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Analysis of Possible Causes of Fukushima Disaster

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***Abstract*—**Fukushima disaster is one of the most publicly exposed accidents in a nuclear facility which has changed the outlook of people towards nuclear power. Some have used it as an example to establish nuclear energy as an unsafe source, while others have tried to find the real reasons behind this accident. Many papers have tried to shed light on the possible causes, some of which are purely based on assumptions while others rely on rigorous data analysis. To our best knowledge, none of the works can say with absolute certainty that there is a single prominent reason that has paved the way to this unexpected incident. This paper attempts to compile all the apparent reasons behind Fukushima disaster and tries to analyze and identify the most likely one.

***Keywords*—**Fuel meltdown, Fukushima disaster, manmade calamity, nuclear facility, tsunami.

I. Introduction

FUKUSHIMA disaster is still fresh in the minds of common people as it is the most recent also a very serious one. People are still divided on this issue whether the failure of Fukushima nuclear facility could be prevented or not. Many argue that it was a dual natural calamity that caused the disaster, which no one could have foreseen. Others may argue that lack of precautions is the main reason behind the disaster and it could have been easily prevented. In order to find a satisfactory answer, this paper goes through the detailed event analysis of the nuclear facility and inspects different opinions held by people regarding the causes of the event. The first portion of the paper focuses on the natural calamity that caused the event and the later portion goes through the possible causes of the disaster.

II. Progression of Fukushima Accident

Baba, in his article, presented the successive events that occurred during Fukushima disaster [1]. In Fukushima-I, there were six units of Boiling Water Reactors (BWRs). These are the oldest generation BWRs, BWR3/4. Each reactor unit consisted of a reactor pressure vessel, a containment vessel and a reactor building. It had a pool for spent fuels in the top floor of the reactor building.

During the earthquake, Units 1-3 were in operation and Units 4-6 were in shutdown for regular inspection. The Unit 4 was just stopped, and the fuels were moved into spent fuel pool. Therefore, the fuels in spent fuel pool of Unit 4 had high decay heat.

Three reactors in operation of Units 1-3 stopped automatically sensing the earthquake and emergency diesel generators for emergency cooling and passive cooling system started up. However, the earthquake destroyed the external power transmission lines. The tsunami arrived about 50 min later, disabled emergency diesel generators and seawater pumps. The loss of external AC power and emergency cooling system caused meltdown of nuclear fuels [1].

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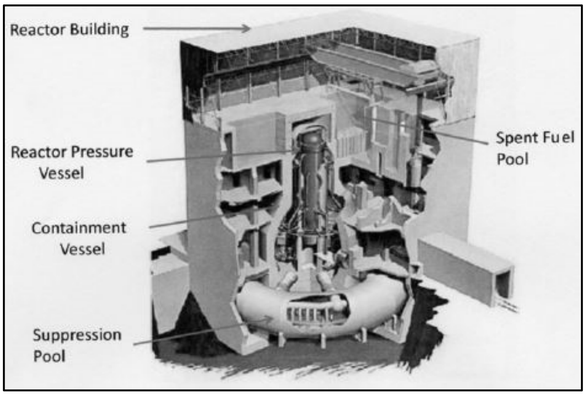

Fig. 1 Schematic Diagram of BWR in Fukushima-1 NPP [2]

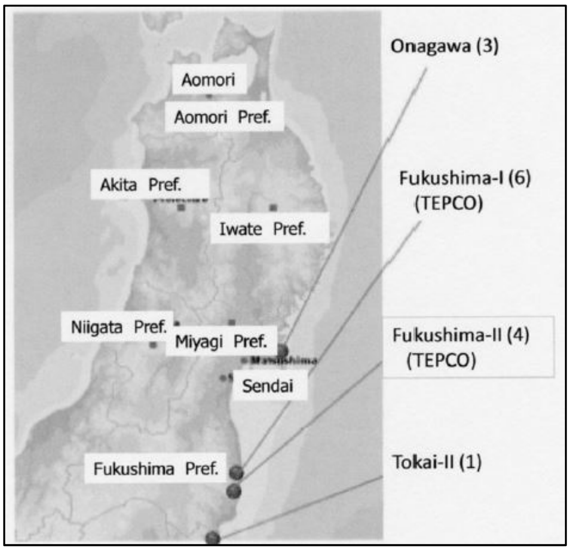

Fig. 2 NPPs hit by earthquake and tsunami on March 11, 2011 [2]

A. Unit 1

At 2:46 pm, March 11, the earthquake (M = 9.0) occurred. The reactor stopped automatically. However, transmission line towers and other equipment on the plant grounds collapsed as a result of the earthquake and it disabled the Units 1 through 6 from receiving external AC power. EDG started up automatically, and further Isolated Condenser (IC) in the Unit 1 driven by battery started operation for core cooling. It is reported, however, that IC was operated only intermittently to avoid too rapid temperature change. At 15:37, tsunami arrived and disabled a) oil tanks for EDG, b) seawater pumps for heat removal which were placed in the sea side without housing, and flooded EDGs inside underground rooms of turbine buildings which were not water-tight. At the stage, no means of core cooling were available, and Nuclear Disaster Special Measures Law was declared by the government (19.03 on March 11). The loss of cooling in reactors led to temperature rise of fuel rods and reaction of high temperature zirconium in fuel clad with water vapor, which produced a large amount of hydrogen, and led finally meltdown of fuels rods [2].

The pressure inside containment vessel raised and exceeded the design limit (4.3 atm) due to a leak of water vapor and hydrogen gas from Pressure vessel to containment vessel. Then, the pressure release was carried out by opening the vent valve of containment vessel manually (14:30 on March 12). This was dry vent without filters and resulted in discharge of a significant amount of radioactivity to the environment. Despite of the vent, hydrogen explosion occurred in the top of reactor building of Unit 1 at 15:36 on March 12, and destroyed upper part of reactor building leading again to discharge of radioactivity. Later, this hydrogen explosion proved to be caused by a backflow of vent gas into RB because of improper action of an anti-backflow valve. At 20:20 on March 12, core cooling was started using seawater via fire-service line with external pumps. Later seawater was changed to fresh water to avoid erosion [2].

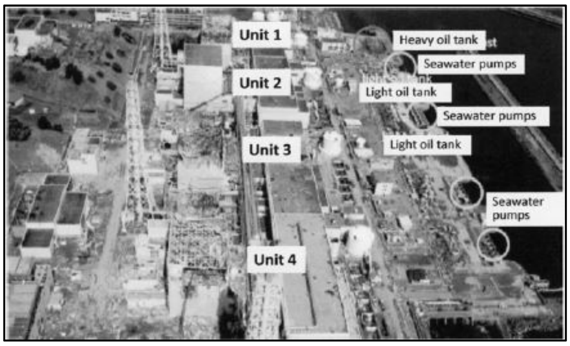

Fig. 3 View of Fukushima-I NPP after the accident [2]

B. Unit 2-4

The situation was similar for the Units 2-4 while the occurrence of explosion was later than in the Unit 1. The Units 2-3 were also equipped steam-driven passive core cooling system, Reactor Core Isolation Cooling system and started automatically or manually after the earthquake. However, similarly with the Unit 1, Reactor Core Isolation Cooling system was operated only intermittently and utilized effectively.

In Unit 3, Reactor Core Isolation Cooling system stopped at 11:36 on March 12, and high pressure coolant injection system started. However, at 2:42 on March 13, the high pressure coolant injection system stopped operating and Reactor Core Isolation Cooling system could not start up. The pressure in pressure vessel and containment building increased rapidly. At around 9:08, containment vessel was vented and seawater was pumped in at 13:12 on March 13. However, at 11:01 on March 14, a hydrogen explosion occurred in reactor building of the Unit 3 and destroyed the building [2].

In Unit 2, the Reactor Core Isolation Cooling system was not stable and the reactor core was not cooled appropriately. At 13:25 on March 14, Reactor Core Isolation Cooling system stopped functioning. At around 16:00, pressure release of pressure vessel was conducted and at 19:57 injection of seawater was started by fire service car. Venting was initiated at 12:02 on March 15, and at 6:00-6:10, an abnormal noise was heard near the pressure suppression chamber and the pressure dropped. It was presumed that there was release of the radioactive materials from containment vessel and it was confirmed by measurements of radiation.

In Unit 4, the reactor core was empty, and all the fuel rods were in the spent fuel pool. However, a hydrogen explosion occurred at 6:14 on March 15, destroying the reactor building as well. The hydrogen explosion proved to be due to the leak of hydrogen produced in Unit 3 core to the Unit 4 reactor building through a conduit connecting the buildings of Units 3 and 4. Therefore, the damage of the spent fuels in the pool was not serious, but the explosion of Unit 4 reactor building gave serious threat to the safety because many fuel rods with high decay heat existed without a containment vessel [2].

C. Recovery Systems

The fuels rods in cores of Units 1-3 were considered to have melted down to the bottom of PV and partly to CV, but they should be cooled continuously as well as fuels in SFP in Unit 4. To establish stable operation of cooling system, AC power was indispensable. Then, restoration of external electricity was carried out on March 21 and 22 for lightening and extended to powers for pumping. In Units 1 through 4, cooling of the reactor cores and the fuel rods at SFPs had to be continued against decay heat. However, as the cooling water circulating pumps were no longer functioning, cooling was temporally provided with seawater through a fire service line using external pumps, and spray of seawater. Later, seawater was changed to fresh water to avoid erosion and deterioration of inside items. The discharge and pumping of water into the reactor cores and spent fuel pools, led to the situation that water containing large quantities of radioactive materials flowed out into the ground below the turbine buildings and other areas. The highly radioactive water in the turbine building must be removed, and therefore, the cooling system should be changed to circulation cooling. Furthermore, it was discovered that highly radioactive water was flowing into the ocean from a crack in the outlet at Unit 2. It was stopped and lower-concentration contaminated water that had been in the waste treatment facility was discharged into the ocean to secure the storage space highly contaminated water. Besides, since April 6, nitrogen was pumped into the containment vessel of Unit 1 to prevent hydrogen explosion and extended to the Units 2 and 3 successively.

It will be important to see what difference was there between Fukushima-I NPP and others which reached cold shutdown safely. The Units 5 and 6 in the Fukushima-I NPP were also hit by the tsunami and flooded, but one EDG in Unit

6 continued to function because it was air-cooled one and stored in a water-tight building. The power line was common for Units 5 and 6. As a result, Units 5 and 6 achieved cold shutdown on March 20. Similarly, in Fukushima-II NPP, the electric equipments were protected from the tsunami in a water-tight building. In the Onagawa NPP, the ground level of the site was 14.8 m and higher than the tsunami, w13 m, and both external AC power and EDGs were available, although there were critical situations during the period reaching cold shutdown in the big aftershock on April 7. The situation was similar in the Tokai-II NPP, but both NPPs could reach to cold shutdown [2].

III. Possible Causes Behind the Disaster

A. Responsibility of the Government and the Company

Japan is one of the most advanced and modern countries with technical resources that very few countries have. However, they are also among the very few countries that have faced disasters related to nuclear power. While the first two came from nuclear attacks from Hiroshima and Nagasaki, which some may not count as they were exceptional cases, there are other cases of accidents also long before Fukushima disaster, according to Nakamura and Kikuchi [3]. In their paper published in 2011 just after the incident, they mentioned two other occurrences, coincidently on the same Fukushima nuclear facility, one in 1978 and another in 1989. In the first case, there was malfunction in the reactor and it leaked radioactive substances in the atmosphere. The second case occurred due to malfunction of the cooling water system. There was another accident in 1999 in a semipublic nuclear reprocessing corporation, JCO, which resulted in death of two employees and exposure of more than 600 workers to high level of radiation. After these incidents, it took almost a decade to face another nuclear disaster, which was again at Fukushima nuclear power plant. In their paper, they focused on finding the reasons which made these incidents possible in such a modern country and identified that the scenario is much more complex than it appears to be. They implied that the responsible persons were not only the government officials but also the private companies that were involved in the operation and development of the nuclear facilities.

The authors also pointed out that there are technical and human dimensions also apart from the political and administrative issues and tried to look it from different perspectives. The first point that the authors identified is that the reason behind the accident, though may seem to be an act of tsunami, is due to the oblivion of the Japanese governments and the industries that were attached to the facility. A number of citizens of the country also hold the same opinion that both the parties were so overconfident that the overlooked the possibility of any kind of malfunction. As the earthquake and tsunami hit the northern part of the country, all the electricity supply to the nuclear power plant were cut off and it was not possible to cool down the nuclear pallets. This led to the meltdown of fuel rods in three of the four vessels, producing radioactive particles that spread into the air and sea. Before the incident, it was claimed by the private company, TEPCO, that the nuclear generators developed by them were absolutely fail-safe. The company also implied that the vessels were able to withstand very high tides and strong tsunami. In order to back their claim, the company stated that they had installed five layers of protective devices for the nuclear reactor. Although many scientists and concerned persons expressed their lack of faith on the claim, the government encouraged the establishment of the facility. However, after the Fukushima disaster, a serious flaw in the design was revealed. In order to ensure proper cooling of the nuclear pallets, the plant was provided with a separate building adjacent to the containment structure in order to circulate electricity to the coolant system. Unfortunately, the structure was just near the sea and the tsunami knocked down the building, resulting in the loss of power to the cooling system, leading to accident. A day later, hydrogen gas accumulated over the containment building exploded and caused the meltdown of fuel rods, resulting in even more serious accident.

A press secretary in the government’s Nuclear and Industrial Safety Agency exposed this incident publicly. However, the government stated that the comment was misleading and there was no meltdown. After almost two months, both the government and the company finally admitted their mistake and confessed that the previous claim was indeed true. The author pointed out that the companies that were controlling the nuclear power generation in Japan were highly protected by the government. The companies kept many of their reactors running even though the reactors had either become old or had serious defects. The author also indicated the possible leniency of the government towards the companies. The policies that the government took made the country highly dependent on nuclear power, which led to the indifference of the companies towards quality assurance. From the point of view of the article, the disaster was a result of a complex dynamics that was fueled by both the government and the companies responsible for the smooth operation of the reactor.

B. Lack of Preparedness

Funabashi and Kitazawa, in their article, pointed out some more aspects of the disaster [4]. The author pointed out that main reasons behind the disastrous consequences were the lack of communication between the government and the company and the lack of preparedness from both sides. They stated that the location of multiple buildings containing reactor vessels had led to chain-reaction accidents in Fukushima, which again led to hydrogen explosion. The author suggested that it was even more serious issue than the loss of coolant itself. It was also evident that a TEPCO worker mistakenly assumed that due to power loss, an IC which controlled the gas ventilation system inside the rector containment building was not functioning correctly. As a result, he removed the IC and it caused even more buildup of pressure of gas inside the containment building, leading to hydrogen explosion. There were many other actions of the higher authorities of the company that proved their lack of preparedness for such a situation. From the point of view of the author, Fukushima disaster was a result of manmade errors.

According to the authors, there were many human errors made at Fukushima. However, the authors also stated that the human errors were not only limited to misjudgment of a single worker, but rather also of the technical chief, the plant director and the nuclear energy sector of TEPCO's headquarter. They mentioned that TECPO actually never addressed the possibility of a prolonged, total loss of power, which led to unpreparedness. When the on-site workers were trying to take help from the severe accident manual, they did not find the answers for such a crisis, which indicated that the company itself never considered the possibility. As a result, TECPO's higher management should be held responsible for this accident primarily, according to the opinion of the authors. To justify the point, they also pointed out that neither the chairman nor the president of TECPO was present at the head office during the most crucial periods of dealing with the accident. Due to this lack of leadership, TECPO was unable to take any quick decisions and it also made the trust of the government weaker towards them regarding decision making.

The government regulatory bodies also are to be blamed for the poor response during the disaster. National Safety Council had no provisions for such an extended loss of power, as they never thought it was needed to be considered at all. It was due to the assumption that the power transmission lines will be online quickly, which was not the case for Fukushima disaster. It took many days for transmission lines of external power sources to be restored, which was indeed a result of the lack of foresight of NSC and NISA. According to the article, the government itself was also much unprepared, which became obvious when the nuclear emergency response headquarters, or otherwise named as off-site center, for the Fukushima plant was unable to do anything effective during the event. The center was established in 1999 after a serious accident at Tokai nuclear fuel conversion facility in order to cope with such situation. But, the center proved to be incapable of doing anything during the event. The authors also pointed out that SPEEDI, a government organization, to account for the radioactive dose related information, could not submit any official reports regarding the disaster at Prime minister's office until 23th of March, which was far from the date of the starting of the disaster. All these indications pointed towards a single reason for this accident, and that was lack of preparedness from all the organizations and even the government.

C. *Profit before Safety*

Funabashi pointed out that the main reason behind such a severe accident was due to putting economic profit before safety, making it a manmade calamity [5]. The author focused on the fact that despite the high frequency of earthquakes in Japan, it kept on constructing nuclear plants in order to ensure reliable source of power at low cost. The six units in Fukushima were located in a very compact area to minimize land cost, ignoring the fact that there is a high possibility of losing all the units at once during any natural calamity. Again, the nuclear power plants in Japan are mostly at coastal area at very small height from the sea level, making them vulnerable to tsunami.

The author also pointed out that the power plant used in Fukushima was Mark I, produced by General Electric, which had become considered old-fashioned by the time the author wrote the paper and many defects had already been identified in the reactor since 1975. All the units were operating for more than 40 years, and a number of problems had already occurred with them. The towers that supported the power lines were not sufficiently earthquake resistant; neither were the emergency power generators located properly so that they might be safe from tsunami strike. All these points indicate only one thing; the safety system of the facility was compromised to reduce the installation and running cost of the power plant. Such lack of vision made the author realize that it was indeed the men who should be held responsible for this unexpected disaster.

In the paper, it was also pointed out that the government and the organizations responsible for the nuclear power generation did try to establish the fact that the reactors were very safe, which was not the case at all. The promoters always told that the reactors were safe because of their multiple technological safeguards built in them, where in reality they were proved inadequate due to the defects mentioned earlier. The government tried to cover the truth, which again paved the way to this serious event. The organizations of the government like Nuclear Commission underestimated the real threat in the face of severe tsunami that could cause catastrophic accidents.

The paper also introduced a term called "Nuclear Complex" which consisted of many actors, electric power companies, nuclear industries, political parties, government organizations, mass media and the academic persons who were involved in promotion of nuclear power sector in Japan. A huge amount of money was spent for the promotion of nuclear power to establish it in the power generation policy in Japan. As a result, the construction costs had to be minimized in order to compensate for that spent money, which led to relaxation of safety features. This was the main reason why such an event was possible in such a technically well-developed country like Japan. The more the companies put their emphasis on profit, the less they cared about safety, which is indeed the case for Fukushima Disaster.

The paper also tried to find a relationship between the calamity and the Japanese nuclear complex by explaining the term "binary combination", a theoretical concept by Mori Arisama. Binary combination is defined as a relation between two persons that is characterized by intimacy and a vertical relationship. "Intimacy" implies a fusion of two persons that is closed to a third person. In this respect, a binary combination shows a private character in relation to a third person located on the outside of the intimate relationship. "Vertical relations" denotes unequal relations between two persons. This relation appears in an established social order. It appears typically between a parent and a child, a teacher and a pupil, a boss and a subordinate, a master and a disciple, and so on [6]. The author believed that this binary combination was responsible for the accident. The logic was that due to the strong influence of binary combination in Japanese culture, they were indifferent to the opinions coming from outside. The decision making and action of the organizations were also highly influenced by this as it developed a tendency towards conformism. As a result, they ignored any defect pointed out by the outsider organizations, which made this disaster possible.

D. Underestimation of the Situation

Hasegawa, in his article, also voiced the same opinion [7]. He stated that though the disaster was triggered by earthquake and tsunami, the main reason behind the accident was the underestimation of the situation as per the investigation report of a committee of the cabinet. The committee held the government and TEPCO very much responsible for the incident. The author explained the reason behind his opinion that the height of the tsunami was underestimated by TEPCO and the Japanese Nuclear Safety Commission (JNSC). Despite the fact that some researchers gave scientific warning of a 15.7-m tsunami in 2008, both the organizations neglected it and the plant remained under-designed for withstanding only 5.7 m tsunami.

Another issue was that the Japanese power companies did not expect a longtime station blackout and didn't prepare for it. When they lost their power sources one by one, they had nothing to do but to observe the situation. Another thing was that the Japanese government did not have for an evacuation plan for more than 24 hours and the radius was also very small, only 10km, despite the recommendation of 30 km by IAEA. This negligence led to even more serious accident.

Another problem that was visible during the Fukushima disaster was confusion and lack of information among the higher authorities. As they did not have adequate information, they could not act instantly and effectively. This disaster exposed the ineffectiveness of NSC and NISA in Japan. The author believed that all these points were enough to justify the fact that underestimation of the situation led to such a massive-scale disaster.

E. Malfunction of Nuclear Disaster Robots

Kawatsuma et al., in their article, identified yet another aspect of the disaster, which is the malfunction of nuclear disaster robots during Fukushima disaster [8]. The robots were developed after the JCO criticality accident in 1999. The robots were developed so that they could work in hostile environments where humans could not. The Nuclear Safety Technology Center (NUSTEC), Japan Atomic Energy Research Institute (JAERI) and Manufacturing and Science Technology Center (MSTC) developed these robots.

NUSTEC developed MoniRobo-A and MoniRobo-B; robots that could monitor the exterior of a building in which an accident had occurred JAERI, now the Japan Atomic Energy Agency (JAEA), developed two REmote Surveillance Squad (RESQ)-A robots that were anticipated to be able to acquire initial information, such as beta and gamma dose level data and neutron data, a REAQ-B robot that was to acquire detailed information, a RESQ-C that was to acquire samples, and a Radiation proof roBOT (RaBOT) that could be resistant to radiation. These robots were planned to monitor the insides of buildings, when accidents have occurred in the buildings, so RESQ-B, RESQ-C and RaBOT were equipped with arms that could deal with opening door handles. MSTC developed an operation assistance robot SMERT-K for quick reconnaissance, an operation assistance robot SMERT-M which could carry SMERT-K and run over rubble, a light operation robot SWAN, an operation robot MARS-A, a heavy transporter robot MARS-T, and an anti-high radiation robot MENHIR [8].

Fig. 4 MoniRobo-A and B [8]

Fig. 5 RESQ-A [8]

Fig. 6 RESQ-B [8]

Fig. 7 RESQ-C [8]

Fig. 8 RaBOT [8]

Fig. 9 SMERT-K [8]

Before Fukushima disaster, NUSTEC had kept MoniRobo-A and MoniRobo-B maintained. JAEA had stored RESQ-A, RESQ-B and RESQ-C but had not maintained them after 2006. These robots were not able to work as a result of some failures. The vendor that had co-operated when the robots were developed, was requested to repair RESQ-A, RESQ-B and RESQ-C, but the vender refused the request because the engineer who had involved had since left, with the result that necessary information had been lost. During Fukushima disaster, NUSTEC sent MoniRobo-A to J-Village, which became the base for the emergency response to Fukushima Daiichi accident. However, it was not deployed because it was considered to be too heavy and could damage cables and hoses that were temporarily setup for electric power supply and water supply [8].

From the above information, it could be concluded by the author that the robots developed for the emergency responses during nuclear disasters were actually not developed enough. The author identified two possible reasons behind it; one is the lack of communication between the developers and the power generation companies and other is the lack of involvement of the power companies in the development process of the robots. As a result, the robots could not be utilized fully the time they were needed the most.

IV. Closing Remarks

This paper tries to give the full picture of the Fukushima disaster and the possible reasons behind it. From the information provided in this paper, it is evident that Fukushima disaster can neither be called natural calamity nor manmade calamity since both have more or less equal contribution to the magnification of the effects of the disaster.

At the first glance, it may seem that there was nothing to do as such a large scale natural calamity can cause any facility to fail. But, after deeply observing the scenario, it can easily be understood that the unpreparedness and lack of safety precautions fueled the disaster and made it a catastrophic one. In order to avoid this type of event in future, it is necessary to establish proper safety equipments in nuclear power facilities. Also, the design should be finalized keeping in mind the geographical position in mind as area selection plays a crucial role in preventing failure. Finally, cost minimization should not be done in such a manner that the overall safety of the facility is compromised.

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