Crossroads of Severe Accident and Cold Shutdown of Nuclear Power Plant Affected by Earthquake and Tsunami

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Abstract: March 11 of 2011 is the day that should be engraved in the heart of nuclear societies. The 2011 earthquake off the Pacific coast of Tohoku occurred at 14:46 Japan Standard Time on March 11. All the nuclear power plants in the Eastern Japan along with the Pacific Ocean coastline have successfully shutdown according to the earthquake ground motion. In 40 minutes, the first tsunami struck the Fukushima Dai-ichi Nuclear Power Station. The tsunami height was 15 m at maximum which was far beyond the design tsunami height. It caused the submergence in seawater of the emergency power supply and seawater systems. It results in the station black out and loss of ultimate heat sink in the units 1-4 of the Fukushima Dai-ichi Nuclear Power Station. To make the matter worse, hydrogen explosion in the reactor building took place, which has every effort for recovery all fail. Consequently the reactor cores were seriously damaged and the nuclear fuel melted which lead to the radioactive material release to the environment. Evidences currently available indicate no seismic structural failure of safety systems and components. The tsunami and the station blackout gave intense impact on the nuclear system resulting in the severe accident. In response to the lessons-learned from the Fukushima Dai-ichi NPS accident [2], the safety margins evaluation and safety enforcement of the nuclear power plants are necessary immediately. The nuclear system should have robustness for the beyond design basis conditions and resilience in case that the multiple levels of defense lines are deteriorated. Accordingly, the best performance in nuclear safety is to be achieved. The key for achieving the ultimate safety is of course the probabilistic risk assessment.

Keywords: *External Event, Sever Accident, Station Black Out, Accident Management*

1. INTRODUCTION

March 11 of 2011 is the day that should be engraved in the heart of nuclear societies in Japan as well as worldwide. The 2011 earthquake off the Pacific coast of Tohoku occurred at 14:46 Japan Standard Time on March 11. All the nuclear power plants (11 out of 15 units were in operation in 5 sites) in the Eastern Japan along with the Pacific Ocean coastline have successfully shutdown according to the excessive earthquake ground motion. In the Fukushima Dai-ichi (F1) Nuclear Power Station (NPS), units 1-3 were in full power operation, units 4-6 are in outage for refuelling. It is noted that, in unit 4, all the nuclear fuels were transferred to the spent fuel pool for the replacement of the reactor vessel shroud. Thus the cooling of the unit 4 reactor core was not necessary

In 40 minutes at 15:27, the first tsunami struck the F1 NPS. Consecutively, other tsunamis rushed one after another, which caused the submergence in seawater of the emergency diesel generators, switchgears, seawater pumps, and so on. The tsunami height was 15 m at maximum while the design tsunami height is 3.1m and the most recent estimate based on Japan Societies of Civil Engineers [1] is 5.7m. The site elevations are 10 m for units 1-4 and 13 m for units 5 and 6 of F1 nuclear power plant, respectively.

In Fukushima Dai-ni (F2) NPS, the first tsunami arrived at 15:23 and the second one that is the largest struck the site at 15:37. The tsunami height was 6.5-7 m at the sea side buildings. On the mountain side 14-15 m run-up was observed. The original design tsunami height is 3.1-3.7 m and the Japan Societies of Civil Engineers [1] estimate is 5.1-5.6 m. The site elevations are around 12 m at the reactor and turbine buildings and 6 m at the sea water pump room in the F2 NPS. It can be said the tsunami severity is much more significant in the F1 site than the F2 site.

It resulted in the station black out (SBO) and the loss of ultimate heat sink (LUHS), i.e., the off-site power, the emergency diesel generators and the seawater systems were lost in the units 1-4 of the F1 NPS. Without recovery of the AC power, the reactor cores were seriously damaged and the nuclear fuel melted which lead to a severe accident and the radioactive material release to environment. To make the matter worse, the hydrogen explosion in the reactor building of unit 1 took place which had every effort of the staffs and workers in units 1, 2 and 3 for recovery all fail. As a result, it provoked the nuclear power plants uncontrollable and loss of cooling capability of the reactor cores as well as the spent fuel pools. As to the units 5 and 6 of F1 NPS, the situation is almost the same as the units 1-4 except that one of the emergency diesel generators survived which could supply AC power to the unit and to the other unit later.

In F2 NPS, the loss of seawater pump took place in units 1, 2 and 4. Also, the emergency diesel generators were lost because of submergence in units 1 and 2. Although the loss of ultimate heat sink occurred in units 1, 2 and 4, sufficient time was available for the recovery of the ultimate heat sink. They used the makeup water cooling (MUWC) system and the reactor core isolation cooling (RCIC) system to supply water to supress the water temperature increase in the suppression chamber. Lastly the sea water pump motors were replaced and let the residual heat removal system in operation. It was excellent accident management procedures and the staffs and operators at F2 site are applaudable.

As can be seen, the final figures of individual units are drastically deferent among the plants in F1 and F2 NPS. Within F1 NPS, the units 1-4 and units 5-6 follows separated scenario although all the units suffered from the earthquake and tsunami of the same characteristics. In the present paper, the author investigates the severe accident progression and tries to identify the crossroads beyond which some go to the severe accident while the others to the cold shutdown.

2. CHRONOLOGICAL TABLE OF FUKUSHIMA ACCIDENT

2.1. March 11, 2011

At 14:46 on March 11, 2011, all the operating nuclear power plants, i.e. units 1-3 in F1 NPS and units 1-4 in F2 NPS shutdown automatically by the control rods insertion. The F1 NPS is connected to the off-site power grid by 6 separate lines. The off-site power was completely lost by the circuit breaker failures, the falling down of a transmission tower and so on. As expected in design, the diesel generators automatically started to supply alternative current (AC) power to all the units. The F2 NPS has four lines connected to the off-site power grid. Three lined were available and one line was disconnected for maintenance. The earthquake caused failures in an electric power substation that resulted in the failure of power supply in two lines. Fortunately, one line in F2 NPS site survived the earthquake and AC power is successfully supplied from the power grid.

At 15:27, the first tsunami hit the F1 NPS followed by the second tsunami in 10 minutes later. The emergency diesel generators of units 1 and 2 failed to continue operation at 15:37 and 15:41, respectively. Units 3 and 4 emergency diesel generators stopped operation at 15:38. Units 1-4 in the F1 NPS have lost the AC power; that is the SBO. Seawater pumps were also lost because the motors went under the seawater; it is the loss of ultimate heat sink (LUHS). Furthermore, the DC batteries of units 1 and 2 were submerged as well. The batteries of the unit 3 were functional. However, they will be depleted sooner or later if the AC power supply is not recovered. Thus the turbine-driven feed water pump could not continue to be in operation. To make the matter worse, the operators were not able to know the plant parameters.

It is the story how the SBO and LUHS happened in the units 1-4 of F1 NPS. The on-site administration staff did not have information on the reactor vessel water level and coolant injection situation. It was unlighted and in darkness. No communication system was available. The severe accident started in the extreme and exceptional conditions.

At 21:51, the radiation dose started to increase in the reactor building of unit 1. In the turbine building, the radiation dose increased to 1.2 mSv/h at 23:00. All night long, every effort was made for the AC power recovery and water injection to the reactor cores. It was hard and tough work under repeating aftershocks and tsunami warning in the darkness.

What should have been done were the containment venting and the emergency water injection. However, they had no electricity. In the on-site administration office, the design information on the containment venting system was collected to judge if manual venting was possible without DC batteries. At 23:51, portable batteries (removed from automobiles) were connected to the containment pressure indicator. It indicated the containment pressure reached to 1.5 times of the design pressure.

As to unit 3, the DC batteries were available and the operator manually started the reactor core isolation cooling (RCIC) system at 16:03. At 2:55 on March 12, the operator went round the reactor building and found that the RCIC system of unit 2 is working. It is confirmed that the water was injected by the RCIC to the reactor cores of units 2 and 3. Emergency response to unit 1 should be with the highest priority.

2.2. March 12, 2011

At 0:30 a.m. midnight, the administrative confirmed that the evacuation of residents within 3km distance had been completed. The containment pressure increased to twice of the design value at 2:30 a.m. At 4:23, the radiation dose at the main gate of the site escalated by ten times in twenty minutes. A fire pump was used at 5:46 a.m. for alternative coolant injection to the reactor core. They were preparing for the containment vent and setting the vent line all the night. However it is difficult task in the total blackout situation.

In the morning at 9:15 a.m., the motor operated valve was of the vent line was manually opened by 25% while a pneumatic operated valve in series could not be opened because of insufficient driving pressure. Finally at 14:30, the containment vent was succeeded and the containment vessel pressure started to decrease. It seemed the containment integrity and its function was maintained. Although they ran out of flesh water for reactor core cooling at 14:53, they were ready to inject seawater using fire engines. In unit 2, power centres were not submerged and were available. They were connecting the power-supply vehicles, which were delivered from other sites, to the terminal of the power centres. In unit 3, the RCIC tripped at 11:36. The reactor water level decreased which automatically start up the high pressure coolant injection (HPCI) system. It supposed to be in operation at least until the battery depletion.

They were setting up the water injection line from the sea to the standby liquid control system. It seemed things were getting better although the reactor core had been already damaged and radioactive material had been released outside to some extent.

The power-supply vehicle was connected to the electricity panel. Water injection via the standby liquid control system was ready. The turning point was 15:36 p.m. A hydrogen explosion occurred in the unit 1 reactor building. The hoses and cables outside were seriously damaged by the explosion. All the preparatory actions were brought to nothing. They had to start from zero.

2.3. March 13, 2011

At 2:42, the HPCI system stopped operation and they could not start the RCIC system in the unit 2. It is loss of cooling capability in unit 2. The containment vent was done at 9:20 and the CV pressure stared to decrease. At 9:25, they used the fire protection line for pure water injection. However, the water tank dried up at 12:20. They started to inject seawater using the fire protection system (FPS) at 13:12. In unit 2, the containment vent was ready at 11:00. However, the containment pressure is too low to break and open the rupture disk.

In unit 3, the HPCI ceased at 2:42. The RCIC system did not work. The staff declared loss of cooling capability at 5:10, which was declared on March 11 for units 1 and 2. At 9:08, the safety relief valve was opened and the reactor pressure vessel was depressurized. At 9:20, the pressure in the dry well decreased and it seemed the containment vent was successfully done. Following the depressurization, water was injected via the FPS at 9:25. However they ran out the pure water at 12:20 and seawater injection started at 13:12.

2.4. March 14, 2011

In unit 3, seawater in the intake pit ran out and seawater injection was temporally stopped at 1:10. They started seawater injection again at 3:20 using fire engines. A wet well vent was actuated at 5:20. Seawater injection rate is not sufficient enough to remove the decay heat. Another hydrogen explosion occurred at

11:01. Eleven workers were injured. However, many things must be done even after. They moved the fire engines to another place and set up the seawater injection line. Seawater was injected at 16:30 again.

The explosion affected significantly the accident management for unit 2. The fire engines and the hoses for seawater injection were destroyed in an instant. Isolation valve in the vent line was closed accidentally and they could not open it. They collected batteries of automobiles and they connected the batteries to opene the safety relief valve to depressurize the reactor pressure vessel. At last at 18:00 they succeeded the depressurization and started low pressure seawater injection at 19:54. However, they could not open the containment vent line and integrity of the containment vessel of unit 2 is the major concern.

2.5. March 15, 2011

Early in the morning, they heard an explosive noise. According to the later investigation, it came from the reactor building of unit 4 which does not have nuclear fuels in the reactor pressure vessel. The hydrogen from unit 3 adversely flowed into the unit 4 reactor building and small explosion and fire occurred. Also in the morning, they found the containment pressure in unit 2 suddenly decreased. The containment vessel of unit 2 failed probably by over pressurization. This is considered to be the major cause of massive radioactive fission product release to environment. At 23:05, the dose at the main gate of F1 NPS reached to as high as 4.5mSv/h

Hydrogen explosions occurred in unit 1 and unit 3. Containment vessel failed in unit 2. Furthermore, minor hydrogen explosion and fire seriously damaged the reactor building of unit 4.

2.6 March 16, 2011

Although units 1-3 reactor cores were damaged, seawater was injected to avoid the core temperature escalation. Problem remained was the cooling of spent fuel pool (SFP). On March 16, the cooling of the spent fuel pools started. A helicopter flew over the reactors and dropped buckets of water to the spent fuel pool of unit 3. Also they observed the water surface sufficiently high above the top of fuel assemblies in unit 4. The following days, concrete pump vehicles were used to pour water directly into the SFP.

Table 1 shows the heat generation from fuel assemblies in individual SFP and allowable days during which no water supply is necessary. It is noted the grace days of unit 4 is 12 days.

Table 1 Available days for spent fuel pool cooling

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Shared pool
# of Fuel SA	292	587	514	1331	946	876	6300
Water inventory (m^3)	1020	1425	1425	1425	1425	1497	3828
Decay heat (Mcal/h)	60	400	200	2000	700	600	1000
Coolant（ton/day）*	2.5	16.3	8.2	81.5	28.5	24.5	40.8
Grace Days（Day）**	278	58	117	12	33	41	63

* Daily water use to cool the fuel SA. Initial water temperature is assumed to be 50℃
**Available outage days until the water level decreases to 4m (top of fuel SA)

2.7. March 23, 2011

As the seawater was injected continuously, the rate is not much enough to cool down the core. On March 23, the situation took a favourable turn. Figure 1 shows the transient course of temperature in the reactor pressure vessel and containment vessel of unit 1. They started to use the feed water system to supply the seawater. Thus the injection rate increased from 2 ton/h to 18 ton/h. From Fig. 1, it is seen that the temperature in the RPV instantly decreased to 200 C from400 C. It was confirmed that the reactor core would be controllable by adjusting the water injection rate. It was the end of confusion. It was the beginning of the accident termination process.

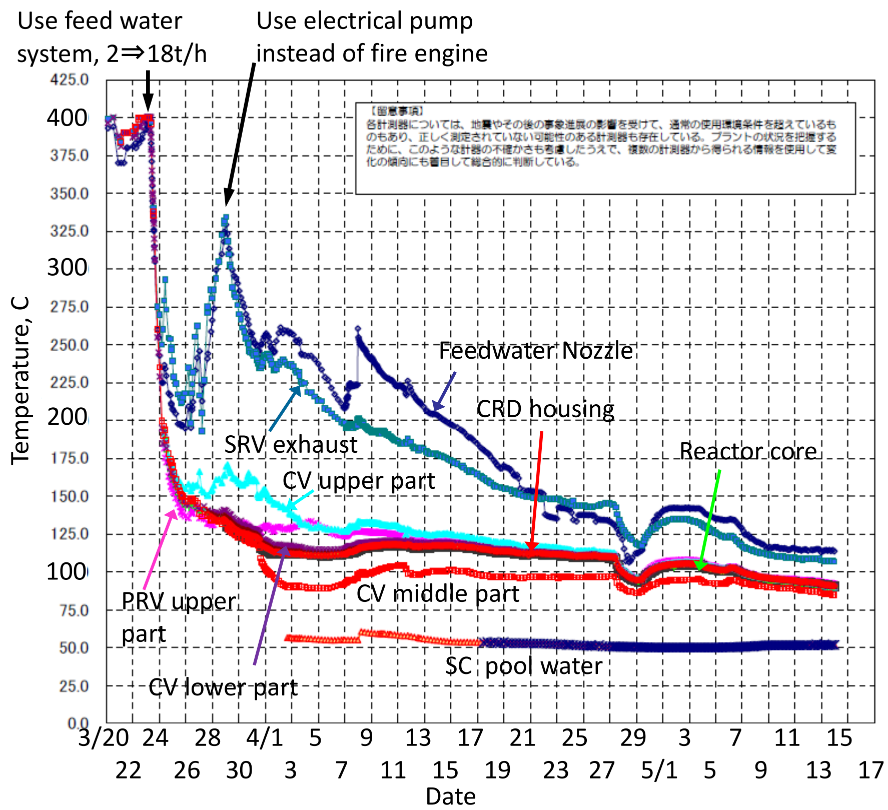

Figure 1. Transient courses of temperatures in RPV and CV.

3. ESSENTIAL CROSSROAD FOR SAFE SHUTDOWN AND SEVERE ACCIDENT

Fundamental concept of the nuclear safety is the defense-in-depth. The first level is the prevention of deviation from normal operation. The second level is the control of abnormal operation. The third level is the control of accidents in design basis. The fourth level is the accident management including confinement protection which relate to the prevention and mitigation of severe accident. The fifth level is the off-site emergency response on the premise of postulated severe accident. The Fukushima accident sequence goes beyond the third defense line, i.e. the design basis conditions. The crossroad of the severe accident and cold shutdown significantly depends on success or failure of the accident management.

	Neutronic SD	Off site power	Sea water pump	Emergency DG	Power provision	OSP Recovery	SWP recovery	EDG recovery	DC battery	HP injection	Depressurization	LP injection	Decay heat removal	Core damage	CV venting	Reactor building	Coolant injection
1F-1	○	×	×	×	×	×	×	×	×	×	×	×	×	M	○	D	○
1F-2	○	×	×	×	×	×	×	×	×	○	×	×	×	M	○	○	○
1F-3	○	×	×	×	×	×	×	×	○	○	×	×	×	M	○	D	○
1F-5	—	×	×	×	○	×	○		○	○			○	C	—		
1F-6	—	×	×	○		×	○		○	○			○	C	—		
2F-1,2	○	○	×	×			○		○	○			○	C	—		
2F-3	○	○	○	○			○		○	○			○	C	—		
2F-4	○	○	×	○			○		○	○			○	C	—		

Figure 2. Safety function and accident management in F1 and F2 nuclear power plants.

Figure 2 shows the list of success or failure of safety functions for F1 and F2 nuclear power plants. Since all the fuel assemblies are removed from the core in unit 4 of F1 NPS for the reactor vessel shroud replacement, it is not included in the list. The reactor core melt occurred in the units 1-3 of F1 NPS. Units 5 and 6 of F1 NPS were in serious situations. However, accident management for severe accident prevention was successful. All the units in F2 NPS achieved cold shutdown.

Figure 3 shows the event tree (ET) of the accident sequence for F1 NPS, units 1-3 and units 5-6 and F2 NPS, units 1-4. The upward and downward branching are success and failure of the safety function, respectively. The numbers in the rightmost column indicate the severity of the scenario. A binary digit 1 or -1 is summed up for each heading of the event tree branches. In other words, -1 is counted if a safety function fails, and +1 is counted if the function is successful. When a failed safety function is recovered, 1 is counted. For example, in the unit 3 of F1 NPS DC power was available (+1), off-site power was lost (-1), emergency DG was lost (-1), HPIS worked (+1), AC power recovery failed (-1), reactor depressurization was successful (+1), residual hear removal failed (-1). Thus th summation of the scores is -1, negative. In this way, the positive number means safe situations and negative number means some safety functions were not successful. It is noted the success of the reactor scram is not counted. The score is -6, -4 and -1 for units 1, 2 and 3 of F1 NPS, respectively. On the other hand, the score is 2 for units 5 and 6 in F1 NPS and 4 or more for F2 NPS.

The crossroad of positive or non-positive score is shown by the thick horizontal line in Fig. 3. It evident that the turning event for avoidance of the severe accident is the AC power availability.

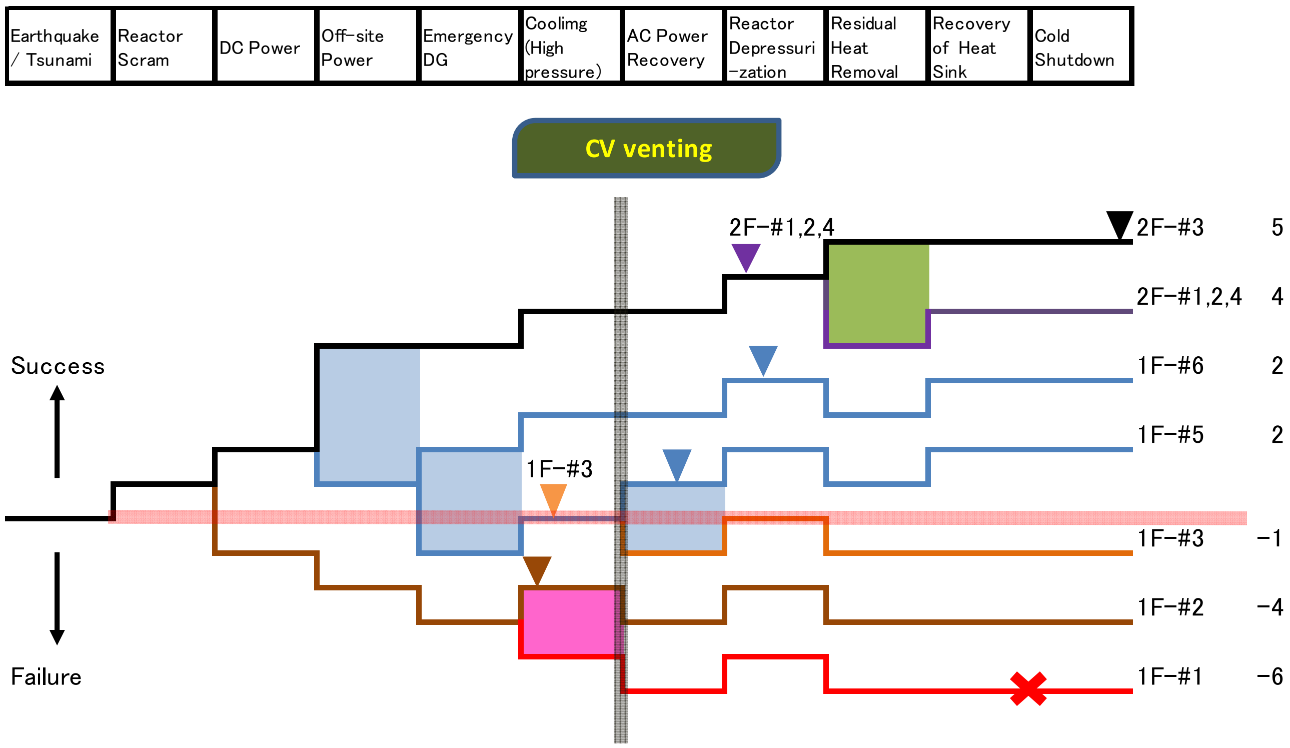

Figure 3. Event tree of the accident progression in Fukushima Dai-ichi and Dai-ni NPSs.

As the author mentioned, the hydrogen explosion took place in the afternoon of March 12, which is an important turning point of the accident progression. The upside-down triangles in the ET is the status of each unit at the time, i.e. 15:36, March 12 when the hydrogen explosion in unit 1 in F1 NPS took place. Unit 3 of F2 NPS was already in the cold shutdown 3 hours in advance. It is the only plant that both of the AC power and ultimate heat sink were available. The others in F2 NPS are in the depressurization phase with AC power. Unit 6 of F1 NPS which emergency diesel generator survived the tsunami was almost in the same situation. Unit 5 of F1 NPS is in the middle of AC power recovery process. On the other hand, the units 1-3 of F1 NPS were trying to inject water in the high pressure situation. In the units 2 and 3, the RCIC and/or HPIS were available and water was injected more or less. During the time, they in the unit 1 were struggling to the high pressure water injection which was not successful since the DC batteries were submerged. The vertical thick line in Fig. 3 suggests another crossroad in term of the time dimesion. At the time of hydrogen explosion in unit 1, the unit 5 and 6 in the F1 NPS and all the units in F2 NPS had the AC power available while the units 2 and 3 in F1 NPS had no AC power.

It is seen that the AC power recovery determines the fate of the reactors. Also, the time available for the recovery action is very important. The recovery actions are essential elements of the fourth defense line, accident management and recovery, of the defense-in-depth concept. One may raise a question if the units 2 and 3 of F1 NPS could lead to the safe shutdown; if we could save the unit 1 which reactor core was damaged in a very early stage. At least, we have to have robust and reliable AC and DC power. Passive heat removal systems such as the isolated condenser and RCIC are very important. Making the most of the passive system and preparation for the accident management is required. The probabilistic risk assessment has to provide those information and stakeholders have to make the most of the output from the probabilistic risk assessment. Definitely, the most effective and practical way is the probabilistic risk assessment in which all the knowledge and information on the reactor plant system as well as the severe accident phenomenology and available accident management procedures up to date are to be involved.

4. CONCLUSIONS

The 2011 earthquake off the Pacific coast of Tohoku occurred at 14:46 Japan Standard Time on March 11 and the tsunami that follows caused severe accident in the Fukushima Dai-ichi Nuclear Power Station. The tsunami height was 15 m at maximum which was far beyond the design tsunami height. It caused the submergence in seawater of the emergency power supply and seawater systems. The station black out and loss of ultimate heat sink gave great impact on the reactor safety protection based on the defense-in-depth concept. To make the matter worse, hydrogen explosion in the reactor building took place, which has every effort for recovery all fail. Consequently the reactor cores were seriously damaged and the nuclear fuel melted which lead to the radioactive material release to the environment. Evidences currently available indicate no seismic structural failure of safety systems and components. The tsunami and the station blackout gave intense impact on the nuclear system resulting in the severe accident.

In response to the lessons-learned from the Fukushima Dai-ichi NPS accident [2], the safety margins evaluation and safety enforcement of the nuclear power plants are necessary immediately. The nuclear system should have robustness for the beyond design basis conditions and resilience in case that the multiple levels of defense lines are deteriorated. Accordingly, the best performance in nuclear safety is to be achieved. The key for achieving the ultimate safety is of course the probabilistic risk assessment.

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