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Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station

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1.0 INTRODUCTION

Visitors to Fukushima Daiichi quickly recognize that something is very different when they enter the guarded and controlled evacuation zone 20 kilometers (12 miles) from the site. The roads are empty, with the exception of cars and trucks traveling to and from the site; and most people seen within the zone are wearing anticontamination clothing and paper masks or respirators.

In the buses carrying visitors to the plant, there is little conversation—just silent reflection as the rural countryside passes by the window. Previously pristine villages and rice paddies are abandoned and overgrown. Earthquake and tsunami damage to homes, commercial buildings, and other structures has not been repaired. The bus must slow occasionally because of earthquake damage to the roads, which were hastily repaired. Undamaged homes are empty and are beginning to show signs of neglect; and commercial properties, with their inventories still intact, sit just as they did on March 11, 2011.

In the Fukushima Prefecture, about 1,000 residents lost their lives during the earthquake and tsunamis, including two operators performing their duties at Fukushima Daiichi Unit 4 who were trapped when flood waters partially filled plant buildings. It is estimated that more than 140,000 residents of the prefecture were displaced from their homes because of the nuclear accident that followed.

At Fukushima Daiichi, conditions have improved significantly since the March 11 event. Much of the debris from buildings, equipment, and vehicles that was left following the tsunami and explosions has been removed, and a large temporary wall has been constructed to help protect against future tsunamis. In contrast, the wreckage of pumps, cranes, buildings, and large equipment that remains is a stark reminder of the power of the tsunamis that struck the site.

> "For nuclear professionals, it is not possible to visit the Fukushima Daiichi site without coming away with a renewed commitment to ensuring nuclear safety." John Conway, Senior Vice President, Energy Supply, Pacific Gas & Electric Company

Conditions were different early on March 11, 2011. Three of Fukushima Daiichi's six boiling water reactors were operating at full power; the others were shut down for maintenance and refueling. About 10 kilometers away, the four Fukushima Daini units were also operating at full power. The plants were in good condition, with well-maintained equipment and well-organized work spaces, even under outage conditions. No one expected or was prepared for the massive earthquakes and the tsunamis that would occur before the day ended.

Over the years, nuclear plant operators around the world have focused on continuously improving plant safety by ensuring compliance with regulations, operating plants within their design bases, and making safety improvements based on worldwide operating experience and best practices, including addressing lessons learned from core-damaging events at Three Mile Island Nuclear Station and Chernobyl Nuclear Power Plant.

Organizations have also worked to improve plant programs, processes, and personnel performance.

Improved performance resulted in a high level of confidence in the ability to protect the core and the health and safety of the public given any of the anticipated accident scenarios. However, the Fukushima Daiichi and Daini events reveal the need to also be prepared for the unexpected—including circumstances that go beyond the design basis. No matter how well plants are operated and maintained, there is always the potential for unexpected and high-consequence situations. On reflection, it is evident that Tokyo Electric Power Company (TEPCO) and the broader commercial nuclear industry were not prepared to respond to maintain critical safety functions or to implement effective emergency response procedures and accident management strategies under the extreme conditions encountered at Fukushima Daiichi.

This is an addendum to INPO 11-005, *Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station.* The document provides lessons learned that nuclear power plant operating organizations should consider in conjunction with action plans already established as a result of the Fukushima event. The addendum does not address regulatory or governmental factors that may have contributed to the event or to difficulties in response to the emergency. Those aspects are well described in other reports, including those developed by the government of Japan, the International Atomic Energy Agency, and TEPCO.

The Institute of Nuclear Power Operations (INPO) developed this report separate and apart from the Institute's normal processes, with no expectation of confidentiality. Its purpose is to share information about the Fukushima Daiichi accident broadly within the nuclear power industry to help inform actions to increase the margin of nuclear safety. The report has been provided to a number of organizations outside of INPO's membership, including the World Association of Nuclear Operators (WANO), the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Nuclear Energy Institute. This broad distribution of lessons learned reflects the unique nature of this report, and the report is not covered by INPO's policies for the control and distribution of confidential information.

The lessons learned and supporting details resulted from an INPO review of the Fukushima Daiichi event and a similar, less consequential event at the Fukushima Daini site in March 2011. The review was conducted by a nine-person team that included individuals with extensive commercial nuclear power experience from INPO, the U.S. nuclear utility industry, and WANO. The team reviewed updated reports, including those provided by TEPCO and the Japanese government. Team members also conducted reviews at TEPCO headquarters and at the Fukushima Daiichi and Daini stations that included interviews with corporate and station personnel who supported the emergency response and performed critical tasks during the first days of the event.

This independent review was conducted at TEPCO's request, and TEPCO management cooperated in the review by making key individuals available for interviews, arranging for visits to the plant sites, and encouraging the team to identify organizational and other lessons that can be shared with the nuclear industry and the public. TEPCO management reviewed this addendum for accuracy but did not influence the team's conclusions regarding the lessons learned for the industry.

During the review, the team developed the utmost respect for the professionalism, courage, dedication, and personal ownership displayed by the managers and workers involved in responding to the events at Fukushima Daiichi and Daini. In this unanticipated, complex, and highly stressful situation, individuals demonstrated great personal commitment, resilience, and ingenuity as they attempted to restore critical safety functions following the tsunami. These actions were taken in spite of widespread devastation and loss of life caused by the earthquakes and tsunamis; uncertainties regarding the fate of family members; and challenges such as adverse weather conditions, lack of rest, and shortages of food and water.

The facts and conclusions in this report are reflective of information and insights developed through investigations over the 15 months since the accident. The information developed through hindsight should not be taken out of context and used to imply that the outcome of the Fukushima Daiichi event could have been completely prevented had operators and emergency response personnel acted differently. The intent of the report is not to find fault with the actions taken, but instead to identify how to reduce the potential for such events and to be better prepared to respond if faced with similar circumstances in the future.

The lessons learned are believed to have broad applicability to all nuclear operating organizations. In many instances, the practices and level of preparation for a severe accident at Fukushima Daiichi and Daini prior to the March 2011 tsunamis were similar to those found at many other nuclear stations around the world. Reviews already conducted in various countries have identified the need for improvement in several of the areas discussed in the report. However, this report contains new lessons learned that may not have been fully considered in the actions already taken. Therefore, it would be appropriate for operating organizations to review the report thoroughly and consider how the lessons learned can be used to further strengthen the barriers against a significant event.

At the time of this event review, TEPCO had not yet completed its final investigation, and the government of Japan had convened an independent investigatory committee that was continuing its event assessment. The results of those investigations may provide additional insights and lessons learned that can be used to further enhance nuclear safety.

2.0 EXECUTIVE SUMMARY

In April 2012, the Institute of Nuclear Power Operations, with participation by the World Association of Nuclear Operators, conducted an independent event review of the nuclear accident at the Fukushima Daiichi Nuclear Power Station that resulted from the Great East Japan Earthquake and Tsunami on March 11, 2011. The review was conducted at the request of Tokyo Electric Power Company (TEPCO) for the purpose of identifying and sharing operational and organizational lessons with other nuclear operating companies.

This report is an addendum to INPO 11-005, *Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station*, and information from the Special Report served as the foundation for the review team's activities. The concurrent event at the Fukushima Daini Nuclear Power Station was also reviewed as a source of operating lessons during the preparation of this addendum.

The following positive elements were critical to TEPCO's response during the event:

- The seismically isolated emergency response centers at the Fukushima Daiichi and Daini nuclear power stations filled a vital need in protecting emergency response personnel and ensuring access to the site could be maintained during the accident.

- Emergency response personnel took innovative and resourceful actions to reestablish critical safety functions and plant monitoring capability. Actions to restore power and heat removal capability at the Fukushima Daini Nuclear Power Station were particularly noteworthy.

- The response of TEPCO employees during and following the event reflected high levels of professionalism, courage, dedication, and personal ownership.

The following are considered the most significant operational lessons from the event:

- When periodic reviews or new information indicates the potential for conditions that could significantly reduce safety margins or exceed current design assumptions, a timely, formal, and comprehensive assessment of the potential for substantial consequences should be conducted. An independent, cross-functional safety review with a plant walkdown should be considered to fully understand the nuclear safety implications. If the consequences could include the potential for common-mode failures of important safety systems, compensatory actions or countermeasures must be established without delay.

- Emergency and accident response strategies and implementing actions must give highest priority to maintaining core cooling. Emergency response centers must maintain continuous awareness of the status of core cooling; changes to the method of core cooling must be made deliberately and with a clear strategy to establish an alternate cooling method; and, when there is reason to question the quality or validity of core cooling information, deliberate actions must be taken immediately to ensure a method of cooling is established.

- Plans must address the immediate emergency response needs for human resources, equipment, and facilities in the first few hours of an event, as well as the need for a long-duration response capability. In addition, plans should address how to engage the domestic and international nuclear industry to obtain needed support and assistance during an event.

- Training and periodic drills must be sufficiently challenging and realistic to prepare operating crews and emergency response personnel to cope with and respond to situations that may occur during a multi-unit nuclear accident, including a nuclear accident resulting from a natural disaster.

- Because the specific sequence of initiation events for beyond-design-basis events is unknown, emergency response strategies must be robust and provide multiple methods to establish and maintain critical safety functions using a defense-in-depth approach.

- Optimum accident management strategies and associated implementing procedures (such as emergency operating procedures and accident management guidelines) should be developed through communications, engagement, and exchange of information among nuclear power plant operating organizations and reactor vendors. Decisions to deviate from these strategies and procedures should be made only after rigorous technical and independent safety reviews that consider the basis of the original standard and potential unintended consequences.

- Emergency response strategies for extreme external events should consider the traumatic human impact of such events on individual responders and leaders and provide for appropriate training, assistance, and contingency plans.

- Nuclear operating organizations should consider the safety culture implications of the Fukushima Daiichi event, focusing on strengthening the application of safety culture principles associated with questioning attitude, decision-making, the special and unique aspects of the nuclear technology, and organizational learning.

3.0 EVENT SUMMARIES

3.1 Fukushima Daiichi

Fukushima Daiichi consists of six boiling water reactors (BWRs). Unit 1 is a BWR 3 reactor, units 2 through 5 are BWR model 4, and Unit 6 is a BWR 5. Units 1 through 5 have Mark I containments, and Unit 6 has a Mark II containment. Units 1, 2, and 3 were operating at full power and units 4, 5, and 6 were out of service for refueling or maintenance early in the afternoon on March 11, 2011 when a magnitude 9.0 earthquake occurred 112 miles (180 kilometers) off Japan's east coast. All the operating units automatically scrammed on seismic reactor protection system trips. The earthquake damaged breakers and distribution towers, causing a loss of all off-site electrical power sources to the site. The available emergency diesel generators automatically started and provided AC power to emergency systems. Three minutes after the earthquake, the Japan Meteorological Association issued a major tsunami warning, indicating the potential for a tsunami at least 3 meters high. Workers were notified of the warning, and operators were instructed to report to the control rooms while non-essential personnel were evacuated to higher ground.

Forty-one minutes after the earthquake, the first of a series of seven tsunamis arrived at the site. The maximum tsunami height impacting the site was estimated to be 46 to 49 feet (14 to 15 meters). This exceeded the design basis tsunami height of 18.7 feet (6.1 meters) and was above the site grade levels of 32.8 feet (10 meters) at units 1–4. All AC power for units 1–5 was lost when emergency diesel generators and switchgear rooms were flooded. The seawater intake structure was severely damaged and was rendered nonfunctional. All DC power was lost on units 1, 2, and 4, while some DC power from batteries remained available on Unit 3 because some of those battery banks were not flooded. One air-cooled emergency diesel generator continued to function and supplied electrical power to Unit 6, and later to Unit 5, to maintain cooling to the reactors and spent fuel pools.

With no core cooling to remove decay heat, core damage began on Unit 1 on the day of the event. Steam-driven injection pumps were used to provide cooling water to the reactors on units 2 and 3, but these pumps eventually stopped working. As a result of inadequate core cooling, fuel damage also occurred in units 2 and 3. After debris caused by the tsunami was removed, fire engines were moved into position and connected to plant systems to restore water injection. Connection points had been installed previously to support fire protection procedures, but the plant staff had difficulty locating them initially because of the debris and because drawings had not been updated to show their locations.

During the event, containment pressure remained high for an extended time, contributing to hydrogen leakage from the primary containment vessel and inhibiting injection of water to the reactors using low-pressure sources.

It is believed that hydrogen generated from the damaged fuel in the reactors accumulated in the reactor buildings—either during venting operations or from other leaks—and ignited, producing explosions in the Unit 1 and Unit 3 reactor buildings and significantly complicating the response. The hydrogen generated in Unit 3 likely migrated into the Unit 4 reactor building, resulting in a subsequent explosion and damage. The loss of primary and secondary containment integrity resulted in ground-level releases of radioactive material. Following the explosion in Unit 4 and the abnormal indications on Unit 2 on the fourth day of the event, the site superintendent directed that all non-essential personnel temporarily evacuate for their safety, leaving approximately 70 people on site to manage the event.

The Fukushima Daiichi event was rated as a level 7 event on the International Nuclear and Radiological Event (INES) scale. The Nuclear Safety Commission of Japan estimated approximately 17 million curies (6.3 E17 Becquerels (Bq)) of iodine-131 equivalent radioactive material was released into the air and 0.127 million curies (4.7 E15 Bq) into the sea between March 11 and April 5. The 1986 accident at Unit 4 of the Chernobyl nuclear power plant was the only other nuclear accident to have a level 7 INES rating. According to the International Atomic Energy Agency, the Chernobyl accident resulted in approximately 378.4 million curies (14 E18 Bq) of radioactive material being released into the environment.[1]

3.2 Fukushima Daini

Fukushima Daini consists of four BWR 5 reactors with Mark II containments. All four units were operating at full power on March 11, 2011 when an earthquake measuring magnitude 9.0 occurred 115 miles (185 kilometers) from the plant. The units automatically scrammed on seismic reactor protection system trips. All but one of the off-site power sources was lost. Shortly after the earthquake, the Japan Meteorological Association issued a major tsunami warning, indicating the potential for a tsunami at least 3 meters high. As at Fukushima Daiichi, operators were called to the control rooms, and non-essential workers were evacuated to higher ground.

Thirty-six minutes after the earthquake, the first of a series of tsunamis arrived at the site. The maximum flood height was estimated to be 23 feet (7 meters) on the seaward side of the plant and 49 feet (15 meters) in the area of the main buildings. This exceeded the design basis tsunami height of 17.1 feet (5.2 meters) and was above the grade level of 13.1 feet (4 meters) on the seaward side of the plant and 39.4 feet (12 meters) at the main buildings.

Two emergency diesel generators (EDGs), three seawater pumps, and two residual heat removal (RHR) pumps on Unit 3 remained operable, as did one EDG on Unit 4 and high pressure core spray pumps on both units. However, other EDGs and seawater pumps were rendered inoperable by the tsunami. In addition, flooding disabled switchgear associated with several safety-related pumps. Unlike Fukushima Daiichi, Daini did not

[1] Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts. The Chernobyl Forum 2003-2005 Second Revision.

lose all off-site AC power or DC power, and control room instrumentation and controls were generally not affected.

Initially, reactor core isolation cooling systems actuated and provided core cooling for all units. Later, all four reactors were depressurized and alternate coolant injection was established using the makeup water condensate (MUWC) system as directed by the emergency operating procedures and accident management guidelines. For Unit 1, this required manual repositioning of motor-operated valves that had lost power following the tsunami. The following day, core cooling for the Unit 4 reactor was switched from MUWC to the high-pressure core spray (HPCS) system. Thereafter, the Unit 4 reactor level was controlled by the starting and stopping of the HPCS system.

Residual heat removal for Unit 3 was operable and was used for core and containment cooling. However, containment temperatures and pressures began to rise in units 1, 2, and 4 because no means of cooling was available. Operators initiated drywell and suppression pool spray using makeup water pumps several times to help reduce pressures. Preparations were also made to vent containments if design limits were reached.

New seawater pump motors and a large quantity of temporary cable were urgently needed to restore cooling capability. The corporate support organization recognized the urgency of restoring cooling. Personnel located replacement seawater pump motors and a source of suitable cable and other needed materials. Even though transportation was difficult, with some roads damaged by the earthquake, arrangements were made for the motors and cable to be transported to the site by helicopter and truck the day following the tsunami. About 200 workers installed new motors and 5.6 miles (9,000 meters) of temporary cable over the next 36 hours.

In the early hours of March 14, before the criteria for venting primary containment were reached, RHR cooling was restored to Unit 1, and containment pressure began to lower. Cooling to the other units followed, and RHR for all units was in service by 15:42 Japan Standard Time on March 14. Cold shutdown was achieved on all four reactors on March 15.

4.0 LESSONS LEARNED

4.1 Prepare for the Unexpected

Lesson Learned: When periodic reviews or new information indicates the potential for conditions that could significantly reduce safety margins or exceed current design assumptions, a timely, formal, and comprehensive assessment of the potential for substantial consequences should be conducted. An independent, cross-functional safety review with a plant walkdown should also be conducted to fully understand the nuclear safety implications. If the consequences could include common-mode failures of important safety systems, compensatory actions or countermeasures must be established without delay.

During the life of the Daiichi site, TEPCO personnel reevaluated design-basis assumptions for tsunami height at least five times; and actions were taken on two occasions to prepare for increasingly large tsunamis. The initial design basis was set at sea level plus 3.1 meters (M) based on a tsunami caused by a 1960 Chilean earthquake. This was the largest documented tsunami that had occurred on the Fukushima coast, and using the tsunami as the design basis was consistent with the standard assessment methodology in place at the time. The licensing basis was never formally changed, although assumptions for tsunami height were increased to sea level plus 5.7M in 2002 and then increased again to sea level plus 6.1M in 2009 to address uncertainties in the calculated values based on improved assessment methods developed by the seismic and tsunami experts associated with the Japan Society of Civil Engineers (JSCE). The JSCE is the recognized authority for specifying seismic and tsunami design criteria, and its instructions are followed by all Japanese nuclear organizations. In response, seawater pump elevation was raised in 2002 and again in 2009 to prevent these pumps from being flooded during the newly postulated tsunami.

TEPCO engineers and managers were satisfied that the JSCE methods produced conservative results and that modifications to the seawater pump elevations provided sufficient margin against any potential tsunamis. However, additional information on the potential for earthquakes and tsunamis from two different sources was subsequently considered. One source was a study of the AD 869 Jogan earthquake and tsunami, and the other was a statement by the Headquarters for Earthquake Research Promotion (HERP) that a magnitude 8.2 earthquake could occur anywhere along the Japanese Trench off the country's east coast.

In 2008, TEPCO engineers used a recently published study regarding the Jogan earthquake to calculate a new postulated tsunami height of 9 meters for the Daiichi and Daini sites. TEPCO calculations used the location and parameters described in the Jogan report and assumed a magnitude 8.4 earthquake. The wave source models in the study were based on deposit surveys in the Sendai and Ishinomaki Plains; however, the location and scale of the tsunami source had not been verified. Calculation results were provided to the Nuclear and Industrial Safety Agency (NISA) in September 2009 and in March 2011. In addition, TEPCO and other electric utilities requested that JSCE review the suitability of the wave source model for the Jogan tsunami.

The validity of the Jogan study assumptions was not known. To further understand the potential for a large tsunami, TEPCO performed core borings at five locations near the Daiichi and Daini sites in 2009 and 2010. The five locations were selected in areas with coastlines most susceptible to tsunamis. Geological data obtained from three of these sites did not reveal deposits that originated from a tsunami. At one site, deposits indicated a 0.5M tsunami from the Jogan earthquake, and deposits at the final site showed that a 3M to 4M tsunami had occurred. Thus, no historical evidence of a very large (plus 10M) tsunami was found near the plant sites.

In 2008, TEPCO also investigated the potential for large tsunamis based on previously published statements by HERP regarding the potential for a large earthquake anywhere along the Japan Trench, including off the Fukushima coast. This statement was not followed up with more specific guidance, and JSCE did not modify its standards to reflect this potential. Additionally, neither the Center for Disaster Management Council nor the Fukushima Prefecture had factored this input into calculations of the potential for large earthquakes and tsunamis that needed to be addressed in emergency planning.

Because HERP did not identify the tsunami source and because there were no previously recorded earthquakes off the Fukushima coast to use as a model for the calculations,[2] engineers postulated a wave source model with characteristics similar to the 1896 magnitude 8.3 Meiji-Sanriku-oki Earthquake. This earthquake occurred off the coast of the Iwate Prefecture, causing a tsunami of 38 meters (125 feet) that killed more than 27,000 people. Calculations using these assumptions resulted in a maximum tsunami height of sea level plus 15.7M at the Daiichi site.

These analysis results were shared with senior managers at TEPCO headquarters and with site management in late 2008 and early 2009. During the discussions, it was recognized that a tsunami as large as this would render seawater pumps inoperable. Other consequences, such as the potential for flooding of site buildings causing a common-mode loss of AC and DC power, were not considered when the need for mitigating actions was determined because of low confidence in the calculation results based on the hypothetical nature of the assumptions.

Senior managers directed that actions be taken to determine the validity of the trial calculations. The calculation approach was shared with JSCE in 2009, and that organization was asked to review the appropriateness of the wave source models and whether it would be appropriate to revise the standards. These questions were still under review by JSCE at the time of the March 2011 event.

TEPCO formed a countermeasures group in 2010 to determine possible actions to protect Daiichi from a large tsunami if JSCE established source models that produced similar calculation results. This group had not completed its work at the time of the March 2011 earthquake, but the recommendations that were under development focused on a

[2] The team found no facts to support reports of "tsunami stones" being located near the Daiichi or Daini sites. (The past maximum tsunami heights are said to have been marked with stones as a warning to future residents.) Some tsunami stones have been found in northeastern Japan in areas with indented coastlines where large tsunamis have occurred.

combination of methods to protect the seawater pumps from a very large tsunami. Interviews indicated that an in-depth safety analysis with plant walkdowns had not been conducted to fully understand the nuclear safety implications and that countermeasures to reduce the potential for the flooding of plant structures were not being considered.

The March 11, 2011 earthquake off the Fukushima coast was magnitude 9.0. The earthquake was larger in magnitude, involved more fault lines and source area, and was in a different location than had been assumed in any previous calculation or assessment. Approximately 41 minutes after the earthquake, a series of tsunamis struck the Daiichi site, with the tsunami height of approximately 15M (45 feet). The waves destroyed the seawater pumps, damaged external tanks and other facilities, and flooded the reactor and turbine buildings through ground-level doorways and ventilation louvers. Safety-related equipment—including emergency diesel generators, batteries, and switchgear— flooded, resulting in a complete loss of AC and DC power (Unit 3 retained limited DC power) and the ultimate heat sink. For TEPCO and the nuclear industry, the unexpected had occurred. Neither was fully prepared for the impact of this beyond-design-basis event.

Lesson Learned: Plant design features and operating procedures alone cannot completely mitigate the risk posed by a beyond-design-basis event. Additional preparations must be made to respond if such an event were to occur.

Over the years, TEPCO had implemented several changes to improve the ability to mitigate the risks of a core-damaging event. Examples are installing air-cooled diesel generators, modifying the plants to allow cross-connection of electrical buses and cooling water systems, adding fire engines for fire protection, and constructing seismically isolated buildings for use during emergency response. Many of these improvements were vital to the response efforts following the tsunami; however, they were not sufficient to prevent or fully mitigate the consequences of the event.

The strategies, equipment, and training required for a response to a beyond-design-basis event were not in place to build an additional layer of defense-in-depth in the face of a prolonged loss of AC and DC power. Many lessons learned in this report describe areas in which preparations for the unexpected should be considered. Examples are design and procedure changes to allow operators to perform vital actions when normal power and other services are not available; and sufficient staffing, facilities, procedures, and training to support emergency response activities if an event were to occur.

Lesson Learned: Corporate enterprise risk management processes should consider the risks associated with low-probability, high-consequence events that could lead to core damage and spread radioactive contamination outside the plant.

TEPCO's enterprise risk management process is similar to that used by many large corporations. Various threats are identified within the organization, are categorized based on the likelihood of occurrence and consequences, and are reviewed twice annually by a committee of key managers. While threats to generating and transmission facilities are included on the risk matrix, the focus is on the potential for the loss of generation capability, the disruption of electrical service, and the cost of equipment repairs. Some of the other risks that are considered to have low probability or low consequences are assumed to be sufficiently addressed by the processes and controls used within each division, even though they are not included in the risk management matrix.

The Nuclear Division did not add the threat of a nuclear accident caused by a large tsunami to the risk matrix because of the uncertainty over the assumptions and methodology. Furthermore, it was assumed that plant design features would mitigate this risk.

Based on lessons learned from the Fukushima Daiichi and Daini events, it is now recognized that low-probability, high-consequence threats need additional attention. For example, if questions regarding the adequacy of defenses against an environmental threat were to arise, TEPCO executives expect managers to include this information in their input to the risk management committee so that additional corporate executive attention can be given to monitoring how the risks are being mitigated.

4.2 Operational Response

4.2.1 Core Cooling

Lesson Learned: Ensure that, as the highest priority, core cooling status is clearly understood and that changes are controlled to ensure continuity of core cooling is maintained. If core cooling is uncertain, direct and timely action should be taken to establish conditions such that core cooling can be ensured.

One of the key differences between nuclear power and other forms of electric power generation is the need for continuous cooling after the reactor is shut down. It is imperative that core cooling be maintained under all conditions. Operators and emergency response decision-makers must have absolute certainty regarding the status of core cooling. For this reason, many organizations maintain a status board in each control room and emergency response center (ERC) to track the statuses of systems in use to provide core cooling and to show which systems are available as a defense-in-depth. This level of tracking and control was not provided during response to the Fukushima Daiichi event.

At Fukushima Daiichi, misunderstandings regarding the status and control of core cooling systems may have adversely affected decision-making and prioritization during the first few days of the event. A number of factors contributed to the misunderstandings, including lack of control room indications, lack of training on the isolation condenser system, an adverse work environment, the need to deal with emergencies at multiple units simultaneously, and that communications between the control room and the site ERC were restricted to two hotlines.

Fukushima Daiichi Unit 1

After the tsunami, the status of Unit 1 core cooling was not clearly communicated to all stakeholders, and the operational condition was not verified adequately. Prior to the tsunami, the isolation condensers (ICs) automatically initiated on increasing pressure in the reactor pressure vessel. Operators appropriately followed normal operating procedures and cycled the ICs in and out of service to prevent exceeding cooldown rate limitations. By design, the AC and DC motor-operated valves in the IC system could not be used for throttling flow because of seal-in control circuitry that only allowed them to be fully open or closed. At the time AC and DC power was lost, strip chart recordings examined as part of the event investigation show that the ICs were out of service; however, in the confusion that followed the loss of control room lighting, the discovery that the buildings were flooding, and the loss of control room indications, the operating crew was not sure of the system status.

Control room indications that would have allowed the status to be determined were unavailable. Initial actions included taking steps to restore reactor water level and containment pressure indications using temporary batteries and generators. Operators were also dispatched from the control room to verify IC status locally, but the lack of proper radiation protection equipment and personnel safety concerns caused by insufficient lighting, debris, and ongoing aftershocks prevented them from reaching the ICs. The IC exhaust pipes are not visible from the main control room, and operators requested that ERC assistance in determining the IC status. ERC personnel reported that steam was coming from the IC exhaust. (However, later information indicates that the ICs may not have actually been in service at this time.)

Containment isolation valves in the IC inlet and outlet lines are designed to close in the event of a steam line break. The design is such that an isolation signal is generated if DC control power is lost. Depending on the relative timing of AC and DC power losses, it is possible that some of the motor-operated valves that were open initially received isolation signals and may have at least partially closed following the tsunami.

About three hours after the loss of power, valve position indications for motor-operated valves in one train of the IC system illuminated briefly, and operators recognized that the valves indicated closed. An operator opened the valves in an attempt to place the IC in service. Operators saw steam coming from the IC exhaust, and the site and corporate ERCs were informed that the IC was operating. However, after a short time, steam was no longer visible. It remains unknown if the IC system was actually returned to service or if this was residual steam from earlier operation. Operators became concerned that condenser water level could be low and that there was a potential for tube rupture and radiological release. Therefore, they closed valves to isolate the system. Once the IC was secured, no method was available to remove decay heat from the reactor, and reactor water level remained unknown. By this point, TEPCO analyses conducted after the event indicate the fuel was likely exposed and core damage was occurring.

During the first few hours following the tsunami, some personnel in the site and corporate ERCs assumed one of the ICs was in operation and cooling the core. After control room operators closed isolation valves to remove the ICs from service as discussed above, this information was communicated to the operations desk in the site ERC. However, personnel did not clearly understand that the ICs were not in service; therefore, this was not communicated to senior managers in the site and corporate ERCs. Preparations were under way to augment core cooling using a diesel-driven fire pump. However, based on the incorrect assumption that the ICs were providing cooling, site

ERC personnel were more concerned with actions to provide core cooling for Unit 2 because the operating status of the Unit 2 reactor core isolation cooling system could not be verified. In fact, urgent attention was most needed for Unit 1.

Fukushima Daiichi Unit 2

Prior to the tsunami, reactor core isolation cooling (RCIC) was in operation on Unit 2; however, after the tsunami, operators were unsure of the status of RCIC and did not have indication of reactor water level. Adverse conditions in the field, including flooding, prevented operators from locally verifying the condition of RCIC. A few hours later, operators were able to check reactor pressure and RCIC pump discharge pressure on an instrument rack in the reactor building and verified that RCIC was in operation. Over the following day, conditions continued to degrade and the failure of RCIC was anticipated.

Efforts to prepare for depressurization and the use of low-pressure injection were under way, but aftershocks and evacuations hindered the ability of personnel to perform continuous fieldwork. In addition, a strategy had to be developed for depressurizing the reactor with a loss of AC and DC power. The hydrogen explosion in the Unit 3 reactor building damaged much of the equipment staged to vent the suppression chamber and to inject water with fire engines. About two hours after the explosion, reactor water level indications showed that RCIC was no longer operating and core injection was lost. At that time, workers had not completed installation of a new water injection line, and work to open a safety relief valve (SRV) and depressurize the reactor had not yet begun.

Fukushima Daiichi Unit 3

After the earthquake and tsunami, both high pressure coolant injection (HPCI) and RCIC were available for injection. Initially, RCIC was placed in service and remained in service until the following day, when the system unexpectedly shut down. One hour after the loss of RCIC injection, HPCI automatically initiated on low-low reactor water level.

HPCI remained in operation for several hours and was effective in reducing reactor pressure vessel (RPV) pressure and providing core cooling. Plans to use diesel fire pumps for injection after HPCI was shut down were discussed and agreed to by site ERC and control room personnel. However, the transition from HPCI to the diesel-driven fire pump was delayed because the fire system pressure was only about half of its normal value, indicating a problem somewhere in the system. With this degraded performance, fire system pressure was not high enough to inject water into the reactor vessel. Later, operations personnel decided to secure the HPCI system over a concern that the HPCI pump would be damaged because it was operating in the cavitation/vibration risk region, the turbine was slowing, and pump discharge pressure was essentially the same as the RPV pressure. The actions to secure the pump were consistent with operator training and procedures, and the pump may not have been providing any appreciable flow into the RPV. However, it is important to consider using a run-to-failure approach for safety system equipment if the equipment is needed to maintain a critical safety function (such as decay heat removal) under accident conditions.

At the time, reactor pressure was low but DC power was failing. This concern and the resulting decision to secure HPCI were discussed in the main control room and within the operations functional group in the site ERC. However, key decision-makers within the site ERC were not involved in these discussions and did not have an opportunity to provide input on how to best secure the pump and transition to low-pressure injection.

The ability to depressurize and inject using a low-pressure source was not verified before HPCI was secured. Operators believed they would be able to open the SRVs and depressurize the unit shortly after securing HPCI because the lamps for the SRVs were initially lit. However, it was later realized that SRVs could not be opened because of the loss of DC power. When HPCI was secured, reactor pressure quickly rose because the heat removal function of the system was lost, and injection with low-pressure systems was not possible.

Fukushima Daini

As stated earlier, tsunami damage at Fukushima Daini was less severe. AC and DC power were available, and plant parameters could be monitored in the control room and in the ERC. Nevertheless, damage to seawater pumps prevented heat removal from three of the four primary containment vessels, and timely action was needed to restore the heat removal capability.

Lesson Learned: Early in the response to an event, clear strategies for core cooling and recovery actions should be developed and communicated to control room and ERC personnel. In addition, leaders should establish clear priorities and provide direction and oversight to enable the strategy to be implemented effectively. After the tsunami, several actions by station and corporate personnel were effective in maintaining core cooling and establishing heat removal capability. These actions are summarized below.

- Senior site managers decided on a strategy that included depressurizing the reactors and providing core cooling using AC-powered makeup pumps. This strategy was clearly communicated to control room and ERC personnel.

- Some senior leaders had in-depth knowledge of the electrical distribution system, and these leaders worked with others to develop plans for replacing seawater pump motors and installing temporary cable to power the pumps from electrical distribution panels in other buildings not affected by the tsunami.

- The headquarters ERC took action to locate needed temporary generators, replacement seawater pump motors, and electrical cable and have these materials transported to the site quickly following the tsunami.

- Ongoing management monitoring and direction were provided to organize the workforce and supervise field activities.

- The station staff and contractor personnel worked under difficult conditions to complete installation of the motors and cabling and restored heat removal capability before pressures reached the point that required containment venting.

4.2.2 Containment Venting

Lesson Learned: Emergency and accident procedures should provide guidance to vent containment to maintain integrity, purge hydrogen, and support injection with low-pressure systems. Procedures should also provide guidance for performing venting under conditions such as loss of power and high radiation levels and high temperatures in areas where vent valves are located.

In general, primary containment vessel (PCV) venting strategies used by Japanese utilities since the 1980s are designed to delay venting as long as possible to avoid the release of radioactive materials. In keeping with this strategy, vent lines include rupture disks sized not to fail until containment pressure reaches the maximum operating value[3]. If fuel damage has occurred, accident management guidelines indicate that venting is warranted when pressure is expected to reach two times the maximum operating value, there is no prospect for the recovery of containment spray, and the water injection amount has not covered the torus vent line. Site superintendent permission is needed to vent the containment.

For comparison, U.S. BWRs typically do not have rupture disks that would prevent early venting, and emergency operating procedures require that venting be initiated before the containment design pressure is reached. If fuel damage has occurred, procedure guidance calls for earlier venting based on hydrogen concentration inside containment to reduce the potential for explosions inside the PCV. The decision to initiate venting is made by the shift manager, with consultation and advice from the site emergency response center.

For Japanese BWRs, procedure guidance to allow containment pressures to approach twice the established pressure limit before venting was developed considering results of containment integrity testing conducted by Sandia National Laboratories. (See NUREG/CR-6906/SAND2006-2274P published in July 2006.) The testing, using scale models, indicated that containment structures will not fail until pressures reach more than twice the rated value. Japanese utilities and reactor vendors also performed detailed calculations to verify that individual components could withstand similarly high pressures without failing. However, the likelihood of increased hydrogen leakage during periods with high containment pressure was not adequately addressed when the decision was made to adopt the strategy of delayed venting.

The Fukushima Daiichi accident shows the importance of taking action to prevent containment pressures from remaining high for prolonged periods. Leakage from the primary containment vessel led to accumulation of hydrogen and other gases in the secondary containments, causing explosions in units 1, 3, and 4. In addition, the effectiveness of low-pressure injection under accident conditions may be reduced. Therefore, procedure guidance should be in place to initiate venting earlier following a

[3] The maximum operating pressure is sometimes referred to in other countries as the containment design pressure.

fuel-damaging accident; and implementing procedures and necessary equipment must be in place to allow the actions to be taken even under unexpected conditions, such as the loss of AC/DC power and compressed air.

During the Fukushima event, factors such as loss of power and tsunami damage significantly hindered efforts to vent the containments. The site superintendent made the decision to vent the Unit 1 primary containment vessel around midnight on March 11 when instrumentation was restored and containment pressure was recognized as being high. Preparations to vent Unit 1 containment were begun; however, efforts required personnel to consult piping and instrumentation drawings, accident management procedures, and valve drawings to develop a procedure to operate the vent valves without power. A plan to manually vent the PCV was developed, but high dose rates in the torus room prevented operators from implementing this strategy. An approach to remotely open the vent valves was developed and implemented. Approximately 24 hours after event initiation, vent valves were opened and containment venting commenced. Prior to venting, indicated containment pressure had reached 122 psia (0.84MPa abs), approximately twice design pressure. The venting was closely followed by a hydrogen explosion within the reactor building.

Similar to Unit 1, preparations were made to vent Unit 2 when reactor water level could not be determined and the status of injection was unknown. These preparations included personnel developing a manual venting plan and reviewing the vent valve locations. Operators planned to manually open the vent valves while the dose in the area was low; however, when the vent lineup was completed, indicated containment pressure was lower than the pressure necessary to open the rupture disk and allow venting. As a result, the rupture disk remained intact and venting did not occur. The Unit 2 PCV was never vented successfully, even after containment pressure reached approximately 109 psia (750 kPa abs), which exceeded the rupture disk setpoint. Drywell pressure decreased the morning of March 15, indicating a probable breach of containment.

Preparations to vent Unit 3 were also made; however, initial attempts to vent the PCV were unsuccessful because of insufficient air pressure to open the air-operated vent valve. A temporary air cylinder was installed and the containment was vented several hours later, but not before containment pressure reached 92.4 psia (0.637 MPa abs).

A fire engine was relied on to provide core cooling for Unit 1 in the early morning hours of March 12 when pressure in the reactor and in containment equalized at approximately 122 psia (0.85 MPa abs). Similarly, fire engines were used beginning in the early evening of March 14 to provide injection to the Unit 2 core after RCIC failed and the reactor was vented to containment. Injection continued intermittently over the next 14 hours. Suppression chamber pressure was stable between 43 to 58 psia (0.3 to 0.4 MPa abs) during this period, but drywell pressure continued to increase, reaching 106 psia (0.73 MPa abs) by early morning.

TEPCO analyses indicate that the fire engines used at Fukushima Daiichi were capable of delivering sufficient cooling water flow to the reactor vessels even though reactor and containment pressures remained relatively high. However, diesel fire pumps installed in plant fire systems might not be capable of delivering sufficient flow under these conditions because of lower discharge pressures, possible elevation differences between the pumps and reactor vessels, and line losses associated with long piping runs.

4.3 Accident Response

Lesson Learned: Nuclear operators must establish the necessary infrastructure to respond effectively to severe accident conditions, mitigate core damage, and stabilize the units if core damage does occur. This infrastructure includes necessary personnel, equipment, training, and supporting procedures to respond to events that may affect multiple units, last for extended periods, and be initiated by beyond-design-basis events. Provisions should also be made to allow an effective corporate and industry response in support of the affected nuclear operating organization.

The earthquake and tsunami that affected Fukushima Daiichi resulted in damage that exceeded the station accident response capabilities. The station emergency response organization did not have the necessary equipment, procedures, and training to respond to such an event affecting multiple units.

Station workers exercised a great deal of initiative and ingenuity in stabilizing the units. This, combined with the bravery exhibited by several workers, prevented the accident from becoming much worse. A review of the actions taken to stabilize the units and the challenges faced by the workers revealed multiple learning opportunities for the nuclear industry. The following sections include lessons learned associated with establishing the necessary infrastructure for responding to a nuclear accident.

4.3.1 Staffing

Lesson Learned: Establish strategies for staffing operating crews, other key plant positions, and site and corporate emergency response organizations quickly in the initial stages of a multi-unit event and over the long duration of the event response.

A strategy is required to ensure that a station is staffed sufficiently in both the control room(s) and in the site and corporate ERCs to respond to a multi-unit, high-stress, long-duration event. This strategy should provide for rotation of personnel and for the appropriate number and skills of personnel needed to address severe accident response. The additional resources could include individuals who assist the shift and assistant shift supervisors in gathering information, monitoring critical parameters, and analyzing event progression.

Fortunately, the March 2011 tsunami occurred on the day shift during a normal workweek when many people were on site at Fukushima Daiichi and Daini. The resources normally present during backshifts and weekends would not have been sufficient to respond in the first few hours following the event. In recognition of this limitation, TEPCO has decided to ensure 40 to 50 additional personnel are available to support operating crews on all shifts. These on-shift resources include individuals with maintenance and radiation protection experience to provide support to the operating crew if an emergency condition were to occur.

When the earthquake and tsunami occurred, the Fukushima Daiichi emergency response organization was immediately responsible for the safety of approximately 6,800 site workers and for stabilizing six units that were in varying states of emergency. At the same time, the corporate ERC was providing support to the four units at Fukushima Daini that had also experienced damage from the tsunamis, requiring implementation of accident management procedures. The corporate and station structure and staffing were not designed to support the number of units that may be affected by a common-cause event.

Operations staffing at Fukushima Daiichi was not sufficient to support multiple days of accident response for multiple units. Shift operators remained on duty for three days without sleep, and in many cases without knowing the statuses of their families. In addition, personnel within the ERC remained in their roles for multiple weeks, with limited breaks. Interviews with station managers who were in the ERC revealed that some of them were awake and responding to the event for as long as 36 hours before they began to lose consciousness in their chairs. Some managers spent multiple weeks in the ERC before leaving the building for the first time—and then they only left for a shower and a meal before returning to the ERC. The physical demands of fieldwork moving wreckage and installing temporary hoses and cables also took its toll on the workforce, and the Japan Self-Defense Force stepped in to help provide needed resources. There was no predefined structure for providing sufficient staffing, turnover, and support in response to extended-duration events.

Site and corporate emergency response organizations need to include individuals with the operations knowledge and experience to support operational decision-making and with the engineering knowledge and experience to support transient analysis. In addition, emergency response personnel need to have access to others (such as radiation protection specialists and reactor vendor and architect engineering personnel) who have specialized knowledge and experience that may be needed during the accident response.

4.3.2 Human Limitations

Lesson Learned: Establish contingency plans, training, and guidance to help personnel cope with the emotional concerns that can impact decision-making and reduce personnel effectiveness during a natural disaster or nuclear accident.

The impact of a high-stress, long-duration event on personnel well-being, morale, and decision-making capability must be recognized and barriers put in place to mitigate the effects of this impact. An individual interviewed was quoted as saying, “It was dark in the main control room and at the site, and I was full of anxiety about whether or not my family was safe and if the outside condition was okay.” Another interviewee stated, “When I could not leave the main control room as the radiation dose started to increase by 0.01 mSv (1 mrem) per 3 seconds, I thought it was the end of my life.” There were no contingency plans to help workers deal with the radiation concerns, and the internet- and telephone-based system established to help identify the location and condition of family members was unavailable because of the power loss across the region.

Immediately following the earthquake and tsunami, one supervisor stated he knew he must urgently dispatch an operator to the reactor building to check on the status of the isolation condensers. Because of the power loss and ongoing aftershocks, he recognized that this was a life-and-death decision and that he was not prepared to make this assignment.

In general, emergency response training across the industry does not include exercises in which individuals must make decisions and provide direction to others under circumstances such as those described above. With this type of training, individuals would likely be better prepared to make the correct decisions if required.

4.3.3 Emergency Preparedness

Lesson Learned: Ensure primary and alternative methods for monitoring critical plant parameters and emergency response functions are available. Use drills and exercises to ensure emergency response personnel are able to use the available monitoring tools and methods.

Following the earthquake and tsunami, several indications were lost, including the safety parameter display system (SPDS). The station ERC expected to use SPDS for certain critical functions, including determining off-site releases and tracking the status of critical safety functions such as core cooling. Personnel did not train without SPDS available and did not have a contingency plan to restore these functions if SPDS was unavailable. This resulted in significant challenges in tracking the status of core cooling and determining off-site releases during containment venting.

The loss of information regarding spent fuel level and temperature and dose rates both on and off site also created confusion and added to the challenges the ERC staff was addressing. For example, considerable effort was expended to deliver water to the spent fuel pools following building explosions. Because the integrity of the pools was in doubt and levels could not be monitored, considerable resources were devoted to deliver water to the pools using helicopters, fire trucks, and other equipment. Had it been possible to monitor spent fuel pool parameters remotely, many of these efforts could have been avoided.

Lesson Learned: On-site and off-site facilities necessary for coordinating emergency response activities should be designed and equipped to remain functional in the event of a natural disaster and/or a nuclear emergency.

The off-site center, which was meant to play a critical role in coordinating TEPCO and government activities, did not function as designed. The center was never fully staffed because representatives from the various organizations had difficulty traveling to the area because of earthquake and tsunami damage. Normal power was lost, and the backup power source also failed. In addition, the facility was not designed with filtered ventilation, and it had to be abandoned as dose rates and contamination levels increased.

There were no contingency plans for relocating the off-site center or for other actions to take if the center were unavailable. In the first few days following the event, various coordination activities normally performed at the off-site center were conducted at TEPCO headquarters and at the national government offices. This added to the workload of the headquarters ERC staff and reduced the effectiveness of communications between the utility and local and national government agencies.

The site ERC was housed in a new building designed to withstand earthquakes and equipped with backup power and filtered ventilation. The building, which is commonly referred to as the seismically isolated building, was built as a corrective action following a 2007 earthquake that damaged the emergency response facilities at TEPCO's Kashiwazaki Kariwa station. After the Fukushima earthquake and tsunami, the seismically isolated building was one of the few administrative buildings at Fukushima Daiichi that was still functional. The emergency response center remains the central location on site for command and control, and the building continues to provide critical shelter from radiological hazards. Without the seismically isolated building, the ability of the station staff to coordinate and manage response activities would have been impeded significantly, and internal radiation exposure and the number of personnel contamination events would have been considerably higher.

Although the seismically isolated building greatly contributed to the ability to address these events, the building was not designed or prepared for the large number of workers who essentially lived in this building during the event response. Shortfalls included insufficient food, water, toilets, showers, and sleeping space. In addition, entry doors did not include an airlock area, and the building had carpeted floors. As a result, it was impossible to prevent contamination from entering as workers entered and exited the building. The carpet was eventually removed because it became contaminated.

Lesson Learned: Ensure those who possess the expertise to operate specialized accident response equipment are available and are prepared to respond to a severe accident. This may be accomplished through contracts or by training and qualifying members of the station emergency response staff to perform these functions.

Similar to several nuclear utilities, TEPCO relied on contractor companies to fulfill a number of routine tasks, ranging from performing plant maintenance activities to providing diesel fuel deliveries to the station. As a result, TEPCO had to request assistance from contractors or train station personnel to perform the required activities during the event. Agreements for contractor support during a nuclear emergency were in place but were not effective in reducing the burden and distraction of having to make additional arrangements during the accident response.

Immediately following the earthquake and tsunami, contractors were asked to operate heavy equipment to repair roads and to assist in removing tsunami debris. Contractors were also providing assistance in operating the mobile generators and fire engines needed to support the accident response. As radiological conditions degraded, however, contract workers were sometimes not willing to provide support near the damaged units.

To overcome this, TEPCO had to provide and train workers to fulfill some critical accident response functions. For example, station workers had to be trained on how to use fire engines to support injection into the reactors and on how to operate some of the mobile generators used to restore electricity. TEPCO workers had to learn to operate fuel tankers to maintain a steady fuel supply for the seismically isolated building emergency generator, which consumed approximately two tanker trucks of fuel per day.

Additionally, station workers were not trained to perform some critical restoration tasks, such as cable splicing and terminations, because contractors were relied on for these tasks. Few contractors possessed the required knowledge and skills. This restricted recovery actions and placed increased the burden on a small number of skilled individuals.

4.3.4 Roles and Responsibilities

Lesson Learned: Clearly define and communicate the roles and responsibilities of emergency response personnel to help ensure effective post-accident communications and decision-making.

A command-and-control structure and the roles and responsibilities assigned to control room, site ERC, headquarters ERC, and government agency personnel did not function as planned during this complex, long-duration, multi-unit event.

Responsibility for overall response management at Fukushima Daiichi was assigned to the site superintendent, in collaboration with the Operations Department general manager, shift supervisors, and assistant shift supervisors. Certain high-level decisions, such as determining relative priorities for recovery actions and deciding when to vent containment, were the responsibility of the site superintendent. However, the severe accident management approach assigned most decision-making responsibilities to the control room crew based on the assumption that crewmembers could make the decisions necessary to implement emergency and accident management procedures.

This decision-making approach did not provide for independent challenge or second checks by other groups within the organization. For example, the site ERC did not independently review and provide feedback prior to decisions by the control room staff to isolate the Unit 1 isolation condensers or to stop the Unit 3 HPCI pump. In addition, while the corporate ERC helped develop plans and strategies, provided advice, and assisted in obtaining needed equipment and support, this group did not view its role as providing independent oversight of site decisions or actions.

During a complex event, designating an independent communicator to share information and respond to external questions could minimize distractions to shift supervisors and ensure an accurate and continuous flow of timely information. This approach could allow shift supervisors to focus on overseeing the operating crew.

Control room crews did not include an individual dedicated to maintaining an independent view of critical safety functions and advising control room management on courses of action to ensure core cooling, inventory control, and containment pressure control were maintained and optimized. In some countries, operating crews include an individual with engineering expertise and training in accident sequences and accident management to provide additional defense-in-depth if an event were to occur. The need for such a “shift technical advisor” was one of the lessons learned from the Three Mile Island Nuclear Station accident.

4.3.5 Communications

Lesson Learned: Communication methods and equipment should support accurate and timely information exchange, consistent and clear communications with the public, and information-sharing between the utility and the government.

Multiple, diverse means of communication are required to ensure an ongoing flow of information that supports maintaining an accurate status of plant conditions. These means should allow for ongoing communication between the main control room and the emergency response organization and continuous contact between field workers and the main control room.

At Fukushima Daiichi, the ability to communicate among the field, the site ERC, and the main control room was extremely limited and hindered worker safety and the rapid flow of accurate information during the event. Normal communications equipment was lost as a result of the tsunami and subsequent loss of power. Backup communications equipment was available, but in some instances only the two hotlines could be used to communicate between each main control room and the site ERC.

A strategy and the infrastructure to receive, organize, and share the enormous amount of information provided during a long-duration, multi-unit event are also needed. For example, one individual stated that those around the table in the site ERC were so overloaded and fatigued that they thought they could not go on. Difficulties with the flow and accuracy of information shared between the site and the corporate ERC also impeded the ability of headquarters personnel to fully grasp what was happening at the site. Procedures, information organizing methods, and communications protocols must be developed and used periodically as part of personnel training.

Redundant means to communicate a unified message to the public need to be developed to ensure consistency in information communicated at the national, local, and utility level. Additional strategies are required to clearly communicate imminent evacuations and releases. Because the off-site center was inside the evacuation zone, it could not function as the press center. Initially, press conferences were held separately (in parallel at TEPCO, the central government, and the local government). This changed later, and joint conferences were held between TEPCO and the government in Tokyo to ensure consistency in their messages.

Multiple, timely methods are needed to communicate information between the utility and the government agencies. In addition, a strategy must be in place to address questions and requests from the government without burdening the control room staff. During the initial stages of the Fukushima Daiichi event, very little information was available; and the information that did reach the Prime Minister’s office from the Minister of Economy, Trade and Industry and TEPCO headquarters was not sufficient to allow the plant status and recovery actions to be understood. As a result, the Prime Minister's staff found it necessary to contact the site superintendent to gather information during the emergency.

4.3.6 Radiation Protection

Lesson Learned: Radiation protection (RP) personnel must have established procedures, equipment, and staffing to support emergency response actions.

Radiation protection equipment and instrumentation should be stored in diverse locations, be protected from damage by initiating events, and be easily accessible for response personnel, especially the operators in the main control rooms. Shortages in RP equipment and staffing resulted in significant challenges during the critical first few hours of the event response. The majority of the RP equipment, including alarm pocket dosimeters (APDs) and protective equipment, was destroyed by the tsunami. Furthermore, respirators and other protective equipment were not stored in the main control room, and control room operators did not typically wear dosimetry. As a result, operators were unsuccessful in their initial attempts to enter the Unit 1 reactor building without protective equipment and using a contamination meter to estimate dose rates.

Sufficient emergency-response-related equipment should be stockpiled to support the large number of workers who may be required following an event. The station had enough pre-staged emergency response equipment to support the minimum emergency response organization staffing, which was approximately 50 people. However, more than 500 people were involved in the initial event response.

When AC power was lost at the site, the computers used to update radiation dose records were lost. In addition, it was necessary to manually reset APDs to zero readings before the devices were given to the next users, and some workers did not reset the devices. A manual system was used to record and track dose, but this method resulted in many errors in the worker dose database. The errors required significant effort to correct to ensure that doses were assigned to site personnel properly. Later, a barcode reader was employed to record worker dose, resulting in fewer errors.

Lesson Learned: Station emergency response plans should allow for prompt RP support of operator actions needed to establish or maintain safe shutdown and should include the needed flexibility to support such actions.

Station evacuation plans should consider the need for radiation protection technicians and other personnel to support operations following an initiating event. At Fukushima Daiichi, RP technicians gathered in the assembly area following the earthquake to survey the workers who had evacuated the site. The technicians were held in the accountability area until the tsunami flooding had receded and further tsunami warnings had elapsed. This resulted in a lack of RP support during the critical first few hours of the event. A possible solution would be to assign RP personnel to the emergency response organization to ensure they are available in the early stages of an event. Alternatively, operators could be trained and provided with needed equipment to monitor their own dose and perform surveys under accident conditions.

Lesson Learned: Dose limits should allow some flexibility such that required actions can be performed during accident situations. In addition, workers should be trained or briefed on the relative risk of higher acute radiation doses.

Limits on radiation dose did not allow flexibility in the event response. While a 10 rem (100 mSv) dose limit had been established for all site workers before the accident, there was no guidance for exceeding this limit if needed. This limited the ability of operators to access containment vent valves and directly contributed to containment remaining at elevated pressures for an extended time, which also restricted injection into the reactors. Shortly after the accident, the government changed the emergency dose limit to 25 rem (250 mSv). This change was not well communicated to the workers, contributing to some loss of trust between the workers, management, and the government.

TEPCO stated that all workers were trained on the biological effects of radiation exposure greater than 10 rem (100 mSv). However, site workers were not briefed on the risks when normal exposure limits were increased after fuel damage resulted in higher-than-normal dose rates in areas of the plant that needed to be accessed during the early stages of the accident. Accurate and timely communication of such risks is key to obtaining informed and knowledgeable volunteers for work in very high radiation areas that could involve doses beyond normal occupational exposure limits.

4.3.7 Off-Site Support

Lesson Learned: Off-site resources and support should be provided on a priority basis following significant events such a loss of off-site power. Emergency response plans and other corporate guiding documents should clearly state that the needs of nuclear stations are to be given highest priority in the event of an emergency situation.

The TEPCO corporate organization responded aggressively to provide the equipment and resources needed at Fukushima Daiichi and Daini. Other nuclear operating organizations should be prepared to provide similar support during a plant event. For example, at Fukushima Daiichi, the loss of all off-site and most on-site power was immediately recognized at headquarters as requiring urgent action. Corporate resources were used to locate and arrange transportation of temporary emergency generators and cable from within TEPCO and from other utilities in neighboring service areas.

Fukushima Daini also had an urgent need for replacement motors for seawater pumps that were damaged by the tsunami. A large amount of electrical cable was also needed to provide temporary power for these motors from operable switchgear in another building. Corporate procurement personnel located motors at the Toshiba factory and at the Kashiwazaki Kariwa Nuclear Power Station, identified a source of the needed cable, and arranged for expedited transportation to the site.

The corporate Transmission and Distribution Department worked on a priority basis to reestablish off-site power to the Daiichi and Daini sites. For example, a second transmission line was restored at Fukushima Daini within about 36 hours, even with the significant damage across the transmission system.

Several days elapsed before nuclear industry technical support and assistance could be organized and factored into recovery efforts. The domestic nuclear industry in Japan and international nuclear plant operators and vendors did not have plans or the infrastructure needed to offer support, and TEPCO personnel were fully engaged in the event response and were not prepared to receive assistance when it was offered. After the significance of the event became apparent, an effort by nuclear plant operators and vendors was organized internationally, and representatives from these organizations began arriving to coordinate assistance efforts. Response to future events would be enhanced if agreements and plans were established in advance at the regional and international level to facilitate obtaining industry support in a more timely and effective manner.

4.4 Design and Equipment

Lesson Learned: Equipment required to respond to a long-term loss of all AC and DC power and loss of the ultimate heat sink should be conveniently staged, protected, and maintained such that it is always ready for use if needed.

This event revealed the need to have equipment and methods developed in advance to allow critical tasks to be performed under emergency conditions, including beyond-design-basis conditions such as total loss of AC and DC power. The following are some of the specific equipment needs identified during the Fukushima Daiichi and Daini events:

- Procedures and equipment are needed to allow operators to monitor key parameters locally and to manually perform critical actions in the field concurrent with a loss of all AC and DC power (including loss of compressed air). Mechanical pressure, differential pressure, and temperature monitors for key parameters and power carts and equipment to locally operate key valves and other components were not installed in the plant.

- Independent battery-powered emergency lights in the main control room and key building walkways are needed in the event that normal AC power and DC power are lost. At Fukushima Daiichi, emergency lighting was powered by station batteries, resulting in a total loss of lighting in Unit 1 when the batteries flooded. The station did not use independent battery-powered lighting for main control rooms and safe-shutdown pathways. Flashlights and batteries also need to be available for use by operators and others.

- Radios with battery-powered repeaters or other communications equipment that will remain operable following a loss of power need to be available. During the event, the ability to communicate between the field, the site ERC, and the main control room was extremely limited and adversely affected worker safety, the rapid flow of accurate information during the event, and event response.

- Supplies of fuel and other consumables must be available and accessible to allow continued operation of temporary and permanently installed equipment needed during accident response. During the response to this event, portable air compressors, diesel-driven generators and pumps, fire trucks, and various batteries (including those removed from cars in the parking lot) were used. The emergency generators in the seismically isolated building also required refueling and maintenance.

Lesson Learned: Plant modifications may be needed to ensure critical safety functions can be maintained during a multi-unit event that involves extended loss of AC power, DC power, and the ultimate heat sink.

- The need for automatic isolation circuitry that could render important safety systems inoperable should be reevaluated. During the Fukushima Daiichi event, loss of DC power to the isolation logic triggered automatic closure signals to the Unit 1 isolation condenser inlet and outlet valves. The outboard DC-powered, motor-operated valves apparently closed before all DC power was lost or when power was partially restored. The inboard AC-powered, motor-operated valves may have partially closed before AC power was lost, potentially restricting flow through the condensers. Because of degrading conditions in the reactor building, operators could not access the valves for manual operation. Similar isolation logic may exist for other systems, including RCIC and HPCI. The consequences of automatic safety system isolation during an event are such that protective circuitry may not be the best option to protect against other postulated events, such as a high energy line break.

- Plant designs should consider installation of air-cooled emergency diesel generators and cross-connections between units to allow sharing of AC and DC power, fresh- and seawater, and compressed air systems during emergencies. The ability to cross-connect mechanical systems and electrical power between units at Fukushima Daiichi units 5 and 6 and Fukushima Daini greatly improved the operator response following the tsunami.

- Plant designs should support timely venting of primary containment even with a loss of power and motive force, such as compressed air. The success path for units 1, 2, and 3 was to depressurize the reactor pressure vessel (RPV) to the primary containment to remove decay heat from the fuel and to permit low-pressure water injection into the core. As containment pressure increased, venting through the hardened vent was required. However, without power or compressed air, it took several hours and work under very hazardous conditions to open the vent valves, and operators were not able to vent Unit 2. In addition, rupture disc settings (1.2 times primary containment pressure) were so high that it was not possible to vent without first exceeding the design pressure.

- The installation of passive hydrogen recombiners in containments could help prevent the buildup of hydrogen during an accident. In addition, the installation of manual vents in each reactor building may be prudent to allow venting of any hydrogen that may have accumulated.

4.5 Procedures

Lesson Learned: Optimum accident management strategies and associated implementing procedures (such as emergency operating procedures and accident management guidelines) should be developed through communications, engagement, and exchange of information among nuclear power plant operating organizations and reactor vendors. Decisions to deviate from these strategies and procedures should be made only after rigorous technical and independent safety reviews that consider the basis of the original standard and the potential unintended consequences.

International collaboration and sharing to identify optimum strategies and procedure guidance are clearly needed, taking into account the lessons learned from the Fukushima events and the need to be prepared for other beyond-design-basis event types.

In the 1980s and afterward, Japanese utilities and vendors made decisions to deviate from accident management strategies developed by the U.S. BWR Owners Group. These decisions were based on results of technical analyses and differing views on the relative risks of different strategies. For example, the Japanese approach to containment venting differs from U.S. BWR Owners Group guidance in that, if fuel damage has occurred, venting is not performed unless primary containment vessel pressure is expected to approach twice the maximum operating value. This deviation from the owners group strategy of early venting was made to prevent early release of radioactive materials, including noble gasses.

Procedures directed that the flammability control system be used for hydrogen control to reduce the potential for explosions; however, this system was not operable because power was unavailable. Other approaches such as venting the PCV to remove hydrogen were not covered in emergency operating procedures (EOPs) or accident management (AM) guidelines. Procedures available at BWRs in other countries allow hydrogen from primary containment to be vented to the atmosphere at lower containment pressures. In addition to increasing the potential for hydrogen explosions in the PCV, delaying venting likely increases hydrogen leakage into the reactor buildings (such as through the drywell gaskets that are susceptible to leakage at higher pressures), reduces the amount of low pressure water that can be injected into the reactor cores, reduces and delays release of decay heat into the atmosphere, and increases the potential for primary containment damage with corresponding increased leakage.

TEPCO EOP and AM guidelines were sufficient to support response to the loss of heat removal capability at Fukushima Daini. However, implementing-level procedures did not exist to address how to accomplish actions, such as reducing RPV pressure and venting containment, under the situation at Fukushima Daiichi in which all power (including compressed air) and indications were lost. This contributed to the delay in implementing actions to depressurize the RPVs and vent the primary containments.

Procedures were developed based on the assumption that a loss of all AC power would not last for more than 30 minutes and that the coping time could be extended up to eight hours using station batteries. This assumption was based on the multiple off-site transmission lines, the availability of backup diesel generators, and extensive features to cross-tie and share electrical power sources among the units. In retrospect, the lack of contingencies to address a longer loss of AC power, together with the lack of extensive damage mitigation guidelines, resulted in the station having no planned alternatives for local operation of equipment necessary to maintain critical safety functions.

Procedures did not exist to facilitate the transition from normal work rules for personnel safety and dose reduction to accident conditions in which higher dose rates and more hazardous conditions were present. As a result, several attempted entries into the Unit 1 reactor building were aborted because of concerns regarding personnel safety or unexpected radiological conditions. Some of these aborted entries had to be performed later under significantly worse conditions. The net effect was increased worker dose and safety risk, as well as delays in preparations for tasks such as venting the primary containment.

Procedures were needed to verify Unit 1 isolation condenser and Unit 2 RCIC operation, line up alternate low pressure injections, and supply temporary power to open safety relief valves and primary containment vent valves. In addition, procedures were needed to compensate for the loss of control room indications and the safety parameter display system, which inhibited the ability to plan for timely responses and may have contributed to decision-making delays. No procedures accounted for widespread loss of equipment, communications, and indications, thereby complicating the response to multi-unit events.

Lesson Learned: Conditions during and following a natural disaster or an internal plant event may significantly impede and delay the ability of plant operators and others to respond and take needed actions. The potential for such delays should be considered when procedures and plans for time-sensitive operator actions are being established.

During the Fukushima Daiichi and Daini events, recurring earthquakes and tsunami warnings prevented operations personnel and others from going into the plant to conduct inspections and verify equipment status for an extended time following the initial tsunami. At Daiichi, loss of power and lighting—and, later, damage from the hydrogen explosions—also greatly hampered recovery efforts. Examples are provided below.

- Earthquakes continued to occur, with more than 300 earthquakes of magnitude 5.0 or greater recorded in the hours and days following the event. Tsunami warnings were also issued for several hours, and many tsunamis eventually struck the site. Under these conditions, it was unsafe for operators to leave the control rooms, and the workers who had been evacuated to higher ground were not allowed to return for several hours because of personnel safety concerns.

- At Daini, unsafe conditions resulted in operators being restricted from going into the plant for about two hours following the initial tsunami, and some damaged areas of the plant could not be accessed for up to six hours.

- At Daiichi, most of the operating crew reported to the control rooms after tsunami warnings were issued. When the blackout occurred, they spent time locating flashlights and trying to assess the extent of the power losses. They were not aware of what caused the loss of the emergency diesel generators and that tsunamis had arrived until a field operator entered the control room with wet clothing and reported that the lower elevations were filling with water.

Later, when operators and others were allowed into the plant, the loss of normal lighting, the debris, and the displaced materials in walkways made movement within buildings hazardous. Lower elevations were also partially flooded, preventing operators from reaching key equipment to confirm the status.

- Earthquake damage to roads, debris from the hydrogen explosions, and increased dose rates and contamination levels created hazardous conditions and significantly slowed recovery efforts.

4.6 Knowledge and Skills

Lesson Learned: On-shift personnel and on- and off-site emergency responders need to have in-depth accident management knowledge and skills to respond to severe accidents effectively. Training materials should be developed and training should be implemented using the systematic approach to training.

Because the event went well beyond existing procedures and previous experience, mastery of reactor and power plant fundamentals, as appropriate to the job position, was essential for sound decisions and effective actions. Many of the actions taken at the Daiichi and Daini sites indicate that the personnel possessed the needed level of knowledge and skills. However, improvement opportunities were identified as operators and emergency response personnel reacted to the impact of the tsunami. Most of the knowledge weaknesses can be traced to training materials and practices that were not developed using the systematic approach to training process.

As part of its post-accident assessment, utility management concluded that emergency plan training had not been sufficiently realistic to address the situations experienced during the event. For example, training on simultaneous casualties at multiple units had not been conducted. Emergency plan drills did not periodically challenge responders by removing information sources (such as the safety parameter display system), equipment, and facilities that might not always be available to them. Drills did not purposely include sources of inaccurate or miscommunicated information to ERC personnel as a way to exercise their questioning attitude, teamwork, and diagnostic skills.

Accident management training was conducted through computer-based learning. Although the training material was sufficiently broad in scope, it lacked the depth and level of detail needed to create a questioning attitude for critical parameter assessment, including recognition of instrumentation limitations in accident environments. For example, training materials did not provide details on the fundamentals of reference leg flashing on RPV level indication. Reliance on the computer-based training setting and on infrequent refresher training (every three years) creates vulnerabilities in knowledge retention and depth of understanding.

Both the site and headquarters ERC technical team members are responsible for performing calculations to compare observed plant response with predicted plant response. They received no specific training for these tasks.

After the loss of AC and DC power and pressure and level indications, shortfalls in detailed knowledge regarding the isolation condenser (IC) system may have contributed to personnel having difficulties diagnosing whether the system was operating properly. Few personnel had operated the system or seen it in operation. Some of the knowledge shortfalls and contributing factors are described below.

- Some response personnel were not aware that the AC-powered inboard isolation valves and the DC-powered outboard isolation valves would close on the loss of power to the DC logic system. Furthermore, some control room operators did not understand that the condenser tanks had sufficient water, without makeup, for about 10 hours of operation. The shift supervisor was aware of the tank capacities and communicated this information to the operating crew but agreed with the crew recommendation to isolate the IC when steam was no longer visible from the exhaust. The decision was made because of a concern that there might be insufficient cooling water for some unknown reason and that operation of the system without cooling water could lead to damage to the IC internals, allowing a pathway for reactor coolant to be released to the environment.

- Operators at Fukushima Daiichi Unit 1 were trained at the BWR Training Center using the Unit 4 plant-referenced simulator, which is a different design that does not contain the IC system. Additionally, when simulator training is conducted, Unit 4 blackout procedures are used. Other training occurred at the Daini site simulator, which models Daini Unit 2.

  Unit 1 operator training on the IC system relies heavily on classroom and on-the-job training. The review team concluded that the level of detail in system training materials does not support the depth of knowledge needed to understand IC system response to a loss of DC power.

  While it is not clear that the isolation condenser could have been placed in operation following the station blackout and loss of DC electrical power, uncertainty over the operating status of the system contributed to priority-setting and decision-making that were not based on accurate plant status. (Note that operator training on a vendor’s control room simulator that differed in certain significant ways from the actual control console was one of the contributing factors to the 1979 accident at Three Mile Island Nuclear Station.)

- Operators had limited experience actually operating the IC system. The IC system valves were tested periodically, but a 25-year-veteran shift supervisor stated that he had never seen the IC system in operation and believed it had not been operated during his career.

4.7 Operating Experience

Lesson Learned: Actively participate and make best use of operating experience information shared in international organizations and forums.

Active participation in international owners group activities and other forums may have helped TEPCO and other Japanese utilities become aware of alternatives to their emergency response and accident management strategies. In addition, any discussions of Japanese approaches to accident management and other topics in these forums may have raised questions or provided for constructive challenge by those with diverse viewpoints and perspectives. Utilities outside of Japan would also have benefitted from operating experience that Japanese utilities could provide.

Lesson Learned: When considering the applicability of significant operating experience from international events, go beyond the event causes and transient initiators and consider the potential to experience the same consequences through other means. Take timely action to strengthen defenses to such vulnerabilities.

TEPCO took extensive action at all of its plants to address lessons learned from the company's own operating experience following a large earthquake at Kashiwazaki Kariwa Nuclear Power Station in 2007. Seismically isolated buildings were constructed at each station, firefighting systems were improved, and modifications were installed to allow fire engines to be used as an alternate injection source to the reactor. Enhancements to site evacuation plans following the 2007 earthquake were instrumental in successfully evacuating about 6,700 workers from the six units at Fukushima Daiichi. These improvements, most notably the seismically isolated building, were vital to the response efforts following the tsunami.

In contrast, opportunities were missed to improve the ability to withstand flooding and to improve emergency response based on international operating experience. In interviews, managers stated that if the direct causes of events described in operating experience reports were considered not to be present at TEPCO stations, the reports were screened as no action needed. They stated that, in hindsight, TEPCO and others would benefit from a broader use of operating experience reports. For example, even if management believes the organization could not experience an event with the same causes that occurred elsewhere, consideration should be given to what other factors could result in the same consequences. The following is an example of how this broader mind-set could have been used to strengthen defenses based on international operating experience:

> The flooding that rendered all trains of low pressure safety injection and containment spray inoperable for two of the four units at Blayais Nuclear Power Plant in France was caused by unanalyzed wind and river conditions. The World Association of Nuclear Operators issued two reports describing the lessons learned from Blayais, including one report with specific recommendations for consideration by all nuclear operating organizations. Fukushima Daiichi personnel did not consider these reports to be applicable to their site because the units are on an ocean and high winds had already been analyzed and bounded by the design basis and regulatory requirements.

Had the consequences of the Blayais flooding been considered and a broader approach used during reviews, the Blayais corrective actions—such as modification of cable galleries and electrical penetrations to improve resistance to flooding and the addition of water-tight doors to halt the ingress of floodwater—might have been considered for implementation even at Fukushima.

4.8 Nuclear Safety Culture

Lesson Learned: Behaviors prior to and during the Fukushima Daiichi event revealed the need to strengthen several aspects of nuclear safety culture. It would be beneficial for all nuclear operating organizations to examine their own practices and behaviors in light of this event and use case studies or other approaches to heighten awareness of safety culture principles and attributes.

History has shown that accidents and their precursors at commercial nuclear electric generating stations result from a series of decisions and actions that reflect flaws in the shared assumptions, values, and beliefs of the operating organization. For example, the Three Mile Island accident involved flawed assumptions about the importance of preventing the pressurizer from completely filling, resulting in operators shutting off safety injection pumps needed for core cooling. The Chernobyl accident involved a lack of appreciation for the unique aspects of nuclear technology (particularly reactivity control) and of the importance of operating the plant in accordance with its design basis and operating procedures, resulting in decisions to disable important safety systems to perform a special test. At Davis-Besse Nuclear Power Station, a flawed assumption that dry boric acid would not corrode the reactor vessel head contributed to wastage of the head material.

TEPCO actions over the past 10 years served to strengthen several aspects of the organization's nuclear safety culture. After an issue with records falsification was discovered in 2002, TEPCO leaders strengthened management processes and controls; for example, by adopting a corrective action program and a quality management system. In 2008, TEPCO developed a set of safety culture principles based on the principles and attributes used by the World Association of Nuclear Operators. Additional practices were also put in place to promote and monitor nuclear safety culture. These practices include the following:

- "Alert" reports are issued to share safety culture implications learned from the events.
- If a problem reported in the corrective action program has safety culture implications, actions are taken to communicate the issue widely.
- Each year, a safety seminar is held, with external expert participation.
- A safety culture performance indicator is used to track the trend of safety culture.
- An employee safety culture survey is conducted annually.

- The chief reactor engineer on each site provides an annual assessment on the state of safety culture for each principle.

Although these and other actions served to strengthen nuclear safety culture, the Fukushima event revealed several aspects of a healthy safety culture that require additional attention. It is likely that other nuclear organizations would also benefit from a close examination and discussion of their own cultures in these areas. The following nuclear safety culture principles and associated questions may be helpful in facilitating these discussions:

- An important nuclear safety culture principle is cultivating a questioning attitude and challenging assumptions. In retrospect, TEPCO would have benefited from additional questioning and challenging of the assumption that a large tsunami capable of flooding the plant could not occur. Additionally, questioning and challenging of assumptions may have helped maintain core cooling during the Fukushima event when communications were difficult and reliable information on plant parameters was unavailable.

  How does your organization avoid “group think” or accepting unverified assumptions when making decisions that could affect nuclear safety?

  How would your organization provide the needed level of questioning and challenging of assumptions so that continuity of core cooling and containment integrity are ensured during a complex event?

  What additional approaches are used during an event when important decisions must be made relatively quickly?

  When discussing issues that could affect plant safety or reliability, how effective is your organization in asking, “What is the worst that could happen?”

- Closely associated with the questioning attitude principle is the need for decision-making to reflect a safety-first mind-set. TEPCO worked to improve the accuracy of tsunami calculations over several years. However, when results using postulated assumptions based on incomplete data showed tsunami heights significantly greater than those determined using the JSCE standards, the issue was referred to others for review without a full examination of the potential consequences and without compensatory actions or countermeasures being established. Other organizations faced with similar situations involving incomplete or inconclusive information would benefit from a more rigorous review of the nuclear safety implications.

  How rigorous are your approaches for problem-solving, determining nuclear safety implications, and taking conservative actions when information is incomplete or inconclusive and the potential consequences of a situation are not fully understood?

How does your organization promote a sense of ownership for resolving potential nuclear safety issues in a timely manner, rather than delegating these issues to outside organizations or regulatory agencies?

How thorough are discussions of issues that potentially impact nuclear safety, and to what extent are the safety implications considered during enterprise business planning and budgeting?

- It is generally recognized that the special and unique aspects of the nuclear technology must be recognized and considered as a key aspect of the nuclear safety culture. TEPCO was prepared for various accident scenarios involving equipment failures and human errors; however, preparations were not sufficient to deal with the accident caused by a beyond-design-basis tsunami. As a result, some confusion developed over the status of systems used for core cooling, and actions to transition to alternate core cooling methods were not well planned and coordinated. In addition, operators and emergency response personnel did not have the procedures, equipment, and training needed to vent primary containment vessels under the conditions that existed during the event. Other nuclear operating organizations may also have vulnerabilities that would be revealed if faced with a similar event.

  How would your organization maintain the needed focus on core cooling and fission product barriers under the conditions experienced at Fukushima Daiichi?

  How effectively have employees at your facility mastered reactor and power plant fundamentals to enable safety-focused decisions and actions under such conditions?

  How has your organization ensured that the necessary equipment, procedures, and training have been provided to allow effective emergency response following a significant event?

- Another important principle involves organizational learning. TEPCO senior managers indicate that, in retrospect, their organization would have benefited from more frequent participation in international forums where operating experience information is shared and differences in accident management strategies are critically discussed. Similarly, they pointed out the need to make greater use of international operating experience information to minimize the potential for plant events.

How effectively does your organization engage in international forums to share information to enhance nuclear safety?

How well does your organization review practices that depart from other nuclear operating organizations to understand potential undesired or unintended consequences?

How does your organization avoid complacency and cultivate an attitude that “it can happen here” when reviewing international operating experience information?

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