2012

Senior Project:

The Leading Contributor of the Fukushima Daiichi Nuclear Power Plant Accident

Christopher Torres

California Polytechnic State University

Liberal Arts & Engineering Studies Department

06.04.2012

Fukushima Daiichi Nuclear Power Plant

The accident at Fukushima Daiichi Nuclear Power Plant on March 11, 2011, has produced significant amount of human suffering with a negative annotation against nuclear energy. The accident result a permanent evacuation of over 200,000 Japanese citizens with a clean-up operation that may take decades and cost hundreds of billions of dollars. A report from the International Atomic Energy Agency (IAEA) in June 2011 has confirmed large quantity of radiation has released into the environment that likely to result in thousands of “excess” cancer cases. The quantity of radiation released into the atmosphere by the accident was about fifteen percent of the radiation releases from the Chernobyl disaster in Ukraine. A much smaller quantity of radiation was released into the Pacific Ocean do to overflow of contaminated water that had been used to cool the reactors. The exact amount of evacuees, cost and time of the clean-up operation, and radiation released by the Fukushima accident has proved controversial and estimate may change as more information becomes available.

Thesis

There are sufficient evidence to suggest the Fukushima accident was the result of failures in regulations and nuclear plant designs and that both were lacked behind international best practices and standards by the plant’s owner, Tokyo Electric Power Company (TEPCO), and Japan’s regulator, Nuclear and Industrial Safety Agency (NISA). Though there is no single reason for the failure of the accident, one major underlying cause can be identified. The lack of tsunami risk resulted in a station blackout and loss of ultimate heat sink. The reasons for a lack of tsunami risk are revealed through several potential causes that are classified as either failure in

regulations or nuclear plant design. The leading contributor of the accident unravels as a cultural phenomenon toward TEPCO and NISA failures in regulation for being overconfidence toward tsunami safety threats.

How Nuclear Power Works

To completely understand the origin of the potential causes of the accident, a basic understanding of nuclear reactors must be considered as well as the sequence of the Fukushima Daiichi Nuclear Plant accident.

A modern commercial nuclear power plant will usually produce an average of one gigawatt of electricity at full power. The nuclear fuel is typically shaped into miniature pellets of about 2.5 centimeters long with approximately the same diameter as a dime. The pallets are enriched uranium that is set inside long rods known as fuel rods. The rods are collected into an assembly and submerged in water inside a pressure vessel. The enriched uranium will undergo nuclear fission to produce heat while the water within the pressure vessel behaves as a coolant in order for the uranium not to overheat and melt. Control rods are inserted with the fuel rods to completely monitor the heat produced by the enriched uranium. A mechanism is used in to raise and lower the control rods in order to allow the operators to control the amount of heat being produce. The heat will naturally boil the water into steam to operate a steam turbine, which spins a generator to produce electricity.

There are two main types of nuclear reactor known as Boiling Water Reactor and Pressurized Water Reactor. TEPCO were operating six Boiling Water Reactors at Fukushima Daiichi Nuclear Power Plant. The design of Boiling Water Reactors is considered more dangerous since the radioactive water/steam contacts the turbine and the risk for radiation

exposure is much greater. Fukushima Daiichi Nuclear Power Plant confronted a severe external accident that allowed all six Boiling Water Reactors to malfunction. The accident sequence can be divided into three stages – the earthquake, and the tsunami that resulted in a station blackout and loss of ultimate heat sink.

The Accident Sequences: The Earthquake

Japan was struck by an earthquake with a magnitude of 9.0 on March 11, 2011, at 2:46 pm local time. The earthquake occurred in the Pacific Ocean about 80 kilometers east of the city of Sendai that triggered a set of powerful tsunamis in motion. According to the United States Geological Survey, it is considered the largest earthquake ever recorded in Japan and the fourth largest recorded worldwide since 1900.

Three of the six reactor units at Fukushima Daiichi Nuclear Power Plant were operating at the time—units 1, 2, and 3 (Figure 1). These three units automatically “scrammed” right after the earthquake hit onshore; a process that allows a set of control rods to be inserted into the reactor core to suppress nuclear fission. Once the process was completed, the reactors were no longer generating electricity, an alternative electricity supply is required in order to operate the emergency cooling system since highly radioactive material still continues to decay and produce heat after a shutdown. The earthquake managed to destroy all six external power lines from Japan’s grid to the plant. Fortunately, the emergency diesel generator began operating and enough electricity was provided to cool unit 2 and 3. For reasons that are not yet known, Unit 1 unexpectedly dropped in temperature and pressure. In order to avoid damage to the reactor and in maintaining with the plant’s operating procedure, the operators repeatedly turned on and off the emergency cooling to slow the rate of cooling.

Unit	MWe	Status
6:	1067	Outage
5:	760	Outage
1:	439	Operating
2:	760	Operating
3:	760	Operating
4:	760	Outage

Figure 1: An image of Fukushima Daichii Nuclear Power Plant and the status of the six boiling water reactors before the accident.

The Accident Sequences: Tsunami – Blackout

About forty-five minutes after the earthquake, the Fukushima Daiichi Nuclear Power Plant was bombarded by a series of tsunami waves that cause serious damage. Eleven of the twelve emergency diesel generators in service at the time failed, only one connected to unit 6 worked. The power distribution that would have allowed an external power source to be connected to the plant were swamped and extensively damaged. This resulted in a station blackout since there was a complete loss of AC power from both internal and external sources for units 1 to 5. DC batteries were equipped in the plant to compensate for the station blackout. The batteries in units 1 and 2 were flooded and rendered ineffectual while batteries in unit 3 continued to function for about thirty hours—far beyond their eight-hour design life.

The seawater pump and their motors, known as the ultimate heat sink, are responsible for transferring heat extracted from the reactor cores to the ocean and for cooling most of the emergency diesel generators. These seawater pumps were located four meters above sea level (Figure 2). They were heavily damaged and became unfeasible after the tsunami hit Fukushima Daiichi.

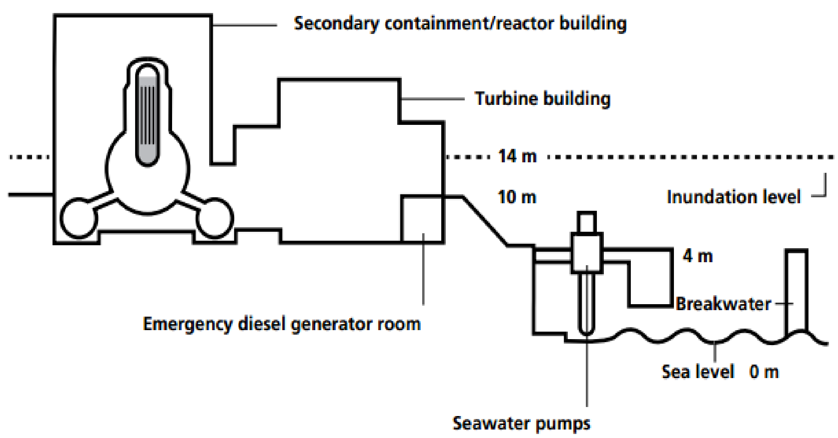

Figure 2: Simplified cross-section through one of the reactors at Fukushima Daiichi showing the approximate location of critical components damaged by the tsunami. Not drawn to scale.

The seawater pumps were no longer supplying coolant into the reactor core and the water within the reactor began to boil off. As the water continued to boil, the top of the fuel rods were exposed until the uranium fuel pellets overheated and cracked. Water entered into the cracks of the fuel rods and began mixing with the fuel pellets where it began generating hydrogen gas. The process is known as thermolysis—if water became hot enough then it will break down into

its constituent hydrogen and oxygen atoms. Pressure from the hydrogen built up so quickly that it exploded inside the reactor building. This same chain of events occurred in several different reactors.

The pressure vessel holding the nuclear cores did not rapture due to these explosions nor did any significant amounts of radiation into the environment. These were simple hydrogen explosions, not nuclear explosions. It did manage to damage the concrete and steel buildings surrounding the pressure vessels. The explosions allowed the operators to realize that things had gotten out of control. The reactors were about to undergo complete meltdown if the water within the core continues boiling off. As a last resort, the operators decided to flood the reactors with seawater. Seawater can completely ruins a reactor since it will mix with boron to act something like a liquid version of the control rods. Boron absorbs neutrons and is one of the main constituents in the control rods. The operator managed to save the reactors from a complete meltdown.

Failure in Nuclear Plant Design

With a simple understanding of the accident a more precise overview can be considered. Several potential causes have been recognized from the accident sequence to determine the actual cause of the accident. Some of these potential causes are categories as failure in nuclear plant design, which lagged behind international best practices and standards. These failures in nuclear plant design are considered as technical problems in historical evidence for large earthquakes and tsunamis, computer modeling of the tsunami, the emergency power supplies for the diesel generators and batteries, the ultimate heat sink, and waterproof containment.

TEPCO and NISA demonstrated insufficient attention to historical evidence of large earthquakes and tsunamis. Best practice, requires the collection of data on pre-historical and historical earthquakes and tsunamis in the region of a nuclear power plant in order to protect the plant against rare extreme seismic events that may occur only once every ten thousand years. Fukushima Daiichi original design-basis for a tsunami was a seawall of 3.1 meters. It was chosen because an earthquake off the coast of Chile created a tsunami of that height on the Fukushima coast in 1960. Although historical data was used in assessing plant design, greater attention should have been paid to evidence from further back in history.

Japanese researchers have discovered layers of sediment that appear to have been deposited by tsunamis and have concluded that the region had been inundated by massive tsunamis about once every one thousand years. The most recent of these events occurred in 869 AD with a magnitude of 8.3 earthquake. A collection of historical recorded for tsunami in and around Japan lists several events since 1498 having maximum amplitude of more than ten meters with six having maximum amplitude of over twenty meters (Tab 1). Provided with the given historical record of tsunami in Japan, TEPCO and NISA should have been much more conservative in defining the design-basis tsunami.

Year	Area	Magnitude	max. high[m]	Casualties
1498	Enshunada Sea	8.3	10.0	31,000
1605	Nankaido	7.9	10.0	5,000
1611	Sanriku	8.1	25.0	5,000
1703	Off Boso Peninsula	8.2	10.5	5,233
1707	Enshunada	8.4	11.0	2,000
1771	Ryukuyu Islands	7.4	85.4	13,486
1854	Nankaido	8.3	28.0	3,000
1896	Sanriku	7.6	38.2	27,122
1923	Sagami Bay	7.9	13.0	2,144
1933	Sanriku	8.4	29.0	3,022
1944	Off Southeast coast of Kii Peninsula	8.1	10.0	1,223
1983	Noshiro	7.8	14.5	100
1993	Sea of Japan	7.7	54.0	208
2011	Northeast Honshu	9.0	23.0	>15,000

Tab 1: List of historically-proven tsunami along the Japanese coast triggered by earthquakes.

Failures in Nuclear Plant Design: Computer Modeling of the Tsunami

A nuclear power plant built on a slope by the sea, such as the Fukushima Daiichi Nuclear Power Plant, must be designed so that it is not damaged as a tsunami runs up the slope. In 2002, Japanese engineers conducted a detailed methodology for determining the maximum run-up of a tsunami at Fukushima Daiichi. The methodology impelled TEPCO to revise their original design-basis for a tsunami from 3.1 to 5.7 meters. However, TEPCO failed to develop adequate computer modeling since the methodology itself is flawed. The methodology focuses exclusively on evaluating run-up on the grounds while neglecting other essential factors such as the hydrodynamic force of the tsunami and the effects of any debris and sediment it may be carrying which can cause extensive damage to a nuclear power plant.

A nine meter tsunami did flood a nearby nuclear power plant, which was built on a 12 meter slope, near Fukushima Daiichi Nuclear Power Plant. The accident raised important questions about whether even a 5.7 sea-wall will be enough to protect Fukushima Daiichi. In 2008, a set of simulations were conducted that suggested the methodology used in 2002 to the nuclear power plant had been seriously underestimated. However, these simulations still

assumed a considerably smaller earthquake than the one that actually struck on March 11. TEPCO appeared to have never implemented the relevant procedures in full. The simulations were not followed up and were never reported to IAEA, only to NISA on March 7, 2011.

Failures in Nuclear Plant Design: Emergency Power Supplies – Diesel Generators and Batteries

During the times when the Fukushima Daiichi Nuclear Power Plant was constructed, the emergency diesel generators and emergency batteries were installed on the inside floor of the nuclear power plant for the protection against earthquakes, but not against tsunamis. Most of the emergency diesel generators and emergency batteries were swamped, extensively damaged, and rendered inadequate to operate. The emergency power supplies and other emergency power equipment should have been installed to higher ground on the plant site. Safety experts have said, moving this emergency power equipment to higher ground would not have increased its vulnerability to seismic shock, provided it as fixed to a platform designed to resist earthquakes.

Failures in Nuclear Plant Design: Ultimate Heat Sink

The seawater pumps and their motors, known as the ultimate heat sink, were located at sea-level outside the Fukushima Daiichi Nuclear Power Plant. After the tsunami arrived, these pumps were flooded and completely destroyed. It became unfeasible to extract and transfer heat to the ocean from the reactor cores and emergency diesel generators. Even if electricity had been available to operate the emergency cooling systems, there would have been no way of dissipating the heat and the engine would have overheated. The protection of these seawater pumps should have been enhanced and/or constructed a backup means to dissipate heat.

TEPCO failed to waterproof the ventilation ducts in the compartment where the emergency power supplies equipment and the ultimate heat sink are located. Waterproofing the connections between emergency power supplies and ultimate heat sink could have resulted in a less serious accident.

Tokai-2 Nuclear Power Plant, located about 100 miles south of Fukushima, experienced the same catastrophe that ravaged Fukushima Daiichi Nuclear Power Plant. However, Tokai-2 plant resulted in a less serious accident since most of their seawater pumps were protected by waterproof containment. Prior to the tsunami, plans had already been established to strengthen the plant against tsunami risks; a seawall was constructed to protect two pits that contained the seawater pumps from being flooded, and make the pits watertight. Japan Atomic Power Company (JAPC), owner of the Tokai-2 plant, had partially implemented these plans. The seawall was erected but only one of the two pits was waterproof. After the tsunami arrived, the non-watertight pit was flooded and the seawater pump that provided cooling for the emergency diesel generator was damaged and unable to function, JAPC was forced to shut down the generator. The other pit did not experience flooding since the pipe penetrations had been made watertight. This saved the cooling pumps and allowed the diesel generators to produced internal electricity through the plant. Tokai-2 Nuclear Power Plant would almost certainly result in a much more serious accident if the seawater pumps were not contained in waterproof containment.

Failures in Regulation

Failures in nuclear power design provides a clear understanding of “what went wrong” but failed to provide the reason of “why it went wrong.” With this notion, the actual cause of the accident was not through nuclear power design, but instead through failures in regulations since it provides a more foundation and accurate explanation. The potential causes that contribute to the failures in regulation are the social problems in worker/management relations, overconfidence, and NISA lack in independent. These leading contributors to the accident unravel as a cultural phenomenon in Japan.

Failures in Regulation: Worker/Management Relations

One apparent difference between Japan’s nuclear culture and that in many other countries is the characteristic of worker/management relations. There has been a great deal of research within the past thirty years concerning the relations between workers and employers. In 1982, a Japanese-American professor wrote a book, *Theory Z*, describing the Japanese approach on hiring new employees do to traditional obligations toward workers. Traditionally, employers must keep all new employees until retirement even if their performances are inadequate. Naturally, these obligations will only apply to large companies of about 300 employees or more. In many cases, employees will remain at one company for the rest of their life. However, with the notion of poor performance can result into a lack of international best practices and standards in nuclear regulations.

A famous Japanese sociologist, Chie Nakane, refers to Japan as a “vertical society” since their social structure heavily emphasis on ranking. Japanese learn the lesson of formal ranking

early in life, in their family, since most Japanese employees will identify their work as a secondary home. Furthermore, Japan is very “group oriented.” A large company will consist of several groups that are ranked accordingly to their seniority, while members within each group are categories the same form. Japan has a rule that the highest status accrues to the oldest member. This establishes a barrier between the younger and older members. No matter how sharp and valuable the youngest member is to the company, they find it natural to submit to the oldest member’s ideas and authorities. Many members will be reluctant to question their senior members and allow flaws within the nuclear plant to be overseen. This may account in part for Japan’s reluctance to embrace methodologies that examined external events in risk informed and probabilistic ways.

Failures in Regulation: Overconfidence

TEPCO became overconfidence that Fukushima Daiichi Nuclear Power Plant would never suffer a severe accident. Extremely confident that apparently the plant owners requested their professional personnel to unwillingly take advice from exports outside the nuclear field, in order to demonstrate their self-assurance in the safety of their power plants to the local populations. The Japanese utilities face unlimited liability in the event of an accident.

The Nuclear Safety Commission from Japan established the 1990 safety guided to cover the condition of a station blackout. The safety guidelines stated that “nuclear reactor facilities shall be designed such that safe shutdown and proper cooling of the reactor after shutting down can be ensured in case of a short term total AC power loss.” The phase “short-term” was interpreted, by a senior Japanese nuclear executive, to mean thirty minutes or less. Once again, overconfidence emerged and a long-term loss of power was not included in the design basis of

nuclear power plants. Another executive said that, compared to the United States and Europe, in Japan there is less concern about station blackout risk because of the great reliability of the Japanese power supply system. “We fundamentally believed that if we lost off-site power, we would be back up on the grid in no more than about half an hour,” he said. Compared to the United States and Europe, he also said, Japan’s nuclear program was not convinced that there was a direct relationship between nuclear safety and nuclear security. For this reason, he said, “Japan was negligent in evaluating the approaches taken by the U.S. after 9/11 from the viewpoint of nuclear safety.”

The 9.0 earthquake that occurred on March 11, had been long anticipated to have a ninety-nine percent probability of a magnitude 7.5 earthquake within thirty years. The increase in magnitude caught seismologists by surprise. This significant underestimation, even though of Japan’s considerable investments in seismology, is a crucial warning against overconfidence in hazard prediction.

Failures in Regulation: NISA Lack in Independent

NISA appears to have failed in its responsibilities to review and update with tsunami safety standards for both emerging new evidence and evolving international standards. Fundamental principle of nuclear safety is the existence of an effective and independent regulator to set safety rules and to ensure complete compliance. The Nuclear Safety Commission has been set as a separate body to review the guidelines for nuclear power plant safety. The Nuclear Safety Commission and NISA are part of an ongoing regulatory reform. The 1990 Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities, established by the Nuclear Safety Commission, does not mention tsunami safety distinctively.

The issue is captured only by a catch-all clause about ensuring safety in the event of "other postulated natural phenomena than [an] earthquake."

TEPCO began an official methodology to evaluate tsunami safety in 2002 while tsunami safety was finally mentioned explicitly for the first time in a revision to a specific guide dealing with seismic safety in 2006. NISA failed to provide a review of the simulations conducted by TEPCO, given that the revised design-basis tsunami was now 1.4 meters above the seawater pumps, such an evaluation should have been conducted. Furthermore, NISA failed to promote the development of appropriate computer modeling tools for TEPCO to analyze the full range of effects of a tsunami. Given the predominance of tsunamis in Japan, these instruments should have been encouraged by NISA to keep with international standards.

Before the accident, TEPCO requested NISA to review the safety of unit 1 and extend its operating time. IAEA peer reviews of some countries' national regulatory systems have criticized that procedures for extending the lifetime of older reactors have neglected other safety issues and are too specifically focused on plant aging. According to Japanese government and industry officials, most Japanese safety rules follow from deterministic assessments. Regulations do not require probabilistic safety assessments to demonstrate that plants are protected against the threat of severe external events.

Conclusion

Nuclear power plants stands on the border between the protection and destruction of humanity. On one hand, nuclear energy provides a clean alternative that frees humanity from the restraints of fossil fuel dependence. On the other, it summons images of disaster that generates fear all across the globe. Unfortunately, the Japanese became well acquainted with this reality, in

March 2011, as thousands of citizens fled from Fukushima prefecture after a powerful earthquake set in motion a chain of tsunamis to the Fukushima Daiichi Nuclear Power Plant.

The Fukushima Daiichi Nuclear Power Plant accident was a series of events that resulted into an enormous catastrophe. The facility was inadequately managed in regulation and nuclear power plant design and that both were lacking behind international best practices and standards. TEPCO and NISA managed to defend the plant from the Great East Japan Earthquake, but failed when the earthquake generated a chain of enormous tsunamis toward the plant. The failures in the power plant design are demonstrated as the plant underwent a station blackout and loss of the ultimate heat sink. These failures in nuclear plant design are technical problems in historical evidence for large earthquakes and tsunamis, computer modeling of the tsunami, the emergency power supplies for the diesel generators and batteries, the ultimate heat sink, and waterproof containment. However, the leading contributor of the accident unravels as a cultural phenomenon demonstrated in TEPCO and NISA failures in regulation.

Overconfidence toward tsunami safety threats reveals as the leading contributor of the entire accident. TEPCO and NISA managed to ignore tsunami safety threats since the notion of an extreme tsunami was improbable. The Fukushima Daiichi Nuclear Power Plant was constructed during a period when safety experts initially were most concerned about the possibility that a serious accident would be caused by a sequence of events unfolding inside the plant. Severe external threats were never expected to exceed the design basis of the nuclear power plant. The risks of tsunamis were not fully considered in the context of severe accident. Therefore minimal preparation was made for in anticipation that a severe accident could be caused by a tsunami. No operational manuals were establish for recovering instrumentation equipment and loss of power supplies, station blackout including DC power supplies, in such

conditions. The staff was incompetent and uneducated to take precautionary measures in anticipation that a severe accident could be caused by a tsunami such as the one in March 2011. For this reason, TEPCO was against open discussion of worst-case scenarios or contingencies toward tsunami threats. For many decades, before the Fukushima accident, tsunami safety was never singled out for intensive public or media scrutiny. Earthquake safety was the subject that generated wide public interest and debate in Japan.

References

Brain, Marshall. “How Japan’s Nuclear Crisis Works.” How stuff Works. n.p. Web. 25 May. 2012.

Brain, Marshall and lamb, Robert. “How Nuclear Power Works:
Introduction to How Nuclear Power Work.” How Stuff Works. n.p. Web. 25 May, 2012

Hibbs, Mark and Acton, James M. “Why Fukushima was Preventable.”
The Carnegie Papers March 2012. Print.

Mohrbach, Ludger. “Tohoku-Kanto Earthquake and Tsunami.” 11 March, 2011.
Online Power Point. world-energy.su. 22 March 2012

Mohrbach, Ludger. “The defense-in-depth safety concept:
Comparison between the Fukushima Daiichi units and German nuclear power units.”
Artw-Internal Journal for Nuclear Power 56 (2011): 3-10. Print

“Nuclear Power in Japan.” World Nuclear Association. 29 March. 2012. Web. 11 May. 2012