gears were wet or flooded and becoming unusable. Units 1, 2 and 4 lost their DC sources, resulting in monitoring instruments being put out of use. Backup seawater facilities necessary for heat removal from reactors had also been flooded; this resulted in inoperability of large pumps and other equipment that required cooling of motors.

Immediately after the tsunami, steam-driven pumps, such as the core-isolation cooling system, were used to inject water into the reactors; these pumps eventually stopped working. Because water injection into the reactor was essential to cool the reactors, depressurization of the pressure containment vessel was unavoidable. Since no power sources were available in order to operate valves, workers had to conduct or devise alternatives; for example, they used car batteries. Preparations for venting were implemented using temporary equipment under harsh conditions after such startling events as the hydrogen explosions.

In short, destruction caused by the tsunami resulted in loss of almost all equipment and power-source functions expected to be activated in case of accidents, including those for accident-management measures. Workers on the site were forced to adapt to sudden changes of circumstances, such as injecting water into the reactors using fire engines, and accident management became extremely difficult.

When AC and DC power failed, no staged emergency equipment was available for injecting cooling water into the reactors. The unavailable functions included steam-driven high-pressure water-injection systems and motor-driven cooling facilities. Instead, fire-protection lines (originally prepared for accident management) were utilized used to inject water. The work was made very difficult due to scattered debris caused by the tsunami, by lack of suitable lighting, and by frequent earthquake aftershocks. Fresh-water injection commenced early in the morning of March 12. Work conditions further deteriorated due to increased on-site radiation levels and the hydrogen explosions. The extraordinary measure of injecting seawater started in the evening of March 12.

An outside review of the accident progression, adapted from a report prepared by an international organization of experienced nuclear plant operators, is presented in a sidebar.

Tenuous Post-Accident Situation

The current condition of Fukushima Units 1, 2, and 3 is relatively static, but those reactors have yet to achieve a stable, cold shutdown. This means that they could still undergo various and uncharted stages of self-destructive disassembly and meltdown.

More than a year after the core meltdowns, the affected reactors remain in uncertain conditions that could still benefit from diagnostic information specific to (1) their existing, but unknown, post-accident coolant level, (2) the current status of undetermined core redistribution, and (3) any other changes that might yet take place in time. The responsible managers simply don't know how much water is in the pressure vessels, nor do they know where the nuclear fuel is now located.

Despite the meltdowns, no known reactor-related fatalities were caused among members of the public or among nuclear workers; however, substantial loss of electric power and economic value has resulted. Moreover, it will take many years or decades to decommission the nuclear reactors in a harmless and systematic manner.

Current estimates of the total earthquake- and tsunami-related economic costs are well over $200 billion, not including tens of billions of dollars attributable to decommissioning and the loss of power from the disabled reactors.

Figure 4 contains a graphic rendition of the typical Fukushima reactor building profile, with callouts for the overhead fuel storage pool, the reactor pressure vessel (RPV), the reactor core, the concrete biological shield, and the 67-foot diameter reactor pressure-containment vessel (PCV) inside the biological shield.

The reactor water level in Fukushima Unit 1 is considered to have receded within a short period of time, leading to exposure of the reactor core and to core damage. Reactor pressure decreased even though no actions were taken to reduce it. On the other hand, PCV pressure increased, implying that reactor-vessel pressure could not be maintained due to stresses on the vessel, and that the core damage had advanced a considerable extent within a short period of time.

For Units 2 and 3, reactor water level started to decrease after cooling circulation stopped. Fire-engine pumps were started and low-pressure water injection was ready, but it couldn't be started quickly enough. The amount of water in the reactors sharply decreased. This resulted in core damage, for Unit 2 about two hours after the earthquake, and for Unit 3 in about 60 hours.

Because of the extraordinary conditions, boric acid and seawater were injected into the unsalvageable reactors in order to quench possible nuclear recriticality.

Remaining Uncertainty About Damaged Reactors

Despite adept and courageous efforts by qualified TEPCO personnel, risk remains of potentially harmful degradation of the reactors at the Fukushima power station. Although nominally out of operation, three of the reactors are not in a consummated state of managed control known as "cold shutdown." Even a year later, each generates many megawatts of heat and radiation.

Before decommissioning can take place, TEPCO will have to manage and control a difficult situation that presents technical and public uncertainty.

Most uncertain is the ongoing condition of the nuclear core and its water coolant — a continuously changing and currently indeterminate situation. Because normal water supply was interrupted by failure of electrical pumps and other emergency measures, extraordinary methods are currently being used to supply sufficient water coolant for the three damaged reactor vessels. In fact, forced external cooling will probably be necessary for many years.

In addition, nuclear fuel in one or more of the reactor cores has been damaged, likely to have been partially or fully melted, such that some or much core material fell to the bottom of their pressure or containment vessels. This problem is compounded because of the small, but finite possibility of "recriticality" in which a reactor might spontaneously renew production of a fission chain reaction that cannot be properly cooled or safely contained. Such nightmarish scenarios are more conceptual than realistic, but properly informed measures are needed to cool, control, and manage the residual nuclear-reactor cores until fully decommissioned.

Getting the disabled Fukushima reactors decommissioned in a safe, timely, and orderly manner is a common goal of public, professional, and international concern. Meanwhile, three reactors remain in a tenuous condition that could yet lead to additional hazardous consequences and public alarm.

In this March 24, 2011 aerial photo taken by a small unmanned drone and released by AIR PHOTO SERVICE, damaged Unit 3, left, and Unit 4 of the crippled Fukushima Dai-ichi nuclear power plant are seen in Okumamachi, Fukushima prefecture, northern Japan. (Air Photo Service Co. Ltd., Japan)

EXPEDITING FUKUSHIMA REACTOR CLEANUP

When the Fukushima-reactor cleanup staff and crew is ready to plan and engage in removal of fuel and core debris, it would be extremely valuable, probably essential, to have updated knowledge of the approximate quantity and geometrical distribution of water and fuel inside the reactor pressure vessel. Such information would help safely and economically manage residual nuclear-criticality and radiation-exposure risks for each disabled reactor.

Based on the decade of TMI-2 field experience and costly delays in removing degraded fuel, it would be wise to consider supplementary diagnostic measures that might help expedite the cleanup at Fukushima.

External instrumentation could be introduced for the specific purpose of determining how much water is currently within the reactor vessels. That same external instrumentation, if based on measurement of penetrating radiation, could be used to map the physical arrangement of the intact and/or crumbled reactor fuel. Such information would be important in safe and methodical dismantlement, which might take up to ten years. Much of this is now cleverly being deduced from indirect instrument data and analysis.

An early step towards directly characterizing the redistributed core fuel could be achieved by introducing specialized instrumentation placed inside the reactor containment building — but outside the pressure vessel. To accomplish this, a modified “fast-neutron/gamma-ray hodoscope” diagnostic system could be installed and operated by remotely-controlled equipment (See technology sidebar). There are two manifestations of this instrumentation, depending on the degree and access available within or inside the biological shield. Of course, a major limiting factor will be safe and practical access to requisite areas inside the reactor building.

The technical term “hodoscope” applies here to a calibrated set of radiation-detecting instruments that differentiate the direction and energy of selected nuclear radiation. Fast neutrons and gamma rays are forms of penetrating radiation that originate inside nuclear reactors, whether operating at full power or closed down after a long history of operation, as at Fukushima. Residual radiation emerging from the now-inoperative reactors provides a way to measure the existing quantity and distribution of water and fuel in the reactor.

Considerable and relevant experience has been accumulated, usedtilized, and published that is relevant to this proposal. Information was obtained and analyzed from very reliable and successful hodoscope operations under severe radiation conditions. The experience base is derived from 30 years of design, experiment, and operation.

Hodoscope-type systems could be installed and operated inside the biological shield, but external to the reactor pressure vessel of each disabled Fukushima reactor. The equipment would be expected to deliver information in real time on the reactor coolant and fuel distribution. These essential items of information are now highly uncertain at the fatally damaged reactors which might have fuel that has drained into the bottom of the containment vessel.

Because this diagnostic approach had been overlooked, it’s function is described here in some detail. The hodoscope system is based on the body of experience and concepts disclosed in patents detailed in the technology sidebar.

Improving Knowledge of Core and Coolant Condition

This particular external equipment was specifically conceptualized as a result of the 1979 TMI-2 nuclear accident in Pennsylvania, and it was formalized in a U.S. patent issued in 1987. (Had this instrument system already been installed at the TMI-2 reactor, it is likely that the traumatic billion-dollar accident could have been averted.)

Implementation at Fukushima can yet assist in preventing further damage by removing uncertainty regarding the ongoing nuclear-fuel condition and water-coolant status. If positioned beforehand, the diagnostic instrument system — designed to survive an accident of the type that occurred — would likely have remained functioning to provide post-accident real-time information on the status of coolant and fuel.

A conceivable alternative or complement to the stationary diagnostic coolant and fuel monitoring system would be a mobile array of collimated detectors. It would have to be positioned within the biological shield and reactor containment, but outside the reactor pressure vessel. Such a system could be remotely operated so as to provide crucial coolant and fuel profiles as needed.

For perspective, it should be recognized that — while the proposed diagnostic instrument system has a solid foundation in prior research, development, testing, and supportive calculations — it has not been actually assembled and tested in a water-cooled power reactor. An evaluation program is under consideration in the Nuclear Engineering Division of Argonne National Laboratory.

DISCUSSION AND CONCLUSIONS

One should ask, why — after the TMI accident — were there no high-level recommendations for external water and fuel monitoring? While major post-accident expert reports identified numerous errors and remedies — in TMI reactor design,

construction, and operation — no requirements seem to have been included for autonomous measurement of bulk water level.

In both the TMI and Fukushima accidents, incorrect operator response and poor control-room organization were major factors in either initiating or aggravating the respective incidents (along with many other contributing factors that have been duly recognized). Nonetheless, during these specific power-reactor emergencies, no direct data on actual coolant immersion or voiding in the core were available to the operators.

Belatedly, without authorizing relevant action, an official 2004 *NRC Fact Sheet on the Accident at Three Mile Island* acknowledged explicitly, “There was no instrument that showed the level of coolant in the core.”

Possible explanations for omitting autonomous bulk water monitoring are that such an objective was deemed technically too speculative, too difficult, or too intrusive to achieve.

Although the worldwide nuclear industry has implemented and touted higher levels of safety, reliability, and training in the operation of nuclear power plants, apparently little has been done to provide supplementary external instrumentation.

Had such an innovation been mandated for the Fukushima reactors, it is plausible that their core meltdowns might have been averted or minimized because operators would have been better informed by direct measurement of ongoing loss of coolant.

It’s not too late for the disabled Fukushima reactors to benefit from *post-hoc* introduction of diagnostic monitoring equipment.

Nor is it too late to develop and test the proposed diagnostic system for a role in commercial power reactors throughout the world. Although a number of measures to prevent or mitigate the same type of accident have been taken in the 30-plus years since the TMI event, no operating nuclear reactors have been retrofitted with failure-resistant autonomous water-level instrumentation positioned external to the pressure vessel.

Of the three major accidents involving nuclear-power reactors, all have ultimately delivered useful lessons about nuclear safety, reactor design, and radiation effects. Moreover, those particular accidents are noteworthy for very few, if any, public casualties. Nevertheless, trauma from their occurrence has shocked the industrial world, while radiation cleanup, power loss, and reactor decommissioning have been expensive. Despite such deplorable events, nuclear safety has duly improved, and important functional lessons have been derived. Even so, more can be learned from the experiences, including better instrumentation to diminish reoccurrences and consequences.

In the aftermath of the TMI nuclear meltdown, massive resources were unleashed in analyzing the accident and advising remedial actions. Many generic reactor improvements were undertaken, but — as indicated by the accident progression at Fukushima — one of the most conspicuous remedial actions to be derived from TMI was never implemented: No autonomous information on the reactor-core water level was available for the Fukushima operators, who erroneously inferred that water was surrounding the reactor fuel.

Several formal post-accident investigations extensively analyzed the TMI event. The Kemeny Commission attributed "operator error" as the decisive factor. Their rationale was that if reactor operators had not erroneously turned off emergency cooling systems, the accident would have been limited. But the operators had no direct indication that coolant water was turning into steam. If there had been in place a means of externally monitoring water level and density, it might have prevented the meltdown.

As best as I can tell, no autonomous water-level monitor has since been prioritized, mandated, or installed in any new reactor construction — despite the imposing array of TMI post-accident reviews, critiques, and interventions involving the Kemeny and Rogovin investigative boards, Nuclear Regulatory Commission follow-ups, Department of Energy government R&D, UK Chief Inspector, Babcock&Wilcox manufacturer improvements, and watchdog groups like the Union of Concerned Scientists.

The tsunami subjected the Fukushima reactors to chaotic conditions. If independent water-level instrumentation had been installed, there is at least a chance that earlier remedial actions based on contemporaneous knowledge of coolant level might have been terminated the accident progression before core meltdown. Because instrument shortcomings at the TMI-2 reactor were never fully addressed, that unrecognized omission might have allowed Fukushima reactor-core damage to have been exacerbated. Even a very recent 2011/2012 NRC Task Force Review of Insights from the Fukushima Dai-ichi Accident failed to make recommendations dealing with the instrumentation highlighted in this paper.

My recommended autonomous instrumentation is designed to collect data years after a reactor has nominally ceased operation. At Fukushima, such supplementary nuclear instrumentation could still provide real-time post-accident monitoring of both water level and fuel distribution until the reactors are defueled.

TMI technical reviews do not seem to have adequately prioritized an essential mandate, namely that power-reactor water coolant is such a fundamental property that it should be directly monitored.

The brutal hazards from core meltdown and subsequent reactor decommissioning might further be minimized by some selected remedial measures and precautions that could be implemented. This article has outlined autonomous external nuclear instrumentation that can still be installed — at Fukushima and at operating power reactors — to independently measure reactor water level and fissile fuel distribution — before, during, and after a reactor accident or routine shutdown. ■

Dr. Alexander DeVolpi, a retired nuclear physicist, has almost 40 years of experience in reactor instrumentation, experimental diagnostics, and specialized technology at Argonne National Laboratory, near Chicago, Illinois. He has a PhD in physics, an MS in nuclear-engineering physics (both from Virginia Tech), and a BA in journalism (from Washington and Lee), as well as being a graduate of the International School of Nuclear Science and Engineering (at Argonne).

Technology Relevant to Important Reactor Properties

By Alexander DeVolpi

Here are descriptions of technology and patents relevant to determining how much water and fuel is in a nuclear reactor, whether the reactor is at full power or shutdown.

The basic patent relates to a device called a hodoscope, which has been designed and developed to measure the rate and direction of specific nuclear radiation. The other two patents are proposed hodoscope applications, the first one for use with operating light-water power reactors, and the second for the dysfunctional Fukushima reactors that are now closed down.

The diagnostic hodoscope device is well anchored by many years of experimental data and supplementary calculations. It is intended to provide an autonomous means of determining water coolant level and the bulk fuel distribution in an operating nuclear-power reactor, even after the reactor has shut down.

These patents and their technology are thus relevant to the tenuous situation that now exists at Fukushima, and the patents also are applicable to other water-cooled nuclear reactors operating around the world. The first two patents have expired and are in the public domain, while the third was recently filed.

Basic Hodoscope Patent

The neutron/gamma hodoscope (1978 US patent 4,092,542, "High-Resolution Radiography by Means of a Hodoscope") is a diagnostic device that has succeeded in producing radiographic-type images of objects inside nuclear reactors under extremely difficult and unusual operational conditions.

In the accompanying block diagram (Figure 1), the neutron source and target would ordinarily be inside the core of the nuclear reactor, while the hodoscope multi-channel collimating and detecting apparatus would be installed within the reactor's biological shield, and the remainder of the data storage and electronic system would be outside the reactor shield.

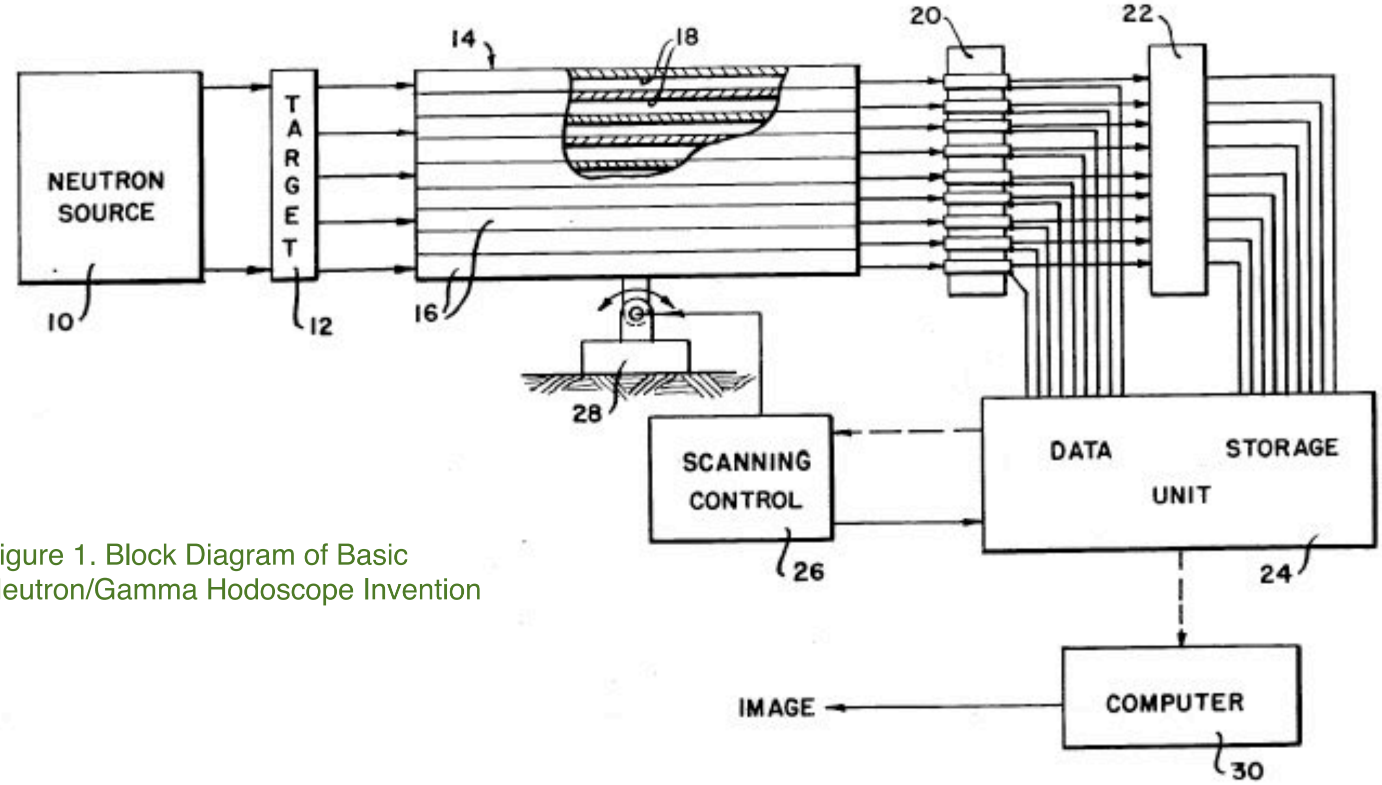


Figure 1. Block Diagram of Basic Neutron/Gamma Hodoscope Invention

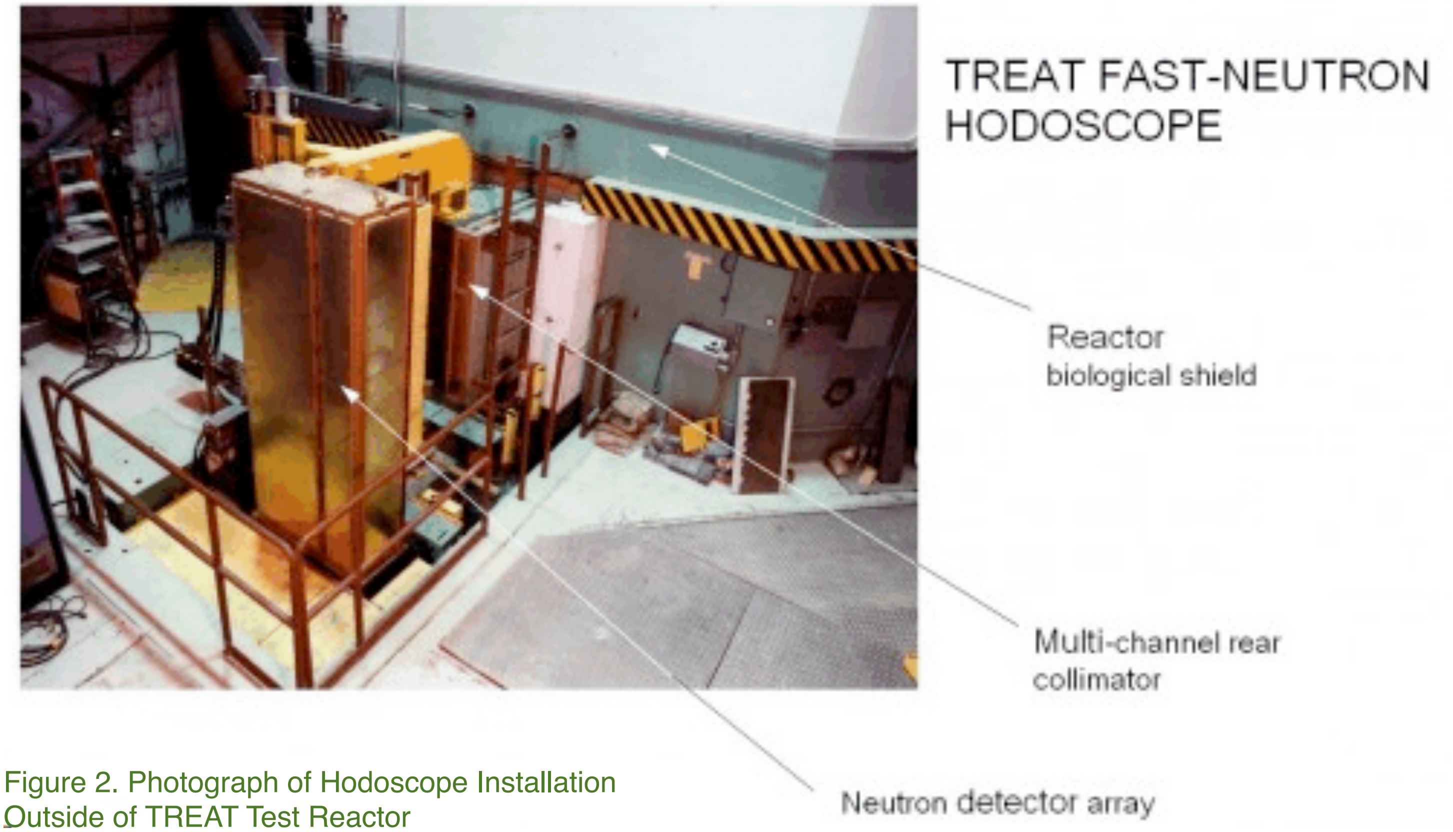


Figure 2. Photograph of Hodoscope Installation Outside of TREAT Test Reactor

The collimator might be installed several meters from the target, as shown in Figure 2, in which case the detectors are over 5 meters from the test element.

In the United States and France, hodoscopes have been installed in a similar manner outside or at the edge of nuclear reactors. The devices have rendered time-resolved image reconstructions of fuel and coolant that have been deliberately subjected to severe test conditions within the reactors.

Figure 3 shows a cross-sectional image of the hodoscope at the TREAT transient test reactor at the Idaho National Laboratory.

These diagnostic-radiation hodoscopes have also been used to geometrically characterize stationary objects irradiated by neutron and gamma sources inside reactors.

TMI-Inspired Hodoscope Patent

Stimulated explicitly by the 1979 loss-of-coolant accident at the TMI-2 reactor in Harrisburg, Pennsylvania, a patent (US 4,649,015, "Monitoring System for a Liquid-cooled Nuclear Fission Reactor," filed in 1984, was issued in 1987 (Figure 4).

This invention, based on substantial and relevant technical experience with the hodoscope, was intended to provide a physically and functionally independent (autonomous) means of monitoring downcomer, core, and plenum liquid levels in water-cooled nuclear reactors.

The reactor-radiation-driven measurement data could collected in real time, as well as after the reactor was shut down.

The ultimate purpose was to provide an independent and durable means for minimizing real-time operational uncertainties about water levels and steam conditions in a reactor. This would address problems that have already aggravated accidents in water-cooled reactors.

This patent was never implemented nor tested in a commercial power reactor — an important limitation that must be acknowledged. However, the design is supported by detailed numerical calculations, experiment-based computer modeling, and an extensive foundation of experimental data obtained under relevant conditions.

New Patent: Monitoring Fukushima Reactors With a Hodoscope

Taking note of unresolved similarities in both the TMI and Fukushima nuclear accidents, a provisional patent was filed this year: "Radiation-

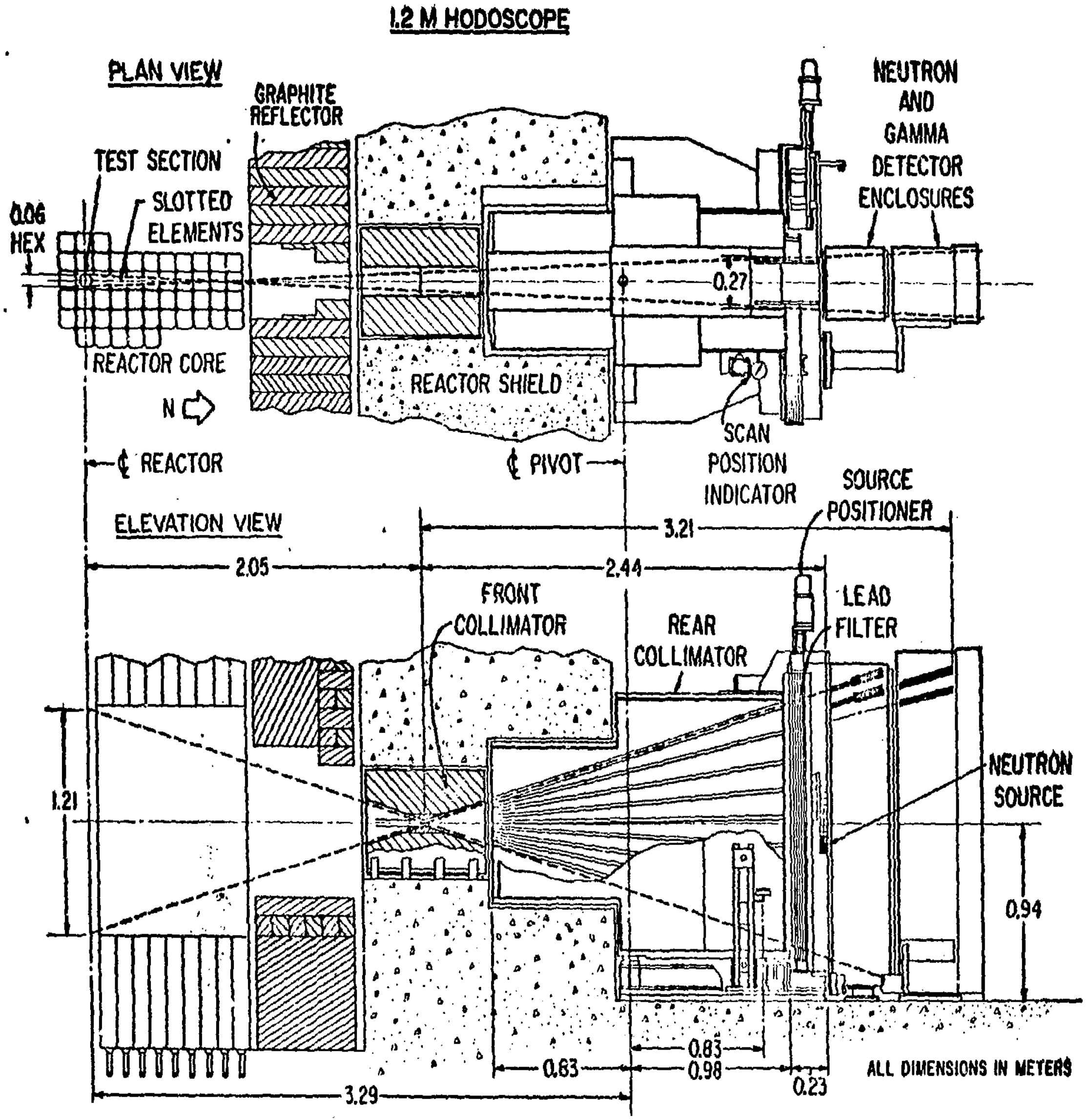


Fig. 3. Schematic diagram of hodoscope

Figure 3. Cross-Sectional Top and Side Views of Newer Hodoscope at TREAT

Monitoring Diagnostic Hodoscope for Fukushima Reactors.”

The objective is to instrument the Fukushima reactors with autonomous remotely-operated radiation sensors located inside the reactor biological shield. In this manner, it would be possible to safely monitor the water and fuel now inside the pressure or containment vessel. Having definitive knowledge of water level and nuclear-fuel distribution is crucial for the safe and timely decommissioning of disabled reactors.

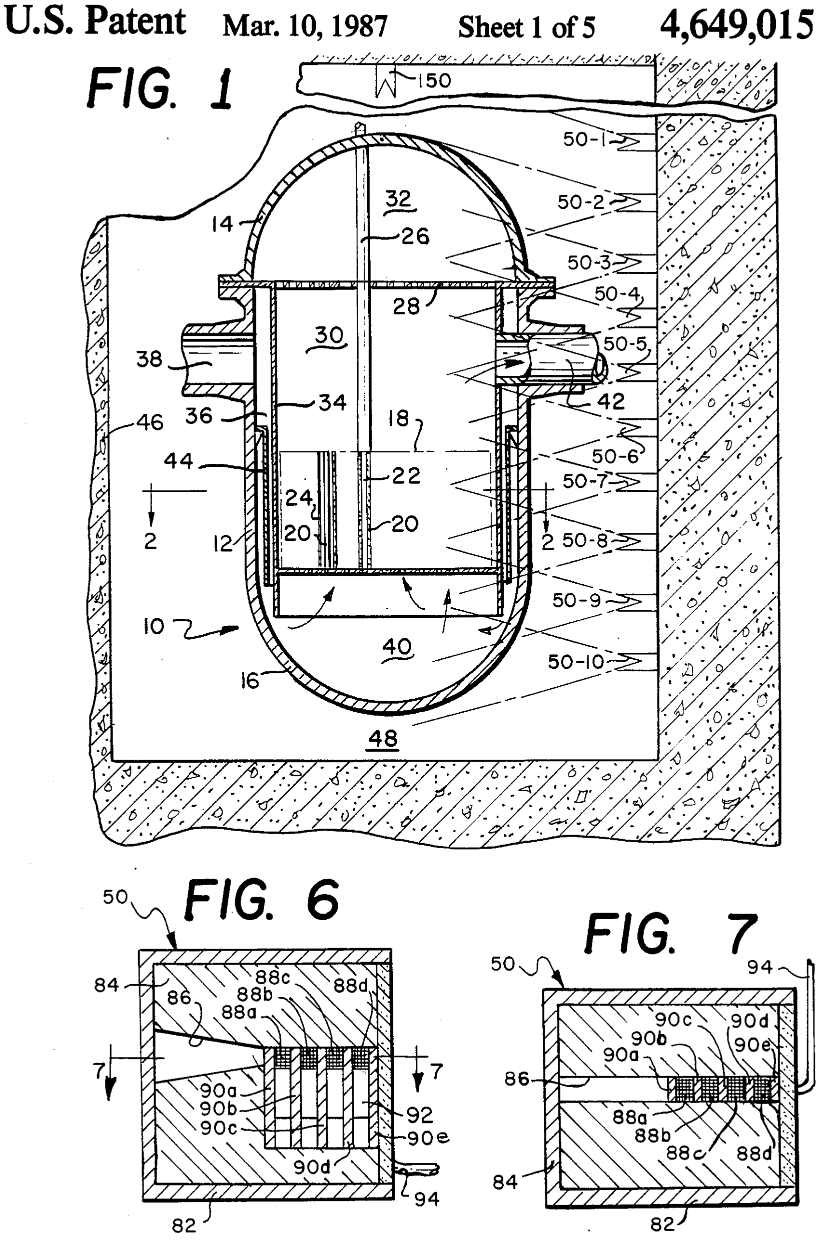
There are two manifestations of this invention: One provides for permanent detector array installation by means of narrow penetrations through the reactor biological shield. The other manifestation offers a mobile detector array that might be emplaced and operated by robotic means inside the biological shield.

Extrapolating from the decades of experience with radiation-detecting hodoscopes, either the mobile or stationary hodoscope arrays ought to suffice at Fukushima, depending on access that can be provided.

For the mobile system, a shielded and collimated hodoscope would have to be introduced through the airlock onto each Fukushima reactor floor at locations adjacent, but external to the reactor pressure vessels. The mobile system would be composed of a remotely linked pre-assembled array of collimated and calibrated radiation detectors, very similar to a arrangement operated at the TREAT reactor in the United States.

Figure 4.
Arrangement of Proposed Autonomous Hodoscope Detectors Inside Containment of a Pressurized Water Reactor.

(Within the drawing, “Fig. 1” shows the elevational distribution of redundant detectors designated 50-1 through 50-10, while “Fig. 6” and “Fig. 7” show horizontal and vertical views of the shielded gamma-ray detectors.)



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The stationary version would be similar in some fundamental respects to that proposed in the TMI-inspired patent: It would consist of a vertical and radial array of detectors inserted in existing small-diameter penetrations through the biological shield, supplemented as necessary by additional drilled narrow holes.

Either system could be operated externally to produce remotely analyzed, reconstructed images of the residual internal core fuel, structural configuration, and coolant level. Validated data reconstructions could be shared as necessary with contractors, managers, government officials, and public stakeholders.

Either or both hodoscope systems, if assembled and operated on the basis of accumulated long-term experience, should provide information specific and essential for safe defueling and decommissioning of the damaged Fukushima reactors.

In addition, the stationary system could provide real-time guidance specific to the eventual removal of residual core and structural components, thus making the Fukushima decommissioning operation safer, while reducing the required dismantlement time.

Years ago, a Japanese nuclear agency (JAEA) supported a project in the United States to compile hodoscope data. As a matter of fact, much of the essential detectors and electronics at the TREAT reactor have been stored and preserved – presumably recoverable.

Foundation of Technical and Operational Experience

The U.S. Department of Energy and the Nuclear Regulatory Commission supported relevant programs of the 1960s through the 1990s to improve nuclear reactor safety. In research and development undertaken primarily at Argonne National Laboratory, very successful external nuclear diagnostic instrumentation was developed to detect fuel, coolant, and structural materials inside a reactor.

This experience led to the two patents, the first being related to specific instrumentation used for real-time detection of such designated materials in a specialized test reactor. The second patent — as an aftermath of the TMI-2 accident — was an application to externally monitor coolant level and fuel disposition in an operating or shutdown water-cooled power reactor. Considerable experimental data and analytical analysis formed the foundation of the now-expired patents.

While the recommended instrumentation for water-cooled reactors was never implemented, hindsight implies it should have been. One major lesson to be derived from the TMI-2 accident is that independent devices are needed to measure and monitor such critical parameters as coolant water level in the reactor vessel. During the TMI-2 accident, the installed conventional instrumentation became operationally ineffective and functionally ambiguous.

For the disabled Fukushima reactor, such diagnostic instrumentation could still be of value. Three reactors remain in a tenuous condition with currently ill-defined distributions of fuel and coolant. These are circumstances that could yet lead to additional hazardous consequences and public alarm.

It is of inestimable value to have autonomous instrumentation that operates under separate physical principles and directly measure (nuclear) properties of importance. Information autonomy is especially important during emergency conditions, such as loss of electrical power.

The separate physical principle involved here uses nuclear detection, rather than indirect conventional information derived from pressure, flow, and temperature instrumentation. The properties of direct significance are the actual water level and fuel integrity.

During the emergencies at TMI and Fukushima, standard reactor instruments became inoperative; moreover, their signal output lacked crucial information value, and they were indirect rather than direct in relevancy.

Post-Accident Conditions at Fukushima

On 29 March 2012, the following informed message was posted on the Internet:

“One of Japan’s crippled nuclear reactors still has fatally high radiation levels and much less water to cool it than officials had estimated, according to an internal examination that renews doubts about the plant’s stability....

“Further analysis carried out by TEPCO [the reactor operator] on the state of the reactor cores after the earthquake on March 11th have revealed that the Unit 1 at Fukushima Daiichi was damaged much earlier than previously predicted.... [Moreover] molten fuel rods in reactors No 1, 2 and 3 have not only melted, but also breached their inner containment vessels and accumulated in the outer steel containment vessels. TEPCO did not acknowledge that even a partial meltdown could have occurred until [months after the accident]....

“The entire episode revealed how little the company actually understood of the conditions inside the plant’s reactors and the fragility of the cold shutdown.”

Because of the still-continuing tenuous circumstances cited above, Japanese government and reactor officials should be interested in utilizing the proposed autonomous hodoscope instrumentation in order to determine the still-uncertain coolant levels and the less-known condition of reactor fuel in the Fukushima reactors. While workers and management in Japan have done remarkable and disciplined work in preventing the loss of life, there is much that yet needs to be done for the safe, orderly, and timely decommissioning of the reactors. ■

Dr. Alexander DeVolpi’s research and development work in reactor safety grew in part from active military service in the U.S. Navy, followed by assignments as a Reservist at the Naval Research Laboratory in Washington, DC, and the Naval Radiological Defense Laboratory in San Francisco. This affiliation lead to specific applications in reactor-safety research and instrumentation later developed and utilized at the Idaho Nuclear Engineering Laboratory. In later years, he moved on to applications involving arms control and treaty verification, which included technical assignments from the Defense Nuclear Agency and professional collaboration with many non-government organizations. He specialized in technology at Argonne National Laboratory, near Chicago, Illinois.