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FACT AND CAUSE OF FUKUSHIMA NUCLEAR POWER PLANTS ACCIDENT

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ABSTRACT: The Fukushima Daiichi Nuclear Power Station was attacked by the big earthquake and the large tsunami on March 11, 2011. The operating three nuclear power plants became the severe accident with the meltdown of nuclear fuels. The fact and cause of the accident is reviewed focusing on the sequence of the accident and the damage of the important components, on the basis of the information from the reports by the Government, the Tokyo Electric Power Company, the Academic Societies and others. The countermeasure for the reactor safety is also discussed.

Key Words: Fukushima Daiichi nuclear power station, loss of AC power, loss of ultimate heat sink, severe accident, meltdown of nuclear fuels

INTRODUCTION

A big earthquake attacked north-eastern Japan at 14:46 on March 11, 2011. After about 40 minutes to one hour from the first earthquake, seven waves of large tsunami attacked the coast of Tohoku and Kanto area, resulting the disaster named as the Great East Japan Earthquake. The earthquake and tsunami affected the Fukushima Daiichi Nuclear Power Station (NPS) of the Tokyo Electric Power Company (TEPCO), resulting the severe accident with the meltdown of nuclear fuels for operating three reactors at Fukushima Daiichi NPS. The operating nuclear power plants were scrammed by detecting the earthquake, though the earthquake caused all off-site AC power loss for the NPS. The emergency diesel generators started to operate in order to supply the AC power and to remove the residual heat of the nuclear fuels. However, the tsunami attacked the NPS, causing the loss of the emergency diesel generator power and the loss of the residual heat removal functions. The emergency cooling systems started. However, they did not work for so long time, and the fuels became to heat up and melt down, resulting the severe accident. The hydrogen was generated by the Zirconium-Water reaction and was accumulated in the pressure vessel and in the containment vessel with the steam and the radioactive materials. The containment vent was carried out for protecting the destruction of the containment vessel. Then the hydrogen explosion occurred at the reactor buildings of Units 1, 3 and 4. The radioactive materials were discharged in atmosphere. The residents around the Nuclear Power Station were evacuated. It will take long time to settle completely the accident and now on the way.

Present paper reviews the damage of the important components, the sequence of the accident, the actions for the settlement of the accident, the lessons learned and the actions for the lessons, and discusses the essential points for the nuclear safety in Japan.

MAIN INFORMATION SOURCES ON THE ACCIDENT

After the accident, the information about the status of nuclear plants was mainly from the TV and news papers. However it was very hard to know the detailed and exact status from them for several days after the occurrence of the accident. We could estimate the hard struggle against the severe situation of the plants by the operators and the employees at the Fukushima NPS.

On April 17, TEPCO announced the Roadmap for the settlement of the accident, in which the Step 1 target for 3 months and Step 2 target for 3 to 6 months after the Step 1 were indicated (TEPCO 2011). Further TEPCO disclosed the details of the plant data of three reactors at the accident and reported to the Nuclear and Industrial Safety Agency (NISA) on May 16 (TEPCO 2011).

The Japanese Government presented the Report on “The Accident at TEPCO's Fukushima Nuclear Power Stations” to the IAEA Ministerial Conference on Nuclear Safety from June 20 (Jap.Gov. 2011). The report included the detailed data of the accident by TEPCO and the data and analyses by the Japan Nuclear Energy Safety Organization (JNES), the Japan Atomic Energy Agency (JAEA), and other organizations, along with the lessons learned from the accident.

On July 19, TEPCO announced that the Step 1 target of the Roadmap was accomplished with 3 months, and showed the activities for the Step 2 (TEPCO 2011).

On September 11, the Japanese Government presented the Additional Report of the Japanese Government to the IAEA, in which the actions for the lessons learned from the accident by the Government were presented (METI 2011). It also explained the activities to strengthen the standards and guidelines, additional safety assessment efforts for the NPSs, and the reform of the regulatory bodies, in which the NISA will be departed from the Ministry of Economy, Trade and Industry (METI), and the Nuclear Regulatory Agency (tentative name) will be established.

At the end of October, the Japan Nuclear Technology Institute (JANTI) reported the Review of Accident at Tokyo Electric Power Company Incorporated's Fukushima Daiichi Nuclear Power Station and Proposal of Countermeasures (Draft), in which the cause of accident was analyzed and the actions to be done by the electric companies was proposed (JANTI 2011).

On December 2, the TEPCO released the Fukushima Nuclear Accidents Investigation Report (interim), in which the detailed explanation of the actions at the accident is included (TEPCO 2011).

On December 16, the Government and TEPCO announced the accomplishment of the Step 2 target of the Roadmap, in which the cold shutdown condition was reached (TEPCO 2011). The next step action was to start the middle and long term Roadmap toward the decommissioning of the Units 1 to 4. The new R&D is necessary for the accomplishment of the decommissioning.

In order to make clear the fundamental cause of the accident, the Japanese Government established the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company on June. The Committee released the interim report on December 26, 2011, in which the behavior and actions by the operators and other relevant persons at the accident in Fukushima Daiichi NPS were explained. The final report will be open at the summer of 2012.

Along with them, the urgent meetings and symposiums were held frequently by the Science Council of Japan and by many academic societies. Further the articles, papers, and explanations on the accident were presented in the journal of academic societies and others.

NUCLEAR POWER PLANTS AT FUKUSHIMA DAIICHI NPS

Fukushima Daiichi Nuclear Power Station is one of the oldest NPS in Japan. It has the 6 BWR Plants and the Unit 1 was started commercial operation on March 1971. By the way, the oldest commercial nuclear power plant in Japan was the carbon dioxide gas cooled reactor of the Tokai Nuclear Power Station of the Japan Atomic Power Company (JAPCO). The plant was introduced from the United Kingdom and started commercial operation in 1966. After the second plant, Japanese Electric

Companies introduced the Light Water Reactors (LWR) from USA. They were the Boiling Water Reactor (BWR) by General Electrics and the Pressurized Water Reactors (PWR) by Westinghouse. The first commercial BWR in Japan is Tsuruga NPS Unit 1 of JAPCO and started commercial operation on March 1970. The first commercial PWR is Mihama NPS Unit 1 of Kansai Electric Power Company and started commercial operation on November 1970. These two plants were located at the Fukui Prefecture, and a part of the electricity was transported to the Osaka Exposition in Osaka. At present, 54 plants with 30 BWR and 24 PWR exist in Japan.

All of the 6 nuclear power plants at Fukushima Daiichi NPS were BWR. The electric output, reactor model, pressure containment model and others were indicated in Table 1. The plants were improved as time passed. The Unit 1 is BWR 3 with 460 MW electric output and Mark-1 containment vessel, though the Tsuruga Unit 1 is BWR 2 with 360 MW electric output and Mark-1 containment vessel. The Units 2 to 5 are BWR4 with 784 MW electric output and Mark-1 containment vessel. The Unit 6 is BWR 5 with 1100 MW electric output and Mark-2 containment vessel. The last Unit 6 started commercial operation on October 1979. Figure 1 shows the main installation of Mark-1 type BWR.

Table 1 Specification of nuclear power plants at Fukushima Daiichi NPS

Plant Number	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Electric Output (MWe)	460	784				1100
Commercial Operation	1971.03	1974.07	1976.03	1978.1	1978.04	1979.1
Reactor Model	BWR3	BWR4				BWR5
Containment Vessel Model	Mark-1					Mark-2
Emergency Core Cooling System	IC	RCIC				
	HPCI					HPCS
						LPCS

HPCS:High Pressure Core Spray System, LPCS:Low Pressure Core Spray System

A	Reactor building	3	Crane
B	Turbine building	4	Nuclear reactor
1	Condenser	5	Drywell of containment vessel
2	Turbine generator	6	Suppression chamber of containment vessel

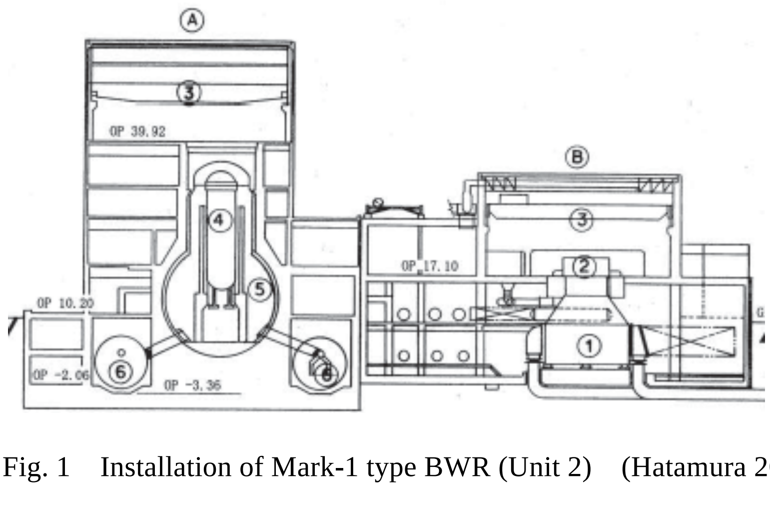


Fig. 1 Installation of Mark-1 type BWR (Unit 2) (Hatamura 2011)

Emergency cooling systems of Units 1, 2 and 3

The emergency cooling systems were equipped in BWR providing for the cooling of nuclear fuels at the accident. In Unit 1 (BWR 3), the Isolation Condenser (IC) and the High Pressure Coolant Injection System (HPCI) were equipped. In Units 2 and 3 (BWR 4), the Reactor Core Isolation Cooling System (RCIC) and the HPCI were equipped. At the accident with the loss of normal fuel cooling function, the IC works to condense the steam in pressure vessel and to supply the generated water back in reactor vessel for the cooling of the nuclear fuels. Both the RCIC and the HPCI, which work by the steam driven pump using the high pressure steam in pressure vessel, inject the water from the Condensate Storage Tank or from the Suppression Pool for the cooling of the fuels. They work without AC power, though the DC power is required to operate the valves.

Further, for the cooling of the reactor core under low pressure condition, the Core Spray System (CS) and the Shutdown Cooling System (SHC) were equipped for Unit 1, and the CS and the Residual Heat Removal System (RHR) were equipped for Units 2 and 3. However the AC power is needed to operate them and they could not work at the accident.

Plant status of the 6 plants before the earthquake

On March 11, 2011, the three plants (Units 1, 2 and 3) were under operation, and the other three plants (Units 4, 5 and 6) were under shutdown for periodic inspection. The fuels of Unit 4 were transferred to the spent fuel pool since exchange of the shroud was underway during the periodic inspection. The fuels of Units 5 and 6 were in the pressure vessel.

OCCURENCE OF THE EARTHQUAKE

At 14:46 on March 11, 2011, the big earthquake occurred at north-eastern Japan. The earthquake was with the scale of moment magnitude 9.0, fourth largest earthquake ever recorded in the world history. The earthquake occurred as the result of faulting on the boundary between the Pacific Plate and North American Plate. The epicenter was about 130 km southeast of Oshika Peninsula with a depth of approximately 24 km. The size of the faulting zone was about 400 km long, and approximately 200 km wide. Figure 2 shows the epicenter of the earthquake and the location of the 5 nuclear power stations in the afflicted area of the disaster.

Nuclear power plants at the afflicted area

In the afflicted area of the disaster, 15 BWR plants have been constructed. They are from the north, 1 plant at the Higasidori NPS of Tohoku Electric Power Co., 3 plants at the Onagawa NPS of Tohoku Electric Power Co., 6 plants at the Fukushima Daiichi NPS of TEPCO, 4 plants at the Fukushima Daini NPS of TEPCO, and 1 plant at the Tokai Daini NPS of JAPCO. Most of the plants have been brought to the cold shutdown condition within several days. However, the tsunami caused the reactor accident with the meltdown of fuels for three plants at the Fukushima Daiichi NPS.

Affect of the earthquake on the Fukushima Daiichi NPS

The three operating plants (Units 1, 2 and 3) were shut down automatically by detecting the earthquake at 14:46 on March 11. However, all external electric power for Units 1 to 6 was lost by the earthquake. Then emergency diesel power generators started and the decay heat of nuclear fuels was removed by the cooling system until the tsunami attack. The emergency cooling systems started automatically or manually. They were the IC for Unit 1 and the RCIC for Units 2 and 3.

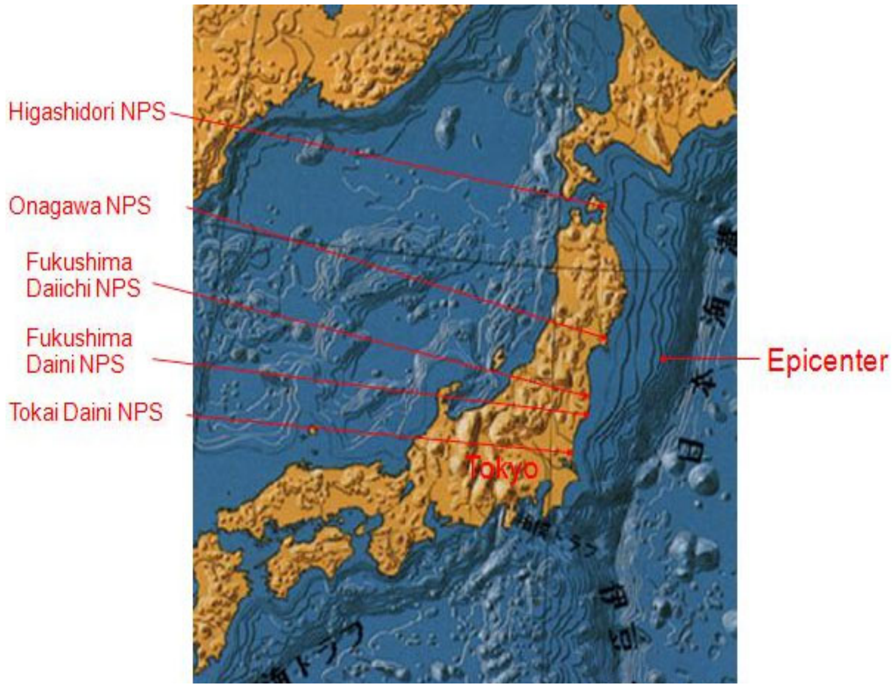


Fig. 2 Epicenter of the Earthquake and the location of five nuclear power stations

Cause of the external AC power loss at Fukushima Daiichi NPS

Now the cause of the external (off-site) AC power loss will be explained. The electric power was supplied through 6 lines for Units 1 to 6. For Units 1 and 2, the electricity was transmitted from Shin-Fukushima Transforming Station through Okuma Nos. 1 & 2 lines to the normal high voltage switchboard of Units 1 and 2 via the switchyards for Units 1 and 2. Further TEPCO nuclear line from Tohoku Electric Power Co. connected as a reserve to the normal high voltage switchboard of Unit 1. Due to the earthquake, several parts of the circuit breakers at the switchyards for Units 1 and 2 were damaged, resulting the actuation of the circuit breakers at the Shin-Fukushima Transforming Station. As for the TEPCO nuclear line, the connecting cables to metal-clad switch gear of Unit 1 were damaged and failed. As for Units 3 and 4, the Okuma Nos. 3 and 4 lines connected to the normal high voltage switchboard of Units 3 and 4. The line cables touched the tower, resulting the short circuit and failed. Further the normal high voltage switchboard was inundated later. These resulted the actuation of the circuit breakers at the Shin-Fukushima Transforming Station. As for Units 5 and 6, the Yonomori Nos. 1 and 2 transmission lines connected to the normal high voltage switchboard of Units 5 and 6. By the earthquake, the line cables touched each other, resulting the actuation of the circuit breakers at the Shin-Fukushima Transforming Station. Further one tower of transmission line connecting to the switchyards for Units 5 and 6 was collapsed. These resulted the loss of all external (off-site) power supplies to Units 1 to 6.

ATTACK BY THE TSUNAMI

At about 40 minutes to one hour later of the first earthquake, seven waves of large tsunami attacked the coast of Tohoku-Kanto area. At the Fukushima Daiichi NPS, the first wave of tsunami reached at 15:27, and the second large tsunami at 15:35 on March 11. The tsunami with 15 m high was getting over the 10 m high sea wall and entered into the reactor and turbine buildings area. The cooling sea water pumps at the sea side with 4.1 m high were inundated. The emergency diesel power generators, metal-clad switch gear, power center, and so on at the lower level of the turbine buildings were also inundated.

Function loss of major machines and components

Emergency diesel power generators

The number of emergency diesel power generators (DG) at Fukushima Daiichi NPS were 13. They supply the power to each Unit through matal-clad switch gear (M/C). Each Unit had 2 (A and B) DG except Unit 6 which had 3. Among them, 10 DG were sea water cooled and 3 DG (Unit 2B, Unit 4B and Unit 6B) were air cooled. By the tsunami attack, all sea water cooled DG lost the function, though 3 air cooled alive. For Unit 1, DG 1A and 1B located at the first basement of the turbine building (T/B) inundated and lost the function. For Unit 2, DG 2A located at the first basement of T/B inundated and lost the function. DG 2B located at the first floor of the common spent fuel pool building was alive, though the M/C inundated and the function was lost. For Unit 3, DG 3A and 3B located at the first basement of T/B was inundated and lost the function. For Unit 4, DG 4A was under periodic inspection. DG 4B located at the first floor of the common spent fuel pool building was alive, though the M/C inundated and the function was lost. For Unit 5, DG 5A and 5B located at the first basement of T/B was alive, though the connected components inundated and the function was lost. For Unit 6, DG 6A and DG 6C located at the first basement of the reactor building was alive, though the sea water pump necessary to cool the DG was inundated and the function was lost. DG 6B located at the first floor of diesel generator building was alive and the function to supply power was alive.

Metal-clad switch gear (M/C) and power center (P/C)

M/C is the 6900 V switch board for high voltage circuit power, and P/C is the 480V switch board for low voltage circuit power. Number of the M/C and the P/C was 15 each. They are three kinds such as for normal operation, for emergency and for common. Due to the earthquake, the M/C and the P/C for normal and for common were lost the function since the external power was lost. By the tsunami, 12 among 15 M/C for emergency were inundated and lost the function, and 9 among 15 P/C for emergency were inundated and lost the function.

Emergency cooling sea water pump

The emergency cooling sea water pumps are equipped to supply the sea water to the heat exchanger of Containment Cooling System (CCS) for Unit 1 and Residual Heat Removal System (RHR) for Units 2 to 6. After the tsunami attack, the emergency cooling sea water pump stopped by the loss of AC power of Units 1 to 5, and the function of the CCS and the RHR was lost.

ACCIDENT SEQUENCE OF UNITS 1 TO 6

Outline of the sequence

The operating Units 1, 2 and 3 were scrammed by detecting the earthquake. Since the external AC power was lost, emergency DG started to work for cooling the nuclear fuels. The emergency cooling systems, such as the IC for Unit 1 and the RCIC for Units 2 and 3, started.

However, about 50 minutes later, all the emergency DG stopped, resulting all AC power loss. All ultimate heat sink were also lost. The emergency cooling systems were only way to cool the nuclear fuels, though control of the systems should be done by DC battery with short life time. During the fuel cooling, recovery of the ultimate heat sink should urgently be done. However, the aftershock, the tsunami remnants and the destroyed road by the earthquake prevented the work to recover the situation from the outside. The batteries did not work for so many days, though operators did the best to prolong the batteries' life time. Finally heat-up and melt-down of the fuels occurred and the severe accident resulted in Units 1, 2 and 3.

Units 4, 5 and 6 were in periodic inspection outage. Unit 4 was on the way to replace the reactor core shroud and all fuel assemblies had been transferred to the spent fuel pool. As for Unit 5, all fuel assemblies was loaded in the reactor core and the pressure leak test for reactor pressure vessel was being conducted. As for Unit 6, all fuel assemblies were loaded in the reactor core that was in cold shutdown condition.

Sequence of the Unit 1

Unit 1 reactor was scrammed by detecting the earthquake, and two emergency DGs started. The two ICs automatically started to cool the fuels. However, the cooling speed was too fast compared with the operation manual, and operators stopped it manually. After then, one IC was used to cool the fuels. The cooling and the stop of the IC was repeated 3 times. The tsunami attacked the NPS at 15:35 and the emergency DGs and the ultimate heat sink were lost. The IC was stopped when the tsunami attacked. Then the cooling water could not be supplied to the reactor core, and the water in the pressure vessel began to decrease. The fuels could not be cooled when the water level decreased below the fuel level, resulting the heat-up of the fuels. The cladding material of the fuel is zircaloy or zirconium alloy, and the zirconium begins to react severely with water (or steam) at above 900 °C, generating the hydrogen and the zirconium oxide. The reaction is the exothermic reaction and the reaction rate increases rapidly above 1200 °C, resulting the increase of the fuel temperature. Thus a large amount of the hydrogen generated and the fuel temperature increased more than the melting temperature of the zircaloy and reached the melting temperature of the fuels.

Since all of the equipped cooling functions were lost, cooling of the fuels by injection of water from outside was necessary. Injection of water through the fire protection system into the pressure vessel by using the fire engine began in the morning on March 12. However, it was too late to cool the fuels. Damage of the fuels began at the evening on March 11, almost 4 hours from the tsunami attack. Considerable amount of the damaged fuels moved to and accumulated at the bottom of the reactor pressure vessel. The pressure vessel was damaged at about 10 hours from the tsunami attack and pressure in the pressure vessel dropped largely. Then the pressure and the temperature in the containment vessel began to increase to the highest pressure at 2:30 on March 12. In order to prevent the rupture of containment vessel, wet well venting from the containment vessel was carried out twice at 10:17 and 14:30 on March 12. After the second venting, a hydrogen explosion occurred in the reactor building of Unit 1, destroying the upper floor of the reactor building at 15:36 on March 12, just 24 hours later of the tsunami attack. After the hydrogen explosion, sea water injection into the pressure vessel was again started at 19:04. However, some of the molten fuels may have dropped on the lower plenum of the pressure vessel on around 20 March, and further they dropped and accumulated on the pedestal of the drywell floor of containment vessel, at almost the end of March. The molten core-concrete reaction may have occurred there.

Sequence of the Unit 2

Unit 2 reactor was also scrammed by detecting the earthquake, and two emergency DGs started. The RCIC was also started manually. After the loss of both emergency DG and ultimate heat sink by the tsunami attack, the RCIC was alive for 3 days until at 13:25 on March 14. The operators conducted the feed and bleed operation, that is, the water was fed into reactor by the RCIC, then the steam pressure rose. The steam was bled through the safety relief valve into the water pool in the suppression chamber. Water temperature of suppression pool increased to almost saturation temperature and gradually steam could not be condensed. The leakage was estimated to occur probably around the suppression chamber of containment vessel before noon on March 14. After 6 and half an hour later from the RCIC stop, sea water was injected into the pressure vessel. During the no cooling period, however, the fuels were exposed to steam and started melting at around 16:30 on March 14, and molten fuels dropped to lower plenum of the pressure vessel. Further the lower part of the pressure vessel was damaged at around 21:30 and some of the molten fuel dropped on the pedestal of the containment vessel before 24:00 on March 14. The drop of the molten fuel on the pedestal of containment vessel was continued for a while. The containment vent was already prepared on March 13, but it was not carried out. Noise of an explosion occurred at around 6:00 on March 15. There is a possibility that any explosion occurred around the torus room of the containment vessel. However

TEPCO reported that the noise might be the sound of the explosion just occurred at Unit 4 at that time.

Sequence of the Unit 3

Unit 3 reactor was also scrammed by detecting the earthquake, and the power was supplied by the emergency diesel power generators. The RCIC was manually controlled. After the tsunami attack, the RCIC was started manually at 16:03 on March 11, since the DC batteries were alive. However the RCIC stopped at 11:36 on March 12. After one hour's later, the HPCI started automatically by detecting the low water level to continue the cooling of the fuels. The operators stopped the HPCI at 2:42 on March 13, since they intended to save the consumption of the batteries. However they could not start the HPCI again, since the batteries were already consumed. The steam relief valve was open to decrease rapidly the pressure in pressure vessel at 9:08 and the water was injected through fire protection system at 9:25 on March 13. During the no cooling period, the fuels exposed and started melting at around 8:00 on March 13. At around 9:00 on March 13, the upper flange gasket of containment drywell was estimated to be damaged. At the same time the lower part in pressure vessel was damaged, and the molten core dropped on the pedestal floor of the containment vessel. The vent from the containment vessel was carried out several times at 9:20, at 12:30 on March 13 and at 5:20 on March 14. A hydrogen explosion occurred in the reactor building at 11:02 on March 14, destroying the reactor building.

Sequence of the Unit 4

Unit 4 reactor had been shut down for periodic inspection, with the nuclear fuels having been transferred to the spent fuel pool. Both the cooling and the water feeding functions for the spent fuel pool were lost by the earthquake and the tsunami. Temperature of the spent fuel pool rose to 84 °C at 4:08 on March 14. At about 6:00 on March 15, an explosion in the reactor building occurred, and destroyed the upper part of the building. At first, the cause of the explosion attributed to the hydrogen generated by the over-heating and melting of the fuels in the pool. Injection of water to the pool was conducted from the helicopter, and by the water discharge car. However it was confirmed that the enough water existed in the spent fuel pool. As the cause of the explosion, an inflow of hydrogen from Unit 3 is possible, since the exhaust pipe for venting, joins with the exhaust pipe from Unit 4 before the exhaust stack.

Sequence of the Units 5 & 6

Unit 5 was in periodic inspection outage. At the accident, all fuel assemblies were loaded in the reactor core and the pressure leak test for reactor pressure vessel was being conducted. By the tsunami attack, all the AC power supply was lost, resulting the loss of the ultimate heat sink. As the cooling function was lost, the reactor pressure continued to increase. The water level and the pressure was maintained by injecting water into the reactor by operating the make-up condensing water pump after the power was supplied from Unit 6. The water in the spent fuel pool was also supplied. On March 19, a temporary seawater pump was activated to operate the RHR, bringing the reactor to a cold shutdown condition at 14:30 on March 20.

Unit 6 was in periodic inspection outage. At the accident, all fuel assemblies were loaded in the reactor core that was in cold shutdown condition. One of the emergency DGs for Unit 6 had been installed at a relatively high location, and its functions were not lost after the tsunami attack. However, the sea water pump lost its function. The reactor water level and the pressure was controlled by injecting water into the reactor by operating the make-up condensing water pump. A temporary seawater pump was activated to operate the RHR on March 19, bringing the reactor to a cold shutdown condition at 19:27 on March 20.

Cooling of the reactors and spent fuel pool

The residual heat from the nuclear fuels for damaged Units 1 to 3 reactors, for Units 5 and 6 reactors under outage, and for spent fuel pools of Units 1 to 6 should continuously be removed. Particularly the damaged molten fuels in reactors and in containment vessels in Units 1 to 3 should be cooled by injecting the water until the cold shutdown condition, in order to decrease the hydrogen generation and also to prevent the release of the radioactive materials in atmosphere. The temperature in the damaged reactor pressure vessels decreased gradually by continuous water injection.

However, the injected water became the contaminated water with the radioactive materials, and leaked to outside of the containment vessel through the damaged part. The contaminated water accumulated at the lower part of the turbine buildings and the pits, and some of them leaked in the sea. A large amount of the accumulated water was a big problem. The circulating water injection cooling system was constructed in order to reuse the accumulated contaminated water for the injection cooling after doing the decontamination and the desalination. The accumulated water was decreased by operating the system. Figure 3 shows the concept of the system.

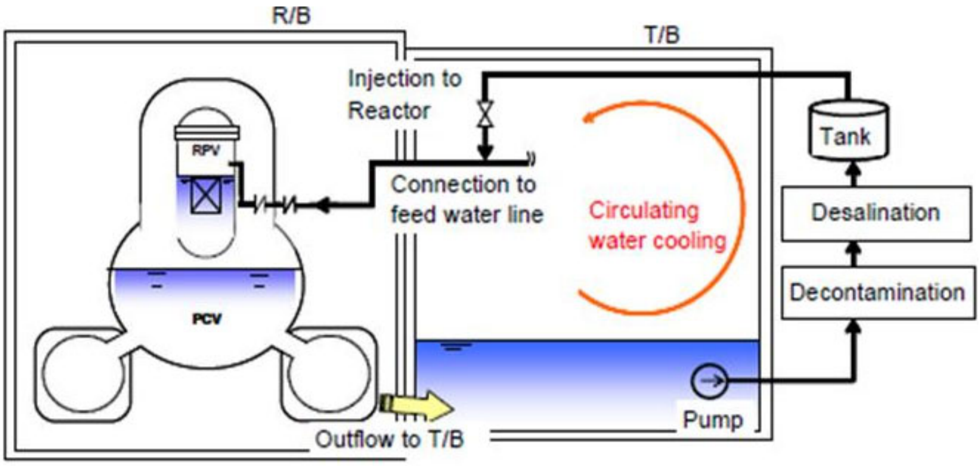


Fig. 3 Circulating injection cooling system (TEPCO 2011)

SEQUENCE OF OTHER 9 PLANTS AT AFFLICTED AREA

Now the situation of other 9 nuclear power plants at the NPSs of the afflicted area will shortly be reviewed. Among 9 plants, eight plants were under operation and one plant was under periodic inspection. The important functions are (1) external (off-site) AC power, (2) emergency diesel power generator (DG), and (3) residual heat removal system (RHR). Whether they were alive or not, then the result changed.

The first is the case that the off-site AC power was alive. They were 6 operating plants. Among them, the RHR or other auxiliary cooling system and the RCIC et al of 3 plants were alive, and the plants could reach cold shutdown condition on March 12. They were Onagawa Units 2 and 3, and Fukushima Daini Unit 3. The RHR of other 3 plants was lost by the tsunami. However the temporary cable for the RHR system was installed within several days. The 3 plants reached cold shutdown condition on March 14 or 15. They were Fukushima Daini Units 1, 2 and 4.

The second is the case that the off-site AC power was lost. They were 3 plants with 2 plants under operation and 1 plant under periodic inspection. For operating 2 plants, both the emergency DG and the RHR were alive, and they reached cold shutdown condition on March 12 and 15. They were Onagawa Unit 1 and Tokai Daini Unit. As for one plant under periodic inspection, emergency DG was alive and the fuels were outside the reactor. It was not so severe situation. That was Higashidori Unit.

Considering the above situations and also the situation of Fukushima Daiichi Units 5 and 6 in which the off-site AC power and the RHR were lost and the emergency DG was alive, we are sure that the plants could reach the cold shutdown condition, when either external AC power or emergency DG was alive.

Release of the radioactive materials

The radiation dose rate around the Fukushima Daiichi NPS increased many times within the first 2 weeks after the occurrence of the accident. This indicates that the radioactive materials released in atmosphere. The release of the radioactive materials were mainly by the venting from the containment vessel, by the explosion of the reactor buildings, and also by the leak through the damaged opening of the containment vessel just after the operation of the safety relief valve or after the water injection over the hot damaged fuels. The radiation dose rate decreased gradually after the end of March. Figure 4 shows the change of the radiation dose rate at the NPS with the estimated causes of the increase (METI 2011).

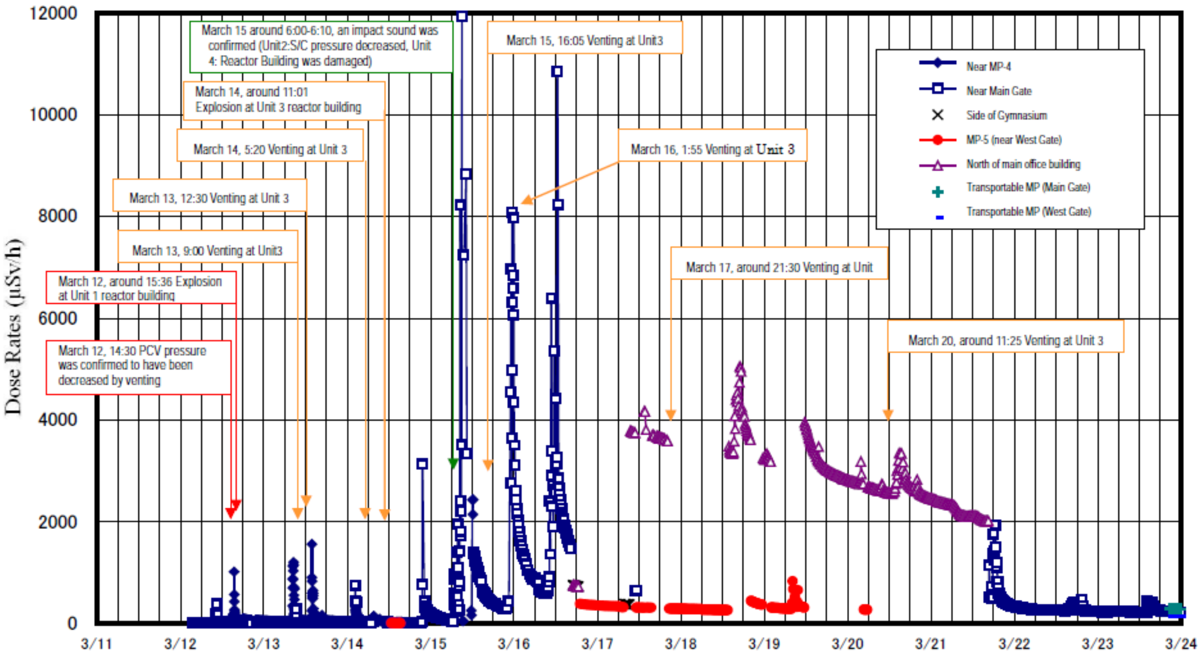


Fig. 4 Changes in dose rates at Fukushima Daiichi (Monitoring car) (METI 2011)

The radiation dose rate at the NPS started to increase at around 4:00 on March 12. This may indicate any damage of the reactor pressure vessel and containment vessel in Unit 1, since the drywell pressure of Unit 1 started to increase rapidly at around 1:00 on March 12. The radiation dose rate increased further by the wetwell venting at 10:17 and at 14:30 on March 12, and also by the leak through any damaged part at lower location of the containment vessel. Radiation dose rate further increased at around 20:00 on March 12. This may be due to the generation of large amount of steam, hydrogen, and radioactive materials by the sea water injection into the reactor pressure vessel at 19:04 on March 12.

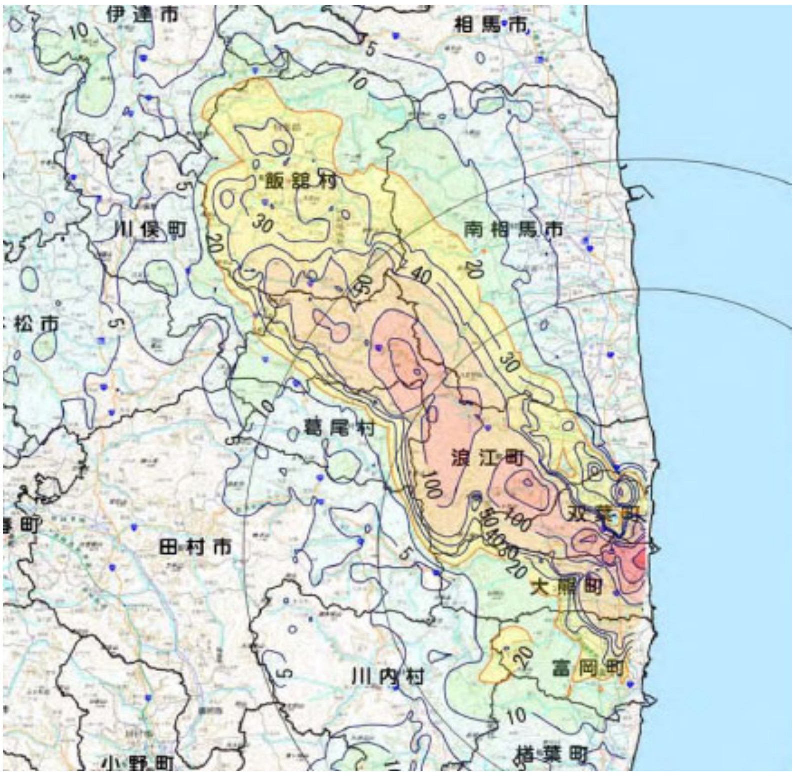
In order to decrease the pressure in pressure vessel of Unit 2 after the stop of the RCIC, the operator opened the safety relief valve at around 18:00 on March 14. Then the steam, hydrogen and radioactive materials in pressure vessel moved to the suppression pool. As any damage may exist at the suppression chamber, as explained in sequence of the Unit 2, the radioactive materials leaked from suppression chamber to outside. This increased the radiation dose rate at around 22:00 on March 14. After the noise of explosion at around 6:00 on March 15, the radiation dose rate increased at the NPS. If the hydrogen explosion occurred at around the torus room and made any crack there, then the radioactive materials may be discharged into atmosphere through the crack. The radiation dose rate increased at around morning to noon of March 15. This corresponds to the time that the damaged core dropped to the lower plenum in pressure vessel of Unit 2.

The radiation dose rate was increased at around 9:00 on March 13. This is estimated that the radioactive materials leaked through the damaged flange gasket at the upper part of the drywell in Unit 3, by the wetwell venting from containment vessel and also by the sea water injection into pressure vessel. On March 16, several very high radiation dose rates were measured, which are estimated to be by the wetwell venting. The reason is that the suppression chamber became full of the water injected from outside at that time, and the wetwell venting resulted the release of the highly contaminated water and steam directly into atmosphere.

Evacuation of the residents

TEPCO recognized that the injection of water via the emergency core cooling system was not certain at Units 1 and 2, and notified the Government of the state of Nuclear Emergency at the evening on March 11. The Prime Minister declared a state of nuclear emergency, and established the Nuclear Emergency Response Headquarters and the local Nuclear Emergency Response Headquarters. The Prime Minister instructed to evacuate the residents within 3 km radius from NPS, and to stay in house within 10 km at 21:30 on March 11. According to the escalation of the events, the evacuation area was expanded to evacuate the residents within 10 km at 5:44 on March 12 and within 20 km at 18:25 from NPS. The area to stay in house was also set as within 20 to 30 km on March 15.

On April, the government changed the area and settled the restricted area within 20 km from the NPS. The deliberate evacuation area and the emergency evacuation preparation area were newly settled beyond 20 km from NPS. The deliberate evacuation area is the area in which the accumulated dose may reach 20 mSv in one year. Figure 5 shows the integrated dose in one year after the accident (METI 2011). The high dose area expands to the north-west direction of the NPS which was reflecting the wind direction and the rain fall at the day that the radioactive materials discharged. In restricted area, the residents can temporarily access to their home.



[Unit: mSv] 30 km line 20 km line

Fig. 5 Estimated Integrated dose for one year up to March 11, 2012 (METI 2011)

ACTIONS FOR THE SETTLEMENT OF THE ACCIDENT AND TOWARDS THE DECOMMISSIONING OF THE DAMAGED REACTORS

Actions for the settlement of the accident

TEPCO announced the "Roadmap towards Restoration from the accident in Fukushima Daiichi Nuclear Power Station" on April 17. The basic policy was for the reactors and the spent fuel pools to be stable condition, and for the release of radioactive materials to be mitigating. Further every effort should be done for evacuees to return to their home and for all citizens to secure a sound life. Two steps were set as the target, as step 1 with the time line target of 3 months and step 2 with the time line target of 3 to 6 months after achieving step 1. The target of the step 1 was the radiation dose in steady decline and that of step 2 was the release of radioactive materials under control and radiation dose being significantly held down. TEPCO announced the accomplishment of the step 1 target on July 19 and that of the step 2 target on December 16, 2011. After the accomplishment of the step 2 target, the middle and long term Roadmap towards the decommissioning of the four damaged reactors should be made and now on the way.

Activities during Step 1

The major items conducted during the step 1 were (1) the continuous fuel cooling by minimum water injection, (2) the transfer of accumulated water in the basement of the turbine buildings into temporary tanks and the installation of the circulation type water purification system, and (3) the design of the cover for destroyed reactor buildings.

The water was continuously injected in order to cool the reactor core of Units 1, 2 and 3. Large amount of water was injected into the reactor core, though it was leaking outside of the containment vessel. The leaked water accumulated in the reactor buildings and turbine buildings. The circulation type water purification facility was designed in order to reuse the decontaminated water for the cooling of the reactor core. The cover for the destroyed reactor building was also very important for decreasing the release of radioactive materials.

During the step 1, the temperature at the bottom of reactor pressure vessel decreased to 100 °C 120 °C, and the radiation dose rate decreased to 1.7 mSv/y at the site boundary.

Activities during Step 2

The major items conducted during the step 2 were the continuation of the step 1. The first is the reactor cooling by the circulating injection cooling along with the treatment of high level radioactive waste water. The operation started on June 27. The second was the spent fuel cooling using the heat exchanger. The third was the mitigation of contamination in the sea through the underground water. Design of the ground water shielding wall started. The fourth was the installation of the cover over the highly damaged reactor buildings, in order to prevent further release of the radioactive materials. The cover of Unit 1 was completed at the end of October 2011. The construction of the cover for Units 3 and 4 has been on the way.

During the step 2, the temperature at the bottom of the reactor pressure vessel decreased sufficiently below 100 °C, and the reactors were brought to a condition equivalent to the cold shutdown. The radiation dose rate decreased to 0.1 mSv/y at the site boundary. Basing on these data, TEPCO announced the accomplishment of the step 2 on December 16, 2011 (TEPCO 2011).

Activities towards the middle and long term roadmap for the decommissioning of the reactors

After the completion of the step 2, the roadmap towards the decommissioning of Units 1 to 4 has to be made, including the implementation of the on-site work and the R&D towards the decommissioning such as the removal of fuels from the spent fuel pools. Now the middle term activities for 3 years until the start of the work for decommissioning has started.

LESSONS LEARNED AND ACTIONS
FOR THE RECONSTRUCTION OF NECLEAR REACTOR SAFETY

Lessons learned and actions

The Japanese Government indicated the lessons learned from the accident in the report to the IAEA Ministerial Conference on Nuclear Safety on July 2011. Lessons were in 5 categories with 28 items. Further the Japanese Government presented the additional report to the IAEA on September 2011, in which the actions for the lessons were explained. The major items relating directly to the cause of the accident and the actions by the Japanese Government will be explained. Further the activities by the Atomic Energy Society of Japan, the JANTI and the TEPCO will shortly be explained.

Lessons learned in Japanese Government report

Among five categories in Japanese government report, major items in three categories which are directly relevant to the cause of the accident will be explained. The first category of the lessons learned is to strengthen preventive measures against severe accident. This requires for the reactors to avoid the severe accident under various kinds of big natural disaster, such as earthquake and tsunami. The reactors and important equipments were not damaged by the big earthquake of this accident. However, off-site electric power supply system was damaged by the earthquake. For tsunami, the wave height estimated before was not enough to prevent the accident. The current guideline indicates the 30 min. loss of AC power. In this disaster, some plants were safely shut down since a part of power supply system was alive and the sea water pump was recovered for the RHR. The consideration for the longer loss of AC power supply was necessary for the reconstruction of the nuclear safety, and it should be included in the safety design guidelines. The loss of emergency DG should also properly be considered. As for the accident management, the alternative water injection system was not sufficient under no power source and high radiation environment.

The second category is the enhancement of response measures against severe accidents. As for the hydrogen explosion, the explosion inside the containment vessel was mainly considered for providing the countermeasures. Hydrogen explosion outside the containment vessel should also be considered. The containment venting system should much be enhanced. Further the radiation dose became very high in the main control room and the operators could not enter the room temporarily. The environment for the accident response work should be improved.

The fourth category is the reinforcement of safety infrastructure. This is to enforce the safety regulatory bodies, legal structures, criteria and guidelines and human resources. Several subjects such as the use of PSA in government examination and such as the consideration of severe accident in the regulatory matter were retarded in Japan. Further the severe accident research should be promoted much more.

Actions by the Government

According to the lessons, the Government started the investigation for several items. The first is the Comprehensive Safety Evaluation, which is similar to the stress test in foreign countries. The Nuclear Safety Commission (NSC) and the NISA decided to perform the evaluation of existing nuclear power plants. The evaluation items are for the earthquake and tsunami as the natural disaster, and for the losses of all AC power and ultimate heat sink as the loss of safety functions. The evaluation will make clear the potential weakness of the plants by assessing the safety margin for the severe external events.

The second is the revision of safety design guidelines. The NSC started to revise the relevant guidelines, such as the seismic safety including the tsunami, loss of the duration of power source, the severe accident, and the nuclear emergency preparedness and response including the evacuation area.

The third is the revise of the regulatory bodies. NISA will be departed from the METI. NISA and NSC along with a part of Ministry of Education, Culture, Sports, Science and Technology (MEXT), will become one Agency, tentatively named as the Nuclear Regulatory Agency. It will be settled at the Ministry of the Environment on April 2012.

The Government organized the Investigation Committee on the Accident at the Fukushima

Nuclear Power Stations. The committee chaired by Professor Hatamura is conducting the comprehensive investigation for the accident and is expected to make clear the fundamental cause of the accident. The interim report was already open at the end of December 2011 (Hatamura 2011). The final report will be accomplished at the summer of 2012.

Actions by the academic society

The Atomic Energy Society of Japan conducted the investigation for the Fukushima Daiichi Nuclear Power Plant Accident at the Committee for Investigation of Nuclear Safety. It raised 12 items from the lessons learned and proposed the measures for them on May 2011 (Ninokata 2011). The seismic design, the tsunami, station blackout, loss of ultimate heat sink, accident management, and hydrogen explosions were included in the 12 items.

Actions by the industries

JANTI reported the Reviews of Accident and Counter-measures for the Cause of the Accident from the industrial standpoint (JANTI 2011). It deduced the issues and proposed the countermeasures in 5 categories, such as preparation for earthquake and tsunami, preparation for power source, measure for heat sink loss, hydrogen countermeasures, and preparation for emergency situations. The important measures were proposed expecting the adoption by all electric companies.

TEPCO analyzed the accident and indicated the issues to be done in the Fukushima Nuclear Accidents Investigation Report (interim) on December 2, 2011 (TEPCO 2011). It emphasized that the reliable water injection and fuel cooling in pressure vessel was the most important issue in this kind of accident, and raised several items, such as quick usage of the high pressure water injection system, the pressure reduction method before the loss of high pressure water injection function, stable low pressure water injection method, reliable venting method from the containment vessel, recovery of the sea water cooling function, and the instrumentation under the accident condition.

ON THE NUCLEAR SAFETY AND THE SEVERE ACCIDENT IN JAPAN

History of the nuclear safety

Here history of the activities for nuclear safety and severe accident in Japan will be reviewed. The light water reactors (LWR) were developed in USA in the nineteen-fifties to -sixties and introduced in Japan. The first plant Tsuruga NPS Unit 1 started the commercial operation in 1970. In the nineteen-seventies, twenty LWRs started the commercial operation in Japan. However, many initial troubles, such as the Stress Corrosion Crack, occurred in the LWRs. Japanese industries conducted active researches supported by the Japanese Government, and solved the problems. These activities were the technological basis for the Japanese industries, and led to the design and construction of the Advanced BWR at Kashiwazaki-Kariwa Units 6 and 7 in 1996 and 97, at Hamaoka Unit 5, and at Shika Unit 2. However, we should remember the lack of the fundamental R & D experience at the initial stage of designing and developing the LWRs in Japan. This may be one of the fundamental causes of the Fukushima accident, particularly regarding the actions under such a severe emergency condition.

For the first 20 years, the design basis accident was the most important issue for the nuclear plant safety. The safety researches were mainly for the development of and for the confirmation of the safety functions, such as the effectiveness of the safety injection system. Computer analysis methods to evaluate the accident behavior were also developed. These results reflected to the development of new reactors and also to the revision of the safety design guideline of the NSC in 1990.

The TMI accident in USA was occurred in 1979, just half a year later of the NSC establishment in Japan. This accident was the severe accident with the meltdown of the reactor core. The NSC extracted the 52 items of lessons learned from the accident. After the accident, Probabilistic Risk (Safety) Assessment (PRA or PSA) method was developed in Japan, though the internal events were the main issues. Only external event considered was the air plane clash on the NPS. However, the severe accident research was not so active in this stage. The Chernobyl accident, the most large and severe accident, occurred in 1986. Since the reactor type was different and the cause of the accident was the illegal operation, there were very few for reflecting directly to Western type nuclear plants including those in Japan. However, the safety culture was recognized as to be very important for nuclear safety in the world. Further the Japanese Government considered the necessity for the severe accident researches and for the severe accident countermeasure policy. The severe accident researches at the Nuclear Power Engineering Center and the investigation for the severe accident countermeasure at the NSC started in 1987. The NSC determined the accident management (AM) policy as the countermeasure for the severe accident in 1992. The policy was that the NSC encouraged intensely the licensees to prepare the AM as a voluntary action, and to enforce it exactly. Though the AM was not the regulatory matter, the NISA and the NSC reviewed them, and then the AM was actually very close to the regulatory matter. Further the AM as the countermeasure for the severe accident at that time in Japan was almost at equal level to that of the foreign countries (Hirano 2011). After then the foreign countries included the severe accident measures into regulatory matter. However the Japanese regulatory bodies have not encouraged more actions for the severe accident, and the research fund for severe accident decreased year by year. This may be one of the fundamental causes of the Fukushima accident.

The regulatory guideline for seismic safety was revised on 2006, and the countermeasure for the tsunami was included in it. According to the revision, the actions for the tsunami were proceeded in every NPS. An example of the action is to place the sea water pump in water-proof building. The action for tsunami seems, however, to be retarded and not sufficient in Fukushima NPS. This may be one of the fundamental causes.

Finally the circumstance of current 20 year's Japanese nuclear was considered. Many issues should be done earlier. The inclusion of the severe accident measure into regulatory matter. The effort for the rational regulation as the same level as in USA and in Europe. The actions to raise the plant capacity factor up to the level in other major countries. The reform of the regulatory system according to the indication by the IAEA that the regulatory bodies for nuclear are divided in several Ministries in Japan and the regulatory body NISA is in the METI which promotes the nuclear. The retard occurred particularly for these 20 years, and they say it as the lost 20 years. It occurred that the Government and people intensely stuck to the issues which occurred at that time, even though they were not so important for the nuclear safety. This accident is a big chance to improve all these issues. We never repeat the same mistakes as in former cases in this accident.

For the reconstruction of nuclear safety and severe accident

Basing on the above mentioned lessons, the actions for the reconstruction of nuclear safety should be done. There are many countermeasures against such severe condition as the Fukushima accident. Major technical issues are the countermeasure (1) for big natural disaster such as earthquake and tsunami, (2) for station black out by all AC power loss including emergency DG and DC battery, (3) for ultimate heat sink loss, (4) for emergency water injection system and (5) for containment venting, (6) for hydrogen explosion particularly outside of containment vessel and (7) for control room habitability and instrumentation measurement under emergency situation. The countermeasures should actually be done by the electric companies and relevant industries. As the urgent action, the NSC and the NISA is now conducting the Comprehensive Safety Review for existing Nuclear Power Plants.

Besides above mentioned conditions, we have to consider the countermeasures for the severe natural disaster such as the big volcano eruption, the river flood, et al, and also for the situation such as the air plane crash, terrorist attack,et al.

As for the severe accident, the NSC issued new framework for preparing against severe accident on October 23, 2011, in which the former Commission's paper on AM in 1992 was abolished. The severe accident will become the regulatory matter. The NSC further recommended the safety assessment pertaining severe accident and the promotion of safety researches. The NSC started to revise the safety design guidelines for relevant issues such as the duration time of all AC power loss, et al.

The NSC will also discuss about the safety target, which is now at draft stage. No person died and there will be no additional increase of cancer death in this accident. These satisfy the current safety target. However, we have to consider the effects of accident on the evacuees and on the contamination of the land including the farmland, et al. how to include these items in safety target is a difficult problem.

As for the reform of the regulatory system, the NISA and the NSC along with a part of the MEXT will be one agency. This is what we wanted. We expect further for new Regulatory Agency to conduct the work on nuclear safety with high technological bases. In today's highly developed science and technological society, the role of the high level specialists is very important for constructing and maintaining the safe and secure society.

CONCLUSIONS

The Fukushima Daiichi Nuclear Power Station was attacked by the Great East Japan Earthquake and the accompanying Tsunami on March 11, 2011. The operating three nuclear power plants became the severe accident with meltdown of the nuclear fuels. The sequence of the accident, damage of the important components, release of the radioactive materials, lessons learned and actions for the lessons, and discussion on the fundamental cause were reviewed basing on the information from various reports including TEPCO, Japanese Government and so on.

The direct cause of the accident was the wrong estimation for the duration of off-site AC power loss and for the height of the tsunami wave. The fundamental cause of the accident was the retard of the improvement actions for the severe accident, for the safety guidelines, for the regulatory systems, and for several other issues.

Fukishima accident showed a week point of the BWR. On the other hand, it showed the robustness of the light water reactors, too. Particularly if either of the off-site AC power or the emergency DG for Units 1 to 4 were alive, then the result of the Fukushima Daiichi accident might be a little different. When we reconsider carefully the function of the nuclear reactors for this kind of severe situations, it is possible to provide sufficient countermeasures for any big natural and man-made disasters, and to operate safely the light water reactors.

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