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A Study of Events Leading to Fukushima Dai-ichi Nuclear Disaster and Suggested Measured that would have Prevented It

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Abstract: Primarily our energy requirements are being met by fossil fuels. The climatic change being ushered in due to the pollution caused by their use has forced the mankind to look for new sources of clean energy such as nuclear energy. But its use has certain disadvantages. Accidents in the Nuclear Power Plants can cause immense damage as we have seen earlier in Chernobyl and now in Fukushima[1]. The Great East Japan Earthquake (magnitude 9) on 11 March 2011 generated a number of large tsunami waves that struck the east coast of Japan, the highest being 38.9 m at Aneyoshi, Miyako. The earthquake and tsunami waves that followed it, caused widespread devastation across a large part of Japan, with 15,391 lives lost. In addition to this, 8, 171 people still remain missing. Many more have been displaced from their homes as towns and villages were destroyed. Many aspects of Japan's infrastructure were ruined by this devastation and loss. Several nuclear power facilities were affected by the earthquake and large multiple tsunami waves: Tokai Dai-ni, Higashi Dori, Onagawa, and TEPCO`s Fukushima Dai-ichi and Dai-ni. The present paper traces the progression of the accident at Fukushima Dai-ichi Nuclear Power Station and the author suggests the ways in which it could have been prevented.

Keywords: Fossil Fuels, Nuclear Power Plants, Earthquake

1. Introduction

The Great East Japan Earthquake on 11 March 2011, a magnitude 9 earthquake, generated a series of large tsunami waves that struck the east coast of Japan, the highest being 38.9 m at Aneyoshi, Miyako[2]. Several nuclear power facilities were affected by the severe ground motions and large multiple tsunami waves including TEPCO`s Fukushima Dai-ichi. The operational units at this facility were successfully shutdown by the automatic systems installed as part of the design of the nuclear power plants to detect earthquakes. However, the large tsunami waves caused serious consequences at Fukushima Dai-ichi. Although all off-site power was lost when the earthquake occurred, the automatic systems at Fukushima Dai-ichi successfully inserted all the control rods into its three operational reactors upon detection of the earthquake, and all available emergency diesel generator power systems were in operation, as designed. The first of a series of large tsunami waves reached the Fukushima Dai-ichi site about 46 minutes after the earthquake. These tsunami waves overwhelmed the defences of the Fukushima Dai-ichi facility, which were only designed to withstand tsunami waves of a maximum of 5.7 m high. The larger waves that impacted this facility on that day were estimated to be over 14 m high. The tsunami waves reached areas deep within the units, causing the loss of all power sources except for one emergency diesel generator (6B), with no other significant power source available on or off the site, and little hope of outside assistance. The station blackout at Fukushima Dai-ichi and the impact of the tsunami caused the loss of all instrumentation and control systems at reactors 1–4, with emergency diesel 6B providing emergency power to be shared between Units 5 and 6. The tsunami and associated large debris caused widespread destruction of many buildings, doors, roads, tanks and other site infrastructure at Fukushima Dai-ichi, including loss of heat sinks. The operators were faced with a catastrophic, unprecedented emergency scenario with no power, reactor control or instrumentation, and in addition, severely affected communications systems both within and external to the site. They had to work in darkness with almost no instrumentation and control systems to secure the safety of six reactors, six nuclear fuel pools, a common fuel pool and dry cask storage facilities. With no means to confirm the parameters of the plant or cool the reactor units, the three reactor units at Fukushima Dai-ichi that were operational up to the time of the earthquake quickly heated up due to the usual reactor decay heating. Despite the brave and sometimes novel attempts of the operational staff to restore control and cool the reactors and spent fuel, there was severe damage to the fuel and a series of explosions occurred. These explosions caused further destruction at the site, making the scene faced by the operators even more demanding and dangerous. Moreover, radiological contamination spread into the environment .These events are provisionally determined to be of the highest rating on the International Nuclear Event Scale.

2. Fukushima Daiichi Nuclear Power Station

Fukushima Daiichi Nuclear Power Station (hereinafter referred to as NPS) is located in Okuma Town and Futaba Town, Futaba County, Fukushima Prefecture.It is facing the Pacific Ocean on the east side. The shape of the site is half oval with the long axis along the coastline and the site area is approximately 3.5 million square meters. This is the first nuclear power station constructed and operated by the Tokyo Electric Power Company, Incorporated (hereinafter referred to as TEPCO). Since the commissioning of the Unit 1 in March 1971, five additional reactors have been constructed and there are in total six reactors now.

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Electric Output (10,000 kW)	78.4	10.0	46.0	78.4	78.4	78.4
Start of Construction	Sep. 1967	May 1969	Oct. 1970	Sep. 1972	Dec. 1971	May 1973
Month of Commissioning	Mar. 1971	Jul. 1974	Mar. 1976	Oct. 1978	Apr. 1978	Oct. 1979
Reactor type	BWR-3	BWR-4				BWR-5
Containment type	MARK-I	MARK-I				MARK-II
Number of fuel assemblies	400	548	548	548	548	764
Number of control rods	97	137	137	137	137	185

Power Generating Facilities of Fukushima Daiichi NPS - Table I [2]

Unit 1	Reactor	In operation (400 fuel assemblies)
	Spent fuel pool	392 fuel assemblies (including 100 new ones)
Unit 2	Reactor	In operation (548 fuel assemblies)
	Spent fuel pool	615 fuel assemblies (including 28 new ones)
Unit 3	Reactor	In operation (548 fuel assemblies, including 32 MOX fuel assemblies)
	Spent fuel pool	566 fuel assemblies (including 52 new ones; no MOX fuel assembly)
Unit 4	Reactor	Undergoing a periodic inspection (disconnection from the grid on November 29, 2010; all fuel assemblies were removed; the pool gate closed; and the reactor well filled with water)
	Spent fuel pool	1,535 fuel assemblies (including 204 new ones)
Unit 5	Reactor	Undergoing a periodic inspection (disconnection from the grid on January2, 2011; RPV pressure tests under way; and the RPV head put in place)
	Spent fuel pool	994 fuel assemblies (including 48 new ones)
Unit 6	Reactor	Undergoing a periodic inspection (disconnection from the grid on August 13, 2010 and the RPV head put in place)
	Spent fuel pool	940 fuel assemblies (including 64 new ones)
Common pool		6,375 fuel assemblies (stored in each Unit's pool for 19 months or more)

Condition of the Fukushima NPSs on the day before the earthquake
Table II [2]

3. Occurrence and Progression of the Accident at the Fukushima Dai-ichi NPS

March 11, 2011

14:46: The earthquake which occurred on March 11, 2011 brought all of the Fukushima Daiichi NPS Units 1 through 3, which were in operation, to an automatic shutdown due to the high earthquake acceleration. Due to the trip of the power generators that followed the automatic shutdown of the reactors, the station power supply was switched to the offsite power supply. The Nuclear Power Station (NPS) was unable to receive electricity from offsite power transmission lines mainly because some of the steel towers for power transmission outside the NPS site collapsed due to the earthquake. For this reason, the emergency diesel generators (hereinafter referred as DGs) for each Unit were automatically started up to maintain the function for cooling the reactors and the spent fuel pools. Later, all the emergency DGs except one for Unit 6 stopped because the emergency DGs, seawater systems that cooled the emergency DGs, and metal-clad switchgears were submerged due to the tsunami that followed the earthquake, and the result was that all Alternate Current (hereinafter referred to as AC) power supply was lost at Units 1 to 5.

15:42: TEPCO determined that this condition fell under the category of specific initial events defined in Article 10 of the Act on Special Measures Concerning Nuclear Emergency Preparedness (hereinafter referred to as Nuclear Emergency Preparedness Act) and notified the Japanese national government, local governments, and other parties concerned.

16:36: TEPCO found the inability to monitor the water level in the reactors of Units 1 and 2, and determined that the conditions of Unit 1 and 2 fell under the category of an event that is — unable to inject water by the emergency core cooling system as defined in Article 15 of the Nuclear Emergency Preparedness Act.

16:45: The Company notified Nuclear and Industrial Safety Agency (hereinafter referred as NISA) and other parties concerned of this information. TEPCO opened the valve of the Isolation Condenser (hereinafter referred as IC) System A of Unit 1 IC, and in an effort to maintain the functions of the IC, it continued to operate it mainly by injecting fresh water into its shell side. Immediately after the tsunami, TEPCO could not confirm the operation of the Reactor Core Isolation Cooling (hereinafter referred to as RCIC) system of Unit 2, but confirmed about 3:00 on March 12 that it was operating properly. Unit 3 was cooled using its RCIC system, and as a result, the Primary Containment Vessel (hereinafter referred to as PCV) pressure and water levels remained stable. In order to recover the power supply, TEPCO took emergency measures such as making arrangements for power supply vehicles while working with the government, but its efforts were going rough.

23:00: Later, it was confirmed that the radiation level in the turbine building of Unit 1 was increasing.

March 12, 2011

0:49 : TEPCO confirmed that there was a possibility that the PCV pressure of the Unit 1 had exceeded the maximum operating pressure and determined that the event corresponded to the event -abnormal increase in the pressure in the primary containment vessel' as defined in the provisions of Article 15 of the Nuclear Emergency Preparedness Act. For this reason, in accordance with Article 64, Paragraph 3 of the Reactor Regulation Act, the Minister of Economy, Trade and Industry ordered TEPCO to reduce the PCV pressure of Units 1 and 2.

5:46: The Company began alternative water injection (fresh water) for Unit 1 using fire engines. In addition, TEPCO began preparations for PCV venting because the PCV pressure was high, but the work ran into trouble because the radiation level in the reactor building was already high.

11:36: Meanwhile, the RCIC system of Unit 3 stopped. But later, the High Pressure Coolant Injection (hereinafter referred to as HPCI) system was automatically activated, which continued to maintain the water level in the reactor at a certain level.

14:30: A decrease in the PCV pressure level in Unit 1 was actually confirmed.

15:36: Subsequently, an explosion considered as a hydrogen explosion, occurred in the upper part of the Unit 1 reactor building.

March 13, 2011

2:42: It was confirmed that the HPCI system of Unit 3 had stopped. After the HPCI system stopped, TEPCO performed wet venting to decrease the PCV pressure.

9:25 Fire engines began alternative water injection (fresh water) into the reactor of Unit 3. In addition, PCV venting was performed several times. As the PCV pressure increased, PCV venting was performed several times. As a result, the PCV pressure was decreased.

11:00: The wet venting line configuration had been completed in Unit 2.

March 14, 2011

11:01: An explosion that was considered as a hydrogen explosion occurred in the upper part of the reactor building in Unit 3.

13:25: TEPCO determined that the RCIC system of Unit 2 had stopped because the reactor water level was decreasing, and began to reduce the Reactor Pressure Vessel (hereinafter referred to as RPV) pressure and inject seawater into the reactor using fire-extinguishing system lines. TEPCO continued to cool the reactor core using the fire pumps loaned by a fire department.

March 15, 2011

6.00: Even though the wet venting line configuration had been completed in Unit 2 by 11.00 on March 13, but the PCV pressure exceeded the maximum operating pressure. An impulsive sound that could be attributed to a hydrogen explosion was confirmed near the suppression chamber (hereinafter referred to as S/C), and later, the S/C pressure decreased sharply.

6.00: The total AC power supply for Unit 4 was also lost due to the earthquake and tsunami, and therefore, the functions of cooling and supplying water to the spent fuel pool were lost. Around on March 15, an explosion that was considered as a hydrogen explosion occurred in the reactor building, damaging part of the building severely.

22:00: In accordance with Article 64, Paragraph 3 of the Reactor Regulation Act, the Minister of Economy, Trade and Industry ordered TEPCO to inject water into the spent fuel pool of Unit 4.

March 17, 2011

A Self-Defense Forces helicopter sprayed seawater into the spent fuel pool of Unit 3 from the air. Later, seawater was sprayed into the pool using high-pressure water-cannon trucks of the National Police Agency’s riot police and fire engines of the Self-Defense Forces.

From March 19, 2011 to March 25, 2011

Tokyo Fire Department, Osaka City Fire Bureau and Kawasaki City Fire Bureau, that were dispatched as Emergency Fire Response Teams, sprayed seawater in Unit 3 for five times by using seawater supply system against fire and squirt fire engines. In addition, Yokohama City Fire Bureau, Nagoya City Fire Bureau, Kyoto City Fire Bureau and Kobe City Fire Bureau dispatched their fire engines to Fukushima Daiichi NPS or in readiness. Niigata City Fire Bureau and Hamamatsu City Fire Bureau assisted to set up large-scale decontamination system.

March 20, 2011

14.30: The total AC power supply for Unit 5 was also lost due to the earthquake and tsunami, resulting in a loss of the ultimate heat sink. As a result, the reactor pressure continued to increase, but TEPCO managed to maintain the water level and pressure by injecting water into the reactor by injecting water into the reactor by operating Make-Up Condensing Water Pump after the power was supplied from Unit 6. Later, the company activated a temporary seawater pump, bringing the reactor to a cold shutdown condition at 14:30 on March 20.

19:27: One of the emergency DGs for Unit 6 had been installed at a relative high location, and as a result, its functions were not lost even when the NPS was hit by the tsunami, but the seawater pump lost all functionality. TEPCO installed a temporary seawater pump while controlling the reactor water level and pressure by injecting water into the reactor and reducing the reactor pressure on a continuous basis. By doing this, the company recovered the cooling functions of the reactor, thus bringing the reactor to a cold shutdown condition at 19:27 on March 20.

March 20, 2011 and March 21, 2011

Fresh water was sprayed into the spent fuel pool of Unit 4.

March 22, 2011

A concrete pump truck started to spray seawater onto the spent fuel pool of Unit 4.

March 27, 2011

Later, the concrete pump truck started to spray seawater into the spent fuel pool of Unit 3

March 30, 2011

The spraying of freshwater instead of seawater started in Unit 4.

March 31, 2011

The concrete pump truck started to spray seawater into the spent fuel pool of Unit 1. After the accident, seawater was used for cooling the reactors and the spent fuel pools for a certain period of time, but the coolant has been switched from seawater to fresh water with consideration given to the influence of salinity.

Main factors that developed the events of accident

This accident caused serious core damage in Units 1 through 3 of Fukushima-Daiichi NPS. The estimated amount of radionuclide released into the air due to the accident is given in Table III. But Units 5 and 6 of Fukushima-Daiichi NPS succeeded in cold shutdown without causing core damage. If any disturbance occurs in a plant during power operation, such as an event of loss of off-site power supply, the following three functions are required to shift the plant into the cold shutdown state; reactor sub-criticality maintenance, core cooling and removal of decay heat from PCV. The main factors that hindered reaching cold shutdown were

a) AC power was not recovered early because:
1: it was impossible to interchange electricity because of simultaneous loss of AC power for neighboring units
2: metal-clad switchgear and other accessory equipment were inundated due to tsunami
3: off-site power supply and emergency DG was not recovered early
b) Due to accident management carried out at the time of total AC power loss, core cooling was maintained for some time but was not sustained up until recovery of power supply.
c) The tsunami caused loss of functions of the system of transporting heat to the sea, which is the ultimate heat sink.
d) There was no sufficient means to substitute for the function of removing decay heat from PCV.

4. Measures that would have Prevented the Nuclear Disaster

1) Ample consideration should have been given to have different pylon for the different power transmission lines that were coming from the external power system to reduce the failure of both due to a common cause. Guideline 48 (Electrical Systems) of the Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities Nuclear Safety Commission (hereinafter referred to as NSC), Japan, specifies that the external power system shall be connected to the electric power system with two or more power transmission lines. But, it did not give ample consideration to remedial measures to reduce possibilities of common cause failures. TEPCO installed at least two emergency DG for each unit, having a sufficient capacity to activate required auxiliary systems. The earthquake PSA did not sufficiently examine measures to prevent loss of off-site power supply in order to reduce occurrence of total AC power loss, with the knowledge that total AC power loss is a critical event leading to core damage.

2) Measures should have been taken to ensure reliability of supplying power to nuclear power stations if a main substation stops supply. As part of accident management, facilities were provided that ensured interchange of the power supply for the working-use AC power supply (6.9 kV) and low-voltage AC power supply (480 V) between adjacent nuclear reactor facilities. For Unit 1 through Unit 4 at Fukushima-Daiichi NPS, however, this accident management system did not function effectively since the adjacent units were also subject to the total loss of the AC power supply.

3) Securement of power supply vehicle should have been considered for alternative AC Power supply as a part of accident management but it was not considered as part of accident management by TEPCO. As a temporary

applicable operation, a power supply vehicle was arranged to be carried in the site. But, this could not be utilized effectively due to the difficult access caused by defects of the heavy machinery for removing rubble and debris generated by the tsunami and water damage of metal-clad switchgear.

4) Securement of Direct Current (hereinafter referred to as DC) power supply for much more than 8 hours should have been made a part of accident management. In the PSA referenced in deriving the accident management system that had been established , a mechanical failure of a storage battery had been considered, and a period of time during which the DC power supply must function had been defined as 8 hours in the event tree of the off-site power supply loss event. If the off-site power supply failed to recover during this period, it was assessed that the RCIC system could not continue running. As a result, it was assessed that the off-site power supply might be more likely to recover, and loss of the DC power supply facilities would not be an event having a significant influence on the risk. Therefore, the preparation of temporary storage batteries was not a matter to be dealt with. During this accident, arrangements were made for carrying the storage batteries to the site. But, since carry-in works were difficult and such a work was performed in the dark due to the impact of the earthquake and tsunami disasters, difficulties arose in the recovery of the operation of the equipment following the accident, and the operation of the instrumentation system for recording plant parameters in the NPS.

5) Simultaneous functional loss of all the sea water pumps should have been considered and alternative arrangements should have been made. In the Probabilistic Safety Assessment (hereinafter referred to as PSA) referenced in deriving the accident management system that had been established, the functional loss of a seawater pump had been considered in a fault tree related to loss of the residual heat removal capability, but no consideration had been given to the simultaneous functional losses of all the seawater pumps due to tsunami and thus the loss of ultimate heat sink.

6) Alternative water injection into the reactors, using heavy machinery such as fire engines should have been designed for the Nuclear Power Plant. It was not considered as part of the accident management, but in this accident, as a temporary applicable operation, water injection into the reactor using a chemical fire engine that was present at the site was attempted. Nevertheless, since the reactor pressure was higher than the pump discharge pressure of the chemical fire engine, injection of freshwater into the reactor was not available in a few cases. Thus the alternative water injection systems such as fire engines should be designed especially for nuclear power plants so that their discharge pressure can be increased and matched with the pressure in the reactor.

7) Measures should have been taken to prevent hydrogen explosion at the reactor building. For measures against a hydrogen explosion at the reactor building, no consideration was given to the facilities or the documented procedures by TEPCO.It was the hydrogen explosion that caused major damage in Chernobyl[1] as well as Fukushima Dai-ichi Nuclear Disasters.

8) Seismic measures for external power lines (power transmission lines) should have been taken so that they didn't collapse during earthquakes.

9) Tsunami countermeasures for power receiving equipment in switching stations should have been taken. It should have been ensured that metal-clad switchgear, storage batteries, and other power supply equipment did not get inundated. An assessment technique for tsunami accompanying earthquake (tsunami PSA) should have been developed. The design tsunami height at Fukushima-Daiichi NPS was estimated to be O.P. + 5.7 m. But experts estimated that tsunami of 10 m or higher arrived. Nevertheless, it is considered that the actual tsunami height exceeded the design tsunami height. Documented procedures did not anticipate the ingress of tsunami, but specified only operation of stopping circulating water pumps used for cooling condensers as measures against undertow.

10) Measures should have been put in place for alternative water Injection into spent fuel pool and its cooling. However, no consideration was given to the facilities or documented procedures related to the injection of seawater into the spent fuel pool. The Guideline 49 (Fuel Storage Facilities and Fuel Handling Facilities) of the Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities requires a system capable of removing the decay heat in the spent fuel pool and transferring it to the sea which is the ultimate heat sink. However, there were no requirements for the capability to perform alternative water injection in preparation for the case of loss of ultimate heat sink. It was considered that the risk presented by the spent fuel pool is sufficiently smaller compared to the reactor.

5. Conclusion

The accident could have been prevented if the reactors were shifted to the cold shutdown state i.e. reactor sub-criticality maintenance, core cooling, and removal of decay heat from PCV. This would have been possible if AC power would have been recovered early .Care should have been taken to prevent the inundation of metal-clad switchgear and other accessory equipment due to tsunami. The loss of the ultimate heat sink was a major factor in the development of this accident. Thus measures should have been taken to prevent the simultaneous loss of all sea water pumps. The need of the hour is to learn a valuable lesson from this accident and ensure these mistakes shall not be committed elsewhere. Right now there is no alternative to nuclear energy as the burning fossil fuel is causing immense damage to the environment and is ushering in climate change.

	Released Amount (PBq)*			
	Rare Gas	^{131}I	^{134}Cs	^{137}Cs
TEPCO	About 500	About 500	About 10	About 10
JAEA Nuclear Safety Commission 12th April 2011		150		13
NISA (Nuclear and Industrial Safety Agency) 12th April 2011		130		6.1
IRSN(Institut de Radioprotection et de Surete Nucleaire)	2000	200		
Accident at Chernobyl Nuclear Power Plant[1]	6500	1800		85

Table III-Estimated amount of radionuclide released into the air due to the accident

***1PBq=1× 10^{15} Bq**

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