Lessons-Learned from the Research on BWR, and its Applicability to PWR

Type	Cause	Events / Issues	Measures / Lessons	Applicable to PWR?	Comments
Earthquake ･Tsunami ①	・Earthquake ・External power outage ・Communication function problem ・Liquefaction of road & infrastructure, and scattered debris from the quake and tsunami.	・Auto stop (scram) of core reactor activated according to design. Recovery operations performed on DG auto activation due to external power failure. Operator responded as planned.	・ Nuclear reactor earthquake response as per design.	○	
	・ Same as above	・ After the auto scram was triggered by earthquake, some DGs were activated by mistake in plants that didn't experience external power outage (because of generator field failure?). DG is an important emergency power source, so we need to consider whether this activation was appropriate.	・Investigate the cause of "false-positive" activation. ・Change to DG auto-activation interlock on earthquake scram.	○ ×	If there is external power, activation of DG is unnecessary. Consider the risk of damage from earthquake during operation.
	・ Same as above	・ No major damage to the facilities from the earthquake. Detailed examination of the earthquake disaster will require some time, so whether lessons learned from Kashiwazaki were effectively applied has yet to be verified.	・ Check lessons learned from Kashiwazaki-Kariwa Nuclear Power Plant on Chuetsu offshore earthquake.	○	
	・ Same as above	・ The earthquake disrupted communications. There were major issues in sharing information, giving instructions or commands, and making decisions. Whether the emergency satellite phone, or the fire department and local government hotlines were functioning and utilized has yet to be verified.	・ Secure and reinforce means of communications in case of disasters such as earthquakes.	○	
	・ Same as above	・ Recovery process delayed due to difficult access over roads to facilities caused by road liquefaction from earthquake and debris from the tsunami.	・ Reinforce main road to prevent liquefaction, and secure multiple access routes.	○	
	・ Same as above	・ The seismic action recorded in Onagawa and Fukushima Dai-Ichi were as predicted. Aside from the movement in some areas where the actual quake was stronger, the readings were on par with predictions. This indicates that the designed seismic parameters are reliable.	・ Anti-earthquake design was appropriate.	○	
	・ Same as above	・ The earthquake happened during the day on a weekday, but we need to verify whether workers would have been able assemble at the power plant according to the manual if it occurred at night time or on a holiday.	・ Consider response procedures for disasters occurring on holidays and at night.	○	
Earthquake ･Tsunami ②	・ Design estimate for tsunami set too low	・ Tsunami impact exceeded the prediction made by the Japan Society of Civil Engineers (JSCE) in 2002. (Fukushima Dai-Ichi = 5.7M, Dai-Ni = 5.2M) This greatly affected the safety of the plant. Furthermore, it's not clear whether the accuracy of the tsunami estimate data had been seriously reviewed for the past 7 years.	・ Is the prediction from JSCE really enough? ・ Automatic and regular assessment for Tsunami need to be considered.	○ ○	
	・ Seawater pump flooded by tsunami	・ The height of the tsunami that hit the Onagawa Power Plant Tokai Dai-Ni Power Plant was on par with that estimated by the Japan Society of Civil Engineers (2002 estimate). However, some areas of the plant were not sealed properly, so seawater still entered the facility. The emergency seawater pump malfunctioned due to flooding, causing the emergency DG to malfunction.	・ Tsunami countermeasures for seawater pumps. (Reinforce pressure and water protection.)	○	
	・ Tsunami risk assessment system based on "height"	・ Tsunami impact destroyed power plant structures and equipment, scattering debris everywhere. The debris became an obstacle during the recovery process. When deliberating anti-tsunami measures the discussion shouldn't be limited to just the height of the tsunami but should also include its power.	・Revise risk assessment to include consideration of power of the tsunami.	○	
	・ Gasoline tanks wiped away by tsunami	・ In Fukushima Dai-ichi and Onagawa power plants the tsunami swept the gasoline tanks onto the road, blocking access to the plant. This affected the speed of the recovery process, while the gasoline was also released into the sea.	・ Bolt down the gasoline tanks	○	
	・ Debris created from the tsunami.	・ The debris scattered by the tsunami greatly affected mobility and supply transport. There needs to be a countermeasure to enable swift actions in securing the safety of the plant.	・ Secure heavy equipment and operators for clearing debris.	○	
	・ Seawater coolant pump vulnerable against tsunami	・ Although the facilities in Fukushima Dai-Ichi and Dai-Ni were built on an area higher than the estimated tsunami height, the seawater pumps were not. The pumps were damaged by the tsunami and malfunctioned.	・ Store additional mobile power supplies and seawater pumps.	○	Large capacity pumps have been placed as substitutes for the sea water pumps (December), currently training operators.
Earthquake ･Tsunami ③	・ Major flooding (seawater) of turbine building from the tsunami	・ Buildings connected to the turbine building and the nuclear reactor building were badly flooded, and equipment in the basement and ground floor were damaged and stopped functioning. The plant's cooling system was greatly affected due to flood damage of the emergency diesel generators, DC and AC power panels, etc.	・ Reconsider the location of Diesel generator, DC power panel, and AC power panel. Stock mobile power supply vehicle.	○	Alternate proposal for watertight countermeasures.
	・ The tsunami hit when the turbine building's supply transport entrance was open.	・ During regular inspections, the turbine building's large entrance is used for delivery of supplies. The entrance was left open during and after the earthquake, allowing seawater from the tsunami to enter the turbine building. The flooding resulted in the loss of the DC power supplies.	・ Revise operations of the wider entrances since they are vulnerable to flooding. Conduct training.	○	
	・ Important quake-proof building emergency power lost from the tsunami.	・ There was no power in the Fukushima Dai-Ni emergency response room following the tsunami. Limitations in the emergency response room's infrastructure affects the speed of the plant's recovery process.	・ Reinforce the durability of important quake-proof buildings against tsunami. Secure emergency power supply.	○	Elevation of important anti-seismic wing.
	・ Seawater pumps malfunctioned due to damage from tsunami.	・ In Fukushima Dai-Ichi, almost all of the seawater pumps malfunctioned from the tsunami. There wasn't much damage to the pumps themselves, but most suffered damage to the motor's insulators.	・ Keep motor coil washing equipment within the site and stock spare parts.	○	
	・ Insufficient AM and training for simultaneous SBO occurrences on all plants.	・ The tsunami instantly compromised the entire power plant. The AM was not designed for response to instant devastating blows to the entire power plant. Further, measures against disasters with low probabilities of occurrence may not have been seriously taken into account because of the application of the PSA method. To learn from this, it's important not just to make hard and soft preparations for responding to instant damage to the entire plant, but to enhance plant-wide trainings as well.	・ Reinforce hard and soft preparations for plant-wide SBO. Reinforce Training.	○	

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Power loss（Fukushima Dai-Ichi）①	・ DC power supply flooded by the tsunami	AC and DC power supplies in the turbine building's first floor and basement were lost due to the tsunami. It is important to improve the facility's air tightness, water-tightness, and pressure resistance to protect the power supplies.	・ Improve air and water protection, and pressure tolerance of power facilities	○	
	・ Flood entered through the air inlet	Emergency DG malfunctioned due to seawater entering the air inlet.	・ Apply water proof solution for air inlet	○	
	・ Instant loss of DC power supply from flooding	DC power is the most important power source in the plant. It powers the high pressure cooling devices and the main control room instrumentation and lighting. In Fukushima Dai-Ichi, the DC battery room was located in the basement of the turbine room, so it was lost instantaneously from flooding. With no power, the high pressure cooling system couldn't function. When the pressure in the reactor dropped, attempts to cool the nuclear reactor core with the alternative low pressure cooling system failed. This resulted in core meltdown and eventually to the hydrogen explosion (Fukushima Unit 1).	・ Secure alternative DC power supply. It's important to have diversity	○	DC main line board DC power was not lost at Unit 3 where it was located 1 floor underground in the turbine building. At Units 1, 2 and 4 where it was located in the control building 1st floor, DC power was lost.
	・ Complete external power outage	Fukushima Dai-Ichi Reactors 1 – 6 lost external power from the earthquake. Plants that didn't experience power outage and those that were able to recover partial power with the emergency power supplies achieved cold shutdown. Securing external power supply directly led to the prevention of fuel damage.	・Improve earthquake resistance of external power supplies ・Increase the number of external power supply routes (multiplex) ・ Link external power to each plant (multiplex)	○	
	・ Emergency power supplies located at altitudes below the tsunami crest ・Power supplies relied on seawater cooling system.	In Fukushima Dai-Ichi, only the Unit 6 emergency diesel generator was functioning. It was located in the northern part of the plant which is at a higher altitude (OP13) than Reactors 1 - 4. The height of the flooding only reached up to 1m. In addition, the Reactor 6 emergency DG used air instead of seawater for its cooling system, so it wasn't affected by the flood.	・Consider placing emergency DGs at higher locations. ・Secure emergency power supplies with various cooling systems and different power types.	○ ○	Current DG relocation is difficult. Substitute power (power supply vehicle, air cooling emergency generator device, 3rd power future location) should be located uphill, and implement air cooling.
Power loss（Fukushima Dai-Ichi）②	・ Not anticipated in AM (SBO AC power recovery rate)	・ Only a short-period station blackout was anticipated in the AM countermeasures. However, in Fukushima Dai-Ichi, the power outage lasted up to a few days. This sort of situation was not covered in the recovery procedure manual.	・ Revise the procedures for anticipating SBO duration.	○	Procedure reevaluated.
	・ Concurrent AC and DC power outage ・Instant power loss of all DC power supplies from flooding. Unable to charge DC power supply batteries.	・ The countermeasures in the AM all assume definite recovery from station blackout, so there aren't any countermeasures against the loss of all AC and DC power at once. The plant was designed to supply 8 hours of DC power in case of AC power outage. In Fukushima Dai-Ichi Unit 3, where DC power was retained, the DC power lasted more than a day (1.5 – 3 days) by cutting off all unnecessary consumption, but they failed to set up the low pressure cooling system for backup during this period. When the batteries were depleted, the plant lost its high pressure cooling system, and instrumentation in the main control room stop functioning.	・ Secure alternative AC power supply ・ Secure alternative DC power supply ・ Create manual for swift installation of these supplies	○	Confirmed in training that substitute AC power connection is completed before battery depletion. Improvement implemented for reducing procedure time in response to the training results.
	・ Dai-Ichi Reactors 5 & 6 shared power; unable to supply power to Reactors 1 - 4	・ The emergency DG in Fukushima Dai-Ichi Unit 6 remained operational and workers were able to connect it to power Unit 5. This together with the use of the power supply vehicle allowed cold shutdown in Dai-Ichi Reactors 5 & 6. There was no power line cross-connecting Units 5 & 6 to Units 1 - 4.	・ Improve power supply lines within the site (per voltage class)	○	Deliberating power accommodation between plants through backup transformer on secondary side.
	・ Delay due to insufficient number of power supply vehicles	・ After the tsunami, some plants were able to partially restore power with the power supply vehicles. Utilization of power supply vehicles was effective.	・ Increase number and variety of power supply vehicles, revise designations, define connection areas and procedures, and reinforce training.	○	
	・ Complete darkness in the main control room due to DC power outage ・Instant loss of parameter monitoring and control functions	・ The greatest fear and cause of despair for operators is the loss of instrumentation. In a severe accident such as this one, operators need to be calm and utilize their knowledge and skills acquired through training to stabilize the plant and bring it to cold shutdown. In order to achieve this, it is crucial to maintain the monitoring functions of the measurement instruments and control switches (and the power for it).	・ Increase number and variety of alternative DC power supplies for maintaining monitoring functionality.	○	
Power loss (Fukushima Dai-ichi, Dai-ni, Higashidori, Onagawa, Tokai Dai-ni) ①	・ Loss of power from earthquake and aftershock	・ External power: On 3/11 Fukushima Dai-Ichi, Tokai Dai-ni, and Higashi Dori experienced external power outage. On 4/7 external power in Higashi Dori was cut-off again (emergency DG automatically activated in both cases). For deep defense it's important to have power transmission equipment that doesn't rely on emergency DG, especially in Higashi Dori where external power outage occurred twice in 1 month. The vulnerability of the power transmission system was evident. Earthquakes caused the power outages in both cases, so it's recommended that the power transmission network be expanded, and earthquake resistance improved on the switching stations and substations.	・ Expand power supply network. ・Reinforce earthquake resistance of power substation facilities and switch stations.	○ ○	
	・ Failure of the emergency DG, seawater coolant pumps, and cooling system caused by the tsunami and flooding.	・ Emergency DG Power: Emergency DGs stopped working either from flooding in the DG or seawater pump facility by the tsunami in Fukushima Dai-Ichi and Dai-Ni, Onagawa, and Tokai Dai-Ni.	・ Identify how the floodwater entered the Emergency DG room and implement countermeasures. ・Flood prevention and reinforcement of water protection for the coolant pump.	○ ○ ○	
	・ No anticipation of, or procedures for handling instant DC power outage and providing alternative power backup.	・ Emergency DG Power: Emergency DGs stopped working either from flooding in the DG or seawater pump facility caused by the tsunami in Fukushima Dai-Ichi and Dai-Ni, Onagawa, and Tokai Dai-Ni.	・ Reconsider location of DC power. ・Flood defense measures. ・Upgrade battery capacity. ・Secure alternative DC power, DC power supply vehicle, and means of chargiing batteries.	○ ○ ○ ○	
	・ Loss of power paths via M/C and P/C due to flooding.	・ The tsunami flood damaged the power paths including the M/C and P/C in Fukushima Dai-Ichi and Dai-Ni. In other plants M/C and P/C stopped functioning from partial loss of power. In both cases, crucial responses such as cooling and venting of the reactor were affected .	・ Consider relocating power panels to higher areas ・Prepare power supply vehicles, cables, connection terminal systems, and connection route ・Equip specific procedures and reinforce training	○ ○ ○	

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Power loss (Fukushima Dai-ichi, Dai-ni, Higashidori, Onagawa, Tokai Dai-ni) ②	・ Insufficient number of power supply vehicles. ・Delay in arrival of additional vehicles. ・Insufficient backup batteries,, temporary orders, compact generators, etc.	・ Power supply vehicles: If necessary load for power supply vehicles had been predetermined, sufficient number of units secured, and vehicles arrived quickly, the result could have turned out better, especially in Fukushima Dai-Ichi.	・ Increase number of permanent power supply vehicles (multiplex) (DC, AC, mix) ・Prepare emergency kit for power blackout (batteries, lights, compact generators, fuel, cables, etc.). ・Create manuals for aforementioned items, and conduct training.	○ ○ ○	
	・ Restoration of power, high pressure cooling system, and depressurization functions under severe and adverse environments, and insufficient AM countermeasures.	・ Emergency DG, all AC power, DC power, and emergency seawater pumps ceased functioning instantly from the tsunami flooding in Fukushima Dai-Ichi. Restoration was conducted in an overwhelmingly adverse environment. It was extremely difficult to maintain the high pressure cooling system and to switch to low pressure cooling (preparations, etc.) This chain of events is one of the main causes of the hydrogen explosion that occurred in the plant.	・ Increase number of permanent power supply vehicles (multiplex) (DC, AC, mix) ・Prepare emergency kit for power blackout (batteries, lights, compact generators, fuel, cables, etc.). ・Create manuals for aforementioned items, and conduct training.	○	
Loss of sea water cooling functions（Fukushima Dai-Ichi）	・ Secure emergency DG ・Power sharing functions ・Reconstruct seawater cooling system that doesn't compromise time requirements	・ The tsunami didn't reach the Fukushima Dai-Ichi Unit 6 air-cooled emergency DG. Power was shared between Reactors 5 and 6, and supplied to the RHR pumps. By preparing temporary seawater pumps and power supply vehicles, workers were able to reconstruct the seawater cooling system and achieve cold shutdown. Learning from this experience, the connection route should be defined (i.e. in the manual) and training conducted periodically to enable prompt response to such situations.	・ Reaffirmed the importance of emergency DG and Power sharing functions ・Conduct periodic training for simulating similar events	○ ○	
	・ Vulnerability of emergency DG (water cool) cooling function (seawater pump, motor, etc.)	・ In Fukushima Dai-Ichi Reactors 1 – 6, all seawater pumps stopped functioning due to flooding by the tsunami, resulting in the loss of the seawater cooling system (ultimate heat sink). Although the emergency DG was also flooded and malfunctioned, even if it did survive the tsunami impact, the DG would still have stopped with the loss the of cooling equipment (seawater pumps, motors, etc.). When emergency DG stops, a chain reaction causes the ECCS pump to stop working as well.	・ Secure seawater cooling system, backup water pump, power supply, fuel, etc. ・Prepare line of air-cooled DG (not dependent on seawater) ・Consider using motor with strong water protection	○ ○ ○	
	・ Loss of seawater cooling function	・ Fukushima Dai-Ichi 1 – 3 was not able to achieve cold shutdown due to loss of seawater cooling function.	・ Same as above.	○	
Compared with other plants	・Retained external power ・Retained main control room function ・Secured time for recovering the high pressure cooling system. ・No delay in the restoration and operation of seawater cooling system.	・Plants that were able to secure external power supply achieved cold shutdown. － Fukushima Dai-Ni was able to secure 1 external power system. － They lost DG and the seawater cooling system from the tsunami impact but with the external power they were able to maintain main control room functions. With DC power, they were able to maintain high pressure cooling by using the RCIC and SR valve. － This bought them time to restore the emergency seawater pumps and power the necessary pumps.	・Reaffirmed the importance of external power. ・Reaffirmed the effectiveness of AM when external power and DC power are available.	○ ○	
	・Same as above.	・ In Onagawa power plant, Reactors 2 & 3 were able to secure 1 external power system which allowed them to maintain the seawater cooling system and succeed in implementing standard cold shutdown. － Unit 1 lost external power, and DG was activated. － Achieved cold shutdown by maintaining seawater cooling function. Cold shutdown can be achieved by maintaining power and securing seawater pump function.	・Same as above. ・Importance of seawater cooling function. ・Secure alternative equipment to replace amaged units ・Affirmed the importance of recovery process	○ ○ ○ ○	
	・Same as above.	・ Partial flooding of seawater pump caused emergency DG to stop in Onagawa Unit 2 and Tokai Dai-Ni. (2 DG units in Onagawa Unit 2, and 1 unit in Tokai Dai-Ni.) － There's no denying that the situation could have been the same as with Fukushima Dai-Ichi 1 – 3 if all external power and DG failed at the same time.	・Plants that achieved cold shutdown shouldn't simply celebrate their successful recovery. They should acknowledge the potential risks faced and review the countermeasures and training needed for improvements.	○	
High pressure cooling function ①	・Loss of all DC power ・Unable to view instrumentation ・Main control tower functions failed	・ 1F Unit 1: Parameter data: The facility lost DC power right after the earthquake and tsunami. Without power, instrument panels weren't functioning, so it was impossible to acquire important parameters such as the core water level. As a result, they weren't able to grasp the actual situation in the core and make appropriate decisions. They started out making the wrong decisions in handling the high pressure cooling system.	・Countermeasure for main control room power outage. ・DC power flood prevention (location, water seal, water protection for batteries), DC power supply flood prevention (location, water seal, water protection for batteries) ・Secure backup batteries (battery, DC power supply vehicle)	○ ○ ○	
	・Loss of all AC/DC power ・IC valve operation failed	・ 1F Unit 1: High pressure IC water injection and depressurization: Similarly, without AC/DC power, operators were unable to adjust the valves of the High pressure system (IC). As a result, operating the high pressure system was almost impossible. It can be inferred that water injection and depressurization failed. Our theory is that the core's water level was decreasing while temperature and pressure kept rising. Damage is estimated to have started 3 hours after the tsunami.	・Restore AC & DC power within 2 hours? ・In addition (to AC), allow direct valve control.? ・Consider valve adjustment mechanism that doesn't rely on electricity (manual & auto).	○ — ○	All valves needed for TDAFWP operation are outside of the containment vessel, and manual operation is possible
	・Loss of all AC/DC power ・HPCI valve operation failed	・ 1F Unit 1: High pressure HPCI water injection and depressurization: Similarly, without AC/DC power, operators were unable to adjust the valves of the HPCI system and failed to perform water injection.	・Same as above.	○	
	・Incomplete multiplexed defense in the AM ・Delay in depressurization and preparations for low pressure cooling	・ 1F Unit 1: AM ineffective due to unavailable measurement data and high pressure cooling system: When the complete AC/DC power outage occured, the plant didn't have enough time to prepare for transition from high pressure to low pressure cooling as given in the AM (+αexpertise of site personnel) because everyone was busy securing AC power (power supply vehicle), securing DC power (car batteries), vent line setup (manual), low pressure coolant injection setup (fire truck, hose, water supply for fire extinguisher), etc.	・Design AM to anticipate instant and concurrent loss of entire AC and DC power (unable to recharge batteries due to flooding).	○	
	・Activation of RCIC	・ Effectiveness of the RCIC: Unit 1lost its IC system and wasn't able to maintain high pressure cooling. But in Unit 2, RCIC was activated and continued working. It is believed that the RCIC kept the pressure in the S/C within the estimated limit of 0Ka (abs) for 3 – 4 days after the tsunami, before the containment vessel was eventually damaged.	・ Reaffirmed effectiveness and importance of maintaining the high pressure cooling system. ・Important to provide procedures and training for preparing and setting up low pressure cooling system while the high pressure cooling system is still working.	○ ○	

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High pressure cooling function ②	・ Fukushima Unit 1 hydrogen explosion	・ 1F Unit 2: High pressure cooling system setup incomplete – repeated interruptions and damage to the water injection line from the hydrogen explosion (3/12): Response unit completed the preparations for backup water injection to the core, and connected the power supply vehicle to a working P/C, but the cables and the power supply vehicle were destroyed when Unit 1 exploded on 3/12 and everything had to be setup from scratch again.	・Review the risks involved in operating multiple plants ・Absolute prevention of hydrogen explosion	○ ○	Problems occurred even when plant was stopped, so what are the risks of multiple site locations?
	・ Same as above. (Unit 3)	・ Same as above (3/14): The response unit was able set up a seawater injection line using fire trucks and hoses, but the 3/14 hydrogen explosion in Unit 3 destroyed the fire trucks and hoses and everything had to be set up from scratch again.	・Review the risks involved in operating multiple plants ・Absolute prevention of hydrogen explosion	○	
	・ Frequent aftershocks	・ 1F Unit 2: Effect of aftershocks: In parallel with previous items, repeated aftershocks interrupted the injection line set up, and as a result the response unit was not able to execute their procedures in time.	・Necessity of AM design and training anticipating overwhelmingly poor environment	○	
	・ Insufficiency in the AM	・ 1F Unit 2: Effect of after quake: In parallel with previous items, repeated after quake interrupted the injection line setup, and as result the response unit was not able to execute in time.	・Necessity of AM design and training anticipating overlaying poor environment	○	
	・Maintain DC power ・Failed to secure alternative power source during this period	・ 1F Unit 3: Importance of DC power and Effectiveness of RCIC: DC power (DC125V Main bus boards 3A and 3B) survived the earthquake and tsunami, and it was used to power the high pressure system (RCIC or HPCI). However, the plant wasn't able to secure backup power, and the DC power depleted 35 hours after activation of RCIC. At this point, HPCI also was already on halt. Consequently, the plant failed to decrease the reactor's pressure and recover the water level. (We were able to verify that the batteries were depleted so our theory is that this is the reason the system stopped.)	・ Reaffirmed importance of DC power and RCIC ・Secure additional power sources; reinforce and conduct training	○ ○	TDAFWP at PWR can be operated even without DC power.
	・Use of car batteries ・Activation of HPCI	・ 1F Unit 3: Effectiveness of HPCI: The batteries depleted on 3/12, at 11:36, causing the RCIC to stop. HPCI was activated on the same day at 12:35. During this period the core pressure dropped from 7.53MPa to 0.58MPa, but went back up to 7.4MPa on 3/13, 2:42, when the batteries for HPCI were depleteed (cause of stoppage is believed to be depleteed batteries since the batteries were found and confirmed).	・ Same as above.	○	
High pressure cooling function ③	・Insufficient coverage in the AM (Secure extra DC power and backup power) ・Same as above.(Devise countermeasures to events when DC power is lost from flood and batteries can't be charged.)	・ 1F Unit 3: Insufficient coverage in the AM (Secure extra DC power supply or backup power supply): 1F Unit 3 was the only reactor among Units 1 - 4 that retained its DC power supply. However, looking at the chronology, there is no evidence of additional backup power source being secured before the DC power supply was consumed (used batteries from employees' cars and other sources when HPCI stopped). Additionally, there is no trace of reserve DC power batteries stored in the reactor building or in the seismically designed building. Storing of reserved batteries for emergency, such as in this case, may not have been specified in the AM (= it seems that they have no other measures than to restore the AC power within 8 hours (battery life) and then to recharge DC batteries when AC power is restored). As a result, high pressure cooling systems such as the RCIC and HPCI had to stop prematurely.	・ Reserve extra DC batteries (multiplex - since batteries can no longer be charged if flooded)	○	TDAFWP at PWR can be operated even without DC power.
	・Insufficient coverage in the AM (No multiplex defense for DC power?)	・ 1F Unit 3: Insufficiency in the AM (multiplex defense): This is related with the previous item. It seems that AM provides only one solution for high pressure system (RCIC/HPCI) power recovery. It only states to "restore AC power within 8 hours (the life span of DC batteries) and recharge the batteries with the AC power." This leads to the conclusion that the facility has weaknesses in its defense multiplexing.	・ Same as above. ・Update AM and training to include responding to instant loss of all DC power supplies from flood (batteries can't be recharged).	○ ○	
	・Restoration process under unexpected field condition (not covered by AM)	・ 1F Unit 3: AM ineffective (core reactor scram): Of all Units in 1F it is believed that only the event in Unit 3 was within the scope of the AM manual (earthquake, AC power outage, core reactor scram, DC power utilization (8hrs)). However, Unit 3 was not able to achieve cold shutdown. Although they were able to prevent damage to the core for 36 hrs by powering the high pressure cooling systems (RCIC and HPIC) with the DC power supply, they were not able to "restore AC power, depressurize the core reactor, and make the transition to low pressure cooling" as indicated in the AM.	・ Same as above.	○	
Ventilation function（Depressurization via SR valve）①	・Loss of all AC & DC power ・SR valve malfunction	・ 1F Unit 1: SRV non-functional due to loss of DC power: The SRV (safety release valve) which is used by the high pressure cooling system stopped functioning due to loss of all AC and DC power by the earthquake and tsunami. In Unit 1, the SRV didn't work at all. Because of this, they decided to reduce core pressure by using IC. However, partially due to the adverse environment the IC didn't function as designed. At the end, site workers failed in reducing the core's pressure, and it continued to build. (Regarding the decrease in the nuclear reactor pressure, the SR valve may have been stuck, and steam may have leaked through the SRV flange section gasket due to the rise in pressure vessel temperature. This may have reduced the pressure in the nuclear reactor, but at this point these are just theories.)	・ Multiplex DC power (extra batteries, and allow charging from battery vehicles and AC power supply vehicle) ・Improve water protection of DC power supplies (batteries) (safer storage location or water seal of the batteries themselves). ・Store spare batteries, and optimize installation time. ・Increase number of response unit members and conduct training to achieve the above. ・What about using a mechanism that doesn't rely on DC power to operate the SRV?	○ ○ ○ ○	Manual opening of the PWR main steam release valve is possible, but reconstruction is planned for greater ease of use.
	・Loss of all AC & DC power ・SR valve malfunction	・ 1F Unit 2: SRV non-functional due to loss of DC power: Same as above. (＝＞ P/C (2A, 2B, 2C, 2D) were working, but like in Unit 1 the entire battery room, where the DC batteries were stored, was flooded. Without power the SRV didn't function.) When the RCIC stopped, they decided to depressurize the nuclear reactor core to perform lower pressure water injection, so workers used spare batteries to power the SRV for the depressurization operation.	・ Same as above.	○	
	・ Same as above. ・Delay in ordering spare batteries. ・Delay in setting up water injection line for fire truck?	・ 1F Unit 3: Delay of depressurization (SRV) due to lack of batteries.: With DC power (3A, 3B) available, plant workers followed the manual and cut-off unnecessary power consumption to buy more time for RCIC/HPCI to work. The batteries provided power for approximately 35 hours until the HPCI was tripped. After the HPCI stopped working, workers attempted to depressurize the reactor to inject water via the fire truck hose, but weren't able to operate the SRV because there was no power. So they collected the car batteries from the employees' cars, and at 9:08, 3/13, they were finally able to operate the SRV and depressurize the reactor (HPCI stopped at 2:42, 3/13; pressure relieved 6 hours after). Later at 9:25 the fire trucks arrived and started the alternative water injection (one truck from 1F 5 & 6, and one more from 2F).	・Same as above. ・Upgrade regular DC power supplies (extended battery life). ・Reduce the time spent for setting up water injection line for fire trucks.	○ ○ ○	

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Type	Cause	Events / Issues	Measures / Lessons	Applicable to PWR?	Comments
Ventilation function（Depressurization via SR valve）②	・Secured external power ・Secured DC power ・RCIC was functioning ・Set up line for low pressure cooling	・ 2F Unit 2: Success in pressure vessel depressurization with the SRV: 2F Unit 2 lost its emergency DG from the tsunami and its ultimate heat sink. However, the facility was able to receive external power supply, and the power panels and DC power supplies were working. They were able to maintain the water level of the nuclear reactor with RCIC, which bought time for setting up the line for the Make-up Water Condensate system (MUWC). After setting up MUWC, operators adjusted the SRV to depressurize the reactor as planned. After that, they performed low pressure coolant injection and achieved cold shutdown => Importance of external and DC power.	・ Reconfirmed the importance of the following: － External and DC power － RCIC (with power) － Low pressure cooling system (with power)	○	
	・Failed to secure power ・Failed in high pressure cooling due to lack of power) ・Failed to depressurize (SRV)	・ 1F1～Unit 3: Limitation of AM (Especially with risks in failing high pressure cooling): Nuclear reactor depressurization operation was performed on Units 1-3 after the high pressure cooling stopped working. Workers weren't able to set up the transition to low pressure cooling while the high pressure cooling system was running. It is believed that the delay was partially caused by the unprecedented adverse field conditions.	・ Same as above. ・Revise AM (integrate unexpected incidents learned from this event) ・Same as above (Provide judgment base for determining plausibility of cold shutdown with the standard operating procedure. Also provide timeframe as when to start setting up low pressure system.) ・ In addition to the previous item, provide alternative action guidelines (the guideline should aim to prevent worst case scenario instead of aiming for perfection. i.e. prevention of hydrogen explosion, venting reactor building, seawater injection, rapid depressurization using IC, etc) ・Maintain worker's ability to respond to emergency situations with regular training.	○ ○ ○ ○ ○	
Ventilation function（Depressurization by SR valve）①	・ AC & DC power outage ・Complete darkness inside the building ・Increasing radiation dosage in the building with the progression of reactor core damage ・Frequent aftershocks (required temporary evacuation) ・Lack of pressure from air compressor ・Delay in arranging and transport of equipment such as air compressor and adapters. ・Delay in venting containment vessel	・ 1F Unit 1: Delay in PCV operation: On 3/12 (00:06), orders were given to prepare for vent operation, when they realized that D/W pressure may have exceeded 600k Pa abs. However, the actual vent operation was performed at 14:30 that day. The operation started at 09:04 but took approx. five and a half hours to complete. The reasons are: No power to the valve (no AC & DC power) Complete darkness inside the building due to blackout (except for main control room) Increasing dosage rates parallel with the progression of reactor core damage (especially basement 1) Orders to stop field work due to frequent aftershocks Work halted until evacuation of neighboring residents completed. Insufficient means of communication on progress updates. Lacking means of communication between main control room and field workers inspecting the vents Failed in vent release due to lack of pressure from air compressor Time consumed by arranging for temporary air compressor, delivering adaptors, and transport. Although they were able to vent the containment vessel and confirm drop in pressure, the reactor building exploded approximately an hour afterward.	・ Secure power (DC, AC and backup power supplies) ・Confirm availability of emergency lights (installed in reactor building and portable lights for field work) ・Secure emergency communication methods ・Secure extra compressors and adaptors ・Change the vent system. It should be operable even in the event of SBO (system that allows vent executed remotely with reserved power (manual release as last resort)).	○ ○ ○ ○ ○	
	・ RD operation pressure	1F Unit 2: S/C vent failure due to high Rupture Disk (RD) operational pressure: In the initial attempt to vent the S/C, the workers had to overcome an obstacle, in which the circuit board for energizing the solenoid valve came off in the explosion in Unit 3. On the same day around 21:00, workers had completed constructing all vent lines except for the RD, but even with the D/W pressure exceeding its max capacity of 427 Pa gage (530k Pa abs), the pressure in S/C was not enough to move the RD. At 23:35, they decided that the operation was a failure and had no choice but to switch to D/W venting.	・ Review RD operational pressure. ・Confirm reason for setting high pressure configuration on vent operation (The operational pressure was set to a little under 2 times the designed pressure value. This was done in the hopes of preventing the release of radioactive material as much as possible. But this action may have contributed to the hydrogen density exceeding 4% when (generated due to fuel damage) it leaked out from the containment vessel.) ・ Consider replacing RDs with valve-operated vent system.	× × ×	There is no rupture disk in PWR
	・ Same as above.	1F Unit 2: D/W vent failure: On 3/15 (apprx. 00:02) after failing with the vent operation in the previous issue, the attempt to open the D/W vent commenced. The preparation of the vent line was completed at 0:02, on 3/15. Although the D/W pressure varied around 750k Pa abs, after a few minutes the vent was confirmed to be shut. Around 6:00 - 6:10 the same day, it is estimated that severe damage to the PCV had occurred, judging from the record that pressure of S/C was 0 k Pa.	・ Same as the above	×	There is no rupture disk in PWR
Ventilation function (PCV vent) ②	・ Insufficient pressure from air compressor ・Faulty solenoid valve ・Delay in vent line setup	・ 1F Unit 2: Delay in vent line set up due to lack of pressure from air compressor and faulty solenoid valve: After the Unit 3 explosion on March 14 (11:01), workers attempted to open the S/C vent valve (large AO valve) but failed. The pressure from the air compressor was too low. It is postulated that the AO valve couldn't be opened in processes with the same line up due to a faulty solenoid valve.	・ Consider a vent system that doesn't use air pressure (prepare temporary compressor, field environment management, line construction that allows connection, change to valve that allows manual operation.)	×	
	・ Complete darkness ・Hot and humid work environment ・Difficult vent line setup	・ 1F Unit 3: Slow W/W vent set up progress due to the dark, hot, and humid work environment: On March 12, at approximately 4:50 (RCIC still running) after energizing the S/C vent solenoid valve with the main control room's compact generator, the shift workers went to the torus room to confirm if the valve was opened. However, they found that the room was in complete darkness, and the temperature and humidity were high because of heated steam coming out from the S/C vent SR valve. The work environment was tough and they were making very slow progress. Also on March 13, around 11:00-12:00, workers once again entered the torus room in an attempt to lock the S/C vent valve (AO valve), but weren't able to complete the task due to increased temperature and vibration from SR valve.	・ Review and reconsider position of the valve	×	

Lessons-Learned from the Research on BWR, and its Applicability to PWR

Type	**Cause**	**Events / Issues**	**Measures / Lessons**	**Applicable to PWR?**	**Comments**
Ventilation function (PCV vent) ③	・ Delay in air cylinder replacement	・ 1F Unit 3: Delay due to air cylinder replacement: On march 12, approx. 5:23, workers attempted to open the S/C vent (AO vent) but failed. Second attempt, after replacing the air cylinder, was successful.	・Secure extra air cylinder for operating vent valve ・Include replacing of air cylinder in the training.	×	
	・ Reduced pressure of air cylinder due to leak	・ 1F Unit 3: Problem keeping the vent open due to defect in the air cylinder: On March 13, after venting was successfully performed, the S/C vent valve (AO large vent) was closed again at approx. 11:17 due to leak in air cylinder.	・Secure extra air cylinder for operating vent valve ・Include replacing of air cylinder in the training.	×	
	・ Insufficient air pressure supplied to the large valve ・Energizing of solenoid valve unstable	・ 1F Unit 3: Difficulty maintaining air pressure for operating the large valve and energizing the air supply line solenoid valve: Although Unit 3 succeeded in venting, workers were having difficulty keeping it open (or failed). The postulated reason is a problem with the air pressure used to operate the large valve, and a problem with the air supply line solenoid valve (unable to energize consistently). This seemed to have occurred 5 times after the explosion.	・Review the entire vent system and reinforce the system to keep vent opened when needed. (Secure the reliability of the air supply line by developing a safety sysytem, and its diversity.)	×	
Low pressure cooling function ①	・Difficulties and delays in supplying water via the fire truck ・Trouble with the diesel-driven fire pump ・Damage to fire hydrant from earthquake and tsunami, and filtered water was gushing out ・Time consumed searching for alternative water source ・Not enough fire trucks ・Fire truck mobility issues due to adverse environment ・Delay in setting up water injection line from fire truck ・Insufficient water injection capacity of fire truck	・1F Unit 1: Difficulties in supplying water from fire truck, delay in commencing: As early as 17:12, on March 11, instructions to consider water injection from the fire line and fire trucks were given. However, the diesel generated fire pump was having trouble, so the decision was made to inject water directly from the fire line, instead of using the fire truck (March 12, 1:48). From the previous item, setting up water injection line from the fire truck (loading to fire truck, transport to reactor building, connecting with water protection system line) was time consuming. The injection process started at 5:46 (3/12). The main reasons are as follow: Trouble with the diesel-driven fire pump Damage to fire hydrant from earthquake and tsunami - filtered water was gushing out (valve closed manually to stop out-rushing water) Time consumed searching for alternative water source (After surveying the site, they discovered that a fire protection tank can be used) Not enough fire trucks (of the 3 trucks, 1 was damaged by the tsunami, 1 was with Units 5 & 6 and was unable to transfer.) Trouble moving the fire trucks due to adverse environment (gasoline tank blocking the road, main gate stuck due to blackout. Workers had to destroy the lock on the gate between Units 2 - 3 to create passage) Delay in setting up water injection line from fire truck (ordering for fire trucks, transport to reactor building, connecting to fire protection system line) Insufficient water injection capacity of fire truck (1000 liters per payload) On March 12 filling of water to the reactor started at 5:46 and finished at 14:53 (total of 80 tons of water). At first they were only able to fill 1000 liters at a time, but later were able to fill water continuously. Before then the fire truck had to make laps for refills. Fast-progressing events require a more efficient response.	・Reinforce and add more backup water sources (install large fire protection tank) ・Increase number of fire trucks and hoses ・Review posting of fire trucks ・Secure predetermined route for fire trucks (for smooth transport during blackouts) ・Secure backup power supplies and pumps; upgrade fire truck; etc. ・ Investigate cause of the diesel-driven fire pump problem, and come up with a countermeasure.	○ ○ ○ ○ ○ ○	
Low pressure cooling function ②	・ Problem with the fire protection tank's design ・Inefficient water injection	・ 1F Unit 1: Inefficient water injection from the fire protection tank: Laps had to be made in loading fresh water from the Unit 3 fire protection tank to and transporting it to Unit 1 fire protection tank. The fire protection tanks only have one hose connection, so workers had no choice but to remove the injection hose and interrupt the injection each time it needed to be refilled.	・ Review the design of the fire protection tank hose connection.	○	
	・ Delay in boric acid injection (SLC)	・ 1F Unit 1: Delay in setting up boric acid injection (SLC): In concurrence with the water injection process (via fire truck), power restoration (via power supply vehicle) and Boric acid injection (SLC), pump restoration processes were on going. Preparation for boric acid injection was completed on March 12 (15:36), but the plant building exploded right after it was completed (15:36). SLC pump cables and the high pressure power supply vehicle were destroyed.	・ Secure backup power supplies (high pressure power supply vehicle) ・Supply more cables and fire trucks	○ ○	
	・ Same as above (due to explosion)	・ 1F Unit 1: Delay in boric acid injection (SLC): After the explosion on March 12 (19:04), seawater injection using the fire protection line fire truck commenced. Injection of seawater mixed with boric acid started later at 20:45.	・ Same as above	○	

Lessons-Learned from the Research on BWR, and its Applicability to PWR

Type	**Cause**	**Events / Issues**	**Measures / Lessons**	**Applicable to PWR?**	**Comments**
General lessons ①	・Difficulties executing countermeasures due to overwhelming, unexpected events, and severe accidents	・ General AM: Overwhelming difficulties and delays in executing countermeasures: As part of accident management the low pressure water injection was modified, and manuals have been distributed. The actual environment of the work field was adverse, and it required time to restore power and perform low pressure water injection. Workers were unable to contain the situation.	・ Improve the AM training to respond to more specific situations, and continue the training on a regular basis (effects of the earthquake and tsunami of this event, setting of specific target completion times for actions, confirm the time required, accrue know-how)	○	
	・Difficulties executing countermeasures due to overwhelming, unexpected events, and severe accidents	・ AM: Anticipate night time / holiday events: The field response to this event was difficult and slow because of the adverse field environment. Debris were scattered by the earthquake and tsunami, and lots of the work had to be done during the night.	・ Practical training simulating power outage during night / holiday ・Improve and standardize night time visibility of valves and gauges (use of fluorescent paint, etc.).	○ ○	
	・Risk of sharing water source and injection line for multiple purposes	・ Water source & water line: Risk of sharing lines for multiple purposes: We learned the importance of the fire protection system from the incident in Kashiwazaki-Kariwa Nuclear Power Plant when the transformer in Unit 3 caught fire during the Chuetsu offshore earthquake. As for this event, the M/C power panel in Onagawa Nuclear Power Plant Unit 1 caught fire. There was no fire in the Fukshima Dai-Ichi Nuclear Power Plant, which allowed them to use the power protection line and water source for lower pressure water injection. But if a fire had occurred, it can't be denied that it could have caused greater problems to the plant water injection operation.	・ Consider segregating water sources ・(Multiplex) Increase number of water source for the most important ones (take into account water source for fire response as well)	○ ○	
	・Risk of positioning several nuclear plants at the same place ・Diffculty of controlling several plants simultaneously during a severe accident and failure to respond to all of them.	・ General AM: Risk of operating multiple plants in the same location: Nuclear Emergency Response Headquarters of Fukushima Dai-Ichi Units 1 – 4 prioritized responding to Unit 1 because it wasn't able to maintain in high pressure cooling with IC. Units 2 & 3 weren't given priority since RCIC high pressure cooling was working. The decision was a right one to make at that time. However, looking at the fuel rod damage chronology of Units 2 & 3, They would have been able to avoid the worst-case scenario if they had been able to setup low pressure cooling system before the RCIC's DC power supply was depleted.	・ Organize the issues with the field response system ・Organize the problems encountered due to severe accidents simultaneously occurring at multiple plants ・Reflect the previous two items in the manual and conduct training.	○ ○ ○	
General lesson ②	・ Rupture disk pressure settings in Dai-Ichi Unit 2 were too high.	・ Dai-Ichi Unit 2: Difficulties venting R/D (required pressure was high) : Dai-Ichi Unit 1 and Unit 3 succeeded in venting the containment vessel suppression chamber (S/C). However, the same vent in Unit 2 failed to open even with the drywell pressure exceeding maximum capacity. The suppression chamber pressure wasn't enough to move the rupture disk (R/D). After that, a system to release the drywell pressure was set up, but S/C was damaged and the venting process was once again unsuccessful.	・ Reconsider the pressure settings of the rupture disk ・ Regular inspection and replacement of rupture disk	× ×	
	・ Relation between the containment vessel vent and the hydrogen explosion ・Hydrogen leak mechanism unclear	・ Dai-Ichi Units 1 & 3: Relation between the containment vessel vent and hydrogen explosion: Hydrogen explosion occurred in Fukushima Unit 1 and Unit 3 one to two hours after successful venting of the containment vessel. The hydrogen produced inside the reactor by molten fuel may have transferred and filled the containment vessel when the SR valve was operated, and released steam to the suppression pool. The hydrogen then probably leaked to the reactor building through the containment vessel's routing and vent line, or back flowed from the SGTS line connected to the exhaust stack. And finally, when the hydrogen accumulation exceeded the combustible limit, the explosion occurred. In this project we have taken into account the possibility that the hydrogen accumulation speeded up when the containment vessel was vented. Actual details and cause and effect are still unclear, so we are hoping that it will be solved in the future.	・ Identify the leak path of hydrogen into the reactor building ・Devise countermeasures for hydrogen leaks ・Review vent in post-core meltdown (nitrogen sealing, operation pressure) ・Prevention of hydrogen accumulation in reactor building and exhaust system	○ ○ × ○	Exhaust procedure established to annulus air cleaning fan by power supply from air cooling type generator device Hydrogen accumulation prevention measures implemented to annulus as stated above. However, concentration of hydrogen in containment vessel is extremely low compared to BWR
	・ Extended external power outage ・Extended DC power outage	・ General: Risk of extended external and DC power outage: External power outage, emergency DG malfunction, and seawater cooling system malfunctions occurred in Fukushima Dai-Ichi, Fukushima Dai-Ni, Onagawa, and Tokai Dai-Ni. Only Fukushima Dai-Ichi lost its DC power. By securing external power, the plant is able to retain its high pressure cooling system, buying time to restore the low pressure cooling system seawater pumps and motors, and deploy power supply vehicle. Prolonged station blackout depleted the DC power, and meant loss of hope of restoring the plant. Without the seawater pump working the DG won't function. This increases the urgency to restore external power for the seawater pump.	・ Increase number of temporary DC and AC power supplies ・Prepare connection devices for alternative power supplies ・Reinforce training	○ ○ ○	
General lesson ③	・ May not have considered the relation between vent operation pressure and hydrogen explosion. ・May have lack of understanding in hydrogen explosion risks, and lack of countermeasures in AM.	・ Fukushima Dai-Ichi (General): Relation between the mechanism of the hydrogen explosion and the vent operation: Compared to other electric companies, TEPCO had configured a higher value for the vent operation pressure. They thought that this would further decrease the chance of releasing radioactive materials to neighboring residences. However, this decision may have been one of the main reasons the hydrogen explosion occurred. It is postulated to have caused massive build up of hydrogen in the containment vessel. Regarding the hydrogen explosion, there is no record of a backup plan in the response chronology of Unit 1. We assume that that this accident was not expected by TEPCO.	・ Solve the mechanism of the hydrogen explosion (leakage path, accumulation path, ignition cause, etc.) ・Prevent hydrogen accumulation (Detector, reactor building vent, etc.) ・Verify the relationship between the vent and the hydrogen explosion ・Reflect in the corresponding manuals	○ ○ ○	
	・ Main control tower functions failed due to SBO	・ Fukushima Dai-Ichi (General): Effect of the incomplete main control room functions: The station blackout disabled the instrumentation and took away the indicator monitoring tasks from the operators.. Without the instruments, it's impossible to plan the next move. Further, when the Nuclear reactor is at high temperature, it's doubtful whether the indications given by the instruments powered by the temporary power supply are accurate. Without indicators the operators will succumb to fear, which affects their ability to make proper judgments. Operators must be equipped in order to be able to make proper judgments.	・ Secure main control room lights, field environment, measuring instruments, etc. (power, lights, work clothes, dosimeters, furniture) ・Reflect to AM and reinforce constant daily training ・Apply remote measuring instruments	○ ○ ○	
	・ Hydrogen explosion ・Leak of radioactive materials from explosion	・ Fukushima Dai-Ichi (General): Radiation leaked out to the environment when Units 1 – 4 exploded, causing enormous damage to the local community. Today, there are many that suffer from the effects of land contamination and radiation exposure. The spread of Cesium 137 (from the explosion) has a long-term effect, and is an especially big problem. The most important things are to prevent a hydrogen explosion at all cost, prevent the spread of radioactive materials, or to minimize the effect.	・ Prevent Hydrogen explosions ・ Create countermeasures against leaks and release of radioactive materials (Consider installation of vent filter, etc.)	○ ○	

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	Safety Measures （High Level）	Safety Measures (Detail)	Valid also with PWR?	Imple-mented or planned?	Comments
Secure power	Secure external DC power	● Improve water seal and pressure resistance of switching stations.	○	○	
		● Switching stations should be located in elevated areas, or sea-walls should be built to protect the equipment from tsunami impact.	○	○	
		● Improve earthquake tolerance of switching stations in the plant and of the transmission lines. Include those improvements in the design guideline as anti-seismic requirements.	○	○	
		● Multiply transmission lines from transformer substation (at least 2 lines), or connect each plant directly to the external power so as to prevent external power loss to such a substantial extent.	○	○	
	Same as above (Mid to long term)	● Regarding the substation power transmission lines, switch from overhead wires to underground cable.	○	×	
		● Remote control: Secure power transmission route and cables for remote supplying of power to the nuclear reactor from a power supply vehicle. (Or is it possible to supply without wires?)	○	×	
		● Improve earthquake resistance of substations and include it in the design requirements.	○	×	
	Secure emergency diesel generators (DG)	● Apply anti-flooding countermeasures to the DG room's air inlet.	○	○	
		● Improve water protection and pressure resistance of the DG rooms.	○	○	
		● Store controlling equipments and power cables to allow power interchange between separate DG rooms.	○	△	Added air cooling emergency DGs. Permanently-installed DG which can be connected with either A/B systems is planned.
	Same as above (Mid to long term)	● Place DG equipment on elevated areas (DG, power panel, etc.).	○	○	Plan to implement with the third power source.
		● Improve DG power interchange function: Interconnect all DGs to allow sharing of power to all nuclear reactors (was able connect power between Units 5 & 6 but not designed so with reactors 1 - 4).	○	○	Other than Ooi Plant, power supply can be shared among all plants through the secondary lines of backup transformer. (Procedure needs to be defined). Regarding Ooi Plant, further construction is necessary.
		● Plant should be designed to function even with minor flooding.	○	×	
		● The plant is vulnerable to disasters during regular inspection since the probability is high that the DGs is also stopped for inspection. Install an additional DG to eliminate this risk. Place air-cooling DG in an elevated area together with the gas turbine. Air-cooling type doesn't require seawater pumps and seawater circulation system. For fresh-water cooling DG, set it on an elevated area to avoid damage from tsunami.	○	○	
		● Place diesel and gasoline tanks on an elevated area to avoid damage from tsunami.	○	△	Already planned for countermeasures for sliding and floating of large tank.
	Same as above (Mid to long term. Mitigation measures)	● Automatically activate a DG if scrammed during earthquakes.	×	×	Because activated DG is weaker than the one stopped (with more effect of axis), automatic activation when external power has not been lost is not recommended.

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	**Safety Measures（High Level）**	**Safety Measures (Detail)**	**Valid also with PWR?**	**Imple-mented or planned?**	**Comments**
	Secure DC power	● Relocate equipment indoors - into a pressure resistant and water-sealed building to avoid flooding by tsunami.	○	○	
		● Station mobile battery vehicles (DC125V, 24V, and 250V) with cables in case of accidents to the DC power supplies.	○	△	There are two ways to supply power to the parameter-monitoring panel, the one via the DC line and the other directly through the AC panel. TD-AFWP can be activated manually even if the DC power is lost. (DC is only 125v).
	Same as above (Mid to long term)	● Relocate DC power supplies to a higher position.	○	△	Planned to either store portable batteries in the anti-seismic isolation tower, or implement the permanently installed DG in a higher place. Movement of facility is not being considered.
		● Upgrade DC power supply capacity (from 8 hrs to 24 hrs or more).	○	△ ×	Have AM procedure to extend battery life by limiting its use only to top priorities, and to bring in regular batteries. But it is difficult to last for 24hrs. The batteries can be re-charged by the air cooling DG.
	Secure AC power	● Improve water protection and pressure resistance of AC power supply equipment.	○	○	
		● Reinforce power supply vehicles: ・ Secure additional permanent units (secure necessary number of units based on the required load capacity). Review locations (i.e. elevated areas). ・ Increase the type of power supply vehicles: DC, AC, combination of AC & DC, w/ generator, w/DG, etc.	○	△	Other than the air cooling emergency DG (2 units at each plant), 2 power supply vehicles are placed at the plants. Those vehicles supply power to the metal clad switching gear (6.6kv). Vehicles with various voltages and back-up powers to P/C have not been deliberated (if voltage is lowered it is necessary to make the cable larger).
		● Set multiple access points of power panels for power supply vehicles and ensure water protection.	○	○	
		● Increase number of backup power supplies besides the power supply vehicles.	○	○	
		● To hasten restoration of AC power, set up power supply cables and store tools for terminal handling in accessible areas for swift response.	○	○	Already set up the connection board and cable from air cooling emergency DG.
	Same as above (Mid to long term)	● Sharing of AC power distribution（Cross-connect all units to allow distribution of power through M/C and P/C）.	○	△	Backup transformer's secondary side is connected to all plants. (In Ooi reactor 3&4, it is also planned). The connection is through M/C, not P/C.
		● Utilize air transport of power supply vehicles and backup power source after the tsunami and earthquake have subsided.（Set helipad on the roof/in the vicinity of the reactor building.）	○	○	Heliport is set on-site and near the site.
		● Transfer the AC power supplies to a higher location.	○	○	Air cooling emergency generators are installed in a higher place.
Secure functions of control room	Secure functions of control room	● Secure livable conditions and monitoring capabilities for operators ・ Main control room has to function as a shelter during emergencies, so protection against radiation should be improved.	△	×	In Fukushima Dai-ichi, it is estimated that operators in the control room were exposed to radiation from fission product that flowed into the room through the duct hoses for ventilation which were brought into the room. As to the improvement of shielding, if it means to enhance the air seal by closing doors, it is also applicable to PWR. However, the phrase of 'improvement of shielding effect' usually means to lower the radiation level in the room by increasing the thickness of concrete wall or ceiling. Revision of terminology may be appropriate.
	Same as above (Mid to long term)	・ To ensure the vent and air conditioning systems in the main control room, emergency power systems such as gas turbines should be installed.	○	○	Already introduced the measure to supply power from air cooling emergency DG to ventilation fan in the control room, and remove fission products with filters.
	Same as above（Mitigation measures）	・ Store spare batteries in case meters and gauges stop working.	○	△	Is now considering to implement connection lines and devices for regular batteries. Will consider to utilize portable batteries.
		・ Store sufficient quantities of protective gear, masks, dosimeters and other supplies. Since the situation in Fukushima lasted several days, there should be adequate supplies stored for the duration.	○	○	
	Same as above (Mitigation measures. Mid to long term)	・ Due to power shut down, parameters such as the reactor's water level and pressure were no longer observable. Portable measuring instruments and alternative measurements should be developed .	○	○	Plan to examine this issue in the research project of the government, "research on parameter-monitoring systems for severe accidents (phase 1)".

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	Safety Measures（High Level）	Safety Measures (Detail)	Valid also with PWR?	Imple-mented or planned?	Comments
Secure high pressure cooling system	Secure high pressure cooling system	● The HPCI and RCIC are installed in the basement of the nuclear reactor plant. Although the reason it stopped working was due to the power loss, it's still necessary to maintain the water seal and pressure resistance of the room to ensure the safety of the pumps and motors inside.	○	○	For PWR, TD-AFWP and MD-AFWP are the high pressure cooling systems. Sealing of the room with these systems for water protection has been implemented to doors of the rooms. In the future, the doors will be replaced with the water-proof ones.
		● Since the nuclear reactor in a high pressure state can be cooled by SLC, CRD, and CUW water injection methods, it's important to secure power supplies for these systems. It is necessary to consider storing temporary power supplies to ensure power for the systems above.	○	○	It is possible to supply power to MD-AFWP (2 units), which supply water to SG in case TD-AFWP is lost, from air cooling emergency DG. The DG can also supply power to a mid-to-high pressure pump which is under planning.
	Same as above（Mitigation measures）	● Night work progress was slow. There was a delay in restoring the high pressure cooling system, which caused the situation in the plant to worsen, and delay the staging of the low-pressure cooling system. To improve efficiency of the field work, mark valves and machines that need to be operated with fluorescent paint for easy observation. Coating the temporary power cables with fluorescent paint will provide easy direction to install.	○	△	Though not in the central control room, fluorescent paint was used in NFB on the DC board, so as to easily lower the battery load during SBO.
	Same as above（Mitigation measures. Mid to long term）	● It takes too much time and causes delays in decision-making if operators are unable to access the site to confirm the state of the high pressure cooling system. We think that it will be effective to have multiple means to observe the site. This will require power but we suggest installing ITV (for vision), sound monitors, and vibration sensors to allow remote monitoring of the status of the pumps, gauges, and valves.	○	△	High performance cameras (approx 50 units) are installed for prompt actions against fire. The cameras can be remotely controlled from the central control room and accident management room. It is possible to check the instrumental devices by some of those cameras. In order to monitor inside of the containment vessel where operators cannot easily access, ITV has been set up.
Secure ventilation functions	Secure containment vessel ventilation functions（Mitigation measures）	● Prepare items for setting up ventilation line (temporary power supplies, air tanks) beforehand for efficiency.	○	○	(As PWR does not have PCV ventilation function, we treat the functions of Main Steam Relief (MSR) valve to release heat of steam outside of PCV as an equivalent to PCV ventilation in BWR). For PWR, though the MSR valve can be operated manually even if air-pressure pump is lost, it is planned to consider to store back-up compressor to open the valve.
		● Given that PCV ventilation operations failed in the reactor No.2, reconsider the vent's pressure requirements (reconsider the pressure limit of the rupture disk).	—	—	MSR valve can be opened/closed by hand.
	Same as above（Mitigation measures. Mid to long term）	● Install a neutron sensor inside the containment vessel to observe the activities inside the core during meltdown.	○	×	Plan to examine this issue in the research project of the government, "research on parameter-monitoring systems for severe accidents (phase 1)".
		● Multiplex the air pressure supply and vent line and classify them to the 'safety-system' class to ensure the reliability.	○	○	Air compressor system for the MSR valve is doubled as a safety system. Further alternatives are being implemented.
		● Too much time was consumed in the construction of the vent line. Consider placing the valve in an accessible area and allow manual operation.	○	○	Access to MSR valve is easy as it is outside of PCV.
		● Given that ventilation with the rupture disk in reactor No.2 was unsuccessful, consider the use of a valve for ventilation without the disk.	—	—	MSR valve can be opened/closed by hand.
	Depressurization with SR valve operation（Mitigation measures）	● Unable to perform depressurization operation using the SR valve due to DC power outage. Prepare batteries in the central control room.	○	△	The MSR valve is operable without any power source. Portable batteries are not prepared yet.
	Same as above（Mitigation measures. Mid to long term）	● Consider SR valve mechanism that doesn't rely solely on DC power	○	○	The MSR valve is operable without any power source.
		● Consider multiple methods for nuclear reactor depressurization	○	○	MSR valves are placed at each steam generator. For Ooi reactor No.3, 4 units were installed. Pumps to cool SG are TD-AFWP (1 unit), MD-AFWP (2 units), mid-to-high pressure pump (1unit under planning), and fire extinguishing pump.

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	**Safety Measures（High Level）**	**Safety Measures (Detail)**	**Valid also with PWR?**	**Imple-mented or planned?**	**Comments**
Secure low pressure cooling system	Secure low pressure cooling system	● Place emergency core cooling pumps, used for low pressure cooling, at a higher location to avoid damage from tsunami; or, secure water protection and pressure resistance.	○	○	
		● Secure appropriate number of fire trucks and hoses, and station them on higher ground. Take into account the water source, water injection range, and water injection capacity when selecting the fire trucks.	○	○	
		● Set multiple water injection points for fire trucks	○	○	
		● Investigate why the diesel-driven fire pump lost its function and develop appropriate countermeasures.	○	—	
	Same as above (Mid to long term）	● Reinforce water sources: Need to supply water from multiple sources, such as a water tank, dam, reservoir, lake, river and/or sea. Also, review whether the water supply methods and available capacity are sufficient. If the water supply will also be used as a coolant, consider the following:	○	△	Anti-seismic tank in an elevated place is being considered.
		・ Whether boric acid can be poured in			Intake to SG: Main water supply - 4 places, supplemental water supply - 4 places.
		・ Design a mechanism that allows contaminated water in the reactor building to be used as coolant in the circulation system.			
		・ Prepare multiple routes for the coolant			
	Same as above（Mitigation measures）	● Reinforcement of water supply paths: Confirm other means of water supply than by fire truck (i.e. air-lift or sea transport)	○	○	Mid-to-high pressure pump, anti-seismic tank in an elevated place (injection to condensate tank by gravity).
		● There was no means of monitoring the spent fuel pool in the field, so temperature and water level monitoring instruments (requires power) need to be installed. As a backup plan in case instruments are not working, prepare portable contactless thermometers and water level indicators.	○	○	Monitoring camera, measuring scale for water level.
		● Multiplex the cooling systems for the spent fuel pool.	○	○	Recover CCW cooling by large volume pump, and recover SPF cooling by SFP pump and cooler.
	Same as above（Mitigation measures. Mid to long term）	● Secure the water source for low pressure water injection while taking into account its cross-use for fire fighting.	○	○	
Secure ultimate heat sink	Secure seawater cooling system	● Need to prepare portable water pump and temporary power supply in case the seawater pumps malfunction from tsunami attack.	○	○	Large volume pump（to be placed in December, 2011）
		● The seawater pump in the building was flooded and malfunctioned. Aside from improving the water seal and pressure resistance of the building, it is also important to completely shut the building doors when there is a tsunami warning.	○	○	
	Same as above (Mid to long term）	● When adding or replacing emergency generators, secure the cooling line for the air-cool types as backup systems (not relying on seawater coolant).	○	○	PWR has an ultimate heat sink that releases steam-heat to the air and does not rely on sea water cooling. An application of air fin cooler is being deliberated.
		● Operate feed-and-bleed cooling with the wet well vent (secure heat sink until cold shutdown.).	—	—	PWR has a method for low-heat shutdown by SG.
		● Diversification of heat release methods for containment vessel when all AC power is lost	○	○	In addition to the method above, PWR has already planned to establish a method for low-heat shutdown by using RHR and reactor auxiliary cooling water system with large volume pump to use ocean as an ultimate heat sink.
		● Build sea-wall or breakwater	○	○	
		● Introduce alternative core cooling systems (water source, power source, and water injection system)	○	○	Power is connected to a M/C panel from the air cooling emergency DG while for water source a large volume pump is connected to sea water pipeline.
	Same as above（Mitigation measures）	● Equip the site with motor cleaning and winding equipment, and secure spare parts.	○	○	A back-up motor for sea water pump has been stored.
	Same as above（Mitigation measures. Mid to long term）	● Since the seawater pumps/motors malfunctioned due to the tsunami, consider using sealed type motors (reinforced pressure resistance and water seal).	○	○	A back-up motor for sea water pump has been stored.

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	Safety Measures（High Level）	Safety Measures (Detail)	Valid also with PWR?	Imple-mented or planned?	Comments
Prevent hydrogen explosion and radiation leakage	Prevent hydrogen explosion	● Install hydrogen ventilation systems in the nuclear reactor building to open before it's filled with hydrogen (vent system with remote control + manual control + radioactive material filtering).	↓	↓	In PWR, if hydrogen leaks from various penetrations of containment vessel, the annulus fan powered by alternative power source can exhaust the gas.
		● Even if large quantities of hydrogen are generated and leak from the containment vessel, before hydrogen detonation occurs, should use a hydrogen release method from the annulus. (PWR) (Release method to include suction filter to remove fission products.)	○	○	
		● Reinforce air-seal of containment vessel: Review the materials in the seals of areas including the D/W flange, electric routing, hatches, etc. Reinforce resistance against high temperature and pressure.	△	—	Damage of various seal in PCV penetrations was caused by the radiation heat due to core meltdown. Because the PWR containment vessel is large, the effect is assumed to be small. Countermeasures are realistically difficult.
		● In case mass hydrogen build-up does occur, prevent it from accumulating in an enclosed space. ・ Install hydrogen detectors in closed spaces (Transmit signals using own battery line or RF). ・ Perform preventive measures such as using a nitrogen seal inside the containment vessel when venting.	○	○	
	Same as above (Mid to long term）	● Reconsider the shape of the upper area/ ceiling of the nuclear reactor, containment vessel, and reactor building so that the hydrogen does not accumulate in one narrow space (i.e. slant ceiling to redirect the gas).	×	×	In the PWR, in preparation for hydrogen leaks through PCV's penetration, an AM procedure to supply power to annulus fan for ventilation has been prepared.
		● Capacity of the PWR containment vessel is large. Even if large quantities of hydrogen are generated, the concentration in the containment vessel will be small compared to BWR. The danger of hydrogen combusting is low, but from the viewpoint of lowering hydrogen concentration over the long term, install a hydrogen depressurizing facility, such as a static catalytic hydrogen recombining device, in the containment vessel.	○	○	
		● Consider reinforcing the concrete or install a debris catcher to prevent debris from penetrating the containment vessel (prevent debris concrete reaction in pedestal).	○	△	Core-catcher is implemented. A water injection hole has been set in the containment cavity (AM countermeasure).
	Same as above（Mitigation measures）	● To prevent the rupture disk from failing, conduct regular inspections and replacement.	—	—	PWR has no containment vessel ventilation or rupture disk.
		● In Fukushima Dai-ichi, although they were apprehensive of radiation leakage in reactor No.1, they weren't anticipating a hydrogen explosion. Add procedures for handling hydrogen explosions in the Accident Manual and conduct training to ensure accurate responses.	○	○	In the PWR, in preparation for hydrogen leaks through PCV's penetration, an AM procedure to supply power to annulus fan for ventilation has been prepared. Trainings have been conducted.
	Prevent radiation leakage（Mid to long term）	● With the hydrogen explosion causing the spread of radioactive materials, evaluate the effectiveness of the wet well vent and consider installing a vent filter.	—	—	PWR can release its decay heat (steam) to the open air via SG even if all the AC powers are lost. The pressure within the PCV are not assumed to rise very much.

Applicability of Safety Measures to PWR, and the Level of Implementation

Purpose	Safety Measures （High Level）	Safety Measures (Detail)	Valid also with PWR?	Imple-mented or planned?	Comments
Disaster response manual・Infra-structure etc.	Update disaster response manual (AM)	● Redesigning AM: How many hours should the plant's water and power sources last? How to get reinforcement from outside? Implement the following:	○	○	
		・ Define the numerical requirements specifically as to the minimum number of hours in which coolant and power should last on-site, and add to the operation manual.	○	○	
		・ In the logistics and accident manuals, specify how to bring in additional power, coolant, and other supplies from off-site before the on-site power and coolant are lost.	○	○	
		・ Reinforcement of training: Do not let the training end with the preparation phase. It's necessary to cover the actual processes (e.g. actual connection of cable terminal) and reflect its mechanism in the training as well.	○	○	
		● Revise the power restoration manual: The manual originally gives guidelines in restoring short term power loss. Revise the manual to anticipate up to a few days of power loss.	○	○	
		● Since earthquake and tsunami can hit all of the reactor units in the power plant at the same time, there should be plant-wide training with night and holiday scenarios as well.	○	○	
	Review the methods of earthquake and tsunami risk	● Revise the organization of the nuclear disaster emergency to handle concurrent accidents on multiple plants.	○	○	
		● Include risk assessment in regards to the power of a tsunami besides its height.	○	○	
		● Assess the risk of tsunami and earthquake more frequently on regular basis	○	○	
	Reinforce infrastructure	● Enforce quick assembly of operators to the plant in case of an earthquake (including at night and during holidays). Secure necessary staff for the emergency response as well (e.g. Require assembly within X hours).	○	○	
		● Communication means among operators in a control room of each plant, accident response members in the field, on-site emergency response headquarter, and the central control room were cut off, thus affecting timely reports. This slows down the emergency response, so it's important to secure and distribute appropriate numbers of communication equipments (means of communication).	○	○	
		● Improve the environment of the emergency response headquarter on site by providing sleeping quarters and bedding.	○	○	
		● Improve the structure of the anti-seismic isolation tower against tsunami (Secure emergency power supplies as well).	○	○	
		● To improve the accessibility to the plant after earthquakes and tsunami:	○	○	
		・ Secure sufficient numbers of heavy machineries and operators for clearing the debris	○	○	
		・ Bolt-down the gasoline tanks to avoid floating.	○	○	
	Same as above (Mid to long term）	● Reinforce roads to the head quarters (including anti-liquefaction)	○	○	Strengthening of the roads on the grounds has been implemented
		● Ensure that the transport path remains after earthquakes and tsunami (Construct a path that won't crack or suffer liquefaction. No manholes).	○	×	Transportation methods by sea and air have been enhanced.
		● Reinforce roads and bridges leading to the power plant.	○	○	Bridges are planned to be strengthened.
		● Secure safety of the workers: Consider responding remotely and with fewer staff. (e.g. Set up long distance hoses beforehand, allow remote control of hoses as with a crane, etc.)	○	○	Enhance the emergency organization, power savings, and safety measures to easily connect emergency equipments are being implemented