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Compare and Contrast Major Nuclear Power Plant Disasters: Lessons Learned from the Past

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ABSTRACT

The construction of nuclear power plants is a major step towards reducing greenhouse gas emissions compared to the conventional coal-fired or oil-fired power plants. However, some of the major nuclear accidents in the past have raised questions about the safety and reliability of nuclear power plants. This paper compares and contrasts the major nuclear accidents of the past for example, the Chernobyl disaster (USSR), the Fukushima Daiichi disaster (Japan), and the Three Mile Island incident (USA). Although each of the accidents was unique, a thorough comparison found some common issues, such as faulty design of reactors and safety systems, safety rules violations, and lack of trained operators.

The primary impacts mostly involved radiation hazards such as exposure to varying doses of radiation, uninhabitable neighborhoods and health problems; the levels of impact varied mostly due to different intensities of warnings and precautionary measures taken by the local governments. The research findings would serve as an important resource for the nuclear professionals to plan proper precautionary measures in order to avoid the major issues that initiated or resulted from the accidents in the past.

1. INTRODUCTION

Nuclear power plants are one of the most complex and sophisticated energy systems designed to produce low carbon electrical energy in contrast to the conventional (e.g., lignite-, coal-, and oil-based) power plants. Table 1 provides a comparative summary of the amount of greenhouse gas emitted in the lifecycle of the nuclear plants and the other conventional plants as published by the World Nuclear Association (WNA [World Nuclear Association, 2011]). A World Health Organization (WHO) study has estimated that greenhouse gases generated from conventional power plants since 1990 caused an extra 150,000 deaths in 2000, which are mostly attributable to the global warming–related climate change combined with malnutrition, diarrhea, cardiovascular diseases, and premature deaths due to air pollution (Markandya & Wilkinson, 2007). However, the recent nuclear accident in Fukushima Daiichi, Japan, in 2011 was a wakeup call to the entire nuclear industry, and questions were raised about the social benefits and costs associated with nuclear power (Aoki & Rothwell, 2013).

This research evaluated the five major nuclear power plant accidents as case studies and compared and contrasted the major causes and related consequences behind those accidents. This paper summarizes the important lessons learned from the past instances which could serve as an information tool for the nuclear professionals to plan for proper preventive measures well in advance to avoid similar accidents in future.

2. RANKING SYSTEM

Nuclear accidents are ranked based on severity using a logarithmic scale called the International

Table 1. Intensity of lifecycle greenhouse gas emission by the different energy facilities Source: World Nuclear Association [WNA], 2011

Generation facilities (Technologies)	Mean	Low	High
	Tonnes CO_2e/Giga-Watt-Hour		
Lignite	1054	790	1372
Coal	888	756	1310
Oil	733	547	935
Natural gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

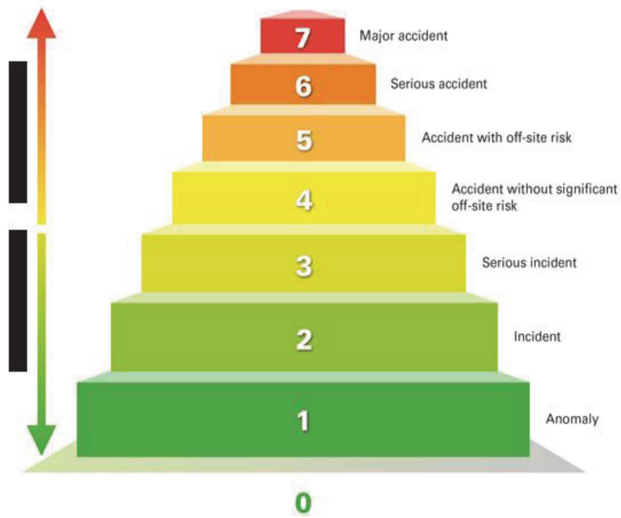

Figure 1. International nuclear and radiological event scale. Source: International Atomic Energy Agency [IAEA], 2013

Nuclear and Radiological Event Scale (INES) developed by the International Atomic Agency in 1990. The scale ranges from 1 to 7, where 1 represents least severe and 7 represents most severe. The ranking is interpreted as follows: "a nuclear event rated 4 in the scale is ten times worse than that rated at 3" (IAEA, 2013). Figure 1 is a pictorial representation of the INES Scale.

3. MAJOR ACCIDENT BACKGROUNDS

A nuclear power plant is a highly complex system, and any type of minor malfunction of a single component, operator error, or even a minor design fault, can cause a catastrophic disaster which may not only have short-term effects but also severe long-term effects due to harmful nuclear radiation. Each of the nuclear accidents was unique and, thus, needs to be analyzed independently to reveal the major causes behind their occurrence. The related consequences and the mitigation strategies that were adopted in each case based on the scenario details are discussed in the following paragraphs.

3.1. Chernobyl, USSR, 1986; INES Rank 7

The Chernobyl disaster that occurred in the city of Pripyat, in the USSR on April 25, 1986, is ranked as the most severe accident by the International Atomic Energy Agency (IAEA) as it involved not only heat transients but also reactivity transients, that is, it released radioactive elements (fission products) in the biosphere in major proportions. It not only killed onsite personnel but also the contamination traveled far and wide to affect the surrounding environment and caused immense health impacts for the people living in the region. The accident, which is referred to as one of the worst disasters in the history of the nuclear industry, resulted from a series of design weaknesses in the reactor that turned into a deadly disaster due to a series of operator errors and safety violations during a botched experiment. The accident occurred while performing a risky experiment of testing if the residual energy from the torque of a turbine could run a turbine generator while the turbines were coasting down in the event of a loss of electric power (a station "blackout"). It was necessary to keep the cooling pumps working in the brief gap (about 100 seconds) of the power outage and the running of the generators. The experiment was performed by turning off many safety signals and safety valves. Huge amounts of radioactivity in the order of $7x10^6$ curies was released, killing 31 onsite operators (Malinauskas, 1987) followed by the death of 7,000–10,000 liquidators who helped in cleaning the site (Dickman, 1991); contaminating air, soil, vegetation and cattle; causing thyroid cancer in children; and impacting the general health of the inhabitants settled in the surrounding areas (30 kilometers in radius [Peplow, 2011; Norman, 1986; Rich, 1989; Balter, 1996; Kazakov, Demidchik, Astakhova, &Baverstock, 1992]).

3.2. Fukushima Daiichi, Japan, 2011; INES Rank 7

The Fukushima Daiichi Nuclear Power Plant disaster is considered the worst disaster after Chernobyl in the history of nuclear power plants. This event took place after the Great East Japan Earthquake (magnitude 9.0 on the Richter Scale), which occurred off the Sanriku coast of Japan on March 11, 2011 (Robertson & Pengilley, 2012). The earthquake generated a series of tsunamis along the coast of Japan, which negatively affected several nuclear plants situated in the coastal area. However, Fukushima Daiichi was the worst, and its subsequent problems resulted in a state of nuclear emergency in Japan. Fukushima Daiichi Nuclear Power Plant is one of the 15 largest power plants in the world. It consisted of six boiling water reactors (BWRs) designed by General Electric (GE) and maintained by the Tokyo Electric Power Company (TEPCO) and generated a combined power of 4.7 gigawatts (Dauer, Zanzonico, Tuttle, Quinn, & Strauss, 2011). The accident was caused due to a series of equipment failures, violation of safety regulations, and faulty design of the plant layout along with underestimation of the "design-basis tsunami height" parameter used in design considerations of the plant. The Fukushima Daiichi nuclear plant was designed initially based on the assumption that the maximum estimated height of a tsunami could be 3.1 meters above the mean sea level although TEPCO used a revised design basis tsunami height of 5.7 meters. However, in 2011, the estimated height of the tsunami waves was 15 meters, on average, just before it caused the landfall (Acton & Hibbs, 2012). All these factors led to consecutive nuclear meltdowns resulting in the release of radioactivity into the environment. The accident was ranked 7 by the INES, on a scale of 1 to 7, and is considered to be the second worst nuclear accident in the history of nuclear power plants since 1952 (IAEA, 2013). Radioactive plumes spread erratically due to the wind, contaminating the sea water and soil (Yamaguchi, 2011; Mathieu, et al., 2012; Testing the waters for radionuclides (Nuclear Energy, n.d.), affecting the livestock industry (Tsuiki & Maeda, 2012), and infecting the human and cattle in the surrounding regions causing rapid depopulation and community breakups (Ishikawa, Kanazawa, Morimoto, & Takahashi, 2012).

3.3. Chalk River Incident, Canada, 1952; INES Rank 5

The Chalk River Laboratories located on the bank of the Chalk River, Ontario, Canada, is a huge facility that was developed by a joint collaboration between Canada, the United States, and Great Britain. Besides conducting several atomic bomb projects during World War II, Canada's National Research Council (NRC) felt the need to expand commercial power production from nuclear energy and started to operate an experimental reactor called NRX beginning in 1947 (The NRX Incident). On December 12, 1952, an accident occurred due to human flaws, operating errors, and miscommunication among the supervisor and operating personnel. Due to the accident, the NRX nuclear reactor was completely destroyed, and a series of steam and hydrogen gas explosions spewed thousands of fission particles into the air (Chalk River Nuclear Accident, n.d.). Although, this accident did not cause any injury to workers or widespread environmental contamination, it completely destroyed the nuclear reactor core. The reactor core could not be decontaminated and had to be buried as nuclear waste (Chalk River Nuclear Accident, n.d.). It was ranked 5 by the INES in terms of its severity. It was followed by a second accident 6 year later in 1958 when the overheated uranium metal fuel rods broke inside the reactor core (Chalk River Nuclear Accident, n.d.). The accident was managed efficiently and the impact of radiation contamination was minimized (Cross, 1980; Chalk River nuclear accident, n.d.).

3.4. TMI (Three Mile Island), US, 1979; INES Rank 5

The Three Mile Island (TMI) nuclear accident, March 28, 1979, was the worst nuclear accident in the United States commercial nuclear industry. Although it involved release of small amounts of radioactive gases, it destroyed the reactor as it had undergone partial meltdown due to a loss-of-coolant –accident (LOCA). The accident that occurred in the TMI nuclear power plant was a combined effect of a series of mechanical failures, lack of proper training of the operators, human errors, and misunderstanding of the system by the operators (human computer interface). In addition, design flaws related to indicators and warning systems resulted in minor mechanical failures in the secondary cooling system of the reactor, which lead to a more severe nuclear incident (Mynatt, 1982; WNA, 2001). A total release of radioactivity in the range of 2.4 million to 13 million curies was recorded, although much less (around 13 to 17 curies) was released into the environment (Mynatt, 1982). Thus, the health impact of the accident on the public was mostly psychological rather than a result of exposure to radiation. (Lavelle, 1999; Pool, 1991; Hatch, Wallenstein, Beyea, Nieves, & Susser, 1991; Goldhaber, Staub, & Tokuhata, 1983).

3.5. SL-1 (Stationary Low-Power Reactor Number 1), US, 1961; INES Rank 4

The Stationary Low-Power Reactor Number One (SL-1) was an experimental power reactor located 40 miles west of Idaho Falls, Idaho, and was operated by the U.S. Army. Its main purpose was to provide electrical power to remote military facilities in the area (U.S. Atomic Energy Commission, 1961). On January 3, 1961, during routine maintenance, the central control rod was removed too far causing the reactor to suffer a *prompt criticality*[1] accident, resulting in a steam explosion and deaths of all the three operators on site. The INES rating of 4 was determined based on the fact that soil and air samples indicated traces of contamination. However, the reactor building was highly effective at enclosing the radioactive materials dispersed from the steam explosion (Horan & Gammill, 1963). Except for the three fatalities, there was not much health and environmental impact as around 99.99% of the total fission products from the reactor were retained inside the reactor building (Adams, 1996).

Table 2 provides a comparative analysis of the major causes and issues, identified through the extensive literature review across the five major accidents.

[1] An assembly is referred to as prompt critical if for each nuclear fission event, one or more of the immediate or prompt neutrons released causes an additional fission event which causes a rapid exponential increase in the number of fission events

Table 2. Comparative analysis of the major issues

Issues	Chernobyl	FDNPP	Chalk-river	TMI	SL-1
Faulty Design	x	x		x	
Equipment Failure				x	
Inadequate Safety & Warning Systems				x	
Violation of Safety Regulations	x	x	x	x	x
Lack of Trained Professionals	x		x		
Operators' error	x	x	x	x	x

4. LESSONS LEARNED FROM THE CASE STUDIES

A thorough literature review of the past nuclear power plant accidents revealed a series of issues that need to be addressed so that the probability of future accidents is significantly lowered. This paper categorizes the lessons learned from three perspectives:

- Safety
- Training
- Response and mitigation strategies

4.1. Safety

Sophisticated and more accurate weather forecasting warning systems are necessary in order to get prepared for the upcoming disaster. After the Fukushima Daiichi Nuclear Power Plant disaster, the Japan government proposed to install a system of ocean-bottom sensors costing around US $402 million so that it can provide more accurate warnings of tsunamis heading towards the coast (Malinauskas, 1987).

Whether a nuclear power plant is in an operating state or undergoing a shutdown phase, safety regulations proposed by the respective nuclear regulatory commission to which the plants are affiliated should be strictly followed (WNA, 2013). For example, one of the major reasons behind the TMI accident was the violation of the safety regulations as proposed by the U.S. Nuclear Regulatory Commission (NRC). According to NRC regulations, if the auxiliary feed water pumps are out of service for 72 hours or more, the nuclear power plant's reactor must be shut down. However, the operators of the TMI nuclear power plant did not shut down the reactor core even when the valves on the reactor's auxiliary feed water pump system were closed for maintenance for 2 weeks before the accident

4.2. Training

Proper training of the all the operating personnel working in a nuclear plant is necessary because a small mistake due to ignorance on part of the operators, in terms of lack of knowledge or violation of safety regulations, can sometimes lead to a major accident. A comparative analysis of the major causes (Table 2) revealed that operator's error is the most common cause behind each of the accidents. For example, in the case of the Chalk River incident, due to a lack of profound knowledge about the nuclear reactor operating switches, the operator blindly followed the supervisor's wrong instructions (Chalk River Nuclear Accident, n.d.). The SL-1 accident was initiated when the operator manually removed the control rod by 50 centimeters instead of 10 centimeters which was required to reconnect the central control rod to the drive mechanism after 11 days of a routine shutdown. This might have also happened due to the ignorance of the operator or his lack of knowledge about the fact that even a lift of 40 centimeters of the control rods would be enough to make the reactor critical (Adams, 1996).

Health physicians working in the hospitals that are included in the emergency plans of the nuclear power plants should be specially trained to manage these emergency situations in case of an accident and offer immediate care to the people exposed to radiation hazards.

4.3. Response and Mitigation Strategies

Efficient response and mitigation strategies require good communication between the public and the government after a nuclear disaster, presence of adequate contingency plans with respect to efficient transportation from the affected site to the hospitals, and the availability of health counseling to reduce the psychological impact of the radiation hazards on the public. Moreover government and nuclear agencies should work collaboratively to develop an efficient debris-removal strategy; in most of the cases, after the nuclear accidents, the affected sites are exposed to high doses of radiation exposure that adversely affect the health of the liquidators responsible for cleaning the affected site.

4.3.1. Efficient Communication and Coordination

After a nuclear disaster, the government should clearly communicate the severity of the disaster and the related health impacts for both in the cases of high radiation and low radiation exposure (Nature, 2011; Peplow, 2011). This was done very efficiently in the case of Fukushima Daiichi Nuclear accident but not at all in the case of Chernobyl accident, when children were even allowed play outside after the accident happened (Peplow, 2011).

An efficient area-wide telecommunication system surrounding a nuclear power plant is important to keep the power plant, hospitals, and other local emergency management agencies in a well-integrated network (Maxwell, 1982).

A postmortem analysis of the TMI nuclear accident suggested that the evacuation planning and disaster response strategies should account for the medical emergencies, and, thus, efficient communication between nuclear engineers and health physicians should be fostered (Maxwell, 1982). A lack of such mitigation strategies led to severe disorganization and mismanagement in the neighboring health care agencies of the TMI nuclear power plant.

4.3.2. Requirements for Efficient Response and Recovery Processes

Adequate contingency plans should be prepared by the hospitals in regards to hospital staffing, as well as transfer of bed-ridden patients from the affected area to another hospital in a safer area in case of an emergency situation. Lack of such plans led to several organizational problems in the neighboring hospitals and health care institutions surrounding the TMI nuclear power plant after the accident (Maxwell, 1982).

The after-accident crises in the TMI incident also suggested that transportation facilities should be readily available to the hospitals and the other health care facilities so that, in case of an emergency, immediate evacuation is possible (Maxwell, 1982).

The sale of milk and food products should be strictly prohibited in the contaminated areas to prevent the spread of radioactivity as the radioactive elements iodine-131 and cesium-137 are highly absorbed by milk and vegetables, respectively. In the Chernobyl disaster, the government did not take any action regarding restricting sales, but after the Fukushima Daiichi disaster, the Japanese government (likely taking a lesson from Chernobyl) strictly stopped the sale of milk and food products in the surrounding regions of the Fukushima Nuclear Power Plant (Fukuda, et al., 2013; Tsuiki & Maeda, 2012).

Funding is essential for the recovery process. However, it is extremely hard to maintain the flow of funds after nuclear disasters occur because of inadequate public relations information (Nature, 2011).

Efficient rescue planning needs to be done in regards to sending the rescue team to the radiation-affected area. This was a lesson learned from the Chalk River and the SL-1 accidents which are looked upon as great examples where well-planned and efficient response strategies were adopted such that radiation contamination did not have severe after effects.

4.3.3. Efficient Health Recovery of Public

Health counseling offered through several workshops, campaigns, and seminars to the public sometimes help in reducing the huge psychological impact and posttraumatic stress on the people. (Peplow, 2011; Kamada, Saito, Endo, Kimura, & Shizuma, 2012; BBC, 2011). For example, after the TMI nuclear accident, a TMI Public Health and Information Series on cancer, radiation, and epidemiology was conducted in the nearby universities to provide more information on the health effects due to a nuclear disaster so that the people could educate themselves about the radiation consequences and relieve themselves from the existing stress and trauma of the disaster.

Special attention should be given to small children and pregnant mothers as they are more likely to be affected by the radioactive iodine-131, as this element is easily absorbed by the thyroid glands of children and can later in life possibly cause thyroid cancer. The USSR government failed to take such precautions after the Chernobyl disaster which resulted in an increased number of thyroid cancer patients, most of whom were children (Balter, 1996; Kazakov et al., 1992).

Systematic distribution of prophylactic potassium iodide (a thyroid blocking agent) to the public and also the nearby health care agencies is essential (Balter, 1996; Maxwell, 1982).

4.3.4. Efficient Evacuation Planning

Immediate evacuation orders should be implemented by the government so that, even if there is a spread of radioactivity in the surrounding areas of the nuclear plant, the inhabitants do not have to encounter a prolonged exposure to radioactivity. The Japanese government did the evacuation planning very efficiently after the nuclear disaster, whereas in the case of Chernobyl disaster, evacuation orders were given 10 days after the accident to the people in the surrounding areas (areas beyond 3 kilometers in radius from the nuclear plant) (Peplow, 2011; Malinauskas, 1987; BBC, 2011; Yamaguchi, 2011).

5. CONCLUSION

This research study considered five major nuclear power plant accidents based on the severity ranking by INES as case studies and analyzes the causes and issues behind those accidents, the consequences of the accidents, and the related mitigation strategies adopted in each case to provide a concrete background for the lessons learned from the history. This paper provides a brief overview of each of the accidents and a comparative analysis of the causes across the five incidents. The outcome of this research is a series of lessons learned from the past instances that could serve as an important information tool for nuclear professionals to plan adequate safety and response strategies which would reduce the probability of a disaster taking place and reduce the impact of a disaster in case it occurs.

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