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THESIS

Decision Making and Risk Management in Nuclear Power

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Υπογραφή

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Decision making and risk management of nuclear power

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Abbreviations

CO_2: Carbon Dioxide

DBA: Design Basis Accident

FR: fast reactor

HEU: highly-enriched uranium

HLW: high-level waste

IAEA: International Atomic Energy Agency

IEA: International Energy Agency

INES: International Nuclear Event Scale

INPO: Institute of Nuclear Power Operations

LWR: light-water reactor

NPP: nuclear power plant

NRC: Nuclear Regulatory Commission

PSA: probabilistic safety assessment

SNF: spent nuclear fuel

TEPCO: Tokyo Electric Power Company

TMI: Three Mile Island

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

WHO: World Health Organization

WWII: World War 2

Chapter 1: Introduction

1.1 Preamble

Nuclear power is considered to be an alternative energy source with tremendous potential due to the energy output and self-preserving attributes that is has. However, the process of creating this energy source demands exceptional decision-making capabilities and techniques in order to timely locate, isolate, avert and prevent risks.

This thesis will attempt to contribute by looking specifically into those two issues, by taking into consideration the early concepts of nuclear power and the tragedies that have occurred through the last century, what could have been done and what can be done in order to avoid similar events. What is of great interest is the duality of nuclear power, capable of providing unlimited amount of clean energy but with the slightest misuse can have destructive, long lasting effects, leaving large areas around the area of the accident desolate for decades at the very least, with prime examples that of the Chernobyl disaster in 1986 and of the Fukushima Daiichi disaster in 2011.

1.2 Structure of thesis

In this thesis we'll go through the process of examining the decision-making processes and risk management involved in nuclear power. To achieve that I will begin with an analysis of the decision-making process, the different levels of applicability of said decisions and strategies and take a closer look at the decision-making process taking place in power plants, the departments operating in them and the various procedures to be followed. Further on we'll see how decision making in nuclear power was shaped by game theory, it's early stages and implementation in the 20th century and how game models can help analyze various approaches from various factors.

Moving on we'll go through risk management in power plants, their different kind of sub categories and how to best learn from them in case of possible future instances, as well as the ever more critical threats of nuclear non-proliferation and weapons disarmament, that pose a safety concern for global security.

Following that we move to set some research questions regarding the effectiveness of risk management capabilities in the development of nuclear power and the reliability of current management processes to the development of nuclear power in order to see to what extend accidents of the past have helped create counter-measures and safety steps for he better harnessing of nuclear power and proceed to view the methodology of the answers provided for the questions at hand.

In order to do that, we'll examine the cases of the Three Mile Island accident, the Chernobyl disaster, the Fukushima Daiichi disaster and a scenario that although is fictional, it portrays with great accuracy what could possibly happen in the event of a possible reactor malfunction.

And finally, we will go through the observations of this thesis to evaluate the efficiency of nuclear power while keeping in mind the costs and benefits it brings to the table.
In short, Chapter 1 will provide a short pretext of the thesis, Chapter 2 will focus on the decision-making risk management involved in nuclear power plants, Chapter 3 will set the research questions, Chapter 4 will provide case studies based on the accidents that have occurred and, lastly, in Chapter 5 a conclusion will be formulated.

Chapter 2: Decision making and risk management

2.1 Introduction

This thesis aims to examine the risks and decision-making process that come with nuclear power and assess the benefits along with the dangers that accompany them. In order to do so I will delve deeper into the processes of the required decision making as well as risk management capabilities in order to take a sound decision with as much less risk as possible for the best possible outcome.

Ours is an age of an ever-increasing energy consumption (Widder, 2009), mainly deriving from electrical power, which is responsible for the production of large quantities of carbon dioxide (CO_2). As technology keeps making leaps into the future, an ever-growing thirst for power becomes apparent. Thus, we turn our gaze to alternative sources of power, such as solar, wind, hydro and nuclear, among others. One issue that acts as a hurdle for the development of nuclear power is the that of the storage solution. Without a sound plan for the disposal of nuclear waste, there can be no development of the nuclear energy sector, which in turn cannot help make the transition from electrical power to nuclear. To add to that, no development of the sector translates to no external investments, having as a result the decommissioning of already existing nuclear reactors. Meaning that the demand for energy will be met by other sources.

In order for nuclear power to start thriving, it is required to have consistent funding, a sustainable foundation for growth as well as an increased presence, mainly achieved through the construction of new reactors. However, this will only bring forth a need for even bigger waste storage capacity.

Another solution could be the reprocessing and recycling of spent nuclear fuel (SNF) in order to reduce the levels of high-level waste (HLW). This approach requires $1/4^{th}$ the amount of amount of fresh uranium and waste storage space but comes at a high cost (Widder, 2009). Additionally, it involves the risk of technology proliferation – given it is considered a "First-of-a-kind" technology –, as well the even greater danger of the proliferation of nuclear weapons, that can be achieved through the separation of SNF. It is through the process of the separation of pure plutonium that comes the possibility of diversion and use in the production of nuclear weapons.

In short, nuclear energy can be a source of cheap, reliable, safe, “carbon-free” electricity generation technology. In order to reap the aforementioned benefits, it is imperative for the sector to be provided with the funding flexibility that will allow it to adapt to surfacing circumstance and ground breaking innovations through the use of sound decision making based on multiple variables and the management of ever changing and evolving risks.

2.2 Decision making

2.2.1 Decision making in nuclear power plants

The process of decision making in an NPP is based on multiple factors and time-tables depending the procedure that is needed to happen. For impermanent operations short-term decisions are required, while procedures like modifications for NPPs, coming with repair strategies and maintaining an NPP are more time consuming. Depending on the urgency of each procedure different means are used to assist in the decision-making process such as decision aids, data and methods.

There are numerous departments involved in the process. Two of them are the operations department and the maintenance department. The operations department is in more direct contact with the plant, the reactors and the equipment and carries out daily tasks, safety systems checks and monitors the conditions of the plant. In case of an anomaly or malfunction, it is this department that has to run through a list of best response options in order to pick the most optimal one and bring the plant to a safer state according to the condition of the plant and systems settings, indicators, the readings of the equipment based on the condition of the plant and the systems settings, auditorial indications, readings of the equipment and procedures to be followed under urgent conditions.

Worst-case scenario factors that may influence the process can be contradicting or misleading symptoms, contradicting goals -meaning that in the time of need there will be reluctance to act properly and in confidence- or overseer anticipations of production and safety, clashing or confusing procedures in unexpected events, and urgency in rapidly shifting circumstances. The Three Mile Island accident of 1979 (Backgrounder on the Three Mile Island Accident, 2018) is such an example of contradicting procedures, while the Chernobyl (The 1986 Chornobyl nuclear power plant accident, 2014) catastrophe was a sum of contradicting objectives, lacking counter-actions and qualifications, as well as emergency time management.

Other factors that shape performances include clarity of alarms, familiarity with the operating environment, systems and procedures, time management and back-up plans in case of mistakes in the original approach. Additionally, an overall proficiency with readings, conditions, establishments and tasks are key-components to taking a successful decision. The maintenance department is another equally important department in a power plant and is responsible for not so direct decisions in a plant, such as inspections, calibrations, tests and long-term planning. Decisions are made about methods to decrease deterioration of the plant, reactors, equipment etc., means of replacement, counter-measure maintenance, or overhauls, repairs in case of failures, as well as spare parts policies and inventory.

In order to do so, the department responsible with maintenance is assisted an on-line database for errors and maintenance history, which gives information related to the plant and the components as well as trends for probabilistic safety assessments (PSAs), evaluates maintenance routines and planning processes. Report given every quarter and every year showcase trends and provide data helpful for spotting monitoring needs, putting in orders for reserve equipment and scaling maintenance activities for either prevention or maintenance. Strategic decision are required about possibly delayed repairs, feasible only during in hot or cold shutdown state, or radiation conditions deemed acceptable. Other parameters that might affect scheduling and the nature of work might be technical specifications, the amount of risk at a given setting, repair costs and possible loss of production and accessibility of spare parts. Another task is the accurate planning and integration of modifications for the plant. Questions that affect modifications are whether or not the work can be achieved while the plant is operational, under hot shutdown or only under cold shutdown, does the risk call for immediate or later action, is the new design standard or a prototype, what are the spare-parts conditions and lead time deliveries and to what extent political interference and reflections affect the safety culture. Major modifications take long periods of time to be completed and the results from partial modifications are not available until before the last decisions. (Vaurio, 1998, pp. 337-338)

Plant modifications are plant-specific, requiring unique approach in every scenario, and provide little alternatives to choose from. The level of importance in each case is different even in cases with the same types of reactors. It is also imperative to take under consideration possible costs and benefits regarding every modification to a reactor, as it is possible that by reducing one risk, another one may increase.

Reducing costs based on information about risks is becoming an ever-growing practice at nuclear power plants, especially in order to reduce test requirements for parts providing marginal safety benefit.

As described, various means and factors govern the decisions regarding day-to-day operations, short-term maintenance meant for preventing or correcting errors, and long-term modifications. PSAs along with cost/benefit evaluations are seeing an increase in the task of providing quality decision standards and a dependable framework.

2.2.2 Nuclear Games

The feelings of peace and justice that commonly follow the end of war, were short lived after the end of World War II. The reason behind this was the fact that ideological differences between the US and Russia led to what came to be known as the Cold War. A term first used by Walter Lippman, which first appeared in the 1930s when Hitler was sizing up France, became popular again in 1947 in order to describe a situation where two waring fronts weigh each other up and build tension. (Freedman, 2013)

However, the term was used earlier, in 1945, by George Orwell while trying to assess the impact of the atomic bombs on international affairs (Freedman, 2013, pp. 145-146). Specifically, Orwell described it as "two or three monstrous super-states, each possessed of a weapon by which millions of people can be wiped out in a few seconds, dividing the world between them." Given the immense power of such weapons, he thought it more likely to lead to a mutual agreement between countries owning such weapons to not use them on each other, while also allowing them to threaten countries lacking such arsenal. In short, this would not only lead to a standoff between super-states but also establish, to some extent, control over states with less power.
The introduction of these new weapons shifted the entire outlook on war. As the historian Bernard Brodie said "Thus far the chief purpose of our military establishment has been to win wars. From now on its chief purpose must be to avert them. It can have almost no other useful purpose." (Freedman, 2013) The fact that political communities could face other entities with the same capacity of inflicting harm upon them, would make them skeptical about inflicting harm in the first place.

Brodie, thought little of the military thinking of his era, which he described in 1949 as "a pointed injunction to use common sense." at best. Instead, he envisioned a field of strategy where the leading role was held by the civilians themselves. He insisted on taking more caution on the ever-evolving nature of military issues, comparing them to how economics work to the best interests of a nation and how in both scenarios one makes the best possible allocation of their resources. Thus, the approach was shifted from character and intuition to intellect and analysis. The importance of this change was made even more urgent in the atomic age, since misjudgment caused by human irrationality could not be tolerated.
The scientific method was used widely during WWII in various ways. From the most efficient deployment of radar, to "safest arrangements for convoys or choosing targets for air raids" (Freedman, 2013, p. 147). The usefulness of those who were involved with mathematics and physics became even more apparent with the Manhattan Project, responsible for the development of the atomic bomb.

The road to applying those theories to practice was paved by RAND Corporation, a prototype think tank, tasked with developing operational research. The organization saw rapid advancements which were largely aided but the technological leaps that kept happening. Complex mathematical problems became more practical, quantitative analyses became stronger and more credible, innovations were made due to the advanced computers it possessed, complex simulations that blurred the lines of reality and simulacra were able to be tested, uncertain data could be explored as did dynamic, ever changing systems instead of plain cause and effect forms. It was now possible to explore abstract models, the likes of which the human mind could not fathom on its own.

Additionally, what lead to what Hedley Bull in 1961 called the "strategic man" was the very creation of nuclear weapons (Freedman, 2013). Man had never before come in contact with a weapon of such magnitude nor waged war with them. Up until then strategy was limited to how to fight wars as policy instrument. However, as Bull said "(strategy) had to understand how to threaten war" and "Studies of actual violence had to be supplemented by discussions of deterrence and the manipulation of risk" thus opening more possibilities on how to conduct war. However, due to the inexperience on the matter, this could only be done in a speculative way.

A great contributor to the rational strategic thinking was Robert McNamara. Although the endgame of his methods left him widely criticized, his "mastery of the evidence and analytical techniques" (Freedman, 2013, p. 150) marked him as the paragon of "the rational strategic man" (Freedman, 2013, p. 150). So much so that in comparison to him the military looked inexperienced even upon discussing matters of operations.

But while it is true that the stereotypical narrow-mindedness and prejudice of the military was indeed confirmed, the new analysts and their methods had their share of flaws. While their contribution to decision-making in the Pentagon was notable, the application of economics to strategy could only take them so far. They failed to take into account political considerations which, due their insensitiveness and intolerance towards the matter, got in the way of their methods. Although, what was even more worrisome than their disregard for political matters was their unawareness of their importance to strategic insight.

The dominant theory that sprang forth from the new strategy was that of game theory (Neumann, 1920). And while it is true that it did little to influence the nuclear strategy, it was regarded as an abstract and formal way of strategic thinking, significantly influencing social sciences. Game theory held a closer resemblance to poker than chess. The reason for that was that chess could only be played within set parameters, with tactics known and available to both players. In poker however everyone plays with unstable and unknown variables to each other, with tactics that change constantly based on how other players react to certain moves, while everyone tries to bluff and mislead each other to create a state that is most favorable to them. In 1928 he observed that the best outcome in a game of poker, where uncertainty was encouraged, was that of "the best of the worst outcomes", the minimax solution. It is this very proof that elevated game theory from merely a representation to a suggestion of how games should be played. However, revolutionizing this method was, it didn't come without come without its limitations. While the theory claimed to be rational, it operated under the fact that all players know the aim of the rest of the players and the rules of the game were mutually agreed upon and accepted. In order to take the theory of von Neumann and Morgenstern to the next level, the limitations of two players and "zero-sum payoffs", which meant that one player's victory was another's loss, had to be overcome.

In 1950, the Prisoners' dilemma game was conceived (Flood, M., Melvin, D., 1950) which came as a breakthrough to the limitations of game theory. However, the one who formulated most famously, was Albert Tucker in 1950. In short, the theory consisted of two prisoners unable to communicate with one another and given three choices to choose from. One to cooperate, one to not cooperate (defect) and one to betray the other in order to help their situation. Unable to communicate between them and out of fear of being betrayed themselves, both players end up betraying the other, ending up cooperating, which was the minimax solution. A notable feature is that the players were forced into conflict whereas if they were able to communicate and trust each other, they would have made a better choice based on the possible outcome.

The theory was further established in the early 1960, since it was believed to have helped shape nuclear strategy. Given the fact that both sides of the Cold War could lose catastrophically, the nuclear game was obviously not one of zero-sum profit. Both alliances gained more by preserving the peace than by confronting each other. And while the theory helped the rival governments by generating strategies to preserve peace, it also reached an impasse when questions popped up regarding how to defend vital interests "without disaster without disaster when war was so dangerous" (Freedman, 2013, p. 155) and how to conduct conventional war without it escalating.

2.3 Risk management

2.3.1 Risks in Nuclear Power Plants

Power plants face daily multi-dimensional risks in production, safety, economics and strategy. However, these risks, if managed successfully, generate benefits for the manager of NPPs such as clearer criteria for decision making, since every risk can be translated to potential experience, that the managers can use effectively in future occurrences to diagnose and tackle a problem faster. Risks can also help in making effective use of the so needed investments, achieve safety and production goals with cost consciousness and innovation and ensure a focused approach that is safe. Productive and economic while under transitioning periods. Lastly, risks render communication improvement mandatory in all levels of an NPP operating organization, in order to effectively relay information and act accurately upon them. Specifically, each risk category entails the following.

Safety related risks

Integrated risk assessment can help in the identification and management of safety-related threats in fields such as radioactive, radiological, manufacturing, and environmental hazards. IAEA Member States are well-versed in nuclear safety concerns. PSA is perhaps the most advanced risk identification technique in the world, since it is used by the NPP industry for nuclear safety analysis. Other safety concerns, such as industrial and environmental safety, have gotten less coverage in most NPPs and would likely benefit from further research. This will be covered by an advanced risk assessment policy. (IAEA, 2001)

Production related risks

The risks associated with the resource and commodity environments in which a company works are known as operation and development risks. Plant and product planning, manufacturing and marketing operations, work force management and organization (human capital and training), technical advances, outage and inventory management, paper processing, and configuration management are among them. Nuclear safety risk evaluation, especially PSA, would have picked up on just a few aspects of these risks. Revisiting this current data from an organizational perspective will result in substantial improvements in operational risk awareness. (IAEA, 2001)

Commercial/financial risks

Movements in financial factors (such as the cost of raw materials and finished goods for export, currency exchange rates, and interest rates) pose threats to companies. These financial factors are likely to become more important as the nuclear power industry transitions from a limited, rate-controlled world to one of competitive electricity sale.
For instance:

• NPP operators compete to supply energy to private entities at contractually agreed-upon rates.
Much like rival utilities can deliver local and long-distance calling coverage over existing installed cable, energy users can gain the ability to purchase electricity from various providers.
• Much like rival utilities can deliver local and long-distance calling coverage over existing installed cable, energy users can gain the ability to purchase electricity from various providers.
• Recent examples of significant fluctuations in wholesale energy markets demonstrate the market's upside and downside.
• Selling nuclear power plant architecture, manufacturing, and construction services across borders exposes the commercial enterprise to currency risk as well as some of the strategic threats addressed in the following section. (IAEA, 2001)

Strategic risks

Fundamental shifts in the global, commercial, or political conditions cause strategic risks. Shifts in governmental types; changes in governmental budget trends; expropriation, nationalization, and privatization challenges; changes in the dynamics of marketplace competition; and shifts in consumer opinion toward certain lines of business; ownership patterns are examples; as well as regulatory and legal improvements in both the industry and the protection arenas. (IAEA, 2001)

2.3.2 Nuclear non-proliferation and nuclear disarmament

Nuclear power is an important factor in climate stabilization; however, it has certain pitfalls, most notably the spread of weapons of mass destruction. Primary oil demand is expected to increase before 2035, with fossil fuels dominating energy sources, posing a threat to climate change. The IEA anticipates that a mix of all electricity sources will provide a solution, with nuclear power serving as a secondary power supply; however, it has been argued that nuclear power could play a more prominent position, with new nuclear energy systems (GEN IV) being introduced to provide long-term viability for large-scale nuclear energy generation.

The primary worries around nuclear power are often waste problems and the possibility of leaking dangerous radioactive content. In the other hand, proponents of nuclear power argue that the gains outweigh the risks. Furthermore, the relationship between nuclear power and nuclear weapons is often discussed, and non-proliferation concerns are raised. The introduction and deployment of GEN IV systems would exacerbate these issues, as broad reprocessing and recycling capacities, which are non-proliferation sensitive technologies, are needed. In the plus side, GEN IV devices have the potential to be a disarmament instrument, capable of efficiently reducing the existing arsenal of nuclear bomb components by converting highly-enriched uranium (HEU) and plutonium to less sensitive materials, as well as providing a management process for the plutonium reserve found in civilian spent nuclear fuel.

In the reactor core of the majority of today's nuclear plants, a moderating material is used, mainly water, to assist in the procedure of producing energy in what are called light-water reactors (LWR), which also acts as coolant. Regarding safety and economy, the LWRs come with benefits but there are also safety concerns after the Three Mile Island accident (1979) (Backgrounder on the Three Mile Island Accident, 2018) and Fukushima Daiichi nuclear disaster (2011) (Fukushima Daiichi Accident, 2021). Furthermore, their long-term viability is called into question due to inefficient use of natural capital and the accumulation of plutonium, a nuclear bomb element. Even if some countries recycle their uranium, the number of cycles is limited, and this results in an increase in total plutonium.

As a result, the GEN IV systems were developed, which are metal-cooled reactors with a fast neutron range, also known as fast reactors (FRs), and no moderator. They address critical issues such as defense, sustainability, economic viability, and non-proliferation. Although they need a higher fraction of fissile material in the core, they can fission a wide variety of heavy elements and can be optimized to either produce (breed) or consume (burn) certain elements, especially plutonium. Another aspect of the GEN IV systems is the capability of multiple recycles.

When the LWR fuel cycle is implemented, long-lived waste in the form of spent nuclear fuel would accumulate and pose a proliferation risk because it includes fissile material that can be used in missiles.

And while it's true that, due to its highly initial radioactivity, it is not immediately accessible, said radioactivity decays over time, leading to an increased risk of proliferation. The incorporation of FRs into the nuclear power supply will further improve it by managing the civil plutonium arsenal rather than contributing to it. In the long run, FRs could help handle the spent nuclear fuel by reusing it to operate themselves further, instead of simply storing it or reprocess it in a limited capacity. The best way to ensure that the material can not be used for weapon manufacture is to transmute it, which is what the GEN IV systems are designed to do.

Another burning issue that goes hand in hand with nuclear power technology proliferation is that of nuclear weapon disarmament. Despite the fact that the global arsenal has been shrinking due to the dedication of the United States and Russia to their bilateral New START Treaty, the rest of the known nuclear weapon owner countries have adopted strategies to reduce their inventory as well, such as program modernization for their nuclear weapon systems, deployment of new systems, or future plans for the procedure. However, no immediate change is expected from either the countries known to own nuclear weapons – those being the United States, Russia, China, the United Kingdom, and France – or those considered to do so – India, Pakistan, Israel, North Korea –.

Both known and considered nuclear weapon owning countries have – to different extent – high-enriched uranium and plutonium, hence solutions for both are needed in order for them to be safely disposed. One example that has been met with success is the “Megatons to Megawatts” with the purpose of down blending 500mt of HEU from Russian nuclear warheads to be used as fuel in commercial nuclear reactors in the U. (Freedman, 2013) (Widder, 2009). In terms of plutonium recycling, the United States and Russia have agreed to dispose of 34 metric tons of weapons-grade plutonium under the joint treaty Plutonium Management and Disposal. Russia intended to turn plutonium into fuel and irradiate it in FRs to generate electricity starting in 2018. Surplus Pu was supposed to be used to fuel LWRs in the United States, but after updating the plutonium disposition policy, new technologies are being considered. While irradiating the Pu in LWRs does reduce its quality, it does not decrease the total amount, contrary to FRs that convert the Pu to other elements.

Nuclear protections were implemented to help prevent proliferation threats by limiting access to classified resources and technologies, conducting nuclear tests, and maintaining reliable and transparent track of materials. Up until the GEN IV systems the safeguards had to be adapted to the given time, however with the implementation of the new systems, nuclear safeguard solutions were designed as preconditions. Given the critical value of nuclear fuel processing and shipping, nuclear protections must be incorporated into the early design of modern technologies. An outstanding advantage of the FRs is that of the breeder function which allows them to produce their own Pu during operation, thus eliminating the need for HEU and by extension the need for such facilities. Overall, the GEN IV systems support the modern nuclear power scene by monitoring and reducing the amount of nuclear waste generated, as well as assisting the nuclear disarmament process by converting warheads into peaceful energy.

2.4 Discussion

Nuclear power could be a solution to a low-cost, energy-rich future, however the process to achieving that future can be a very arduous task. Careful planning, with close-to-none room for errors is mandatory for the successful and safe operation of a nuclear plant. From the more practical aspects, such as operating a nuclear power plant, to more theoretical, namely game theory and how it correlates to the application of nuclear power and its byproducts, the decision making of nuclear power is a process consisting of multiple variables that need to be taken into account. And along with these variables follow risks that make nuclear power the so debated topic that it is. Risks that range from the correct operation of a power plant, accidents attributed to both human error and technical and structural mistakes, the topic of nuclear waste, as well as external factors seeking to utilize nuclear power for personal ends. To name some of the benefits, nuclear power is a low-carbon energy source since, it does not produce any greenhouse gas emission, specifically methane and CO_2, while producing roughly the same amount of energy as other renewable sources. However, contrary to other renewable energy sources, nuclear energy is not intermittent, meaning that nuclear power plants can run – uninterrupted – for large periods of time, sometimes with no maintenance, rendering it a more reliable energy source. Adding to that, running the plants is cheaper when compared to their coal or gas rivals, while also producing superior amounts of energy than other forms.

On the other hand, there have been accidents that shaped the history of nuclear power in a frightful way. The Three Mile accident (1979) (Backgrounder on the Three Mile Island Accident, 2018), the Chernobyl disaster (1986) (The 1986 Chornobyl nuclear power plant accident, 2014) and the Fukushima Daiichi disaster (2011) (Fukushima Daiichi Accident, 2021) have been the prime examples to the question “what if it goes wrong” with devastating short-term and long-term effects for the environment and the locals who had to be evacuated to safe areas. Additionally, the nuclear waste produced by the current plants that is estimated to be almost 35.000m^3, other than being targeted for proliferation purposes once its radioactivity has been considerably reduced, takes years to degrade. Lastly, true that it may be that nuclear power plants are cheaper to run than other energy producing establishments, they require vast amount of initial costs and funding in order to be built with an estimate of $3.5bn to $6bn with the added costs of maintaining the facilities.

In short, nuclear power still remains a much-debated issue. Under the correct circumstances, nuclear power could prove a source of unlimited, clear, eco-friendly energy. However, given its eventful past, the risks it encompasses and the financial requirements, its progress remains to be seen. (Unwin, 2019)

Chapter 3: Methodology

3.1 Research questions

Seeing nuclear energy as an energy source falling under the concept of “high risk - high reward”, it is imperative that we examine it under two scopes. First, it is important to examine the effectiveness of risk management capabilities in the development of nuclear power. Undeniably, such broad topic is broken down in smaller questions that will guide the aim of the research. Such questions would be the following; which are the capabilities of risk management in the field of nuclear power? And to what extent such capacities can affect the development of nuclear power? As mentioned in Chapter 2, risk in the process of harnessing nuclear power comes in various forms. However, what is truly important is to learn how to anticipate, react and prevent those risks from occurring, or in case of occurrence, how to minimize the damage done. Risks regarding safety, economics, strategy and production can seriously impede the development of nuclear power or boost it if handled correctly.

Secondly, we have to examine the reliability of current management processes to the development of nuclear power. No matter how many steps are taken in order to ensure safety during the development process, it is futile if they don’t offer substantial results in a time of need. Gauging the effectiveness of risk management capabilities in the development of nuclear power is pivotal in picking the right counter measure for any given circumstance. Lastly, what strategies, if any, can be adopted to enhance the effectiveness of risk management techniques? Which are the precise areas that need improvement?

Those are some questions to be answered through my research and the adopted qualitative methodology. All the resources proved very useful since they altogether acted as a guided instructions handbook in my effort to write up the dissertation.

Archival research does not always clearly fit into the clinical/ experimental model of research environment by most institutional ethical reviews panels. Nonetheless, it promotes a more qualitative way of inquiry, which gives a more in-depth understanding of the subject studied and in doing so represent a deep analysis of authors, writings and journals of the case studied.

3.2 Methodology

In order to answer the questions aforementioned, we will perform an analysis on the three most known nuclear accidents:

1. the Three Mile Island accident,
2. the Chernobyl disaster and
3. the Fukushima Daiichi disaster.

For each case we will review the accident itself, what caused it, the counter measures at the time of the accident and what steps were taken after the accident in order to prevent a possible similar event from happening in the future.

Additionally, we will examine a fourth case, that of the China Syndrome. While not a real, but rather, a fictional event, the movie and the situation it presents could very well be a real situation happening in a real nuclear power plant with the political, economic and public factors playing the same role as the one in the film. Thus, we decided to include it in our research.

Lastly, a comparative table will be formed and analyzed by combining and asserting the causes, decisions and risks that constitute each accident, as well as the outcomes that they had, in order to create a solid, total overview of all cases.
Considering that the research is qualitative and not quantitative, the analysis will be done through facts and other relative researches on a theoretical level, rather than experiments and trials.

Chapter 4: Results

4.1 Introduction

Since the first nuclear reactors' construction in 1954, the impact of nuclear accidents has been widely debated and has been a key factor in public concern about nuclear facilities (Ramana, 2009). A nuclear and radiation accident is defined as "an event that has led to significant consequences to people, the environment or the facility. Examples include lethal effects to individuals, large radioactivity release to the environment, reactor core melt" (Staff, IAEA, & AEN/NEA). For instance, the disaster of Chernobyl and Fukushima Daiichi, where the reactor core is damaged and considerable amounts of radioactive isotopes are released, are considered to be prime examples of such accidents.

Given that the human factor plays a role in the operation of a nuclear power plant, no matter the effort to reduce the risk of accidents and minimize the amount of released radioactivity in the environment, the threat of an accident still looms in the air. As of 2014, more than 100 serious nuclear accidents have occurred from the use of nuclear power. Since the Chernobyl disaster, more than fifty accidents or severe incidents have happened with about 60% of the total amount occurring in the USA. Some of the most serious accidents, namely the Three Mile Island accident, the Chernobyl disaster and the Fukushima Daiichi disaster will be further studied below. Generally, "nuclear power accidents can involve loss of life and large monetary costs for remediation work" (Gralla, et al., 2015)

4.2 Three Mile Island accident

On March 28th, 1979, in Dauphin County, Pennsylvania, a reactor of the Three Mile Island Nuclear Generating Station suffered a partial meltdown. Rated as a five on the seven-point International Nuclear Event Scale, this event and the subsequent radiation leak came to be known as the Three Mile Island accident. The rating itself was so high due the wider consequences of the accident.

The accident, caused by a relief valve that was stuck open allowing nuclear reactor coolant to escape, was attributed mainly to human factors and inadequate training of the staff.

Specifically, the inability to recognize the loss of coolant and the human-computer interaction design oversights regarding the indicators of the control room's user interface, leading an operator to manually override the automatic emergency cooling system due to his lack of knowledge to a hidden indicator.

Specifically, as TMI 2 was operating at full capacity it suddenly experienced a shut down due to a cooling pump that stopped working. A pressure relief valve opened to release excess steam and water but was stuck in that state instead of closing back again when the pressure returned to normal levels. However, the instruments in the reactor's control room showed that the valve was closed resulting to too much water pumping in the reactor, which was not replaced by the operators.

As pressure kept falling, coolant kept turning to steam, causing the pumps to vibrate, misleading the operators to shutting them down. With the water and pressure diminishing, a steam bubble formed and blocked the cooling water from running through the core, resulting to temperatures rising high over the melting point of the fuel cladding and uranium fuel thus losing approximately half of the fuel, while all of it was damaged. Furthermore, some hot fuel rods shattered due to cold water flowing through them.

Consequently, vast amount of contaminated coolant accumulated at the basement of TMI 2 as well as storage units of the auxiliary building, which, in order to relieve pressure, released trace amounts of radioactive material into the atmosphere. (Lessons From the 1979 Accident at Three Mile Island, 2019)

The anti-nuclear safety concerns were crystalized for a large part of the population and new regulations were introduced for the industry. The event played a contributing role to the already existing decline that the new reactor construction program was facing. Despite the release of radioactive gases and iodine to the environment and the health concerns that come with them, epidemiological studies revealed that the event had no visible statistical increase on the levels of cancer around the area. The total clean-up cost came to around $1 billion. Following the accident, two weeks later in 1979, US President Jimmy Carter set up a commission of 12 members with John Kemeny in the lead, president of Dartmouth College at the time, tasked with investigating what had taken place and what the possible aftereffects of

the accidents could be on the health and safety of both personnel occupied by the plant as well as the public itself. (Lessons From the 1979 Accident at Three Mile Island, 2019)
As per the commission's report, the industry developed its own excellence standards as well as training facilities credited by the agency aimed for NPP operators and direct supervisors for the various operations.

Additionally, the Nuclear Regulatory Commission (NRC) promptly set up a committee to investigate the incident, which came to results significantly similar to the Kemeny Commission. (Lessons From the 1979 Accident at Three Mile Island, 2019)
No longer than a year after the TMI accident the Institute for Nuclear Power Operations was established, tasked with promoting the utmost levels of reliability and stability regarding operations of NPPs.

To further enhance personnel training, the National Academy for Nuclear training was formed in 1985 to review and certify the training regiments for critical posts at each NPP. Nearly 30 years after the TMI accident, the steady improvement in the performance of the NPPs is a profound indicator of the success of the INPO in the management and operation of Nuclear Power Plants.

Currently, the active reactors operate at peak efficiency, safety and reliability as observed and stated by the NRC and the World Association of Nuclear Reactors. (Lessons From the 1979 Accident at Three Mile Island, 2019)

4.3 Chernobyl disaster

On the 26th of April 1986, the world would come to know what is considered to be the worst nuclear disaster in history, with after-effects that last long after the accident itself. Rated with at seven – the maximum severity – on the International Nuclear Event Scale, it shares its place with the only other disaster of that scale, the Fukushima Daiichi nuclear disaster of 2011 in Japan. The disaster is accurately depicted by a series under the name Chernobyl, aired in 2019 and shows how political and financial interests as well as human error led to such a tragic event.

The accident happened during a safety test meant to provide data on whether or not the turbine of the reactor could generate enough power to supply the reactor until the back-up generator could come online in case of a power outage or any disruption that could prevent power from being supplied to the reactor. After failing thrice, a fourth attempt was made, which however was affected by both human and political factors.

Regarding the human factor, the test was left to be carried out by a team not experienced with that task before, ran by a supervisor who didn't allow his authority and presumed expertise to be questioned. A series of faulty decisions led to the reactor almost completely losing power then causing a reaction so intense that led to water instantly vaporizing and the core itself exploding.

Regarding the political factors, which are tied to the financial factor as well, it was a matter of state credibility. Specifically, a crucial part of information about the structure of the reactor's control rods was deducted from the specifications of the RBMK reactors by the KGB, in order to not show the quality of the equipment of the Soviet Union's assets. This very specific detail however about how the control rods were made was the very factor that led to explosion of the reactor's core.

The reactor explosion had a number of results, with the immediate being the death of staff members working at the reactor. Many others who were near the site were admitted to hospitals with acute radiation syndrome after absorbing large doses of ionizing radiation. Those that did not die shortly after their exposure, died later from suspected radiation-induced cancer. Cancer rates spiked in the years that followed, the area around was contaminated reaching out to thousands of kilometers, with byproducts of this explosion being noticed in Sweden. An exclusion zone was set, and later expanded around the disaster site, and many were evacuated. To contain the spread of radioactive contamination, the reactor was enclosed in a protective sarcophagus on December 1986, which also served as a radiological protection for the crew working in the still operating reactors of the site. However, due to fast deterioration, the sarcophagus was further enclosed in a larger confinement, which allows for a safe clean-up of the confined area.

“The Chernobyl disaster is considered the worst nuclear power plant accident in history, both in terms of cost and casualties.” (Black, 2011). More than 500000 personnel and roughly US$68 billion were required for the initial emergency response and the later decontamination of the environment.
The tragedy greatly affected the global community and altered the safety-related attitude of the nations towards nuclear energy. Following the nuclear disaster, new standards and techniques for strengthening nuclear and radiation security, emergency management, and disaster prevention were established. After the Chernobyl disaster, the International Atomic Energy Association (IAEA) has introduced a number of security-related regulatory mechanisms to improve nuclear safety and security on a global and domestic scale. (Van Trigt, 2016)

Prior to the Chernobyl nuclear accident, nuclear energy legislation was mostly made up of international scientific guidelines that were not legally binding until they were adopted into domestic law or bilateral or multilateral treaties.

The regulatory system for nuclear energy, nuclear safety, and nuclear security has changed greatly since the Chernobyl nuclear disaster. Over everything, nuclear safety is the responsibility of sovereign governments. International collaboration, on the other hand, is required. A nuclear disaster may have transboundary consequences, affecting other countries as well. (Van Trigt, 2016)

To improve nuclear safety, the IAEA increased safety requirements. Since 1986, numerous relevant international legal conventions, such as the Convention on Nuclear Safety, have been implemented to improve nuclear safety and emergency preparedness and response. The IAEA has also developed a peer review framework in which foreign teams of experts can advise countries on nuclear safety, operating safety, architecture safety, emergency preparedness and response, and regulatory effectiveness.

Despite the advancement of the international legal system governing nuclear safety and security, as well as disaster preparedness, nuclear incidents will also occur. The nuclear disaster at Japan's Fukushima Daiichi nuclear power plant in 2011 exemplifies this. Such incidents occur even in a technologically advanced nation with a proven nuclear program, such as Japan. Following Fukushima, new programs have been launched under the auspices of the IAEA to improve nuclear safety. (Van Trigt, 2016)

The 1986 Chernobyl tragedy had an effect on the nuclear liability regime as well; the nuclear disaster revealed the flaws of the proposed nuclear liability rules. It was not necessary to award legal damages to affected people under the current legal system (individuals and states).

The established legal structure (Paris Convention on Third Party Liability in the Field of Nuclear Energy (Paris Convention, 1960), which was primarily signed by Western European countries, and Vienna Convention on Civil Liability for Nuclear Damage (Vienna Convention, 1963), which was primarily signed by Eastern European countries), was clear that it needed to be revised. At the moment, liability limits were so low and needed to be raised. (Van Trigt, 2016)

The Fukushima nuclear tragedy in 2011 demonstrated that, after previous success, there was still no reliable regulatory system, no universally harmonized legal regime. The IAEA introduced a Draft Action Plan on Nuclear Safety the same year as a result of the Fukushima crisis.

Some progress has been made in the field of international nuclear liability law since the Chernobyl nuclear disaster. However, in order for the international legislative system to become more successful, a substantial revision of financial responsibilities for nuclear accidents is urgently needed. Nuclear power countries must now ratify international legislative instruments and cooperate with and enforce the legal nuclear liability policy and IAEA plans, such as the Draft Action Plan on Nuclear Safety, in order for there to be harmonization and an appropriate universal legal framework for nuclear liability regulation. (Van Trigt, 2016)

4.4 Fukushima Daiichi nuclear disaster

In 2011, an earthquake followed by a tsunami caused a nuclear accident at the Fukushima Daiichi Nuclear Power Plant in Okuma, Japan. Rated with as level 7 on the INES scale, its severity was second only to the Chernobyl disaster of 1986, with which they share their INES classification, attributed based on the impact of the accident on the population. Namely, the Chernobyl accident caused 335.000 people to be evacuated and the Fukushima Daiichi accident 154.000.

The incident happened when upon detection of an earthquake, the active reactors shut down their normal power-generating fission reactions, that, combined with other electrical grid supply issues, the reactors' electricity supplies failed and the emergency diesel reactors turned on automatically, which were responsible for powering the pumps circulating coolant through the cores of the reactor. Moreover, as an after-effect of the earthquake, a tsunami was generated, sweeping over the plant's seawall and flooding the lower parts of the reactor, causing the failure of the emergency generators and loss of power to the circulating pumps. As a result, the loss of reactor core cooling led to a series of nuclear meltdowns, hydrogen explosions and release of radioactive contamination.

In the post-accident period, due to atmospheric radiation and the rising ambient off-site levels of ionizing radiation, an evacuation zone of a 20 km radius was established. Vast amounts of contaminated water were released in the Pacific Ocean both during and after the disaster. Ince then counter-measures have been taken to prevent the flow of contaminated water, namely new walls along the coast and a 1.5 km long "ice wall" of frozen earth.

Although health-related concerns were raised, a report in 2014 by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the World Health Organization (WHO) presented no increase of side-effects caused by the accident, such as miscarriages, stillbirths or disorders both physical and mental.

The causes of the accident were later, in 2012, determined to have been foreseeable and that plant operator, Tokyo Electric Power Company (TEPCO), had failed to meet basic safety requirements – risk management, containment of collateral damage, development of evacuation plans –. Later that year, TEPCO admitted that it had indeed failed to take the necessary precautions out of fear of attracting unwanted attention against its power plants. Furthermore, issues that led to the Fukushima Daiichi accident can be further attributed to the factors listed in the table below;

Table 4.1. The Explanation of the Issues in the Fukushima Dai-Ichi Accidents (Yang, 2014)

Issues	Explanations
Underestimated Tsunami Hazard	- The countermeasures against tsunami are a voluntary work of utilities. There was no regulatory provision against the tsunami beyond the design basis. - It seems there was no consideration of the tsunami hazards in determining the location of EDGs.
Combined Hazards	- The earthquake damaged the infrastructure including roads and delayed the support from the off-site - The loop caused by the tsunami was not recovered for a long period due to the damage by the earthquake to another NPPs
Delayed Power Recovery (Long Term SBO)	- It assumed that LOOP can be recovered within a short time period with the help of other units and the nearby sites. However, the same accident causes impacted the multi-unit at the site and the sites nearby at the same time. - The recovery of LOOP was delayed due to the destruction of the infrastructures such as roads, and the harsh working environment such as the debris caused by the tsunami.
Loss of I&C	- Most I&C systems failed after the SBO - Some instruments provided incorrect signals (unreliable information on reactor water levels) - Incorrect signals resulted in misinterpretation of the states of the damaged cores, resulting in making inappropriate decisions.
Multi-Unit Accident	- The hydrogen explosion at unit 1 caused the delay of power restoration at unit 2 - The hydrogen explosion at unit 4 caused by the accident in unit 3 - The onsite resources were not enough to handle the simultaneous multi-unit accident
Hydrogen Explosion at Unanticipated Locations	- Hydrogen explosions occurred at the unanticipated locations (i.e., top floor and the adjacent unit) and the efforts to prevent explosions did not work well. - The physical impact and the radioactivity release due to hydrogen explosion delayed the accident management.
Damage to Spent Fuel Pool	- The earthquake and hydrogen explosions damaged the integrity of SFP. The SFP of unit 3 was damaged due to hydrogen explosion. The SFP of unit 4 is not severely damaged, however. - Since the conditions of SFP was unknown, there were major concerns on the re-criticality and fire of spent fuel rods with the loss of cooling in the SFP. Several cooling water sources were used for the cooling of the SFP.
Safety vs. Security	- The main gates of the NPPs were designed based on the fail-closed concept for the security. The closed gates from the power loss prevented entering of fire trucks into the site.
Safety of the Damaged NPPs	- There are concerns about the integrity of structure, systems and component of damaged NPPs - The contamination of underground water becomes an important issue
Human Error/Miss Communication in IC/HPCI Operation	- In unit 1, operators did not notice the loss of IC. In addition, it was not report to emergency response center after switched off the IC. - In unit 3, the shift operators switched off HPCI before an alternative water injection was prepared (without checking the status of the DC batteries to open SRVs). The reporting of the erroneous action was also delayed.

Harsh Working Environment	- The working condition was extremely harsh due to the combined hazard and the radiation - It caused many problems in mitigating the accidents - No dosimeters were provided with some operators
Delayed Venting	- The vent valves (AOV) could not be accessed due to high dose level. - The start of venting operation was delayed for several hours. - Poor operation of containment vent valves
Emergency Preparedness	- The evacuation instructions to local government were not specific nor in detail. - Insufficient/ineffective information sharing among major players

In order to enhance nuclear safety from a point of view regarding safety, some framework needs to be laid down. The safety features of industrial facilities guarantee their safety, which is validated by safety tests. To avoid such accidents in the future, we must find a way to address the found core concerns in the design of safety features and/or safety evaluation aspects. As a result, we need a formal method for identifying the characteristics of the main problems. (Yang, 2014)

All industrial facilities, including nuclear power plants, have inherent threats. We aim to monitor and reduce these risks by incorporating protective measures into the installations. We intend to eliminate the intrinsic danger entirely. Unfortunately, even though all protective mechanisms function correctly in accordance with the specification goals, achieving zero risk in the real world is unlikely. This is due to the inherent shortcomings of safety features. (Yang, 2014)

When we design safety features, we make predictions about the risk source of the facilities, such as the Design Basis Accident (DBA) of nuclear power plants. Such conclusions, however, cannot account for all potential sources of risk. There may be many risk factors that were not considered when developing the safety features. Furthermore, many of the assumptions used to determine nuclear safety are invalid. In certain cases, the DBA's sole failure criterion, for example, are unrealistic. (Yang, 2014)
In the real world, safety features struggle to function for a variety of reasons, including structural flaws, corrosion, production and repair issues, and human error, among others. As a result, even though we add more safety features and improve their availability, all installations would have residual risks that cannot be removed by safety features. (Yang, 2014)

An additional problem is known as an unknown risk. There may be certain danger sources whose presence or behavior we are unaware of. This type of danger arises as a result of the current state of human intelligence. Actually, residual and/or unexplained threats are linked to a well-known problem in PSA known as the completeness question. It is obvious that no safety feature or safety evaluation tool will account for all risk contributors. (Yang, 2014)
The risk evaluation and management systems can play an important role in improving the design of safety features and safety assessments in the future to ensure nuclear safety.
The new risk evaluation and management system, on the other hand, should be changed. In this part, we will go through some of the main topics that need to be addressed in relation to the existing risk evaluation and management process and/or procedures, such as the PSA. Since the 1979 TMI-2 explosion, PSA has been widely used in many countries to recognize the design and/or operating shortcomings of nuclear power plants. Using the PSA, we can also find valuable countermeasures to improve defense. PSA combines different elements, such as deterministic assessments on various accident scenarios, SSC and human reliability, and so on, to derive the overall risk profile of nuclear facilities. PSA findings have since been commonly used in risk assessment, such as the regulatory decision-making process, in the United States. We previously believed that PSA could forecast the majority of serious accident scenarios that could occur in nuclear facilities, i.e., that PSA's main strength is identifying unanticipated accident scenarios. (Yang, 2014)

4.5 The China Syndrome

The human factor plays a critical role in the decision-making process and risk management involved in nuclear power. That factor can be swayed by moral compassed, ideals, interests and political agendas to name a few and there's always room for human error. These aspects are perfectly portrayed in the movie The China Syndrome. And while the events depicted are fictional, the whole concept is based upon events that could and have happened at nuclear plants, like in Dresden, Chicago as pointed out by Roger Ebert in 1979 in his review for the movie. The China Syndrome is a theory that claims that in case that the nuclear materials are exposed, due to their superheated condition they could melt through the plant floor and keep on going until the reach through to the other side of the Earth in China. In praxis, it would cause an explosion that would "release radioactive materials sufficient to poison an enormous area" (Ebert, 1979), much like what happened in Chernobyl in April of 1986.

In the movie, an earthquake shakes a powerplant and is immediately followed by an aftershock felt only by the chief supervisor. At that time a stuck pen indicating the water level of the reactor tips the operators that they need to lower the pressure. However, once the pen gets unstuck, they realize that the water levels are already too low and that they almost uncovered the reactor core.

The whole accident is observed and filmed by a news crew that had been there for a routine tour. The chief supervisor, upon further investigation, uncovers that the welding plans for the reactor were falsified. Meanwhile, the news crew tries to bring the story on air but is being halted by the NPP company's public relations.

The reason behind that was mainly financial. While the safe procedure would be to shut the reactor down and proceed to a thorough check of the reactor and repair faulty parts, the owner of the company that owned the plant decided not to do so. Every day the reactor was offline it cost almost half a million dollars. And while the potential threat that the reactor could cause was enormous, instead it was kept operational for financial reasons. Adding to that, the company was getting a license for a second installation and accepting that an accident did indeed occur would put a hold to getting the license. Not only that but after consecutive warnings about not using the reactor at all, the reactor is pushed over its limit, brushing off the warnings of the chief supervisor.

As he mentioned in the movie, NPPs are built having in mind that an accident will happen. Thus, taking precautionary measures for every possible scenario that might come up during their operation. However, all the counter-measures that one can think in order to prevent an accident are rendered useless when incompetence and political/financial interests get in the way. Inability to correctly read indicators, make the appropriate decisions, adapt and properly communicate lead directly to a certain path to catastrophe.

The Fukushima Dai-Ichi disaster strongly demonstrated PSA's capabilities and shortcomings. There has been considerable debate about the utility of PSA after the Fukushima Dai-Ichi disaster, in which PSA failed to accurately estimate the tsunami risk at the Fukushima Dai-

Ichi site. In Japan, however, compliance with the PSA was entirely voluntary. Given the Japanese site requirements, the majority of Japanese NPPs based on the seismic PSA. The seismic PSA for the Fukushima Dai-Ichi NPPs was conducted, but the PSAs for other external disasters, such as floods, were not. There was also no tsunami PSA.

There are some well-known intrinsic issues regarding the risk assessment and management such as the completeness and uncertainty, etc. There are also some emerging issues in the risk assessment field such as a dynamic PSA, digital I&C PSA, etc. (Yang, 2014)

To sum everything up, the safety features guarantee nuclear safety, which is demonstrated by the safety tests. The Fukushima Daiichi disaster exposed several flaws in the traditional methods used to guarantee and validate the safety of nuclear facilities, including NPPs. We must learn from the crash in order to avoid such incidents in the future. Following that, based on the lessons learnt, we would strengthen the traditional methods used to ensure and validate nuclear protection. (Yang, 2014)

To begin, we must consider the inherent essence of the danger faced by nuclear facilities in order to reduce the risk of the installation in a systemic manner. As a basis for systemic risk control, we proposed the following.

- A more rigorous screening out process, such as a risk-informed screening process, should be introduced to reduce the residual risks created by screened out initiating incidents.
-The risk assessment's spectrum should be expanded in order to reduce the residual risk area.
- Prevention mechanisms must be designed for severe situations in order to deal with not only residual risks but also uncertain risks. The deterministic and probabilistic dimensions of the countermeasures for a serious accident must be updated.

Risk assessment is helpful for identifying device vulnerabilities. However, risk assessment is a more critical consideration. TEPCO was also aware of the threat of a massive tsunami. However, it appears that they neglected to adequately handle the tsunami danger based on the details provided. As a result, risk evaluation should result in effective risk control. For risk control, the following should be enhanced and/or created.

The safety features for serious injury prevention should be improved in light of the risks. - Given the multi-unit crash, we need a serious accident response system at the site level. Risk-informed emergency preparedness is needed.

It is unlikely to have a nuclear installation that is fully risk-free. However, if we take a more holistic approach and consider the essence of the risk as outlined above, we will find a way to reduce the risk quickly and efficiently. For example, we can improve DID by using lessons from risk evaluation and management, or we can create a new risk-informed DID system. Based on the risk exposure studies, we will assess the necessary safety margins or classify the cliff edge consequences.
Finally, the risk-informed approach can be used to improve nuclear safety in a variety of ways. To use the risk-informed approach effectively, we must first consider the inherent value of risk, as outlined in this article.

4.6 Comparative table of events

Having gone through the aforementioned cases it would be valuable to examine them not separately but collectively. As seen in Table 1, there are both similarities and differences in the nuclear disasters.

Easily distinguishable is the factor of human error. In all cases, the lack of experience on behalf of the operators played a crucial role to how the crisis manifested. Specifically, the lack of training in Chernobyl and TMI on behalf of the operators had as a result the meltdown of the reactors and the contamination of the area around the Nuclear Power Plant. Additionally, in all cases the fault can be traced beyond the operators' inexperience to external political and economic factors, such as lobbies and political parties.

Other than the case of Fukushima Daiichi, that the root cause of the disaster was attributed to external factors, it is observable that the risk perception of the personnel was lacking and were in no position to prevent the accident from happening, either due to wrong decisions or hurdles that, if avoided, could have had a different outcome.

Lastly, in all cases, although in different magnitudes, the outcome was nothing less than dreadful. From the threat of a reactor explosion as shown in the China Syndrome to the actual meltdown and even explosion of the reactor, the gravity of a slight mistake was made abundantly clear.

Table 4.2: Comparative table of nuclear accidents

Name of event	Comparative characteristics	Risk perception	Decision accuracy	Outcome
Three Mile Island accident	Operator inexperience, contamination	No operator experience, unawareness	Wrong decision making	Reactor meltdown, radiation leak
Chernobyl disaster	Operator inexperience, Contamination, Political and financial factors involved	Wrong decision making based on governmentally withheld information	Low accuracy due to political reasons and technical misinformation	Reactor explosion, Radiation contamination, Lasting side effects
Fukushima Daiichi nuclear disaster	Operator's lack of precaution for safety measures	External factors	Post-accident safety measures established	Reactor meltdown, atmospheric, land and aquatic contamination
The China Syndrome	Operator's lack of precaution for safety measures	Risk perceived late due to technical issues	Inaccurate counter-actions influenced by political and financial factors	Reactor almost exploded

Chapter 5: Conclusions

This thesis attempted to show the effectiveness of risk management capabilities in the development of nuclear power and to examine the reliability of current management processes to the development of nuclear power. In order to do so, we examined the cases of the Chernobyl disaster, the Three Mile Island accident, the Fukushima Daiichi disaster and the scenario of the China Syndrome. In the case of the Chernobyl disaster the study revealed that the root of the disaster was the lack of experience on behalf of the operators, a series of wrong decisions issued by the plant supervisor, as well as political factors that obscured critical manufacture details regarding the reactor's control rods. The results of the disaster ranged from immediate death to those present during the accident, to acute radiation poisoning and cancer rates raising drastically in the following years. In order to prevent such events from reoccurring several measures were taken to enhance safety and transparency in the operation of Nuclear Power Plants. In the case of the Three Mile Island accident, the accident was attributed to inexperienced personnel as well as faulty equipment, leading to false understanding of the escalating situation and inaccurate preventive decisions. Committees were set up in order to enhance the training of the personnel and to boost excellence standards in order to improve the overall performance of the Nuclear Power Plants. Regarding the case of the Fukushima Daiichi disaster, the cause of the disaster was attributed both to external factors, those being the earthquake and the tsunami that followed as an aftereffect, as well negligence in implementing basic safety standards to foreseeable accidents causes, as the ones that took place. The safety framework regarding nuclear power plant safety was enhanced and measures were taken to improve the structural integrity of the plant. Finally, in the fictional scenario of the China Syndrome, the cause was once more the inexperienced personal that failed to correctly read the situation at hand, negligence in the manufacture details of the plant, as well as political and economic factors that obscured critical details of the plant and tried to cover up the incident in order to boost profit at the expense of security. It becomes apparent from the cases studied that in order to prevent such accidents for repeating themselves it is beyond imperative to be able to fully comprehend nuclear power and how to properly handle it all times. The operating personnel must be adequately trained to spot, recognize and counter any and all possible risks that might appear. In every part of the decision-making process in an NPP, be that short term operations or long-term procedures, planning, maintenance and modifications to name a few, the personnel must be able to adapt accordingly depending on the urgency of the situation and be able to comprehend all the indicators in a case of emergency. Additionally, having clear and accurate plans and equipment can help avoid misleading and contracting actions that has been the cause of the nuclear accidents of TMI, Chernobyl and in the case of the China Syndrome, the plant at hand. It is also mandatory to understand the complexity of the risks themselves that are involved in the operation of a power plant. Due to them being multi-dimensional, their nature is even harder to collectively foresee and formulate countermeasures. However, if handled correctly they can be translated to potential experience and help magnify the benefits by helping make sound decisions, more cost-aware investments and improve communicational skills that will divert resources directly to where they are required. The safety, production, commercial/financial and strategic risks that may appear in the operation of an NPP often extend to factors outside the plants as well. Affecting the environment, organizations and institutions, companies and other external factors, NPPs need to be at all times steadfast to thwart an operational threat.

This thesis has, of course, its limitations. Given that it is a qualitative research, it focuses more on analysing data and research materials of other experts and institutions. It is a small-scale study with precise word limit which eventually minimizes the depth of evaluation. In other words, this study gave emphasis on the reasons that caused the accidents, the effect that they had and the steps taken to prevent them in the future and didn't expand to a greater extent on tested management techniques of nuclear power. Additionally, examining current researches on the field using a qualitative approach doesn't provide empirical evidence on the research topic. Nonetheless, this paper may stand as a way for further research.

Further research is needed both in the theoretical as well as in the empirical field in order to evaluate and adopt more efficient and effective methods to manage nuclear power. For future recommendations, one could consider including more case studies of other nuclear accidents that have happened to enrich the cases presented in this thesis and provide a larger scope of the status of nuclear power plant safety. Furthermore, one could possibly involve quantitative decision models to provide hard data regarding the aftereffect of the disasters and the impact they had regarding area of effect affected by the accidents, the impact on the population, the rise of the radiation -and possibly cancer- levels after the accident and the environmental impact they had on the surrounding areas. Lastly, one could possibly inquire a group of experts for a more detailed scientific approach, plant operators for a more in-depth analysis on how the plants operate as well as legislators to discuss further on the current frameworks regarding nuclear power.

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