# Advanced technological solutions to the negative perceptions of nuclear power plants

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## DECLARATION

I, Gideon Daniel Joubert, declare that the contents of this dissertation represent my own unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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## ABSTRACT

Worldwide a movement is underway to replace the burning of limited fossil fuel reserves for power generation with a cleaner, more efficient, yet still reliable and cost-effective method. Even though renewable technologies are often among the most common proposed, they are still limited by factors such as cost when considering large scale generation. Further requirements for replacing fossil fuel generation methods include the need to provide a continuous and reliable output for base load requirements, which is difficult to guarantee when making use of renewables alone. The proposed alternative is nuclear energy, as it is a reliable and cleaner method of power generation as compared to fossil fuels, capable of providing cost effective energy in the long run. The downside to nuclear energy, however, is the negative perception and general dislike of this method of generation, especially among the public who have been around this technology since its early days of implementation. The aim of this study is, therefore, to inform and prove that nuclear technology has evolved and come a long way since its early days, by making use of advanced technological solutions to address the fears associated with this technology from many years ago. The study further aims to prove that technologies such as advanced safety systems, new generations of reactors, advanced containment structures for both reactors and waste containment, as well as new waste disposal methods, have evolved nuclear energy into a safer and cleaner alternative method of power generation.

This is achieved by first considering the origin of the negative perceptions surrounding the technology, and the nuclear accidents of the past, which have greatly influenced opinions about nuclear technology even up until today. After identifying the concerns and fears surrounding nuclear energy, research was conducted concerning how the latest technologies and innovations in safety systems are used to address these concerns, and ultimately eliminate the threats where possible. With the biggest concern identified, namely a core meltdown event leading to the release of radioactive material into the environment, two simulations were conducted to illustrate the unlikelihood of such an event occurring. The purpose of these simulations was, moreover, to illustrate the complexity and reliability of the various safety systems incorporated into the design of a nuclear power plant, preventing such a feared release of radioactivity from occurring. The research also importantly revealed that the dangers and possible threats posed by nuclear technology are often grossly overestimated, as under normal operating conditions a coal power plant, in fact, releases more radiation into the environment than a nuclear power plant. Further research reveals that the feared nuclear waste, produced by the nuclear industry yet regulated and disposed of properly, is only a small fraction of the highly

hazardous waste produced on an annual basis worldwide. It is also revealed that in terms of fatalities, fossil fuel generation, on average, is responsible for more deaths annually than the biggest nuclear disasters that have ever occurred. Addressing the fears and concerns surrounding nuclear technology is therefore important, as this valuable resource may otherwise remain under-appreciated and under-utilised because of the misperceptions which currently exist amongst the public. This furthermore results in the unnecessary exhaustion of fossil fuel reserves, and concomitant pollution of the environment – all due to antiquated fears surrounding nuclear power plants.

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## GLOSSARY

RBMK Reactor

Cold shutdown

ACC – Accumulators

ADS – Automatic Depressurization System

ADS-4 – Automatic Depressurization System stage four valves

AFWS – Auxiliary Feed Water System

APR1000 – Advanced Power Reactor 1000 MW, generation II reactor

APR1400 – Advanced Power Reactor 1400 MW, generation III reactor

BWR – Boiling Water Reactors

CDF – Core Damage Frequency

CMT - Core Make-up Tank

CRP – Coordinated Research Project

CSS – Containment Spray System

CTI – Advanced Passive PWR Simulator software

DGSA – Dangerous Goods Safety Adviser

DVI – Direct Vessel Injection System

ECCS – Emergency Core Cooling System

ESBWR - Economic Simplified Boiling Water Reactor, generation III+ reactor

FD – Fluidic Device

GDCS – Gravity Driven Cooling System

He – Helium

HLW – High-Level Waste

HPSI – High Pressure Safety Injection

IAEA – International Atomic Energy Agency

ICS – Isolation Condenser System

ILW – Intermediate-Level Waste

INES – International Nuclear and radiological Event Scale

IRWST – In-containment Refuelling Water Storage Tank

KAERI – Advanced PWR Simulator software

Li – Lithium

LLW – Low-Level Waste

LOCA – Loss of Coolant Accident

LPSI – Low Pressure Safety Injection

LRF – Large Release Frequency

LWR – Light Water Reactors

MFW – Main Feed Water

MOX fabrication plant

MSIVs – Main Steam Isolation Valves

mSv/yr. – millisievert per year, a measure of the amount of radiation a person can safely receive per year

MTHM – Metric Tons of Heavy Metal

NEA – Nuclear Energy Agency

NRC – Nuclear Regulatory Commission

NSSS – Nuclear Steam Supply System

OECD - Organization for Economic Co-operation and Development

P – Phosphorus

PCCS – Containment and Passive Containment Cooling System

PCCS* – Passive Containment Cooling System

PGSFR – Prototype Gen-IV Sodium-cooled Fast Reactor, generation IV reactor

POSRV – Pilot Operated Safety Release Valve

PRHR – Passive Residual Heat Removal System

PSA - Probabilistic Safety Assessment

PINCs – Passive IN-core Cooling System

PWR – Pressurized Water Reactor

PWT – Refuelling Water Tank

RCP – Reactor Cooling Pump

RCS – Reactor Coolant System

RHR – Residual Heat Removal

RPV – Reactor Pressure Vessel

SCS – Shutdown Cooling System

SDVS – Safety Depressurization and Vent System

SFR – Sodium-cooled Fast Reactor

SG – Steam Generator

SIP – Safety Injection Pump

SIS – Safety Injection System

SIT – Safety Injection Tank

SMART – System-integrated Modular Advanced Reactor

SMR – Small Modular Reactor

TWR – Travelling Wave Reactor

VLLW – Very Low-Level Waste

VSLW – Very Short-Lived Waste

# CHAPTER 1: GENERAL CONCEPT OF THE STUDY

## 1.1 Background and introduction

Since the early days of power generation, the burning of fossil fuels to generate electricity has always been the preferred method, as this allowed for electricity to be generated reliably on a large scale at affordable prices. This method of generation has been so successful that up until today the largest percentage of electricity produced is still through the burning of fossil fuels. However, it has since been realized that the exploration of alternative power sources is vital, as our total reliance on the burning of fossil fuels to go about our daily tasks is resulting in permanent damage to the environment, while fossil fuel reserves are becoming scarcer by the day. Research and innovations in technology have since brought about several alternative methods of generation, such as nuclear and renewables. While the aim is to find a suitable replacement for fossil fuels, technologies such as renewables are still facing several challenges such as reliability, stability and cost, especially when considering large scale installations and the supply of base load electricity. This study, then, proposes that nuclear be used as an alternative to conventional methods of power generation.

## 1.2 Problem statement

Nuclear power plants have been in use for a considerable amount of time, proving to be a valuable resource and alternative to fossil fuels, yet its implementation remains minimal today and often comes with immense resistance from the public. This can largely be attributed to fear and apparent dangers associated with nuclear energy, leading power utilities to often invest in older and 'safer' technologies, avoiding unnecessary altercations and minimising resistance from the public. In recent years, significant advances, however, have been made in reactor design and safety systems, addressing the concerns raised in the past. This, though, has had little impact on the negativity towards nuclear power which still lingers today, raising the questions of why, and what would it take to re-gain support for this technology.

## 1.3 Research objectives

The primary research objectives, which this thesis aims to address and achieve, are as follows.

- to identify and investigate the concerns surrounding nuclear energy safety; and
- to then identify the modern technologies that can and should prevent such fears from realizing;
- to prove that the concerns identified are largely based on outdated and inaccurate information, and not applicable to modern nuclear power plants;

- to find an effective and efficient way of informing the public by providing all the information needed to make an informed and educated decision regarding nuclear energy safety; and
- to promote the use of nuclear energy as an alternative to the burning of fossil fuels.

## 1.4 Research methodology

The need to investigate the latest technological solutions to curb the negative perceptions of nuclear power plants stems from the negative attitude towards this technology prevalent among the general public. This negativity and often out-right fear for nuclear technology have forced many countries and power utilities to abandon plans for new nuclear power plants, as the public refused and opposed the approval of new nuclear facilities. Considering this resistance towards nuclear energy, it is assumed that the public feels nuclear technology is a high risk and possible serious threat as compared to alternative generation technologies. This then begs the question of whether public perceptions and assumptions are erroneously based on a limited understanding and vague knowledge of the technology.

This question is addressed by considering the advanced multiple safety layers and latest technological innovations incorporated into nuclear power plants, which are specifically aimed at addressing the concerns surrounding nuclear technology. To achieve this, information was gathered primarily in the form of published reports, journal articles and books obtained from reliable sources such as IEEE Xplore Digital Library and ScienceDirect. Information gathered from alternative or unpublished sources such as websites received special consideration to confirm the validity of the information. The use of websites is, however, deemed as important to this study, as the opinions and fears of the public are often raised and mentioned in website articles. Alternatively, information was also gathered from respected organizations such as the International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA). Still further information was obtained from reactor and component manufacturer manuals. The software used in this paper for simulation purposes was applied for and obtained directly from the International Atomic Energy Agency (IAEA), made available to member states of the IAEA.

The first step was to obtain information, such as the International Nuclear and Radiological Event Scale (INES), from the nuclear institutions mentioned above as a means of locating information on past events and disasters surrounding the nuclear industry. The INES allowed the most severe accidents of the past, including the causes of these incidents, to be identified, which is significant due to the lasting effects they had, not only on the affected communities and environment, but especially on the opinions surrounding this technology. As an additional cause of the negativity surrounding nuclear energy, past mistakes such as the dearth of risk communication to the public during the early days of nuclear technology, were also investigated, as this, according to some, is the origin of the negativity still shrouding nuclear energy today. Investigating the advanced safety systems incorporated into nuclear power plants required an understanding of the different types of nuclear reactors, as well as of the different generations of reactors available. This then allowed the advantages associated with the latest innovations, not only in safety systems but also efficiency and automation, to come to light. Special consideration was given to the latest passive safety systems incorporated into new reactor designs and retrofits, due to their ability to operate under extreme conditions as compared to conventional active safety systems.

Since the current focus of nuclear power plant safety centres on increasing the use of passive safety systems to deal with the primary safety concerns surrounding nuclear technology, the focus of the simulation was to demonstrate and thereby confirm the advantages of using passive safety systems over active safety systems. Two simulations are included – the first simulating a power plant incorporating newer passive safety systems; and the second simulating a power plant incorporating more of the conventional active safety systems – thereby allowing the differences and advantages to be visually illustrated and confirmed. The waste produced by nuclear power plants was also considered, as this, next to safety, is the most prevalent concern associated with nuclear technology. This included considering the precautions and safety measures taken during the initial classification of waste, as well as the treatment, containment selection, transport, storage and ultimate method of disposal to follow.

After conducting the above-mentioned research, the findings led to a conclusion concerning whether or not the public's concerns about nuclear safety are indeed realistic. Furthermore, the study concludes on how the safety of nuclear power plants compares to that of fossil fuel generation methods, as fossil fuels continue to be the largest producer of base load electricity worldwide. The study intends to determine, then, based on research, which of these technologies hold the least danger to the public and environment, not only during accident conditions, but also during normal operating conditions.

The biggest obstacle faced in regaining support for nuclear power plants is finding an effective way of informing the public about the latest technological solutions addressing the concerns associated with this technology. This step is vital, as research has already shown that one of the major contributors to the negative perceptions is the absence of risk communication, the inability to inform the public sufficiently about the workings of nuclear technology during its early days. In response, this study considers proven methods for informing the public of new technologies which have, simultaneously, both significant advantages and associated risks.

Applying the knowledge gained, an effective method is duly proposed to inform the public, with the aim of making all necessary information available for engendering an educated and informed decision on whether or to support or oppose the use of nuclear.

## 1.5 Delineation of study

This study, generated from the research topic of advanced technological solutions to the negative perceptions of nuclear power plants, is centred on the following.

- nuclear technology used for electricity generation purposes;
- opinions and concerns raised about nuclear power plants by the public;
- past mistakes leading to present negative perceptions about nuclear power;
- how technology today addresses the fears and concerns raised; and
- a comparison of the effectiveness of new nuclear power plant safety systems with a Loss of Coolant Accident (LOCA) simulation.

Although mentioned, detailed research about the following fell outside the scope of the study and is therefore not covered by this research:

- early plutonium producing reactors;
- long term cost comparisons between nuclear power plants and alternatives; and
- the viability of nuclear power plants to a specific country.

Key assumptions are made based on information gathered from reliable sources. The primary assumption is that negative perceptions surrounding nuclear technology is among the main reasons for its lack of implementation and use. The other is that the possible dangers of nuclear power plants, as well as the consequences of radiation exposure, is often drastically overestimated, resulting in nuclear power being *perceived* as more dangerous than it actually is.

## 1.6 Literature study

The section reviews existing literature on nuclear power plants and the perceived dangers frequently associated with this form of power generation. The section further reviews articles and papers on reactor safety, future reactor designs and design requirements for new safety systems, including literature on the radioactive waste produced, and the classification of waste based on its origin and level of radioactivity. Papers on the respective treatment and disposal methods currently in use are also reviewed.

## 1.7 Modelling and simulation

The two projects conducted both simulate a Loss of Coolant Accident (LOCA) using software applied for and obtained directly from the International Atomic Energy Agency (IAEA). The first simulation represents a nuclear power plant making use of newer modern safety systems, while the second represents a more conventional setup. Other than the difference in safety systems, the simulation conditions will be identical, making use of generation II Light Water Reactors (LWR) operating at 100% capacity when a break is inserted on one of the cold legs feeding coolant to the core. This type of simulation has been selected to illustrate the difference between newer passive and older active safety systems in terms of reliability, method of initiation and working principal. The fault chosen is a LOCA, as this type of fault is among those most feared by the nuclear industry, having the potential to escalate into a nuclear disaster if not contained effectively. This type of fault, allowing the safety systems to activate and shut down the reactor, is needed to compare the two safety systems in terms of the criteria mentioned above.

The Advanced Passive PWR Simulator (CTI) is used for simulation one, developed by using PCTRAN software by Micro- Simulation Technology of USA. The simulator, developed in such a way as to represent a Framatome, Westinghouse or KWU reactor design, is essentially a generic 600 MWe two-loop pressurized water reactor with inverted U-bend steam generators and dry containment system (Cassiopeia Technologies Inc. 2011). The Advanced Pressurized Water Reactor (APWR) simulator is used for simulation two, based on the Korean Optimized Pressurized water Reactor-1000MWe-class (OPR1000), applying nuclear technology from Combustion Engineering in the USA (Korea Atomic Energy Research Institute, 2004).

Two different simulators are used for the two simulations as each represents a specific plant and safety system design which cannot be altered. As such, the safety systems can be compared, with the differences clearly illustrated.

## 1.8 Thesis outline

- *Chapter 2:* presents revision of literature on the fears associated with nuclear, reactor safety, safety system design, future reactor technology and nuclear waste.
- *Chapter 3:* presents the theory and background on past disasters, reactors and safety systems, waste classification, treatment, storage and comparisons to other hazardous waste, as well as risk communication.
- *Chapter 4:* presents the research results on why fears loom, importance of effective risk communication, fatalities comparison, addressing the concerns, future safety systems and nuclear technology.
- *Chapter 5:* presents case studies conducted through the simulations as discussed in 1.7.
- *Chapter 6:* presents the research summary and analysis of results.
- *Chapter 7:* presents the conclusion and recommendations for future work.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 History and the origin of the public’s fears

It is widely accepted that nuclear as a source of electrical power could be considered an essential part in supplying future base load electricity. The reason for this worldwide move towards alternative power sources is largely driven by the intention to reduce the harmful greenhouse gas (GHG) emissions by replacing conventional generation methods such as coal-fired power plants (Ongena & Ogawa, 2016). Although nuclear technology appears attractive considering its advantages, a dark cloud has hovered over this technology since its early days of development, with suggestions of new nuclear power plants often inducing fear and resistance from the public, even up until today (Otway, 2000). To address these concerns and identify the latest technological solutions to prevent these fears from realizing, it is important to first identify where these fears originate from, and what they entail.

These negative perceptions – and even outright fear – can often be traced back to the earlier development of nuclear energy and the disasters involving nuclear which occurred in the past. During the early stages of development and implementation in the 1950s, the decision was taken to not inform or survey the public regarding their opinion on the implementation of nuclear as a new method of power generation (Otway, 2000). It can be argued that this might have been the origin of the negativity towards nuclear energy, as the public inadvertently gained knowledge about the workings of this technology and the possible dangers thereof. With no large-scale fatal disasters having occurred at the time, public confidence in nuclear technology grew, with a survey in the 70s showing that over half of the American public favoured the continued development and construction of new nuclear power plants. Of those remaining, a small percentage indicated that they were unsure, while about 28% opposed the technology at the time (Otway, 2000).

This quickly changed, however, with the first nuclear power plant disaster at Three Mile Island in April, 1979. This had, understandably, a substantial (predominantly negative) impact on the public. Investigations into the cause of the accident revealed that a combination of poor maintenance, faulty equipment and operational errors led to the loss of coolant in the reactor, resulting in a reactor meltdown (Otway, 2000). The disaster caused a sharp spike in those opposing the technology, while those who previously favoured the increased use of nuclear dropped rapidly. The decreased faith in nuclear technology meant that by the early 80s, nuclear ranked as one of the least favoured methods of generating power, ranking even lower than fossil fuel generation methods such as coal. However, as the negative effects of burning fossil fuels became more widely known among the public, people once again considered the use of nuclear as a possible solution to the problem. Nevertheless, even of those considering nuclear a possible solution to the generation industry's GHG emission problem, more than 50% still felt that the technology was unsafe (Otway, 2000).

During the years following the accident, a certain degree of confidence did return, yet even up until today many still oppose the construction of new nuclear power plants. Since the first catastrophic accident at Three Mile Island, several other near disaster and disastrous accidents have occurred, such as Fukushima and Chernobyl, re-fuelling the public's fears regarding reactor safety (Otway, 2000). Numerous debates have taken place amongst experts surrounding the safety of nuclear power plants, fuelled by reports of weak utility management surfacing in the past, often to blame for poor operating performance at some nuclear facilities. This is also believed to have contributed to accidents which have occurred in the past, not only disintegrating the public's faith in the safety features of reactors, but also in the personnel operating them (Otway, 2000). These fears are often enhanced by downplaying the nearness of partial reactor meltdowns which have occurred in the past, leaving the public to acknowledge that the complete truth is often not reported. This in turn results in the public's lack of trust in the government and industries, further decreasing the chances of the public accepting the technology. Surveys conducted in the aftermath of nuclear disasters frequently reveal that the public believes more such accidents are possible, and that even the smallest incidents should be considered a warning of greater accidents that could possibly kill thousands (Otway, 2000).

It can be noted that the public acceptance is critical for the successful implementation of a new technology. This has been proven over the years by the implementation of nuclear and the opinions of the public which have often limited and delayed the implementation thereof. Fuelling the overwhelming negativity towards nuclear power if often attributed to nuclear critics, blamed to an extent for the unnecessary increase in public opposition (Otway, 2000). It is felt that critics are inducing unnecessary fears when it comes to nuclear energy, resulting in the voters of a state, essentially the 'public', deciding against approving plans to develop and implement such technologies (Otway, 2000).

In addition to the concerns surrounding reactor safety, another area of major concern is nuclear waste disposal. Many states in the past have faced the problem of not being able to obtain the necessary licensing to construct new nuclear plants, specifically due to their inability to put forth a clear plan for the disposal of their radioactive waste (Otway, 2000). Those who have managed to obtain the necessary licensing will likely still face an opposing public, as the news of a nuclear waste site *anywhere* in the vicinity of a residential area is typically met with substantial resistance (Ferreira *et al.*, 2009), a resistance which stems from fear rooted in the minds of the public as the potential impact of nuclear is regarded as highly dangerous. The dangers associated with nuclear waste storage are, however, often misinterpreted, as with reactor safety, due to a lack of proper knowledge (Ferreira *et al.,* 2009). As in the case of nuclear power plants, public opinions were often ignored during the early days when it came to the selection of nuclear waste disposal sites, which in recent years were identified as an important consideration (Ferreira *et al.*, 2009). Disregarding the opinion of the public could have serious consequences, even leading to complete failure of an project When an identified storage site succeeds in entering the construction stage, the most common practices for storing the waste would include near surface deposition, deposition in intermediate caves, boreholes and geological formations (Ferreira *et al.,* 2009).

The overwhelming concern from the public regarding both reactor safety and nuclear waste storage has resulted in the NRC conducting several additional safety studies and led to the implementation of new regulatory requirements. This in turn resulted in rising costs of nuclear energy, slowing its development and decreasing its attractiveness (Otway, 2000). Even though the opinion of the public is a major determining factor, it is not necessarily always accurate. For this reason, it is also important to consider the opinions of energy experts and supporters of future nuclear power development. At the time of the study, approximately 74% of the scientists and energy experts considered the benefits of using nuclear energy to be greater than the risks, while at the same time, approximately only 55% of the public supported the same view (Otway, 2000). These figures show that the public is often blind-sided by the possible risks associated with reactor safety, rather than also considering the advantages, and comparing nuclear to other technologies currently in use. Nevertheless, whether supported or opposed, nuclear energy will have some advantages over conventional fossil fuel power plants, such as possible cost advantages to the public and reduction in greenhouse gas (GHG) emissions (Otway, 2000).

It is therefore generally agreed upon that a lack of knowledge from the public results in public opposition to the use of nuclear energy. This view is also undergirded by studies conducted in the past, showing that experts with sufficient understanding and knowledge of nuclear energy will be much more likely to support its use. A closer look at these studies has revealed that the findings often support a selective perception, meaning that those for or against nuclear will often select results strategically to support their arguments (Otway, 2000; Harris *et al.,* 2018). Even though the complete set of results showed that in-depth knowledge of nuclear power plants had a minimal impact on the number of people opposing the technology, it would, however, be wise to inform the public on the basic workings of these power plants and their possible dangers.

Although the opposition to the technology has had an impact on the rate of implementation, new nuclear power plants will continue to be constructed, albeit at a much slower rate (Otway, 2000). This slowed rate of implementation means that as older power plants are being decommissioned, they will not necessarily be replaced with nuclear. This results in a requirement for alternative forms of energy, such as coal or renewables, although this can become quite expensive depending on the technology opted for (Otway, 2000; Shellenberger, 2018a).

To successfully reduce resistance against nuclear technology, the relatively slow rate of implementation will have to be maintained, with the absence of *any* events that could potentially engender bad publicity (Otway, 2000). If this can be achieved, the possibility exists for the public to regain faith in nuclear power; however it is expected that this will take time.

It is worth noting that since the publication of Otway's article in 2000, the Fukushima disaster of 2011 had a significant debilitating effect on the support for nuclear, which would only have begun to return with the passing of time. The article, therefore, although older, could still be applicable today as a disaster such as Fukushima would once again set back the support for nuclear by many years. This means that in order to again restore confidence in the technology similar to what it was before the accident, methods proposed in older articles can once again be applied today.

## 2.2 Reactor safety

Through the revision of the above literature discussing the history and origin of the public's fears, it became evident that the two main concerns consist of nuclear reactor safety and nuclear waste storage. For this reason, special attention will be given to the safety systems used in the latest nuclear reactors, as well as the latest methods used for the storage of nuclear waste. Ultimately, public fear stems from the possibility of a nuclear disaster, which essentially refers to the release of radioactive material, whether from a core meltdown at the power plant itself, or from improper storage at a radioactive waste storage facility.

Incorporated into the design of a nuclear reactor are several layers of active and passive safety systems, designed with the aim of eliminating the possibility of radioactivity being released. These systems are also designed in such a way that if an unforeseen worst case scenario were to occur, the effects will be restrained to a minimum and in a reliable manner (Degeneff, 2006). Dangerous scenarios these safety systems must prevent primarily include over-temperatures in the reactor core caused by an imbalance between heat produced from the fission reaction and the rate of cooling. If such a disturbance were to occur, safety control systems, as well as limiting and safety shut down systems, will automatically intervene, reducing the power production of the reactor or alternatively completely shutting it down (Degeneff, 2006).

One of the major differences between conventional power plants and nuclear power plants is that after complete shutdown of a nuclear power plant, a small amount of decay heat will still be produced. This decay heat is roughly 6% of the operational heat after complete shutdown, and can still be around 0.006% after as long as three years (Degeneff, 2006). For this reason, continuous cooling is required after complete shutdown to dissipate the heat. Loss of cooling after shutdown is one of the scenarios intended to be prevented by safety systems, as loss of cooling could result in the reactor core entering meltdown, leading to a nuclear disaster in an absolute worst case scenario (Degeneff, 2006).

To prevent such scenarios from occurring, the following simplified goals of reactor protection are vital:

- Safe shutdown of the reactor should be achievable at all times, including the option of keeping the reactor in the shutdown state for any period of time (Degeneff, 2006).
- The reactor should be sufficiently cooled at all times, including operational and shut down states (Degeneff, 2006).
- The containment structure should provide protection against the release of malfunction-induced radioactivity on both the workers inside the reactor, as well as the public on the outside (Degeneff, 2006).

Except for the sophisticated shutdown and control system requirements mentioned above, the power plant, specifically the reactor, is also surrounded by multiple layers of containment structure. This forms part of the multiple safety layers superimposed upon one another, creating multiple backup systems and layers ensuring that even the most unforeseen circumstances are covered (Degeneff, 2006). The four layers forming part of this multi-layer protection scheme superimposed on one another are as follows.

### 2.2.1 Safety Level 1

As mentioned above, the safety of a nuclear power plant consists of several layers. The first of these safety layers requires that all reactors are properly designed, manufactured and safe in terms of reactor physics. This refers to the design of all reactor components and cooling systems, including the reactor pressure vessel, pipes and pumps, to the highest safety standards (Degeneff, 2006). This demands that components are quality manufactured using approved materials which meet specified standards. The first layer of protection also requires regular inspection and replacement of components once a plant becomes operational, as well as proper training of the operational staff. Scheduled inspections ensure that a plant maintains a high degree of technical safety throughout its operational lifespan (Degeneff, 2006). Regular inspections will also render the likelihood of malfunctions highly unlikely.

### 2.2.2 Safety Level 2

The second layer of protection consists of all the measurement, detection, control, monitoring and limiting systems (Degeneff, 2006). The control of the systems is not as much a safety system, as it is meant to counteract disturbances within the system. This happens through self-regulation of control rods and the control of main cooling pumps. The system also includes the temperature sensors, pump control and pressure monitoring, helping to prevent accidents through early detection of any malfunctions or inconsistencies (Degeneff, 2006). Through constant monitoring of these sensors, the system can detect when the reactor power becomes too high, water levels start to drop or pump speeds become too low. Left unattended, any of these scenarios could potentially evolve into a bigger problem, resulting in reactor meltdown. This layer of protection also includes extremely sensitive pressure sensors monitoring the pressure vessel, sensors designed to detect minute cracks long before they pose any potential risk, significantly increasing the safety (Degeneff, 2006).

### 2.2.3 Safety Level 3

The third safety layer includes safety related systems such as the reactor protection and shutdown system, the emergency and backup cooling systems, and the residual heat removal system (Degeneff, 2006). After any of these systems have been initiated by the reactor protection system, the systems contained in the third safety level take over and operate automatically to a large extent. These systems will then limit any damages as best possible, and prevent abnormal events from escalating to a dangerous level (Degeneff, 2006). An example problem dealt with by the third level of protection would be if the system notices that the coolant temperatures have reached the upper temperature level. In this case, the reactor will be shut down by inserting the control rods into the core, stopping the fission reaction. If this process is interrupted by a lack of power for example, the backup generators will be started in order to supply the curtail instruments with power, allowing for safe shutdown of the reactor. This is only an example; however, it is useful in giving an idea of how the system will deal with problems automatically as they arise, ultimately shutting down the reactor before any permanent damage is caused. These third level systems will also consider that systems from one of the previous safety levels might not be working, or that some might not be available. These assumptions made by the systems of the third level are essential, as this protection will essentially only come into play as a result of other levels having failed to resolve the problem (Degeneff, 2006).

### 2.2.4 Safety Level 4

The fourth and final level of protection consists of additionally installed components which are to be used in the event of an in-plant protection system failure. Risk studies have shown that accident control methods can still be implemented successfully after a near complete failure of safety levels 1 through 3. One way to achieve this is through operating personnel intervening by manually opening pressure release valves, as this could be the difference between core meltdown and successfully controlling potentially dangerous events (Degeneff, 2006). Depending on the situation, the release of pressure on the primary cooling system side could allow for the high-pressure safety feed pumps to activate when pressure drops to a sufficient level. Other systems which would activate after the release of such pressure would include the pressure accumulators and the residual heat removal systems. Accident management measures also form part of this level, including problems caused by human intervention or unlikely events such as an airplane crash or chemical explosion damaging the plant (Degeneff, 2006).

## 2.3 Design of the safety systems

To successfully design and implement the several safety layers, it is necessary that proof be provided showing that certain limits – such as temperature of the fuel elements, stresses and strains of components as well as pressure – will not be reached under any predictable circumstances. A successful safety layer design also demands that no manual intervention measures be required during the first 30 minutes of an event occurring (Degeneff, 2006).

The completed design of the safety systems should also have undergone a probabilistic safety analysis (PSA) proving that the probability of an accident occurring, one that is not able to be controlled by the safety systems, is less than 10-5 to 10-6 per annum (Degeneff, 2006). These types of accidents would include a chain of unforeseen occurrences exceeding the design capabilities of the safety systems, possibly having the potential to result in a nuclear disaster. PSAs are not an official part of a new plant's licensing procedures, as it is purely based on deterministic criteria, even though such an analysis has proven its worthiness as it considers the possibility of multiple malfunctions and defects in plant components (Degeneff, 2006). This would further include the possible effects of external components such as an earthquake, as in the case of the Fukushima disaster, where a chain of unforeseen and unpredicted events following an earthquake resulted in a nuclear disaster. Results of studies have shown that the likelihood of incidents occurring decreases dramatically from safety level 1 to 4, with the likelihood of an incident reaching beyond safety level 4 being in the range of 10-5 to 10-6 per year (Degeneff, 2006).

Detailed and extensive safety guides and power plant requirements are also set out by the IAEA, ensuring that a high level of safety is maintained to ensure as minimal risk as possible. These extensive documents detailing the standards and codes nuclear power plants must adhere to can be found at the following reference (International Atomic Energy Agency, 2008). These standards include those for new nuclear installations, containment system requirements, fire safety, accident management, maintenance, licencing requirements, waste management, safety, and decommissioning requirements, among many other.

An additional concern forming part of reactor safety often raised by the public is the possibility of reactor sabotage or deliberate destruction by terrorists with the aim of releasing harmful radioactive material. To prevent such occurrences, the “Act on the Peaceful Uses of Nuclear Energy and the Protection against Its Hazards”, or “Atomic Energy Act”, has been established (Degeneff, 2006). Currently most countries operating nuclear reactors have issued this Act, as it is dedicated to keeping the public safe from any intentional release of nuclear radiation, and establishes a framework for peaceful utilization of nuclear energy (Degeneff, 2006).

## 2.4 Future nuclear reactor technology

### 2.4.1 Nuclear fusion

All nuclear power plants and nuclear reactors currently in use commercially generate power through the process of nuclear fission. Lately, however, research has shifted to alternative forms of nuclear reactors which could potentially be safer, more stable, and have higher efficiencies. One of the nuclear technologies currently in the research stage is that of nuclear fusion, which if developed successfully will have a virtually inexhaustible supply of fuel resources, increased safety and low environmental impact as compared to other available technologies (Ongena & Ogawa, 2016).

When development reaches a stage where nuclear fusion power plants can be implemented, the overall safety will increase significantly as compared to conventional fission power plants. This can be achieved as fusion reactors only have enough fuel at each instance to produce energy for a few tens of a second, as compared to fission reactors containing enough fuel for several years of operation (Ongena & Ogawa, 2016). If any malfunctions or human errors occur, the fusion reaction will halt because of the limited fuel available at each instance, and also since fusion reactions are not based on a neutron multiplication reaction (Ongena & Ogawa, 2016). Operation of the system can also be stopped immediately by cutting the gas or pellet supply to the reactor. In the unlikely event of total loss of cooling, the low residual heat produced by these type of reactors will also exclude the possibility of a reactor meltdown (Ongena & Ogawa, 2016; Reyes *et al.*, 2015). The working principle of this type of nuclear technology will thus prohibit the possibility of an uncontrolled burn or nuclear runaway occurring, currently one of the biggest dangers posed by conventional reactors.

When working with nuclear fission reactors, the possibility of nuclear materials escaping is very real, especially since the waste produced by these power plants are radioactive. In contrast to this, the basic fuels needed for nuclear fusion, D and Li, are not radioactive and neither is 4He, the direct end product after the fusion reaction (Ongena & Ogawa, 2016). Fusion reactors will, however, require some level of containment, as radio isotopes will be present inside the reactor due to the materials used and reaction thereof. Studies and research of this technology have proven that by carefully choosing the materials activated by the neutrons during the reaction process, the radioactivity induced can be kept to a minimum (Ongena & Ogawa, 2016). These materials can also be recycled within decades to a century, a much shorter time as compared to conventional nuclear waste which needs to be stored for a significantly extensive period of time (Ongena & Ogawa, 2016).

### 2.4.2 Small Modular Reactors (SMR)

In addition to developing a completely different type of reactor, an alternative would be to make use of the same type of reactors currently in use, but on a smaller scale in the form of Small Modular Reactors (SMR). An SMR is classified as a reactor producing less than 300 MW, considerably less than the nuclear reactors currently used to generate commercial power (Vujić *et al.,* 2012). However, most of these power plants will have the same basic working principle of a conventional large nuclear power plant (Vujić *et al.,* 2012). The smaller sized SMRs provide substantial advantages when compared to large nuclear reactors, as they can be factory built and transported by rail, truck or barge to the site of installation (Richter, 2014; Vegel & Quinn, 2017). This translates into simpler and thus safer standardized nuclear power plants which will require a significantly smaller initial investment and shorter construction time (Richter, 2014; Vujić *et al.,* 2012; Nawaz *et al.,* 2016).

In summary, the key advantages of an SMR can be listed as follows (Richter, 2014; Vujić *et al.,* 2012; Vegel & Quinn, 2017; Nawaz *et al.,* 2016):

- It could prove ideal for rural, hard to access areas, where the transportation of other fuels such as diesel is nearly impossible on a regular basis.
- Offsite construction reduces onsite installation time, thus reducing costs.
- It has a long life span and fuel life cycle, as refuelling will only be required after as long as 10 to 15 years, depending on the design.
- It has a simplified design, thus improving safety.

- It required minimal operation and maintenance costs.
- Its low initial cost means limited risk to investors as compared to conventional large nuclear power plants.

### 2.4.3 Travelling Wave Reactor (TWR)

Since 2006, the development of an improved nuclear reactor, known as a Travelling Wave Reactor (TWR), has been underway by TerraPower, with several hundred million dollars invested in the project thus far (Hejzlar *et al.,* 2013; Gilleland *et al.,* 2016; Mistry *et al.,* 2014).

The TWR determined to be most promising was a sodium cooled reactor utilizing metal uranium, offering the cooling efficiency and thermal conductivity required while still maintaining a realistic structural design and fuel requirement (Hejzlar *et al.,* 2013; Gilleland *et al.,* 2016). Although this reactor required some conventional low enriched uranium to start, thereafter it will be refuelled approximately every 40 years with natural un-enriched uranium, with the potential to continue running for hundreds of years (Hejzlar *et al.,* 2013; Gilleland *et al.,* 2016; Mistry *et al.,* 2014). This is thanks to the TWR's ability to burn the fissile fuel bred in the core directly, thereby eliminating the need for future reprocessing and fuel enrichment plants (Gilleland *et al.,* 2016). This ability of TWRs to run on natural un-enriched uranium, as compared to conventional reactors which only utilize 1% of the enriched uranium fuel's power potential, results in an overall efficiency improvement of about 33% to about 41% (Gilleland *et al.,* 2016; Mistry *et al.,* 2014). Utilizing a large portion of the reaming 99% of uranium, which is considered waste by conventional nuclear power plants, results in a 30 to 40-fold gain in fuel utilization, in the end producing substantially more power with the same amount of fuel (Hejzlar *et al.,* 2013; Mistry *et al.,* 2014). From an economic and environmental point of view, this is an exceptional advantage and breakthrough, as the higher efficiency results in an approximate 80% reduction in nuclear waste production (Gilleland *et al.,* 2016).

Before commercialization of this new cleaner, safer and more economical form of nuclear fission technology, it is essential that all aspects be addressed and developed fully (Gilleland *et al.*, 2016). One of the concerns regarding nuclear have always been safety although nuclear disaster is uncommon. But if something does go wrong the consequences can certainly be devastating. The basic working of TWRs is similar to conventional sodium-cooled fast reactors (SFRs), containing a primary reactor cooling loop consisting of sodium, followed by an intermediate cooling loop also consisting of sodium, and lastly a stem power convection cycle used to power the turbines (Gilleland *et al.,* 2016). The presence of these three independent loops surrounding the reactor core acts likes a safety barrier so that if one of the inner loops becomes compromised by a leak, the outer primary coolant loop will remain unaffected and prevent catastrophic failure (Gilleland *et al.,* 2016). The reactor also consists of several barriers to further prevent the release of radioactive material into the environment during a catastrophic failure (Gilleland *et al.,* 2016). Several active and passive systems are also established to ensure rector shutdown by monitoring control and feedback systems under all circumstances. Furthermore, TWRs are designed to reduce coolant piping as much as possible, reducing the likelihood of coolant leaks (Gilleland *et al.,* 2016). All of these precautions make the likelihood of a catastrophic reactor meltdown, as in the case of the Fukushima disaster, highly unlikely, if not nearly impossible (Gilleland *et al.,* 2016).

### 2.5 Nuclear waste storage

As mentioned, one of the other major concerns regarding nuclear energy is the storage of the nuclear waste produced. If equipment producing nuclear waste, whether from the military, power plants or medical industry, is to be expected by the public, the important issue of safe radioactive waste storage or disposal will have to be addressed sufficiently. This not only includes finding a safe method of storing the waste, but also convincing the public that the methods used are indeed safe (Ojovan & Lee, 2014). An important change in mindset and realization which needs to occur is that the waste produced today is the responsibility of the current generation, and that temporary solutions are not always acceptable solutions. For example, an average 1 GW nuclear power plant produces approximately 30 t of nuclear waste annually which needs to be stored safely (Ojovan & Lee, 2014). In the past, there have been some occurrences, like at Hanford, where nuclear waste was stored improperly, resulting in the steel containers leaking radioactivity into the nearby environment. Incidents like these resulted in massive and expensive cleanup efforts, attracting media coverage and accelerating fears of radiation exposure (Ojovan & Lee, 2014).

Management of the nuclear waste can be divided into two sections: the first is predisposal, referring to treatment, conditioning, immobilization and transportation of waste to reduce its quantity or to make it less radioactive (Ojovan & Lee, 2014); the second is the actual disposal of the waste, which refers to the final step of placing the contained waste in geological repositories, or disposing thereof in some form of storage facility (Ojovan & Lee, 2014). It is important here to distinguish between the terms *storage* and *disposal*. When waste is stored, it remains retrievable if the need for it would arise in the future, while disposal is intended to be permanent. A disposal site will therefore have to be safe from unintentional disturbances and able to contain the radioactive waste for hundreds of thousands, if not millions, of years. Due to the extended time period, such facilities should have no reliance on surveillance, and require no maintenance over the radioactive life span of the waste (Ojovan & Lee, 2014). Another term often referred to is a waste *repository*, a temporary place of storage with the intention of eventually becoming a permanent disposal site (Ojovan & Lee, 2014).

### 2.5.1 Storing waste in cementitious materials

Lately, one of the preferred methods of disposing nuclear waste has shifted towards cementitious materials. This method is primarily used for the disposal of low and intermediate level wastes (Bart *et al.,* 2013; Ojovan & Lee, 2014). In 2007, the Coordinated Research Project (CRP) on cementitious materials for radioactive waste managed to gather 26 research organizations to share their research regarding the storage of nuclear waste in cementitious materials with a two-fold aim: improving radioactive waste management by resolving existing problems which still existed, and improving the general efficiency and safety of the process (Bart *et al.,* 2013). Before this could be done, though, the behaviour and performance of cementitious materials first had to be investigated to determine its suitability for radioactive waste storage when used for both short and long term applications (Bart *et al.,* 2013). This is important as the ultimate objective is to ensure overall safe storage and disposal of waste, without *any* problems occurring in the future.

Cement as a storage medium and barrier for encapsulation of toxic radioactive waste has many favourable properties, both physically and chemically. From a physical perspective, when hardened, cement is a durable and solid material capable of safely enclosing the waste, preventing it from escaping. Cement also has the advantage of low permeability, making it a favourable material for the storage of both liquid and solid forms of nuclear waste. Additionally, cement is readily available and relatively inexpensive, making it an overall attractive option for use in waste storage and management (Bart *et al.,* 2013). This is also backed up by literature (Ojovan & Lee, 2014) which finds several advantages of using cement, is it has the following properties:

- readily available, thus making it inexpensive;
- simple and low-cost processing, which can be done at room temperature;
- cement matrix acts as a diffusion barrier;
- suitable for all forms of waste, including sludge, liquids and dry solids;
- good thermal, chemical and physical stability for all waste forms;
- alkaline chemistry, ensuring low solubility for many key radionuclides;
- non-flammable;
- good compressive strength which facilitates handling and storage;

- easily processed remotely; and
- flexible, so it can be modified or moulded to accommodate any waste-form.

The type of cement used can be divided into conventional cement, or novel types of cement. Conventional cement refers to the cement commonly used in construction for the building of houses, or essentially the cement available at most hardware stores (Bart *et al.,* 2013). When used to immobilize radioactive waste, the cement mixture will consist of the actual cement in powder, radioactive waste and water. The order and quantities used in the mixing process is quite important to ensure that the mixture is strong enough to contain the radioactive waste. The mixture will vary depending on the type of waste enclosed, and whether the waste is in a liquid or solid state (Bart *et al.,* 2013). The main variables to consider for optimization of the mixture are the amount of waste added, the waste to cement ratio, the water to cement ratio, the type of waste added, the type of cement used, the order of mixing and finally, the emplacement and curing procedure. Complete curing of the cement is generally achieved in 28 to 90 days, depending on the process employed and the humidity (Bart *et al.,* 2013).

There are also four main types of novel cements, some of which are still relatively new while others have managed to prove their effectiveness with time. These differ from conventional cement mostly in their composite mixture (Bart *et al.,* 2013). Such types are being designed with the aim of improving conventional cement, by having faster curing times, for example. Some of these novel types have proven promising with the possibility of future with secure radioactive waste confinement. Such novel types of cement have also proven to be free of compatibility issues when used with conventional cement. The biggest problem with these are that most of them have not been around nearly as long as the conventional type, thus raising the question of whether or not they can endure the test of time when applied in real world conditions (Bart *et al.,* 2013).

Preparation of the waste-cement mixture can either be done directly in the storage container, or prior to pouring into the container (Ojovan & Lee, 2014). If in-drum mixing is used, the mixture is mixed in the container itself and allowed to set. A different composite of cement will then be added on top after the initial curing to cap the container, which minimizes the void spaces in the container and preventing surface contamination (Ojovan & Lee, 2014). Alternatively, the process of in-line mixing can be used, where the mixing is done outside the container. This, however, introduces the risk of contamination unless the mixing paddles are cleaned and decontaminated regularly (Ojovan & Lee, 2014). The final steps of the process will include adding a lid and sealing the container, decontaminating the outside of the container, and monitoring it for a while prior to storage (Ojovan & Lee, 2014).

### 2.5.2 Turn waste into glass, or enclose in cement

An alternative process to that of enclosing radioactive waste in cement is turning it into glass logs using a process known as *vitrification*. A vitrification plant costing $17 billion is currently under construction at the Hanford waste storage site in the U.S. The reason for the construction of this large treatment facility is to treat the more than 211 million litres of radioactive waste currently being stored at Hanford, with another 159 million litres being stored at the Savannah River Site (Geranios, 2017). These large quantities of waste were produced by the weapons industry during World War II.

The question now under dispute concerns whether to continue with the original decision made over two decades ago to turn the waste into glass logs, or to use a newer alternative method which entails enclosing it in cement. Although the process of turning it into glass logs is considered the better option, the problem has arisen that the waste storage tanks have begun leaking, releasing radioactive waste into the environment (Geranios, 2017). Although enclosing the radioactive material in cement is only suitable for low level waste, it should be noted that about 90% of the waste stored at these facilities is graded as being low level waste. Enclosing the waste in cement could potentially allow for faster processing; however, it is understandable that due to the substantial investment in the vitrification plant currently under construction, convincing the U.S. government of such a change is unlikely to be easy (Geranios, 2017). To date, no waste has been treated at either of the storage sites, leaving the question of whether decisions are being made in the interest of the environment and public safety, or to protect the substantial investments lingering from a decision made two decades ago (Geranios, 2017).

From the literature reviewed, the initial impression is that although there have been occurrences in the past which could be cause for concern surrounding the use of nuclear technology, most of these seem to be based on events dating back to the early days of nuclear technology. Considering the literature on current safety systems and the specifications to be adhered to, including a layered scheme of protection where one system acts as a backup to another, it is evident that nuclear power plants have made significant improvements in terms of safety in recent years, with continuously ongoing improvements underway. The same is true for waste disposal methods discussed: from the literature reviewed, it seems the nuclear industry has a clear plan to properly dispose of all nuclear waste produced. It is therefore worth further investigation into these safety systems implemented at nuclear power plants, as well as the methods used to dispose of the waste, as this will ultimately determine if the concerns surrounding nuclear energy are still justifiable today, considering the latest safety systems and waste disposal methods presently in use.

# CHAPTER 3: THEORY BACKGROUND

## 3.1 Chapter introduction

To better understand the concerns surrounding the nuclear industry, it is important to consider where these concerns originated from. Past events are undeniably significant, as it has already been established that the concerns surrounding nuclear technology date back to its early days. The development of nuclear power is therefore considered carefully in this chapter, from its early days to where we are today, including the development of the different generations of reactors, as well at the methods which have been used to store the radioactive waste. Radioactive waste, or essentially radioactive material in general, refers to anything which is either inherently radioactive or has been contaminated by radioactivity. Radioactivity is not permanent, as all radioactive waste decays with time back into its non-radioactive elements.

## 3.2 Nuclear disasters of the past

To understand how the latest technological solutions will assist in convincing the public of the safety of new nuclear power plants, the past disasters surrounding these types of plants need to be fully understood. This can be achieved by thorough investigating and assessing the nuclear power plant accidents which have occurred since the first electricity-producing nuclear reactor opened in December of 1951. This, though, was not the very first nuclear reactor to exist, as earlier nuclear reactors were used mainly to produce plutonium, a key part in the production process of nuclear weapons during World War II (world-nuclear.org 2018). This early use of nuclear technology for the development of nuclear weapons has had a significant influence on the negative perceptions surrounding nuclear technology, even before this technology was implemented to generate electricity.

The focus of this study will be to prove the safety of nuclear reactors for electricity generating purposes, which is why previous disasters and their causes are of significance. All accidents and disasters surrounding nuclear power plants since their implementation for commercial electricity generation purposes are recorded and rated. Accidents are rated on a scale from 1 to 7, with 1 being the least significant, and 7 a major accident. Further detail surrounding the rating system, including a description of each level, can also be found at reference (DATABLOG 2016; IAEA 2018). Figure 1 below illustrates the rated list of all known nuclear power plant accidents, from 1952 until the present.

| Year | Incident | INES level | Country | IAEA description |
|---|---|---|---|---|
| **2011** | **Fukushima** | **5** | **Japan** | **Reactor shutdown after the 2011 Sendai earthquake and tsunami; failure of emergency cooling caused an explosion** |
| **2011** | **Onagawa** | | **Japan** | **Reactor shutdown after the 2011 Sendai earthquake and tsunami caused a fire** |
| 2006 | Fleurus | 4 | Belgium | Severe health effects for a worker at a commercial irradiation facility as a result of high doses of radiation |
| 2006 | Forsmark | 2 | Sweden | Degraded safety functions for common cause failure in the emergency power supply system at nuclear power plant |
| 2006 | Erwin | | US | Thirty-five litres of a highly enriched uranium solution leaked during transfer |
| 2005 | Sellafield | 3 | UK | Release of large quantity of radioactive material, contained within the installation |
| 2005 | Atucha | 2 | Argentina | Overexposure of a worker at a power reactor exceeding the annual limit |
| 2005 | Braidwood | | US | Nuclear material leak |
| 2003 | Paks | 3 | Hungary | Partially spent fuel rods undergoing cleaning in a tank of heavy water ruptured and spilled fuel pellets |
| 1999 | Tokaimura | 4 | Japan | Fatal overexposures of workers following a criticality event at a nuclear facility |
| 1999 | Yanangio | 3 | Peru | Incident with radiography source resulting in severe radiation burns |
| 1989 | Greifswald | | Germany | Excessive heating which damaged ten fuel rods |
| 1986 | Chernobyl | 7 | Ukraine (USSR) | Widespread health and environmental effects. External release of a significant fraction of reactor core inventory |
| 1986 | Hamm-Uentrop | | Germany | Spherical fuel pebble became lodged in the pipe used to deliver fuel elements to the reactor |
| 1981 | Tsuraga | 2 | Japan | More than 100 workers were exposed to doses of up to 155 millirem per day radiation |
| 1980 | Saint Laurent des Eaux | 4 | France | Melting of one channel of fuel in the reactor with no release outside the site |
| 1979 | Three Mile Island | 5 | US | Severe damage to the reactor core |
| 1977 | Jaslovské Bohunice | 4 | Czechoslovakia | Damaged fuel integrity, extensive corrosion damage of fuel cladding and release of radioactivity |
| 1969 | Lucens | | Switzerland | Total loss of coolant led to a power excursion and explosion of experimental reactor |
| 1967 | Chapelcross | | UK | Graphite debris partially blocked a fuel channel causing a fuel element to melt and catch fire |
| 1966 | Monroe | | US | Sodium cooling system malfunction |
| 1964 | Charlestown | | US | Error by a worker at a United Nuclear Corporation fuel facility led to an accidental criticality |
| 1959 | Santa Susana Field Laboratory | | US | Partial core meltdown |
| 1958 | Chalk River | | Canada | Due to inadequate cooling a damaged uranium fuel rod caught fire and was torn in two |
| 1958 | Vinča | | Yugoslavia | During a subcritical counting experiment a power buildup went undetected - six scientists received high doses |
| 1957 | Kyshtym | 6 | Russia | Significant release of radioactive material to the environment from explosion of a high activity waste tank. |
| 1957 | Windscale Pile | 5 | UK | Release of radioactive material to the environment following a fire in a reactor core |
| 1952 | Chalk River | 5 | Canada | A reactor shutoff rod failure, combined with several operator errors, led to a major power excursion of more than double the reactor's rated output at AECL's NRX reactor |

**Figure 1: INES table of all known nuclear accidents since the 1950s (DATABLOG, 2016)**

Considering the table in Figure 1, it is worth examining the causes of some of the worst nuclear power plant disasters, as these contributed significantly to the fears and opposition suffered by the nuclear power industry today. The largest nuclear disasters of the past are therefore considered, analyzing the causes and events leading up to each major disaster in great detail to better understand how each of these could have been prevented.

### 3.2.1 Chernobyl

The Chernobyl disaster occurred during the early morning hours on April 26, 1986, while a safety test to determine how the system would act in the event of a power failure was being conducted at the plant's newest number 4 reactor. The types of reactors used at Chernobyl were known as RBMK-1000 reactors. The backup generators that were to supply the electricity for the water pumps in the event of a power failure would take between 60 and 75 seconds to reach the output required for the pumps. The safety tests conducted on the day were aimed at proving that the rotational energy of the main turbine would be sufficient to supply electricity to the pumps until the backup power was sufficient to take over, thus bridging the gap. It is worth noting that this was the fourth attempt at doing this test, as the outcome was unsatisfactory the previous three times. After several mistakes having been made, partially due to poor communication between the core and pump operators, the system slipped into a dangerously unstable state (The Learning Network, 2012; Chernobyl Gallery, 2016; McCall, 2016).

Leading up to the disaster, while completing the preparations to perform the test, water cooling the reactor core while generating steam to drive the turbines was set to enter the reactor core too fast, lowering the core temperature to a state where not enough steam was being produced to drive the turbines. The core operator then attempted to fix this problem by removing some of the core control rods, accelerating the nuclear reaction and heating the core. The minimum number of control rods to stay inserted was set at 26 for the type of reactor used; however, the inexperienced operator at the time continued to remove all but six control rods, exposing the core to a high risk of overheating. With only six control rods inserted, the pump operator realized that access water was flowing into the reactor. Without communicating his actions to the core operator, the pump operator then lowered the pump flow rate. This in turn resulted in the core heating up to dangerous levels, producing access steam, resulting in dangerously high-pressure levels within the system. The investigation afterwards revealed that the EPS-5 button, which inserts all the control rods to stop the reaction in an emergency to cool down the core, was in fact pressed. The control rods take between 18 and 20 seconds to fully insert down the seven meter height of the core; however, during this time the reactor already entered core meltdown, resulting in the majority of rods becoming stuck about one third of the way down (The Learning Network, 2012; Chernobyl Gallery, 2016; McCall, 2016).

It was later determined that the reason why the multiple safety systems within the nuclear plant did not prevent the disaster was because most were switched off so that they weren't to interfere with the test. The test was also considered irrelevant in terms of any effect on the safety and stability of the reactor, which is why the reactor's chief designer and the scientific manager were not present to coordinate the test. In fact, only the director of the plant approved the test before it was conducted, a situation not consistent with approved procedures. This resulted in a lack of planning surrounding the test conditions, leaving the operators to start the test without the reactor in a stable state. As a result, 31 fire fighters passed away from exposure to deadly amounts of radiation, while many others were left with radiation poisoning. It is also estimated that thousands of people were ultimately affected by other illnesses such as cancer, with the number of patients skyrocketing in subsequent years (Chernobyl Gallery, 2016; The Learning Network, 2012).

As with most disasters, blame for the accident cannot be shifted to a singular person or flaw in the design, but is rather a result of a chain of unfortunate events and mistakes. Below follows a list of some of the main mistakes and areas which require improvement, ultimately contributing to the disaster occurring (Chernobyl Gallery, 2016; McCall, 2016):

- lack of proper communication between the pump and core operators;
- lack of proper planning before the tests were conducted;
- not following established procedures, such as involving the scientific manager and chief designer;
- lack of experience in the personnel and lack of training in performing such a test;
- violation of plant operating rules and regulations, involving the disconnection of vital safety systems;
- an initial flawed power plant design, leaving 60 to 75 seconds where the cooling pumps did not function in the event of a power failure;
- a flawed graphite-tip control rod design, initially significantly increasing the reaction rate in the lower half of the core when all rods are inserted in an emergency;
- lack of automated and passive safety systems to take over when the core reached a dangerous state; and
- weak core containment structure, resulting in the release of large amounts of radioactive material.

### 3.2.2 Fukushima

The Fukushima accident occurred on the 11th of March 2011, making it the most recent nuclear disaster on the list. Leading up to the disaster, Japan was hit by a magnitude 9.0 earthquake lasting about three minutes and causing significant damage in the area. When the earthquake hit, the safety systems incorporated into nuclear power plants managed to safely shut down 10 nuclear reactors located at four nuclear power plants in the area which were operational at the time. Upon initial inspection, it was revealed that none of Fukushima's 10 nuclear reactors sustained any damage from the earthquake. The earthquake did, however, cause a widespread power outage, leaving many nuclear power plants without an electrical supply. This was not a problem, though, as the backup generators present at all nuclear power plants managed to supply the water pumps with vital electricity to circulate water, cooling the reactors. It is worth noting that even though the reactors were shut down at this stage, continuous cooling was still vital as heat is still continually produced by the reactors. Achieving the stable shutdown stage of a reactor, known as a 'cold shutdown', takes about four days (World Nuclear Association, 2017a; On the Globe, 2012; Thomas, 2012).

Because of the earthquake, a tsunami was triggered and headed towards the coast of Japan where most of the nuclear power plants are situated. The first 15-meter high waves hit about 41 minutes after the initial earthquake, bringing devastation to one of Fukushima's power plants known as Daiichi, where three nuclear reactors were online at the time of the initial earthquake. The tsunami flooded Daiichi nuclear power plant, damaging and disabling 12 of its 13 backup generators located below ground in the basement. The tsunami also destroyed the heat exchangers used for dumping or relaying reactor waste heat and decay to the sea. The water also damaged and disabled the seawater cooling pumps, the main and auxiliary condenser and cooling circuits. At this stage, the Daiichi power plant was without any electricity or the working equipment needed to run the Residual Heat Removal (RHR) system. The situation was further complicated by the fact that most of the roads in the surrounding area were destroyed, which made gaining access to the plant extremely difficult (World Nuclear Association, 2017a).

Following these devastating circumstances, a nuclear emergency was declared. People were evacuated within a two-kilometre radius of the plant, an evacuation area later extended to a three-kilometre radius, and for a third time to a ten-kilometre radius by the prime minister, as the possibility of a nuclear disaster began to loom (World Nuclear Association, 2017a).

In the days following the disaster, several attempts were made to get water flowing to the reactor core to cool the 1.5% decay heat still being produced by the reactors after shutdown. The other looming trend came from releasing the build-up of pressure in the reactor vessel which threatened to escape, releasing radioactive steam into the environment. The steam contained, among other things, hydrogen produced by the zirconium coating around the fuel rods when meeting water at abnormally high temperatures. Fire trucks eventually managed to reach the power plant, where they were used to pump water into the reactors for cooling. Unfortunately, in struggling to reach the power plant, the water level in the reactors already dropped below the level of the fuel rods, raising the temperature to about 2800 0C, causing them to start melting, while producing highly flammable hydrogen gasses (World Nuclear Association, 2017a).

Ultimately reactors 1, 3 and 4 exploded due to the hydrogen gasses escaping and encountering oxygen. Reactor 2 managed to avoid exploding, as gasses found a way to escape, reliving the pressure. This, however, allowed large quantities of radioactive gas to be released into the environment, contributing significantly to the devastating aftermath. Reactor 4, even though turned off for maintenance at the time of the earthquake, exploded due to hydrogen gas gathering in the reactor building through a shared blow off stack between reactors 3 and 4 (World Nuclear Association, 2017a).

Even though the safety systems reacted as designed, shutting the reactors down safely, it was ultimately the inability to continue operating the RHR system which led to the disaster. As with Chernobyl, the Fukushima disaster can largely be attributed to a chain of unpredictable and unforeseen circumstances never thought possible. Nevertheless, following the disaster, there are some lessons to be learned and improvements that could prevent a similar disaster from occurring. These areas of improvement are listed below (World Nuclear Association, 2017a; Thomas, 2012):

- Poor power plant design, locating all the electrical systems in the basement, especially in an area where tsunamis are to be expected.
- Reactors sharing blow off stacks, allowing gasses to flow from one to the other in the event of a meltdown.

### 3.2.3 Three Mile Island

The Three Mile Island partial meltdown of a reactor occurred on March 28, 1979, making it one of the first serious nuclear accidents. Leading up to the disaster, the plant experienced some difficulties with their main feed water pumps, causing the safety systems to react, shutting down the turbine and reactor. To relieve the build-up of steam, the pilot-operated relieve valves were opened. Up until this stage, even though they were experiencing a malfunction with the feed water pumps, everything was still under control. The relief valves, however, never closed after relieving the pressure, even though the control room instrumentation indicated the valve was closed (U.S.NRC, 2014; World Nuclear, 2012).

With the operators unaware of the open valve, coolant from the primary system was now flowing through the open valve, reducing pressure in the primary system to the extent that the coolant pumps were shut down to prevent them from damaging themselves due to excessive vibrations. One of the fatal flaws in the power plant design was that there were no instruments directly indicating the amount of water in the core. Instead, operators relied on the pressurized water level, leaving them to assume that if there is enough water in the pressurizer, the core would be covered. This assumption was a fatal mistake, as this was not the case. To prevent the pressurizer from filling up completely, the operators then also decreased the amount of emergency cooling entering the system, unknowingly starving the reactor of vital cooling (U.S.NRC, 2014; World Nuclear, 2012).

With an inefficient amount of coolant entering the core, and some still escaping through the open valve, the core began to overheat. A message from the designers of the core fortunately managed to reach the operators, ordering them to increase and maintain the amount of coolant entering the core under all circumstances. At this stage, the core was already melted about half way; however, the action of increasing the coolant managed to prevent a catastrophic release of radioactive material into the environment, as the core managed to cool sufficiently, preventing an explosion. Tests did confirm that although there was some evidence of radiation escaping from the power plant, the amount was nothing to worry about, as the reactor vessel managed to contain the radiation from the melted core (U.S.NRC, 2014; World Nuclear, 2012).

In the end, the only evacuations occurring were those of pregnant woman and pre-school-aged children in the immediate vicinity of the plant. This partial evacuation is, however, significant, as the spokesperson for the plant at the time made the events seem insignificant, as is there was nothing to fear. This was not the case, though, as the reactor came very close to complete meltdown, rendering an explosion very possible, which would have released large quantities of radioactivity into the surrounding areas. When the partial evacuation was announced, the public suspected that the whole truth was likely not conveyed to them, and that the events at the plant might in fact be much more serious than they were told. Events such as this, where the severity and closeness of a disaster are miscommunicated to the public, are a major contributor to the fear that continues to shroud nuclear technology today (U.S.NRC, 2014; World Nuclear, 2012).

On a positive note, the accident at Three Mile Island did help to improve the safety of nuclear power plants and reactor designs that followed. Below are some of the contributing factors to the accident that were addressed in power plants that came later (U.S.NRC, 2014; Fushiki, 2013):

- Operator error in reducing coolant to the core, largely due to a lack of accurate information about the core and coolant status.
- The slow way in which information was conveyed to the operators, which involved printing information and then analyzing it.
- A major error made by the owners of the plant, underplaying the severity of the situation at the plant, leaving the public to believe that everything was under control and safe.

- Lack of a direct telephone line to emergency services, so critical information and individuals like designers of the core could not reach the control room operators quickly and efficiently.

It was later suggested that the plant's automated safety systems would have prevented the core from melting if operators did not intervene. While this will never be known, it is fair to assume that the plant operators did their best with the information available to them at the time, in trying to stabilize the reactor.

### 3.2.4 The Kyshtym disaster

The Kyshtym disaster is one of the older and lesser known incidents involving nuclear technology, in the time when nuclear reactors were used to produce weapons-grade plutonium to create nuclear weapons. The reason for this disaster was significant because it was one of the first accidents evoking fear of nuclear among the public. It is regarded as the third biggest nuclear disaster, following Fukushima and Chernobyl.

Contrary to what the name suggests, the 1957 Kyshtym disaster occurred in Chelyabinsk-65, now known as the town of Ozyorsk in the Ural Mountains of the Soviet Union. The secretive site consisted of six plutonium producing reactors, hastily constructed just after World War II in an attempt by the Russians to catch up with the Americans in terms of nuclear weapon technology. Comparing the practices used back then to modern safety precautions and systems, the site and entire design was a disaster from the day it was constructed. Safety for the forced labourers at the plant was minimal, while the radioactive waste produced by the plant was irreverently dumped into the Techa River as a method of waste disposal. Solid waste was simply dumped on site, while steam from the reactors was vented into the air. This utter disregard for proper disposal of radioactive waste is why this site later become known as 'the most contaminated place on earth' (Cellania, 2015; Jones, 2008).

The Kyshtym disaster, unlike the Chernobyl, Fukushima and Three Mile Island accidents, cannot be considered a singular accident. It should rather be considered a combination of dozens of incidents which occurred at the site, exposing several workers to radiation over time. Due to the lack of safety systems and concerns, radiation released from the reactors also often went unnoticed until the workers began to develop signs of radiation sickness. In 1957, a worker received radiation burns to the extent where amputation of his legs was necessary, while several others developed radiation sickness caused by radiation leaks that went unnoticed. This was, however, only a minor incident as compared to the 17 245 employees who suffered radiation overdoses between 1949 and 1952 (Cellania, 2015; Rabl, 2012).

Of the dozens of incidents which occurred at the plant, the largest one, spreading the widest devastation, occurred on September 29, 1957. One of the reactor's cooling systems failed, and as with previous accidents, it went unnoticed. This caused one of the nuclear waste tanks to explode sending radioactive material into the air, contaminating approximately 20 000 square kilometres around the plant, home to around 270 000 people. In the nearby village of Korabolka, 300 of the village's 5 000 residents passed away from radiation poisoning within a few days. Plans to evacuate the contaminated area were as poor as the safety systems at the plant, with only 11 000 of the 270 000 people ever being evacuated over the course of the subsequent two years. In the case of Korabolka, only ethnic Russians were ever evacuated and relocated, leaving roughly half of the village's residents within the contaminated area (Cellania, 2015; Rabl, 2012; Jones, 2008).

As this occurred in what can now be considered the earlier days of nuclear, many of the residents who remained in the village realized that they were left there as an experiment for determining the effect of nuclear war on humans. In the 50 years to follow, a cancer rate five times higher than normal was noted, as well as a multitude of other illnesses and genetic abnormalities. A combination of this accident, the dozens of other accidents at the plant, and the reckless dumping of radioactive waste contributed to the estimated 90% of the village's children suffering from genetic abnormalities. Only 7% of the villagers' children born since the accident were healthy and normal (Cellania, 2015; Jones, 2008).

The causes of these multiple releases of high doses of radioactive material were due to several factors such as a lack of safety systems, as well as a blatant disregard for any safety at the plant. The methods of disposing of the nuclear waste were also a major contributing factor to this area being considered the most contaminated area on earth. The significance of this accident in terms of this study is primarily in the way the workers and public were treated. Workers were knowingly exposed to environments where radiation exposure was evident, while being aware of the effects this would have on them. The people were lied to, left to linger in the highly contaminated surroundings while being used as experiments. This and the high number of genetic abnormalities in children to follow many years after the accident created, as expected, a deep-rooted fear and ingrained hatred towards nuclear technologies for many generations to follow. Accidents such as these which occurred from a clear disregard to safety and lack of care and consideration of how their actions would detrimentally impact those around, have resulted in an exceptionally negative perception about nuclear, to the extent that people are still strongly opinionated against this technology even today (Cellania, 2015; Jones, 2008).

### 3.3 Nuclear reactors and safety

Nuclear reactors are categorized by *generation*. The generation of a reactor depends on its cost effectiveness, safety, security, grid appropriateness, commercialization roadmap and its fuel cycle, categorizing it as a generation I, II, III, III+, or IV reactor. Figure 2 below illustrates the timeline of when each of these generations of reactors came into use (Farkas 2010).

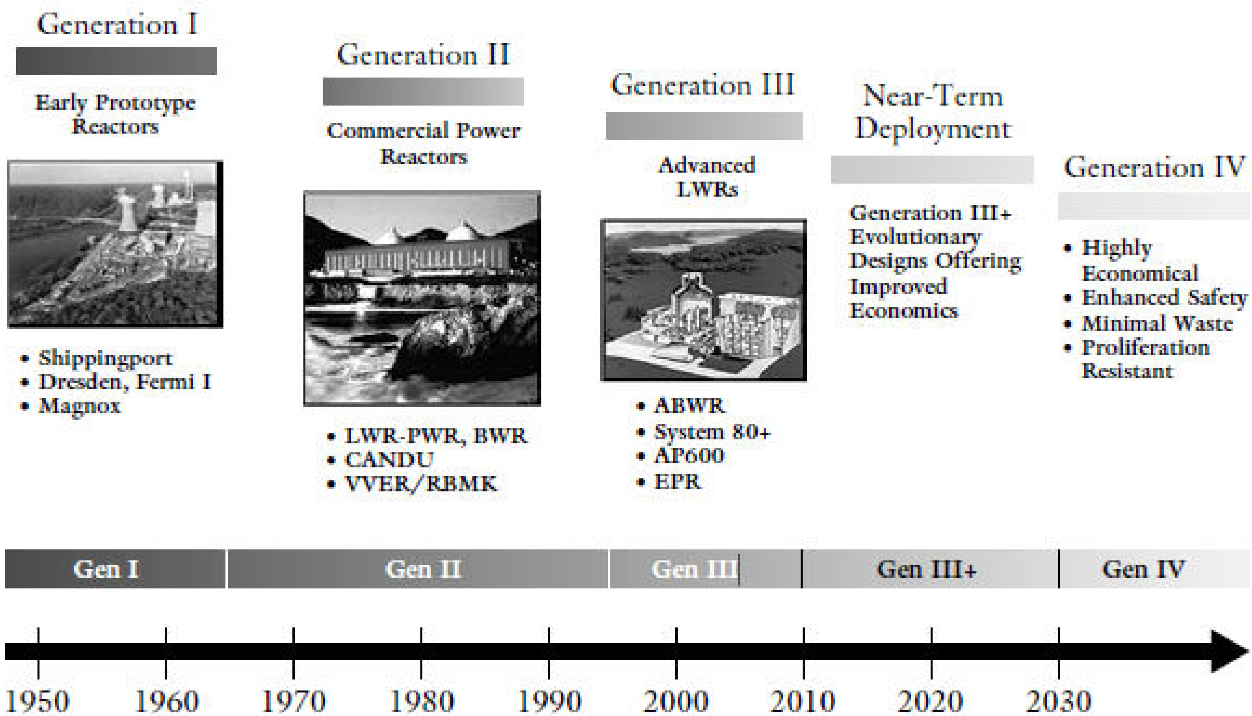



**Figure 2: Timeline illustrating when each generation of reactor came into use (Goldberg & Rosner 2011b)**

The timeline in Figure 2 makes it evident that generation I reactors are essentially a thing of the past, with the last two operating generation I reactors at Wylfa Nuclear Power Station being decommissioned in 2012 and 2015, respectively (Goldberg & Rosner, 2011b; World Nuclear News, 2015).

When considering the timeframe of each generation reactor, the bulk of the 400+ nuclear reactors in operation today are generation II reactors, designed to be economical and reliable. These reactors have by now proven themselves to be both economically viable and reliable, producing electricity at record low prices of around 1.66 cents/kWh. These were also the first reactors built with the primary objective of generating electricity, as compared to generation I reactors whose designs were adapted for defence applications. Other than efficiency, the major difference between generation I and II reactors is in terms of safety. Generation II reactors introduced a third barrier of protection in the form of a reactor containment, which significantly reduced the chances of radioactive material escaping into the environment. The human factor and influence required to operate these reactors were also decreased, lowering the possibility of human error during operation and thereby increasing safety (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010; Radioactivity.eu, 2009). Although there are several different types of generation II reactors, they are commonly referred to as *Light Water Reactors* (LWR). In terms of safety, generation II reactors traditionally rely on active safety features involving electrical and mechanical operations initiated automatically or manually by operators if the need arises. Passive safety systems are also incorporated, and include systems such as pressure relief valves which operate independent to operator control and do not require any power. The advantage of passive safety systems over active safety systems is their ability to operate under extreme conditions, as in the case of the Fukushima disaster discussed earlier, where the plant experienced the unpredicted scenario of a complete blackout. These passive systems are also unaffected by operator error, which is a real threat evident from the Three Mile Island and Chernobyl disasters. Even though the primary causes of these previous accidents were not human errors, the situation is often worsened by operators attempting to stabilize the plant using inefficient or inaccurate information. Generation II reactors have proven their capabilities and reliability through time, a feat which still needs to be accomplished by some of the newer generation reactors. They do, however, have other disadvantages as compared to newer generations of reactors, such as producing significantly more waste, rendering them less efficient (Goldberg & Rosner, 2011b; Goldberg & Rosner, 2011a).

Since most nuclear disasters, including those already discussed, have occurred at nuclear power plants making use of generation II reactors, designers have been able to analyze these events to determine the specific areas where improvements are necessary. This led to the development of generation III reactors which focused on improved safety systems, cooling capabilities in the event of loss of emergency backup power, fuel performance, and a safety analysis of the fuel cooling pool designs. The design also focused on better maintaining the core's integrity during abnormal external events, such as an earthquake or the possibility of an aircraft crashing into the reactor. The improved safety systems also focused on incorporating additional passive safety systems into the design, lowering the impact of possible human error. The improvements made to generation III reactors resulted in an estimated ten to a one hundred time reduction in possible core damage (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). It can, therefore, be claimed that generation III reactors are essentially improved, more efficient and safer than generation II reactors with a lengthened lifespan of about 60 years. When it came to improving safety, focus intensified on making use of passive safety systems rather than active safety systems. Through this decision, the possibility of interfering or unwillingly jeopardizing the working of the safety systems by an operator is significantly reduced. The increased use of passive safety features also addresses the scenario of a complete station blackout, such as the Fukushima accident, as passive safety systems will continue to operate without the need for power. However, there are not many generation III nuclear power plants in operation today, with only four producing power by 2011 (Goldberg & Rosner, 2011b; Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

Alternatively, there are also generation III+ reactors, which aimed at further improving the safety features. Once again, this was achieved through the increased use of passive safety systems. If an abnormal event were to occur, these systems will operate without the intervention of operators, relying on gravity and natural convection to contain the problem at hand. The use of passive safety systems is also thought to simplify safety equipment, increasing their reliability while helping to shorten the construction time of new nuclear power plants. These reactors are also expected to have a higher fuel burn up than previous generations, thereby increasing efficiency while lowering the amount of radioactive waste produced. This will also contribute to strengthening the safety of the power plants, as less refuelling will be required (Goldberg & Rosner, 2011b).

Generation IV reactors is a class reserved for those which still require a considerable amount of research and testing before being implemented for commercial use. Although generation IV reactor designs may become available within the decade, realistically these reactors are at least two to four decades away from being implemented. Features of generation IV reactors include the economical production of hydrogen, further improvements in safety, and possibly even desalination capabilities, among many others new aspects. Attempts will be made to try and close the fuel cycle, limiting waste production and specifically the production of plutonium (Goldberg & Rosner, 2011b).

The two questions continually asked by the public, which new generations of reactors are attempting to address, are these: “Is it safe enough?” and “What is done with the waste produced?” The first question is addressed by switching from active safety systems to passive safety systems. In doing this, the risk of operator interference with the safety systems at work is reduced, thus increasing reliability. Long term dry cask storage is proposed as a solution to the second question; however, a method of nuclear waste disposal for the very long term is still required (Goldberg & Rosner, 2011b; Yano *et al.,* 2018).

### 3.4 The role of passive safety systems and their downsides

Passive safety systems have many important advantages over the active safety systems commonly used in generation II reactors in service today. The most well-known of these must be the ability of passive safety systems to operate during a complete station blackout, a scenario which did not receive much consideration until the 2011 Fukushima accident. This sparked a renewed interest in the importance of making use of a combination of active and passive safety systems, rather than just one or the other, as both have their advantages and shortcomings. The shortcomings of active safety systems became apparent during a critical time at Fukushima nuclear power plant, resulting in a scenario threatening the release of large quantities of radioactivity, endangering countless people's lives (Bucknor *et al.,* 2017).

It is, therefore, vital to consider the shortcomings and imperfections of passive systems to find the most effective combination of the two in an attempt to prevent another Fukushima-type accident from occurring. Passive safety systems rely on boundary conditions to initiate a movement or induce a force, thus activating the system. If a deviation in the boundary conditions were to occur, the system could possibly fail to operate, or alternatively initiate at the wrong time. This failure in operation is not a failure of the safety system but occurs because the set boundary conditions are either never reached or reached too early. The boundary dependency of passive safety systems also does not allow for time dependent boundary conditions. In comparison, an active safety system's ability to activate is dependent mainly on the physical failure of another component or system, rendering them faster to respond to an abnormal event. Another consideration is that passive safety systems frequently operate in intermediate or degraded modes, further complicating the ability to characterize or determine a passive safety system's reliability and operational accuracy (Bucknor *et al.,* 2017).

### 3.5 Nuclear waste

The second of the two major concerns surrounding nuclear power plants is regarding the waste it produces and the storage and disposal thereof. Before attending to the concerns surrounding the waste produced, it is first important to understand the differences between the various types of radioactive waste. Radioactive waste is classified as either low-level waste (LLW), intermediate-level waste (ILW), or high-level waste (HLW), of which most concerns surround the latter. There is another category known as very low-level waste (VLLW); however, since this type of waste is considered short lived and non-harmful to humans while mostly produced by food processing, medical and chemical production industries, minimal consideration will be given to VLLW in this paper. The nuclear industry has also assisted in evolving and developing the nuclear power generating industry, and industries such as weapons development and medical diagnostics, among its many uses and applications. All industries making use of radioactive material produce some form of radioactive waste, yet some radioactive waste such as those produced by medical industries tend to be more acceptable than those produced by nuclear power plants (World-Nuclear, 2017; Zatloukal *et al.,* 2017; Sorenson, 2015).

Nevertheless, all radioactive waste needs to be immobilized and contained: the containment structures and immobilization techniques used to do so will depend on the type of waste. All radioactive waste containment structures adhere to basic three-layer containment: 1) the first layer of containment consists of the internal container or primary waste packaging. These are usually made of metallic drums or concrete containers used to hold or essentially contain the conditioned and immobilized waste; 2) the second layer consists of the external container or secondary waste packaging. This containment is usually made of reinforced or unreinforced concrete; 3) the final layer consists of grouting used to confine the outer waste packaging. This essentially refers to filling the gap between the outer waste packaging and the surrounding rock, limiting the inflow of groundwater (Zatloukal *et al.,* 2017).

While LLW is responsible for roughly 90% of the total radioactive waste produced by a nuclear power plant, it contains only 1% of the total radioactivity produced through waste. As LLW is responsible for a large amount of the waste in terms of quantity, it is often compacted before storage. There are only a limited number of long-lived radionuclides present in LLW, but this is still enough for isolation barriers to be required during storage, mostly in near surface repositories for up to a few hundred years. This type of waste is suitable for handling and transportation without requiring excessive shielding, as relatively low levels of radiation are present. Except for the most well-known way of producing LLW as part of the nuclear fuel cycle in nuclear power plants, it is worth noting that this type of waste is also produced by hospitals and several other industries (World-Nuclear, 2017; Zatloukal *et al.,* 2017).

ILW accounts for somewhere around 7% of the total waste produced by a nuclear power plant but makes up only 4% of the total radioactivity produced through waste. ILW contains more long-lived radionuclides than LLW, requiring it to be solidified in concrete or bitumen before being sent for storage or disposal. Additional shielding during transport and handling will also be required, before it is stored tens to hundreds of meters below ground in more advanced isolation and containment structures than that needed for LLW (World-Nuclear, 2017; Zatloukal *et al.,* 2017).

HLW makes up only 3% of the total waste produced yet is responsible for 95% of the total radioactivity produced through waste. HLW contains the highest consecrations of long-lived radionuclide, requiring proper immobilization and multiple barrier containment structures while being stored hundreds of meters below ground in stable geological formations. HLW primarily consists of burnt fuel removed from the reactor core, which includes the separated waste after reprocessing of used fuel. HLW therefore continues to produce a significant amount of heat, requiring continual cooling and proper shielding. Considering the high levels of radioactivity associated with HLW, it is often this small percentage of the total waste produced which sparks the fears surrounding nuclear waste (World-Nuclear, 2017; Zatloukal *et al.,* 2017).

### 3.5.1 Quantifying nuclear waste, and comparing it to other types of hazardous waste

The figures above present evidence that the quantity of HLW produced by a nuclear power plant is actually not much. It is estimated by the International Atomic Energy Agency (IAEA) that the combined amount of HLW in the form of heavy metals produced by all nuclear power plants since their initial implementation for producing electricity on a commercial scale is 370 000 MTHM (Metric Tons of Heavy Metal). Of the 370 000 MTHM, it is estimated that about 120 000 MTHM have been reprocessed, leaving only 250 000 MTHM which remains in storage. This amount of HLW will occupy approximately 22 000 m3, which put into perspective, is equal to a three-meter-tall structure the size of a soccer field (World-Nuclear, 2017).

To further put the amount of nuclear waste produced by nuclear power plants into perspective, the expected combined waste produced by all nuclear power plants in the UK since day one of operation until 2125, will be approximately 4.9 million tons. This includes VLLW, LLW, ILW and HLW, of which HLW only makes up 0.03% of the total. This can be compared to the annual 200 million tons of conventional waste produced in the UK, of which 4.3 million tons are considered to be highly hazardous (World-Nuclear, 2017). It is evident that all waste produced by nuclear power plants in the UK, as well as that forecasted to be produced up until the 2125, is almost the same as the amount of conventional highly hazardous waste produced *per year* in the UK. Considering these figures, a picture starts to emerge from which we can realize that the highly feared waste produced by nuclear power plants is only a minute fraction of the highly dangerous and hazardous waste produced in a country annually. Furthermore, nuclear waste is not particularly hazardous or hard to manage, especially as compared to some other forms of conventional hazardous waste, primarily because of the proven safe methods of disposing of nuclear waste which already exist such as geological disposal, internationally considered to be most effective (World-Nuclear, 2017).

Another important consideration often overlooked due to the public's blinding concerns surrounding nuclear waste is the amount of waste and pollution which would have been produced if, instead of nuclear, a more conventional method of generation was used. If for example the approximately 11% of the world's total consumption which is now being supplied by nuclear, were to be replaced with gas-fired power plants, an additional 2 388 million tons of $CO_2$ emissions will be released into the atmosphere. And this figure, we must note, is for gas-fired power plants, the cleanest of the fossil fuel supplies. If these were oil or coal-fired power plants, which are essentially a high possibility, the additional amount of $CO_2$ emissions would skyrocket even higher. This then raises the question, without going into detail about the negative effects of $CO_2$ emissions, is it better to be able to contain the waste (such as in the case of nuclear), or to release the waste into the atmosphere where it causes irreversible damage for future generations (World-Nuclear, 2017; World Nuclear Association, 2017b; Shellenberger, 2018a; Schrope, 2013)?

In addition to the $CO_2$ emissions produced by fossil fuel plants, these plants are also responsible for the release of radioactivity in the form of fly ash (coal ash). For nuclear power plants, the release of radioactivity into the atmosphere is highly regulated, which is why the amount released into the atmosphere is miniscule and does not pose any danger to the public under normal circumstances. Contrary to this, the fossil fuel industry for generating electricity is largely unregulated in terms of the release of radioactivity, yet fly ash released as a by-product of burning coal is to a large extent radioactive. This means coal-fired power plants are in fact releasing around 280 million tons of radioactive material containing among other dangerous materials uranium-238 and thorium-232: this is roughly 100 times more radioactive material released than that from nuclear power plants. This ash is simply disposed of through burning or alternatively used as constitute in building materials. To the contrary, waste from a nuclear power plant containing the same radionuclide at the same concentration as fly ash will need to be disposed of via deep disposal, the same type of radioactive waste that gets used in building materials when it comes from a coal power plant. In addition to this, the hydrocarbon industry which produces radioactive material as a waste product from gas and oil production is also responsible for significant amounts of radioactive waste. This waste generally takes the form of scale build-up in pipes and equipment and is roughly 1 000 times more radioactive than the allowed clearance level for recycled waste acceptable from nuclear power plants. So the question is whether or not the public's concerns surrounding the release of radioactive materials might not be aimed at the wrong industry, as nuclear power plants are *not responsible* for the radioactive material disposed of improperly (World-Nuclear, 2017).

The reality is that of the various methods of generating electricity, nuclear energy is the only large-scale generation method which takes full responsibility for the waste it generates. Although the method of obtaining the funds to do so depends on the country, most do this by incorporating the cost of proper disposal of all waste, as well as the decommissioning of the power plant at the end of its life cycle, into the cost of the electricity generated. By 2015, the funds set aside worldwide by the nuclear power industry for waste disposal and decommissioning totalled nearly $100 billion. It should also be noted that even with the added financial responsibility of waste disposal and decommissioning, nuclear power plants are still able to compete with other generation methods such as fossil fuels in terms of price per kWh (World-Nuclear, 2017; World Nuclear Association, 2017b).

### 3.5.2 Storage, treatment and disposal of nuclear waste

There is, however, still the general perception among the public that the nuclear industry does not have a solution to the waste it generates. The truth is that the nuclear industry has already developed and implemented the necessary technologies to dispose of all the waste produced. The problem with nuclear waste disposal is rather with the acceptance by the public of the methods used, rather than the effectiveness of the methods themselves. Methods such as deep burial of HLW, or surface burial of lower levels of waste might be deemed unacceptable by the public; however, this does not actually mean that the methods are unsafe or technologically infeasible. All wastes from nuclear power plants are dealt with, even though it is undeniable that the waste produced can indeed be harmful if not treated in an appropriate manner, or if an accidental release occurs. Since the funds to deal with waste are already available thanks to the way in which most nuclear power plants operate, the only lingering question concerns the best and safest method for doing so. One of the steps for dealing with waste would be to reduce its volume by as much as possible. In the case of the feared HLW, its volume can be reduced by as much as 85% through reprocessing. By reprocessing HLW, plutonium is removed from the used fuel to be mixed with depleted uranium in a MOX fabrication plant, thereby producing fresh fuel to be used in reactors (World-Nuclear, 2017; World Nuclear Association, 2017b).

The remaining waste after reprocessing, or waste that cannot be reprocessed, is then treated to reduce its volume and improve stability and safety. Treatment techniques can involve compacting the waste to further reduce its volume, filtration to reduce radioactivity, or precipitation to induce changes in the composition of the waste. Wastes are then prepared for transportation to be stored or disposed of. This is done by immobilizing the waste in one of several ways depending on the type of waste, whereafter it is stored in containers (World-Nuclear, 2017).

After proper treatment and packaging of waste for safe handling and transportation, the waste can either be sent for storage or disposal. Whether or not it is better to store or dispose of nuclear waste has been widely debated; to enter this debate it is necessary to first understand the difference between the two. Storing nuclear waste involves maintaining the waste in a state such that it is retrievable at any time, while still isolating it from the environment in a safe manner so it is unable to cause any harm. Storage of waste will thus allow for natural radioactive decay, while remaining retrievable if needed in the future. Disposal of waste refers to the method of dealing with nuclear waste where it would be unable to be used or retrieved in the future (World-Nuclear, 2017).

Currently worldwide, most LLW and short-lived ILW are sent for land-based disposal after immobilization by solidifying the waste in cement. This is currently accepted as the best way to deal with LLW and short-lived ILW. The preferred method of disposing of HLW, on the other hand, is by making use of deep geological disposal after immobilization through calcined/drying the waste and then vitrifying it in a glass matrix. This is the chosen method among many others, as HLW will remain radioactive for many years before having decayed to a safe state. Disposing of HLW which continues to produce heat starts by immediately stacking the spent fuel in metal racks with neutron absorbers incorporated into them. These 4m high racks are then stacked in 7-12m deep cooling ponds on site, completely submerging the HLW for cooling. The HLW will remain in the cooling ponds for a minimum of five years, until is moved to dry storage for air cooling inside a concrete containment. Alternatively, the waste can be transferred to sealed steel casks using inert gas for cooling purposes as using steel containers provides the added advantage of use during transportation of the HLW to the intended disposal site, which cannot be done as easily when using concrete containments. If the HLW is first sent for reprocessing before disposal, the reprocessed waste usually returns in liquid form and therefore must be solidified, done by vitrifying the liquid waste into glass, until it is sealed in 1.3m high stainless-steel containers and send for storage before being disposed of. After vitrification, the waste it is still producing heat which is why it is first sent for storage while being cooled, which would also be the case if left unprocessed. After being disposed of through deep geological disposal, the waste will take approximately 40 to 50 years before it is decayed to a point where the heat and radioactivity produced will have reduced by 99%. As mentioned, deep geological disposal is considered a safe disposal method for HLW, as the waste is not only deep underground out of harm's way, but is also contained and safeguarded by several layers of containment protection. Deep disposal thus situates the waste at depths below the biosphere in stable geological formations unaffected by any movement such as earthquakes, making the chance of waste escaping highly unlikely (World-Nuclear, 2017; World Nuclear Association, 2017b; Sartori, 2013).

In choosing the correct disposal and containment methods, it is important to keep in mind that the factors affecting near surface repositories will differ from those affecting deep geological repositories. For example, near surface repositories and containment structures will need to deal with several short-term fluctuations such as thermal cycles, wet-dry cycles, possible flooding and climate change. But these are factors which are not of concern for deep geological disposal sites and containment structures. Other factors, such as temperature increase with concrete hydration as well as pressure increases due to bentonite swelling, are of concern when making use of deep geological disposal sites. Awareness of these challenges are important, as this allows for secondary protection barriers to be designed and engineered specifically to overcome these challenges, ensuring safe and robust containment structures (Zatloukal *et al.,* 2017).

Concrete, or cement, as a barrier or shielding material against radioactivity is widely used, as it has proven effective in containing radioactivity from radioactive materials over extended periods of time. Use of concrete and cement composites over an extended period have culminated in vast amounts of knowledge regarding its use, reliability, durability and performance for such purposes. Concrete as a form of containment for radioactive materials is used for both primary and secondary shielding purposes, meaning that it is used in the immobilization process of the waste itself as well as for the secondary barrier or containment structure. Cement is ideal for this purpose as its high retention capabilities, as well as its high sorption and uptake capabilities, act in both a chemical and physical manner to immobilize and contain waste. Of the many different types of cement available, Portland cement is probably the most well-known and researched. Research by Ojovan has summarized the retention mechanisms of Portland cement as a combination of its surface and bulk sorption, ion exchange, characteristic phase formation and oxy/hydroxyl precipitation. Concrete is not only a reliable way of immobilizing and containing radioactive waste, but also has the added advantage of being cheap when compared to alternative immobilization and containment methods, thanks to it being readily available. The use of cement to immobilize radioactive waste is best suited for VLLW, LLW and ILW, while it is additionally used as a secondary barrier for LLW and ILW containment (Zatloukal *et al.,* 2017).

Containment and immobilization methods, as well as the type of disposal repository used for different levels of radioactive waste, do differ. The criteria which determines the before mentioned containment and disposal method is the radioactivity of the waste, as well as its radioactive lifespan. This method of classifying waste is also adopted by the IAEA, which classifies waste according to its radionuclide half-life and radioactivity. It can therefore be expressed that the higher the radioactivity and longer the radionuclide half-life of the waste, the higher the requirements of multi-barrier protection systems needed. The classification and processing procedure of the different types of waste can be demonstrated by the diagram in Figure 3 below (Zatloukal *et al.,* 2017).

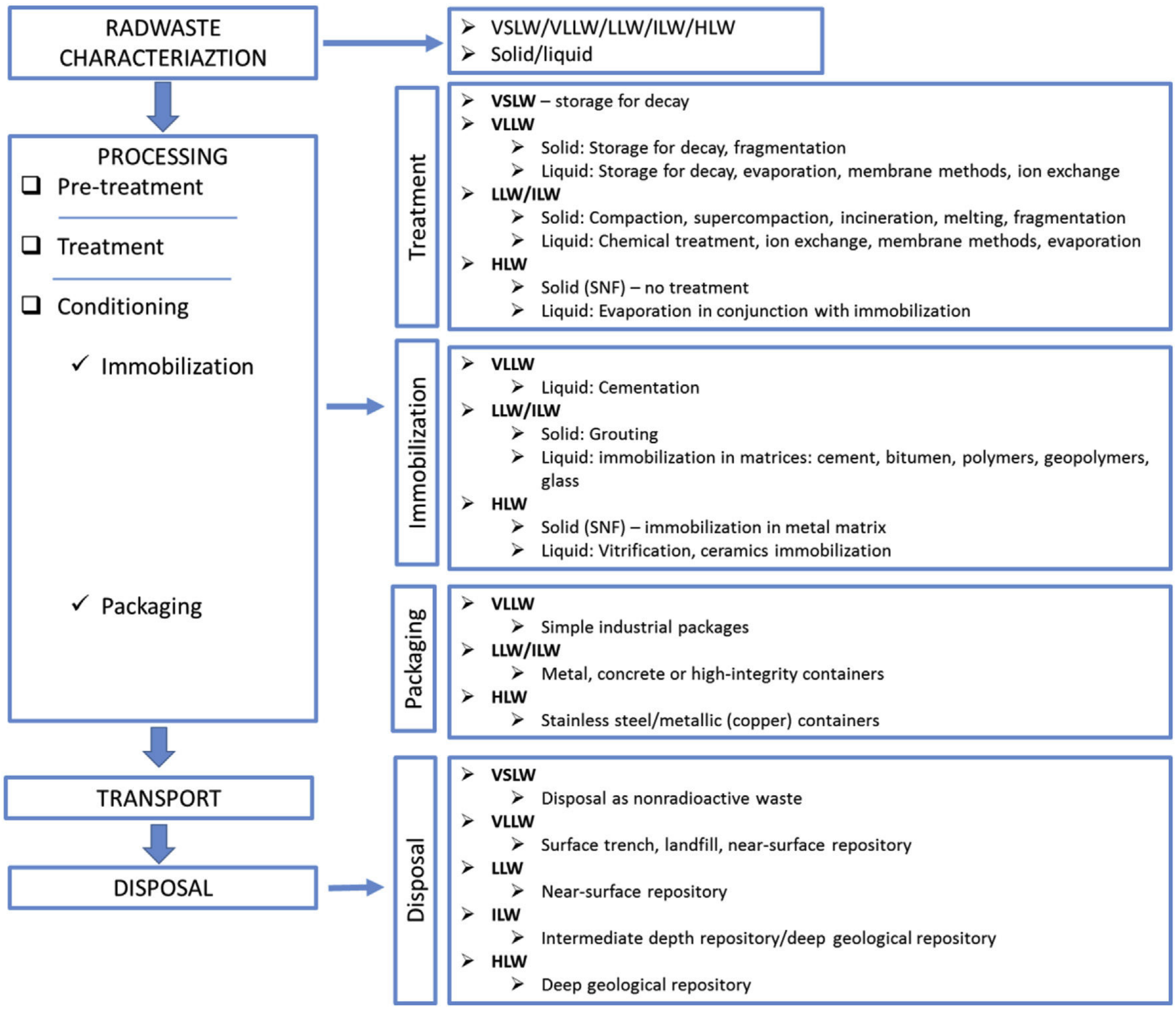



**Figure 3: Summary diagram of treatment, immobilization, packaging and disposal techniques used for each type of waste (Zatloukal *et al.*, 2017)**

As mentioned, the first step in dealing with the waste is to classify it as VSLW, VLLW, LLW, ILW or HLW, depending on its radioactivity and radionuclide half-life. The waste is then also further separated depending on whether it is a solid or liquid. This is noted when considering the first block to the right in Figure 3. Following the diagram above, the waste is then processed and conditioned accordingly, whereafter it is stored before being disposed of. Processing of the waste is mainly to reduce the volume while also modifying it chemically to achieve stability. Conditioning of the waste is necessary to further transform it into a suitable immobilized state for handling and storage purposes. Cement comes into play during the process of conditioning and immobilization as it is used to solidify and imbed the waste into a matrix, preventing the waste from escaping or leaking. After solidifying the waste, it is further packaged according to its classification. The final steps when following the diagram above include transporting the waste to its final disposal site, which will again depend on the type and classification of the waste (Zatloukal *et al.,* 2017).

The cement discussed until this point essentially refers to Portland cement; however, there are also several other types of special cements and geopolymers which can be used in the process of immobilizing radioactive waste. Special cements differ from the more common Portland cement in their composition, which in theory could mean that they are possibly better suited to immobilize certain types of waste than Portland cement. Geopolymers, on the other hand, are made up of a mixture of silicas, aluminates and an alkali activator. This type of mixture is claimed to have been used in the construction of the pyramids, known for their durability, which is an important consideration in the immobilization of radioactive waste. The problem with these types of cements and geopolymers when compared to Portland cement is the lack of knowledge surrounding their long-term performance when applied to immobilize radioactive waste. There is no doubt that other immobilization techniques may have advantages and disadvantages over the use of Portland cement; however, their biggest problem, the lack of knowledge surrounding their long-term immobilization performance, cannot be overlooked. These will still need to withstand the test of time before they can be accepted as viable alternatives to Portland cement (Zatloukal *et al.,* 2017).

### 3.6 Waste transportation

Forming part of the concerns surrounding nuclear waste is the transportation thereof, and the possible consequences if a shipment of waste were to be in an accident during transportation, allowing the waste to escape. Research on the containment structures used during the transportation of radioactive waste revealed that the chance of any waste escaping during even a severe accident or unforeseen event is highly unlikely. The packaging and containment structures used during transportation are designed by the IAEA and differ according to the type of waste being transported. One factor which is often not appreciated by the public is the amount of research, testing, sophistication and safety consideration which goes into designing a transportation enclosure for radioactive waste, rendering it much more than simply containment. The five types of packaging used for transporting radioactive waste are listed below, each with their own set of regulations specifying what type of waste they can contain as well as their quantity limits (World-Nuclear, 2017; Sorenson, 2015):

- Excepted;
- Industrial: Types 1, 2 and 3;
- Type A: Solid and solid/liquid;

- Type B; and
- Type C.

‘Excepted’ containments are designed to carry small samples or amounts of VLLW. ‘Industrial’ containments are used for waste materials such as decommissioning debris, coveralls, soil and bricks. During transportation these radioactive materials will get spread evenly throughout a large amount of nonradioactive material, lowering its concentration. “Type A” containments can contain a variety of different radioactive materials, including anything from irradiated reactor components to radiopharmaceuticals. “Type B” containments are designed for high radioactive source containment, including the transportation of spent fuel in flasks, plutonium materials and other highly radioactive waste. “Type C” containments are designed and used for transporting waste by air, and have the capability to contain highly active easily dispersible materials such as plutonium oxide powders (Sorenson, 2015; World-Nuclear, 2017). An example of a Type A enclosure can be seen in Figure 4 (Sorenson, 2015).


**Figure 4: Type A packaging for transporting radioactive waste (Sorenson, 2015)**

As part of the performance requirements of these containments, there are some basic packaging requirements to which they must adhere, primarily including that the contents should always remain contained, shielding the environment and operators from the radiation inside. While preventing radiation from escaping, they should also be able to manage the heat of the contents, as some radioactive waste tends to continue producing heat. Further requirements include withstanding all transportation conditions, which are divided into three main categories: *routine conditions* refer to circumstances where nothing unusual happens to the package, getting delivered without any incident; *normal conditions* may include rough handling of the package during transportation, as well as dropping the package during handling, or even the conveyance having a minor accident. The package itself, however, will get delivered without any serious damage; *accident conditions* are when the conveyance is involved in a major accident, which may include a high-speed collusion or fire. As the packaging is designed to handle abnormal conditions such as high speed impacts or fire, there should not be any release of radioactive waste during such an event (World-Nuclear, 2017; Sorenson, 2015).

Each of these types of containments is unique in design and capabilities. Taking one as an example, Type B containments consist of a stainless-steel flask surrounded by a 25 cm thick steel cask, weighing approximately 125 tons. Of the radioactive wastes which have been transported using the above mentioned five enclosures, there has never been an accident resulting in significant release of radiation, even while the enclosures have been involved in several serious accidents which have resulted in death and the destruction of transportation vehicles, once again validating the effectiveness and containment capabilities of these enclosures. Considering the amount of waste transported using these sophisticated enclosures, it should be noted – as in the case of the amount of hazardous waste of all hazardous material transported. Of the 5% of nuclear waste transported, only 10% originates from nuclear power plants, once again raising the question of whether or not the public should in fact rather be worrying about the bigger percentage of hazardous waste (World Nuclear Association, 2017b).

Participating in the transportation of radioactive waste entails some requirements that should be adhered to. This includes mandatory training for the consignor, carrier, driver, consignee, loader, packer, filler, unloader and dangerous goods safety advisor (DGSA). Basic training to be completed successfully by all the above-mentioned personnel includes general awareness training, function specific training, safety training, security training and emergency training. Additional training may be required depending on a specific individual's responsibilities, as well as refresher training courses for all personnel.

The plutonium found in nuclear waste is one of the most dangerous materials on earth. Although plutonium is a hazardous material which should be treated with extreme caution, there are many other substances which are just as dangerous, if not more dangerous, than plutonium. If comparing plutonium to other substances on a gram-to-gram basis, toxins such as ricin, cyanide and even caffeine have the potential to be deadlier than plutonium. When plutonium is ingested, it escalates the chance of a person getting cancer within the coming years significantly, while some other toxins mentioned could kill a person almost instantly (World Nuclear Association, 2017b).

The time needed for nuclear waste to return to its natural state of radiation is also a major concern, as some nuclear waste may require between 1 000 and 10 000 years to decay to its natural radioactive state. It should be noted, however, that this type of waste makes up only a small percentage of the total waste as discussed earlier, approximately 3%. This waste is also by no means discarded indiscriminately, but it undergoes strict treatment, storage and disposal procedures conducted over time, ensuring that the waste is in a stable form that will not pose any danger to the public or surroundings (World Nuclear Association, 2017b).

Other concerns include the potential for terrorists to exploit radioactive waste, by means of what is known as a “dirty bomb”. This essentially refers to a possible terrorist attack by damaging a waste containment structure in such a way that the toxic waste is released, potentially leading to wide spread deaths and radiation poisoning. The NRC have responded to such fears in the past, reassuring the public that nuclear waste is stored at secure, hard to breach facilities inside thick steel-reinforced concrete with stainless steel lining the inside of the structures. Most stored HLWs are also already solidified in ceramic or glass, a stable state, significantly reducing the chances of dangerous radioactive material spreading uncontrollably in the unlikely scenario of a terrorist attack breaching the containment structures. As for the concerns surrounding the possible terroristic use of the plutonium produced as a by-product during the nuclear fuel cycle, the latest methods of reprocessing HLW allow for removal of the plutonium for reprocessing into fresh fuel. The plutonium is reused in the reactor core as part of fresh fuel, which should leave no accessible plutonium to be used in the possible manufacturing of weapons (World Nuclear Association, 2017b).

Moreover, there is no difference between naturally occurring radiation and man-made radiation. The same types of radiation given off by nuclear waste are also naturally emitted by rocks, soil, food and building materials. Therefore, the ability of radiation to cause harm does not depend on where it comes from, but rather on the amount or concentration of radiation received. Typically, a person will receive between 2 mSv and 3 mSv of naturally occurring radiation per year. Regulations specify that the additional radiation a member of the public is exposed to due to human activities may not exceed 1 mSv/yr., which is less than the natural occurring radiation people are exposed to annually. Furthermore, the regulated amount for occupational exposure is not allowed to exceed an average of 20 mSv/yr. To put these amounts into perspective, levels of up to 50 mSv/yr. have been proven harmless, with some people receiving lifelong natural exposure to levels higher than 50 mSv/yr. without any negative effects (World Nuclear Association, 2017b; White, 2016).

One study supporting the claim that the effects of radiation exposure is overestimated is the Life Span study which considered the long-term effects of a wide range of radiation exposure caused by the atomic bombings of Hiroshima and Nagasaki. Although tragic accidents, these became vital in determining the long-term effects of high levels of radiation exposure, as the study included a large group of nearly 100 000 individuals, as well as almost 77 000 children born to bombing survivors. The study noted limited but measurable health effects in survivors, but no detectable abnormalities in their offspring. It was expected that the radiation exposure would significantly elevate cancer rates; however, ultimately an increase of only 10% was noted, significantly lower than is often believed. The study further revealed that the life expectancies of those exposed to radiation during the bombings, depending on the amount of radiation received, were reduced by between a month and a year, which is again much less than previously thought. It can again be reiterated that there is a significant difference between the perceived dangers of radiation exposure and the actual facts (White, 2016; Smoll *et al.,* 2016).

### 3.7 Risk communication

Historically, there has always been a tendency among regulators and the nuclear industry alike to reveal as little information regarding nuclear power plants, waste transportation, waste management and disposal as possible. The information that is revealed is usually aimed at reassuring the public, often downplaying the possible risks involved with nuclear technology by making use of generic statements such as that there are “no significant risks involved”. The reason for doing this is that the scientific complexity that accompanies nuclear energy is such that the public is regarded as incapable of making accurate conclusions regarding risk assessment by considering the advantages and risks themselves. For this reason, it is believed better to not provide detailed information about the technology, but rather to sum up the risks associated through statements such as “no significant risks involved”, as mentioned above. Although this has been considered reassuring to the public for the safety of nuclear energy, the opposite is in fact true. With time, more and more detailed information became available regarding the workings of this technology, especially during times when accidents occurred such as those covered earlier, escalating demand from the public for better transparency. The amount of accessible information also increased dramatically as the Internet became more widely available, making it virtually impossible for the industry to hide any information regarding nuclear workings and risks involved. The realization of the public that only limited and selective information had been made available to them while risks were downplayed created an atmosphere of tension and distrust which has been difficult to overcome (Sorenson, 2015; Turchin & Denkenberger, 2018).

### 3.8 Chapter conclusion

Chapter 3 provides a clearer understanding of why the public tends to fear the use of nuclear technology, considering past disasters such as Chernobyl, the lack of specific risk communication and the initial lack of availability of information about the process of nuclear power generation. Contrary to this, the more recent advances made within the industry in terms of reactor safety in developing generations II, III, III+, and future generation IV reactors, is also admirable as it drastically improves the safety of this technology as compared to generation I reactors. In terms of waste produced, it have also became reassuringly evident that the methods used in treating, storing, transporting and disposing of all types of nuclear waste is highly regulated, ensuring that none is disposed of in such a way as to pose any danger to the environment or public. It has also became evident that when considering the harmful waste produced in general, nuclear waste is among those wastes best treated and securely disposed, raising the question of whether or not our concerns are directed at the correct industry.

# CHAPTER 4: RESEARCH RESULTS

## 4.1 Chapter introduction

The chapter investigates the reasons behind why the few disasters, which occurred a long time ago, still have such a strong influence on opinions about nuclear technology today. This is accomplished by considering how the human brain perceives risks, and our desire to try and predict when the next disaster might occur. Additionally, the safety of nuclear power plants is compared to alternative fossil fuel generation methods in terms of the number of accidents and fatalities during a given period. The advances in nuclear power plant safety are further analyzed by considering the number of unplanned automatic trips, which indicates the stability and reliability of a power plant. Power plant and reactor safety is also once again discussed, considering the requirements applicable to new nuclear power plants constructed, and what the future might hold in terms of reactor design and waste disposal methods. This chapter lastly considers risk communication, including the mistakes made in the past, while suggesting how the risks could be communicated to the public in a more effective, positive and appropriate manner.

## 4.2 The lingering negativity towards nuclear technology

As illustrated in the table of Figure 1, the number of serious nuclear accidents which have occurred in the past can be counted as minimal. The safety systems discussed have confirmed that significant precautions are now taken to ensure the safe operation of these plants, while ensuring that risk to the public is marginal even during unforeseen and highly unlikely, unanticipated events. Nuclear power plants are the only form of power generation taking full responsibility for the waste produced, ensuring that all waste is disposed of and stored properly (World-Nuclear, 2017). Yet despite the significant and admirable actions taken by the nuclear industry to advance and ensure safety and reliability, the overall negative perception surrounding this technology has remained almost unchanged.

It has already been revealed that past accidents are among the major contributors to contemporary fears, as support for nuclear tends to plummet after any accident. The reality is that there have been only a handful of nuclear accidents serious enough to result in fatalities. Another contributor to the prolonged fear includes the lack of transparent risk communication and information made available to the public in the past, leaving the public to fear the unknown. Today the risks are, however, more widely known as information about the workings and dangers associated with nuclear can be easily discovered online. Another contributor to the fears is the government, originating from the ways in which past disasters were handled. During the aftermath of disasters, it is felt that the government of some countries in which disasters have occurred panicked, sometimes evacuating hundreds of thousands of people unnecessarily. An example of this is Chernobyl, where studies later revealed that five to ten times more people were evacuated from the area between 1986 and 1990 than necessary, fuelling the overestimations of dangers associated with nuclear by the public (Shellenberger, 2018b). Although information about the risks, advanced safety systems and actual fatalities and damage caused by the very minimal number of past accidents is now readily available, fear surrounding nuclear does not seem to have subsided. Why is this so?

Research into this question often points to the conclusion that the concerns surrounding nuclear power are not based on the facts about nuclear energy, but rather are stemming from the way in which the human brain works. Studies conducted on how the human mind perceives risks showed that we tend to overestimate low probabilities while underestimating high probabilities. Relating this to nuclear, the research proposes that the human mind will generally overestimate the probability of accidents and dangers associated with nuclear power. At the same time the human mind will underestimate the consequences of, for example, the $CO^2$ emissions continually produced by coal fired power plants and released into the atmosphere (Lévêque, 2013; Harris *et al.,* 2018).

### 4.3 Future disaster estimations

It is a fact that if and when a significant nuclear disaster occurs, the consequences could be substantial and catastrophic. However, due to continual advances in safety, it is expected that the frequency of major disasters would decrease with time. This is difficult to prove, as there have only really been three major accidents since the initial implementation of nuclear energy for power generation. The first of these was the Three Mile Island accident in 1979, followed by the Chernobyl accident seven years later in 1986. The most recent, the Fukushima accident, occurred in 2011, roughly twenty-five years after the previous one (DATABLOG, 2016; Lévêque, 2013). Considering these three major accidents in conjunction with the table in Figure 1, also including the smaller accidents, it does appear as if the accidents are decreasing as the technology matures. Nevertheless, the number of accidents is simply not enough to definitively claim that they have decreased and will most probably continue to reduce with more time. Furthermore, considering the causes of the accidents, specifically of the three major ones mentioned, there is no singular event or even a handful of specific events which leads to a nuclear accident. Instead, the cause is most often a combination of several errors or unforeseen occurrences which combined to create a unique chain of unexpected events, causing the reactor core to destabilize and enter a meltdown stage.

As with any potentially dangerous situation or technology, people desire to know the chances of a disaster reoccurring in terms of a physical value. Although there are several studies and papers attempting to calculate the probability of a major nuclear disaster reoccurring or attempting to calculate when the next nuclear disaster will occur, the values tend to differ significantly depending on the calculation methods used. The data gathered to calculate when the next nuclear disaster might occur can either be based on the frequency and type of past disasters, or on conditional probability which includes event trees and probabilistic safety assessments. The third option would be to use a combination of the two to estimate when a disaster might occur again (Lévêque, 2013).

Studies which obtained a prediction by making use of the first option, through disasters and occurrences of the past, are deemed inaccurate due to the limited number of significant radiation releases at nuclear power plants in the past (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). Furthermore, the nuclear power industry has seen a significant increase in safety factors and regulations since the time at which most accidents of the past occurred, which in theory should reduce the number of future accidents substantially. Factors such as these make predictions regarding future disasters difficult, and in many instances inaccurate (Lévêque, 2013).

The next option would be to perform a probability safety assessment (PSA) which considers three main criteria for predicting future events. The first is the possible initiating faults or events, as well as possible combinations of occurrences which can lead to core damage. The second is the possible consequences if core damage occurs, as well as the chances of if leading to radioactivity being released, which will depend on the severity of the damage. Lastly, a PSA considers how likely each of the events considered are to occur (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). This, on one hand, can become extremely difficult, as the number of scenarios can range anywhere from operator error, component failure or natural disasters, to a plane falling and colliding with a nuclear power plant. To further complicate this type of analysis, many of the circumstances or events responsible for past and possibly future disasters are the ones which were thought unnecessary to include in the analysis as they might have seemed too unlikely or even impossible at the time (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010; Lévêque 2013). An example of this is the 2011 disaster at Fukushima where an earthquake triggered a tsunami causing the plant to flood and lose all power for an extended period. It was later found that studies prior to the accident never imagined the possibility of an earthquake triggering a tsunami knocking out all power to the plant for an extended period. At the time, this was probably thought to be to highly unlikely, as power plants have several safety systems in place shutting down and protecting the reactors during an earthquake. Furthermore, there were also sea walls positioned to break large waves in the event of a tsunami, preventing waves from reaching and damaging the power plant. Lastly, if an earthquake or tsunami does manage to completely knock out the electrical supply to the plant, there are also several backup generators and systems that can be relied on to cool and shut down the reactors until normal supplies are re-established. The ultimate reason for what were thought to be a virtually impossible chain of events was an earthquake larger than anyone predicted, causing a tsunami which dwarfed the walls built to protect the plant, flooding the electrical systems and backup generators, rendering them useless, while at the same time cutting off all external power feeds to the plant (Lévêque, 2013; Seong *et al.,* 2018). The Fukushima accident once again proved that all possible scenarios can never be included when trying to predict when the next nuclear disaster might occur. Studies attempting to make such predictions have concluded with an actual predicted value of one accident every 10 000 to 100 000 reactor years. Considering an accident as an event where the reactor core is damaged, there have been 11 partial or complete reactor core meltdowns during the approximately 14 400 reactor years to date. Using simple division, this equates to about one accident every 1 300 reactor years, which is significantly more than the one every 10 000 to 100 000 reactor years predicted (Lévêque, 2013; Seong *et al.,* 2018). It can be argued that studies consider most of the latest advances in nuclear safety expected to reduce the number of accidents in the future; however, the difference seems to be too substantial.

Several explanations have been proffered for the significant 10 to 100-fold difference between the two numbers. While some argue that the difference may simply be attributed to bad luck, it has already been established that the number of accidents to date is simply not enough to provide a meaningful baseline value. This means that the higher than predicted number of accidents to date may in fact simply be bad luck as suggested, and will even out to near the predicted value with time. This standpoint potentially holds some truth and could move closer to the predicted values with time as newer reactors have advanced designs and improved safety features such as passive safety systems. The disasters of the past can certainly not be ignored, which is why the most effective solution would be to find a value by considering both predicted and past occurrences (Lévêque, 2013).

Another reason for the significant difference in values could also be an incomplete consideration of scenarios during the probabilistic studies. It has already been established that it is impossible to consider every single scenario using event trees and predictions, as proven by the Fukushima accident in 2011. Considering an event tree used during a probabilistic assessment, the more scenarios added, even is considered extremely unlikely, will continue to increase the probability of another disaster occurring. The accuracy of this method can be further doubted considering that several of the past accidents were caused by a chain of events never included in any studies, as they were considered almost too farfetched to be a threat. The method itself is well known and successfully applied in many other fields, basing its results on realistic data such as equipment failure rates, the possibility of human error and the probability of natural disasters (Lévêque, 2013). When applied to nuclear, however, the results it yields may be inaccurate due to the method's inability to consider a chain of unanticipated or unconsidered events, which has been the case in nuclear accidents. The results it yields are based on actual probabilities and can therefore still be of use. It is again suggested that these results should be combined with actual accident rates of the past, improving accuracy by considering the chances of an unforeseen chain of events, as with some previous accidents.

A third opinion on why the two values differ as much is that disasters are often a result of unique one-off events, thus making any predictions on future disasters, whether based on probabilities or past data, virtually impossible (Lévêque, 2013). Although one can see the reasoning behind this statement, this must be rejected. The statement could apply when considering only past events, where it has been established that a larger number of accidents would be required before an accurate future prediction can be made. However, this will require the repetition of similar circumstances leading up to a disaster, which is rarely the case. The unique and one-off events leading to a nuclear disaster thus render predictions based on past events extremely difficult, as the causes will very rarely repeat themselves (Lévêque, 2013). This leaves the probability analysis, where it is felt that the statement does not apply at all. Using probability analysis to predict future events is largely based on the knowledge of the individual conducting the study, as this person determines which scenarios are included in the event trees for predicting the outcomes. This gives the person the omniscient choice to include or not include events, however likely or highly unlikely they might be. It seems, though, that special consideration should be given to unlikely events, as disasters of the past have shown accidents are caused by a combination of several events rarely thought possible.

A fourth possible explanation for the significant difference between the different predicted numbers of the various studies is possibly due to faulty models or erroneous parameters being used (Lévêque, 2013). Once again, if we take the 2011 Fukushima accident, while the planning and construction of the Fukushima Daiichi plant was still underway, probability and safety studies conducted at the time considered an earthquake magnitude 7.9 and 3.1-meter tsunami wave as the worst possible cases. On 11 March 2011, at 14:46, an earthquake of magnitude 9 struck the area, triggering a tsunami with waves more than 10 meters high, causing destruction and an unanticipated nuclear accident. The original calculations included that the chances of an earthquake exceeding a magnitude of 8 in that area were less than 2x10-5 per year (Lévêque, 2013). Investigations after the accident revealed, however, that the predicted worst-case earthquake and tsunami, on which many of the safety systems were based, such as the height of the wall placed to protect the plant against tsunamis, were grossly underestimated. It was determined that the original studies did not consider the worst tsunamis of the past, resulting in a protective wall must smaller than it should have been. Similarly, when recalculating the chances of a larger than magnitude 8 earthquake hitting the area, the new results based on more complete data revealed that the chances of such a large earthquake were in fact 100 times higher than originally calculated. Incorrect predictions due to insufficient or flawed data is therefore a very real possibility (Lévêque, 2013). For this reason, when calculating the possibility of future disasters, it is imperative that special care be taken when selecting the data and opinions on which event trees are based, including as many even remotely likely possibilities as possible. The opinions and contributions of as many experts as possible should also be included, as this will refine the accuracy of the predictions, rather than basing event trees solely on the opinion of a mere handful of experts.

Although possible, it is not fair to attempt to calculate when a next nuclear disaster might occur, as none of the methods used in studies are able to generate convincing predictions based on methods that yield accuracy. This is because predicting a nuclear disaster is not the same as trying to predict which card will be drawn next from a deck of cards, for example. Unlike a deck of cards, which has a limited number of outcomes for selecting a card, nuclear disasters can be triggered by a virtually incomprehensible number of scenarios (Lévêque, 2013). Since the aim of this study is to convince the public of nuclear power plant safety, it's debatable if trying to prove this by considering inaccurate methods of predicting future events is really the most effective. Probabilistic studies are better suited for identifying areas requiring improvement, rather than predicting when disasters might occur, thereby helping the industry to better manage and apply their resources and funds.

### 4.4 Finding an efficient way of informing the public

The immense distrust which has been stirred up in the nuclear industry could have been avoided through effective risk communication to the public from the start. One such way which this can now be achieved is by first highlighting the advantages of the newer technology prior to addressing the risks. This method, often applied by the media, has shown to be much more successful in informing the public on any matter than starting with the negatives first and then mentioning the advantages second. This method of informing the public allows for all information to be conveyed, leaving people to draw their own conclusion based on the advantages vs. the risks of nuclear energy. People tend to downplay the risks themselves the greater they perceive the advantages to be; but this is only true if people believe that they are fully aware of *both* the advantages and the risks. When communicating the safety features incorporated into nuclear power plants or nuclear waste storage facilities, it is important not to make use of statements such as that "an accident at a nuclear power plant is virtually impossible". Instead, the statement could read that the safety features are indelibly incorporated into these plants so that when an operational error or unexpected event does occur, the active and passive safety systems will automatically maintain the plant in a stable state, preventing any damage to the plant and or harm to the environment and public (Sorenson, 2015; Ropeik, 2010; Anderson, 2017).

The essential part, however, is not to assess the risks on behalf of the public, but to provide them with all the information in an effective manner to enable them to draw their individual conclusions. This is also the view of Ropeik in his book "How Risky Is It, Really?" After considering contemporary alternative methods as well as the methods used in the past, he determined this to be most effective as it is based on an existing method that has proven successful. If the methods above, also discussed in Ropeik's book, were followed from the initial implementation of nuclear, the perception of this technology would have been very different today (Sorenson, 2015; Ropeik, 2010).

To convince the public of nuclear safety, one could alternatively focus on all the latest safety systems incorporated into new reactors or retrofitted to existing reactors, such as the passive safety systems already mentioned. However, since most individuals only have a basic understanding of the workings of nuclear reactors and the multiple safety systems incorporated, convincing them that adding additional safety systems to the multiple existing safety systems will make reactors significantly safer would likely make very little impact on their overall perception of the technology. It is anyway felt that this is not an effective means of investing in nuclear technology, as this may lead to expensive investments in safety systems which ultimately may have little to no effect on the overall safety of nuclear reactors. While safety is an incredibly important aspect of nuclear reactors that must receive continuous investment and upgrading, the point should also never be reached where we overinvest in safety, adding expensive additional systems with minimal effect as a means of easing our fears surrounding the technology (Lévêque, 2013; Frantal & Maly, 2017; Anderson, 2017).

In agreement with the opinion of François Lévêque (Lévêque, 2013), a more effective way of getting the public to favour nuclear over other forms of generation is to focus on the advantages of nuclear over these other technologies (Lévêque, 2013). This method is expected to be more effective as it focuses on the positive advantages of nuclear rather than the negatives, such as when and how disasters might occur in the future. In doing this, questions should be asked such as what determines that one technology is safer or better than another? A criteria for answering this question is to investigate the number of fatalities caused by each respective method of generating power.

### 4.5 Comparing nuclear in terms of fatalities caused

One such study which set out to determine just that, was conducted by the Organization for Economic Co-operation and Development (OECD) (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). The study considered all known accidents relating to the generation industry responsible for five or more fatalities between 1969 and 2000. The study not only considered immediate fatalities, but also latent fatalities due to the lasting consequences of some types of accidents. Due to the nature of the OECD study, figures and statistics for OECD member countries are kept separate from non-OECD member countries; however, for the purposes of this study, the figures will be combined as the numbers are of greater significance than the locations of the accidents. Between 1969 and 2000, only one nuclear disaster occurred, namely the Chernobyl accident; however Chernobyl can be considered as one of, if not the biggest nuclear disaster which has ever occurred. Chernobyl resulted in 31 direct or immediate fatalities, with numerous latent fatalities to follow over the years to come. These latent fatalities mainly took the form of cancer and other conditions related to radiation exposure, making it difficult to ascertain which deaths were caused by radiation from Chernobyl an which were caused by natural radiation exposure and other factors. Estimations predicted that in the 70 years following the disaster, latent fatalities would reach between 9 000 and 33 000 (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). However, considering how the numbers came about, 33 000 fatalities seems a bit excessive as this considers all possible latent fatalities which could have been caused by any level of radiation, even lower than the natural background radiation for the entire northern hemisphere.

These figures can be compared to those of fossil fuels, where coal and oil were responsible for 20 276 and 20 218 fatalities, respectively, during the same period. It is further estimated that fossil fuel power generation is responsible for approximately 30% of the outdoor fine particle air pollution, which in total causes approximately 960 000 premature deaths annually (Nuclear

Energy Agency Organisation for Economic Co-operation and Development, 2010; Windridge, 2011; Schrope, 2013). Not many people are aware of these figures regarding fine particle pollution caused by fossil fuels, as information and statistics on this matter is extremely limited, often severely downplayed. Latent deaths from nuclear disasters are therefore, in reality, considerably lower than those caused by fine partial pollution from fossil fuels. Like nuclear, hydropower also only had one major accident during the above-mentioned time frame, this on resulting in a staggering 29 924 deaths (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). Data originally provided by the NEA are summarized for convenience in Figure 5 below.

| | OECD | | | Non-OECD | | |
|---|---|---|---|---|---|---|
| **Energy chain** | **Accidents** | **Fatalities** | **Fatalities/ GWey** | **Accidents** | **Fatalities** | **Fatalities/ GWey** |
| Coal | 75 | 2 259 | 0.157 | 1 044 | 18 017 | 0.597 |
| Coal (data for China 1994-1999) | | | | 819 | 11 334 | 6.169 |
| Coal (without China) | | | | 102 | 4831 | 0.597 |
| Oil | 165 | 3 713 | 0.132 | 232 | 16 505 | 0.897 |
| Natural Gas | 90 | 1 043 | 0.085 | 45 | 1 000 | 0.111 |
| LPG | 59 | 1 905 | 1.957 | 46 | 2 016 | 14.896 |
| Hydro | 1 | 14 | 0.003 | 10 | 29 924 | 10.285 |
| Nuclear | 0 | 0 | – | 1 | 31* | 0.048 |
| **Total** | **390** | **8 934** | | **1 480** | **72 324** | |

**Figure 5: Fatality summary caused by different generation methods (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010)**

This data once again illustrates just how much the perceived dangers of nuclear differ from reality, and that contrary to expectation, nuclear power is in reality a low risk generation method in terms of fatalities as compared to fossil fuel alternatives (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010; Shellenberger, 2018b).

### 4.6 Reliability, stability and safety of nuclear power plants

The ever-improving reliability, stability and safety of nuclear reactors can also be proven by considering parameters such as the unplanned automatic trip rate, core damage frequency (CDF) and large release frequency (LRF). The unplanned automatic trip rate of a reactor refers to the number of times per 7 000 hours of operation that a reactor is shut down automatically by its safety systems due to a fault or problem (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). A low number will indicate that the reactor and power plant are operating under stable and safe conditions. The graph in Figure 6 below illustrates how the number of unplanned automatic trips has decreased with time. Moreover, it is expected that the number of unplanned automatic trips will continue to decrease as nuclear reactors become increasingly sophisticated and safer.

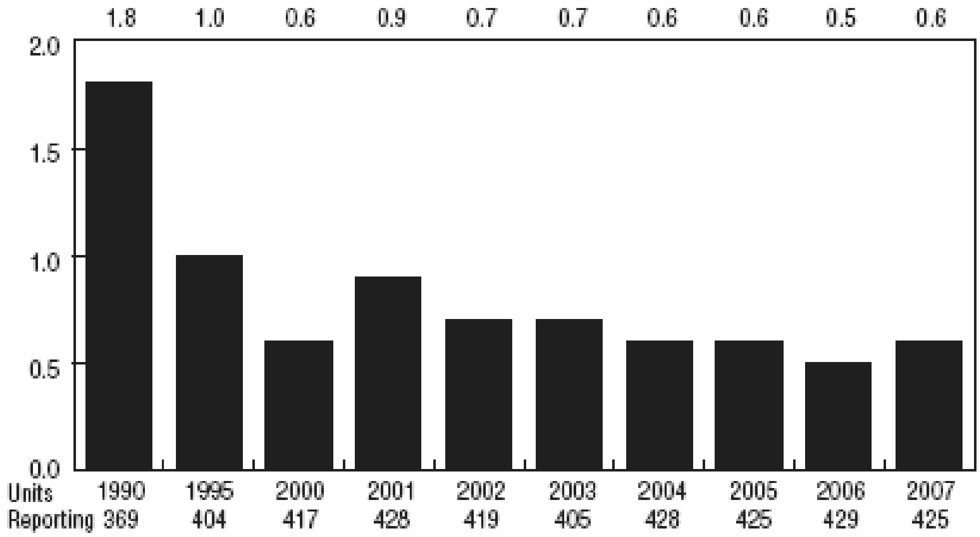



**Figure 6: Number of unplanned trips per 7 000 hours (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010)**

Even though the graph only represents the average unplanned trip rate between 1990 and 2007, this rate has continued to decrease up until today. As illustrated by the graph, the most significant drop occurred between 1990 and 1995, while by 2007 the rate dropped to one third of that in 1990. And it is even lower today.

Safety improvements can further be demonstrated by considering the CDF and LRF of different generation reactors. The CDF refers to any event or problem involving a nuclear reactor resulting in damage to the core, while the LRF refers to events resulting in the release of radioactive material into the environment, for example the venting of radioactive steam in the event of pressure reaching dangerous levels inside the reactor (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010; U.S.NRC, 2018; Yan *et al.,* 2013). As discussed previously, since the above-mentioned events are extremely rare, figures cannot be based on previous events. Instead, they are determined using a probabilistic safety assessment (PSA) method and should therefore be considered as indicators rather than precise data. Figure 7 below, generated by the IAEA, estimates the CDF and LRF using PSA methods between existing generation I and II reactors, as well as generation III reactors which are not yet as commonly used.

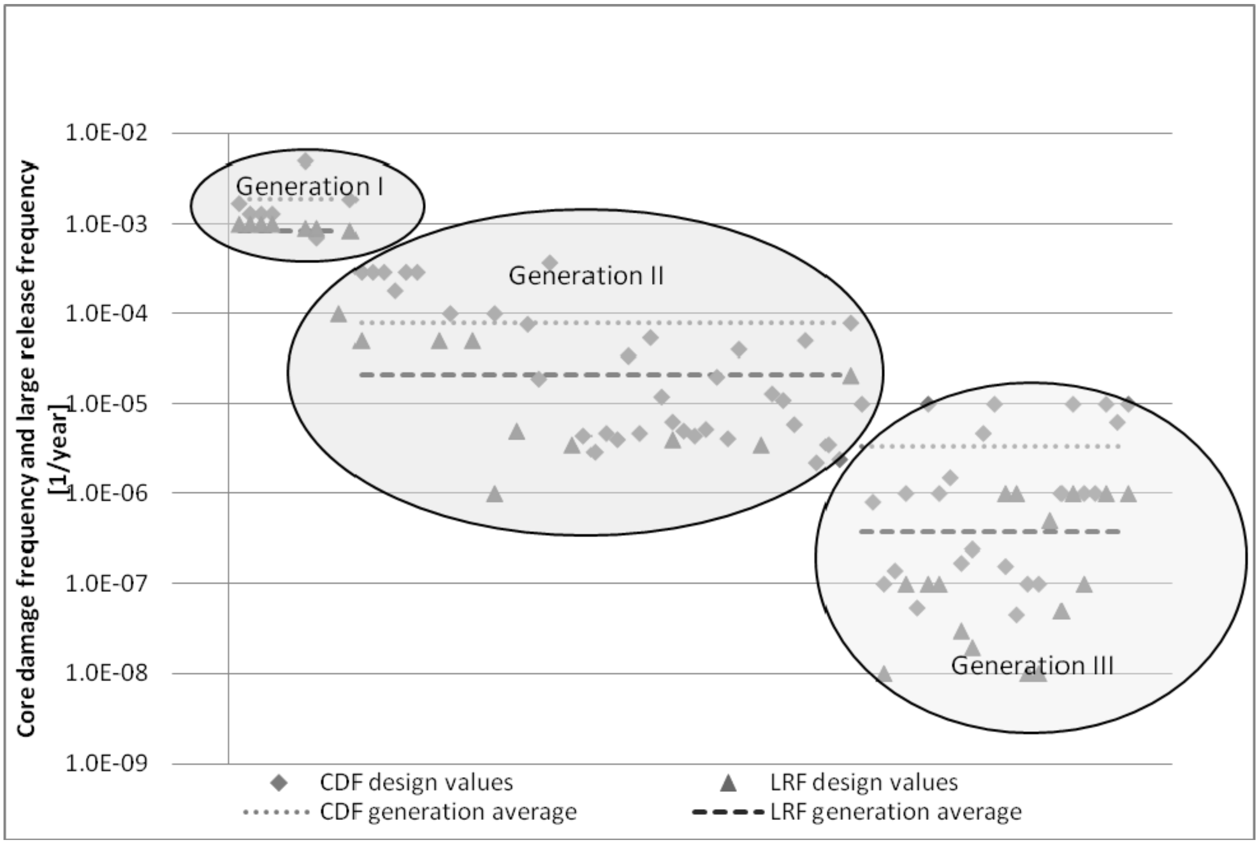



**Figure 7: CDF and LRF indicators determined through PSA for generation I, II and III reactors (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010)**

It is important to note that the above graph demonstrates the CDF and LRD of the various generation reactors considering their "as originally designed" parameters, meaning that no retrofits such as added safety systems or alterations are considered. The graph indicates that nuclear reactors have come a long way since the early generation I reactors, with the chances of an accident resulting in the release of radioactive material having been reduced by a factor of 1 600 (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). Furthermore, the gap between the CDF and LRF data points increased with newer reactors. This shows that the chances of damage to the core resulting in the release of radiation have decreased by about ten times as compared to generation I reactors where damage to the core could have easily resulted in the release of radiation (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). This enhancement in safety can once again be attributed to the advanced technological safety systems in place today, including engineering improvements to the fuel, reactor containment and primary circuit, allowing the reactor to shut down and maintain stability without any external intervention.

The continuous improvements and reductions in parameters such as the unplanned automatic trip rate, core damage frequency (CDF) and large release frequency (LRF) do not necessarily reduce because of new reactors being implemented, or the replacement of existing reactors. Instead, new safety systems are designed in such a way as to be compatible with most older types of reactors, allowing retrofitting of previous generation reactors to improve safety. Therefore, a power plant with older generation II reactors does not mean that it is in any way unsafe as compared to newer nuclear plants, as it is more than likely that these reactors have been retrofitted several times with the latest in safety systems and designs. Further improvements come from standardization of components and safety systems, as well as better training for operators and personnel thanks to the development and implementation of training programmes (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

### 4.7 Layers of protection

When it comes to the different safety systems applied to nuclear reactors, it is important to notice that unlike most other types of power plants, nuclear power plants have several safety systems protecting against the same types of events or incidents, providing backup if one of the systems were to fail. These are referred to as 'different layers of protection', operating independent from each other to ensure greater reliability and safety. The different layers will ensure that no singular fault or failure will be able to give rise to an event with harmful consequences to the environment or people. Although the type of safety system and precautions may differ between layers depending on the type and generation of reactor, the basic layers of protection usually consist of the following five layers (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

The first layer of protection comes from selecting an appropriate site to construct a nuclear power plant, ensuring that resources such as a reliable water source and access to a sufficient external power feed are available among other requirements. Furthermore, it is also important to ensure that the workmanship is of a high standard during the initial construction phase, as this will reduce deviations from normal operations and failures due to human error in the future (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

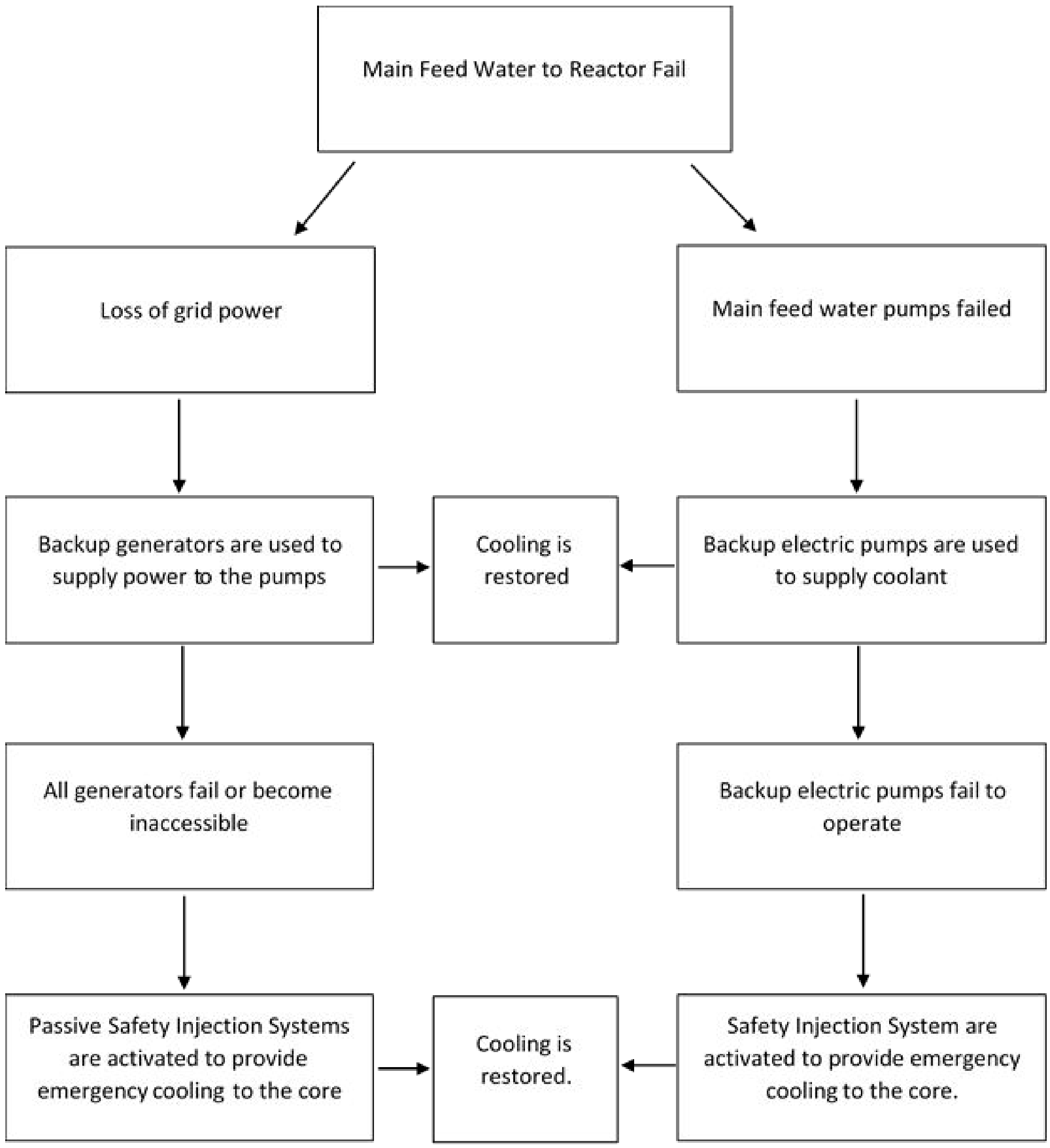
The second layer of protection comes from the implementation of control and protection systems used to manage any abnormal conditions at the plant, thereby ensuring that such conditions do not escalate into dangerous situations. This layer also includes monitoring and detection equipment used by the automated systems and plant operators to detect any abnormalities as soon as possible (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

The third line of defence comes from the design of the reactor, which includes additional safety features combined with accident response procedures incorporated into the infrastructure. The design of these systems largely focuses on the prevention of core damage, and incorporates a core containment structure with adequate retention capabilities to prevent an incident resulting in the uncontrollable release of radioactive material, in the event that core damage does occur (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

The forth line of defence also involves the core containment structure, and its design capabilities, to contain a severe accident even beyond what is deemed possible. The containment structure should therefore be designed to not only be able to contain accidents like those of the past, but also accidents even larger, which just may occur in the future. The importance of the containment structure becomes evident when comparing two of the biggest accidents of the past: Three Mile Island and Chernobyl. The Three Mile Island reactor containment managed to contain the melted radioactive fuel in the core, in the end releasing a very limited amount of radioactive material into the environment. Contrary to this, the Chernobyl accident resulted in a very large amount of radioactive material being released into the environment, as the core containment structures were weak and inefficient by today's standards. If a proper containment structure were originally incorporated into the design, the outcome of the accident might have been drastically different (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010).

The fifth and final layer of protection comes in the form of off-site monitoring and emergency plans. This involves the assessment of an accident once it has occurred, and the implementation of the appropriate procedures to minimize its impact. This layer of protection is also responsible for the implementation of short- and long-term plans and evacuations if an incident manages to progress to a stage where radioactivity is released. This level ensures that even during a worst-case scenario, public safety comes first and that people's exposure to radioactivity is prevented or at least as minimal as possible (Nuclear Energy Agency Organisation for Economic Co-operation and Development, 2010). To improve the efficiency of this level of protection, software and support systems such as the Multiple Radiological Emergency Assistance Systems for Urgent Response, often referred to as "MEASURES", have also been developed. This system works by providing real time feedback about a nuclear power plant in the event of an emergency or disaster, allowing emergency response personnel to react accordingly. The system also makes use of various techniques and parallel processing for future predictions based on air current distribution analyses, the plant's current state and various other parameters. The system is therefore beneficially able to predict the outcome of an emergency at a nuclear power plant while it is still ongoing. Using this knowledge, the situation can then be handled is such a way so as to minimize the impact on the environment and surrounding inhabitants (Nukatsuka *et al.,* 2004).

To better illustrate the concept of layered protection, a scenario where the main feed water to the reactor core is lost can be used as an example.




The diagram illustrates how if one backup safety system were to fail, another will be available to attend to the problem, ensuring that no singular or even multiple failure of safety systems will result in a catastrophic accident. It is worth noting that the scenario illustrated is only one of many examples, and that the systems activated to ensure stability of the core will depend on the type of reactor, fault and the circumstances surrounding the problem.

## 4.8 Addressing the concerns surrounding nuclear energy using the latest available reactor designs

The importance of passive safety systems in future reactor designs has long been recognized. An example is the generation III+ Economic Simplified Boiling Water Reactor (ESBWR), which as the name suggests, is designed with an aim toward simplicity and component standardization while incorporating several passive safety systems. ESBWRs, for example, make use of naturally circulating cooling systems rather than forced circulation through pumping, thereby simplifying the system by making use of a passive method of cooling (Rassame *et al.,* 2017).

The three most important passive safety systems incorporated into ESBWRs can be identified as follows. In the event of a loss of coolant accident (LOCA) removal of the decay heat from the reactor core becomes crucial to prevent core damage. For this purpose, the ESBWR makes use of an Isolation Condenser System (ICS) and Passive Containment Cooling System (PCCS) to remove the decay heat from the reactor core and containment. The ICS activates after receiving a signal of either the Main Steam Isolation Valves (MSIVs) closing, high reactor pressure or low reactor pressure vessel (RPV) water level. The steam created by the core due to a LOCA is then directed to the ICS tube heat exchangers situated in the ICS water pools, allowing the steam to cool and condense, whereafter it is returned to the RPV. The system is passive and does not require any forced circulation components. The PCCS, on the other hand, focuses on keeping the containment pressure and heat within safe limits. This is done by directing the air-steam mixture created in the containment during a LOCA to the PCCS tubes situated in the PCCS water pools for cooling. After condensing of the air-steam mixture, the water is returned to the GDCS pools to be used for RPV refilling, while the non-condensable gasses are safely vented (Rassame *et al.,* 2017).

The third of the main passive safety systems used by ESBWRs is known as a Gravity Driven Cooling System (GDCS) and replaces the active Emergency Cooling System (ECCS) in typical Light Water Reactors (LWRs). This new passive system works independently of external power control, increasing its reliability during unforeseen accident conditions. The GDCS is initiated after the Automatic Depressurization System (ADS) depressurizes the RPV during a LOCA. Due to the limited reliance on active components in the ADS, and its ability to operate without requiring power or operator intervention, it is also considered a passive system by the IAEA. After the RPV have been depressurized by making use of the ADSs 10 safety valves and eight depressurization valves, the GDCS can allow for cool water to enter the reactor core. The main objective of the GDCS is to keep the core completely submerged in water by allowing water to enter from the GDCS pools (Rassame *et al.,* 2017).

Safety is further improved by the cylindrical reinforced concrete structure housing most of the safety equipment, safety systems and water pools mentioned above. This containment is also designed to contain the radioactivity in the unlikely event of some escaping the reactor vessel during a LOCA or similar accident. A basic layout of the passive safety systems mentioned above can be seen in Figure 8, illustrating the configuration of a ESBWR containment structure (Rassame *et al.,* 2017).

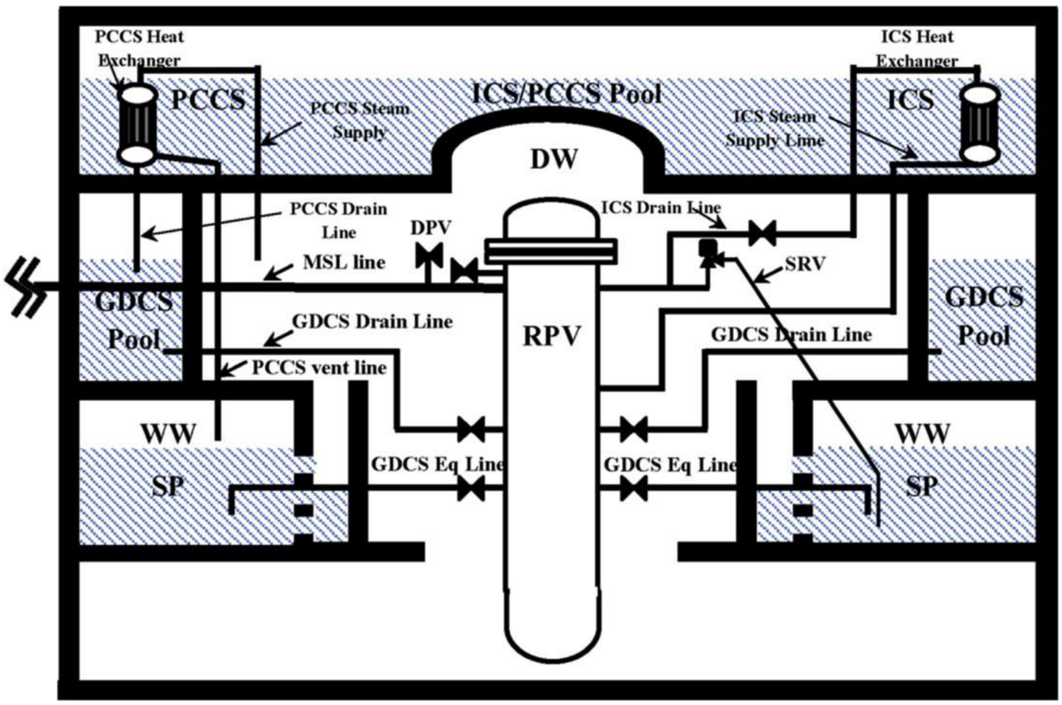



**Figure 8: Configuration of an ESBWR containment structure (Rassame *et al.,* 2017)**

### 4.9 Proposed passive safety systems of the future

The latest nuclear disaster at Fukushima once again highlighted the importance of greater reliance on passive safety systems, leading to a significant increase in new safety system designs and, specifically, passive safety system proposals. The Fukushima disaster also highlighted the need to reinforce certain parts of the safety systems incorporated into nuclear power plants, increasing the ability of existing safety features to deal with extreme natural hazards and events (Gjorgiev *et al.,* 2017). Passive safety systems refer to those making use of natural phenomena to operate, such as natural convection, gravity and pressure difference, enabling these systems to operate independently from external operations or from needing electricity. One such proposed system which has received some attention in terms of research is known as a Passive IN-core Cooling system (PINCs). The aim of the PINCs was to design a singular passive safety system which could shut down the reactor in an accident condition, while simultaneously providing enough cooling to remove core decay heat. To achieve this, PINCs propose replacing the conventional control rods of a reactor used to control reactor power, and to halt the nuclear reaction in an emergency with a hybrid control rod heat-pipe system, essentially using the control rods as a passive cooling system (Kim & Bang, 2017; Seo *et al.,* 2018).

As mentioned, the PINC system will replace the conventional control rods, meaning that the new system will have to be installed inside the reactor vessel and therefore must satisfy the aspects accomplished by the conventional control rods sufficiently. To achieve this, modification of a conventional pressure vessel design is required. The replacement hybrid control rods will consist of two layers of metal cladding with a fluid inside used to transport the heat. Neutron absorbers in the form of B4C pellets enriched with B10 will also be inserted inside the metal cladding. The basic working principal of the system is based on the transfer of heat between the reactor core and a condenser as this drives the convection process of the cooling fluid present within the hybrid control rods, transferring heat between the reactor core and condenser. A cooling section then transfers the heat from the condenser to a heat sink which dissipates the heat (Kim & Bang, 2017; Seo *et al.,* 2018; Fewell *et al.,* 2001).

The PINC system has been developed to allow retrofitting and incorporation into several existing and future reactor designs, including the APR1400, PGSFR and SMART reactors. Performance testing was conducted using and 1:12 scale 4-finger control rod assembly, with the aim of proving that the system is stable and accurate under normal operating conditions, and to achieve reactor scram in a time less than that required by design requirements. The small scale results determined that these requirements should be achievable, and that the implementation of PINCs significantly reduces the chance of core damage in the event of total loss of power and cooling, as in the Fukushima case (Kim & Bang, 2017; Seo *et al.,* 2018; Fewell *et al.,* 2001).

Another proposed passive safety system which has received careful attention in terms of research likewise aims at protecting against a loss of coolant accident (LOCA) in the core during a station blackout. Moreover, the system is once again aimed at dealing with a scenario where a complete loss of AC power occurs, like that at Fukushima in 2011. As the proposed system is intended to be a supplementary system to the existing safety systems and operate independently, the main objective of the system is to remove decay heat from the reactor core during a station blackout, resulting in loss of coolant in the core causing the core to overheat. The design components and requirements will consist of a water source, pipes, valves and portable fossil-fuel driven pump (Gjorgiev *et al.,* 2017).

A recent study (Gjorgiev *et al.,* 2017) aimed at proving the effectiveness of such a system during the above mentioned conditions, specifically aiming at system effectiveness when implemented with generation II light water reactors. Even though the focus of this study is on generation II reactors, generation III and III+ are also covered. The use of generation II reactors in the study is significant, as most nuclear reactors in service today are of this type. Many studies propose passive safety systems and prove their effectiveness, but these are often aimed at newer generation reactors which are of importance for future installations but cannot be implemented with the larger percentage of existing reactors. LOCA events in generation II reactors were the main consideration of the study considered, as this type of accident is the largest contributor to core damage frequency in generation II reactors (Gjorgiev *et al.,* 2017).

Design specifications of the proposed system include the requirement that the system be able to provide cooling to the primary and secondary cooling loops for a minimum of 72 hours after a complete station blackout (Gjorgiev *et al.,* 2017). The diagram in Figure 9 below explains the basic working principal of the proposed system.

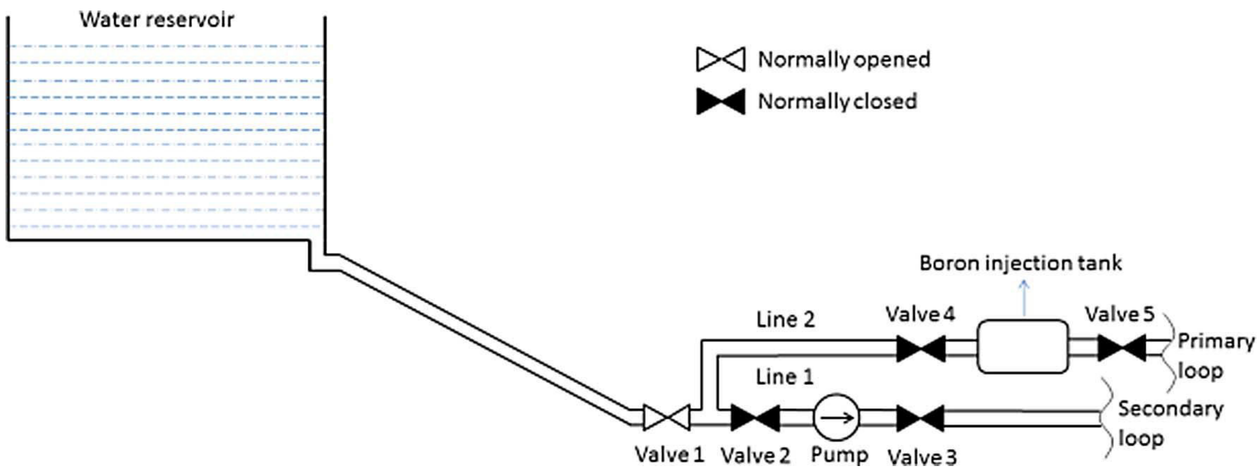



**Figure 9: Proposed new passive safety system design (Gjorgiev *et al.,* 2017)**

Considering this diagram, the system will require an on-site or off-site water source independent of the main and existing systems, which is important as this will increase the system's reliability and ability to operate under extreme and unforeseen conditions. Line 2 and 1 in the diagram are connected to the existing primary and secondary cooling loops of the nuclear power plant, respectively. In the event of a station blackout, decay heat removal and cooling of the core must continue. To maintain cooling the plant's primary backup system in such an event, the auxiliary feed water system will attempt to activate using auxiliary power from the backup generators. If the auxiliary feed water turbine-driven pump and check valves fail to operate due to unforeseen external events, such as in Fukushima, the second backup system proposed will need to provide cooling. The next step would then be to start the independent diesel pump connected in line 1, and open valves 2 and 3 to allow cold water to be injected into the secondary loop, where it is vaporized as it cools down the steam generators of the power plant. The system should be able to operate using gravitational feed without the pump in an extreme emergency where the pump becomes unavailable; however, to achieve effective cooling, a pressure of above 80 bars will be ideal. For this reason, it is also important that the water supply be situated to allow for gravitational feed, and that the diesel pump be situated in a secure area to prevent it from inoperability under any conditions (Gjorgiev *et al.,* 2017).

Considering line 2, when a station blackout occurs, the primary backup system known as the low-pressure coolant injection system will activate using power from the backup generators, providing coolant to the primary loop. Once again, if this backup system fails, as in the case of Fukushima, the proposed system will be able to act as a secondary backup system. In such a scenario, valve 4 and 5 will be opened, allowing for cold water to be gravity fed into the primary loop to provide essential cooling. Depending on the pressure achievable through gravity feed alone, an additional diesel pump may need to be installed; however this should preferably be avoided as this escalates the possibility of malfunctions in the system (Gjorgiev *et al.,* 2017).

Risk probability and result analysis concluded that the addition of the proposed system will have a significant influence on power plant safety. Results show that the probability of both the core damage frequency and extreme loss of coolant accidents (LOCA) are reduced by 26% and 23%, respectively, making this an effective backup system to the primary backup systems in the event of extreme unforeseen circumstances leading to a station blackout and loss of coolant (Gjorgiev *et al.,* 2017).

### 4.10 Future waste disposal methods

Although the current methods for disposing of nuclear waste have been discussed, there is continuous research into discovering ways to reduce and reuse the waste generated by nuclear power plants. This is not only to reduce the amount of waste to be stored and disposed of, but useful because the waste is potentially a valuable resource, consisting mainly of uranium and some plutonium. One way to reduce and reuse waste, which is still to be implemented commercially, is a process known as the Purex process. This hydrometallurgical process works by recovering all actinide anions such as uranium and plutonium, allowing reuse whilst reducing the radioactivity of the remaining waste to a level which will only need 300 years to return to original mined level of radioactivity. Another method which has yet to take hold commercially is the Australian Synroc system, a sophisticated system consisting of several containment or barrier layers to maintain and prevent the release of radioactive material into the environment for tens of thousands of years, by which time the waste would have decayed into harmless elements. This technique is aimed at immobilizing the radioactive elements mainly in HLW and long lived ILW. The containment, or barrier layers, will initially immobilize the waste in an insoluble matrix such as glass or synthetic rock. The moulded immobilized waste will then be sealed in a corrosion-proof stainless steel containment structure, whereafter it will be located deep underground away from all people and the environment. The final layer of containment will involve surrounding the stainless steel containment structures with an impermeable backfill able to delay the migration of any radionuclides if any were to escape from the containment structure (World-Nuclear, 2017; Pandy *et al.,* 2016).

### 4.11 Chapter conclusion

Considering the findings of Chapter 5, it is evident that the risks and fatalities of nuclear are frequently grossly overestimated when compared to fossil fuel alternatives (Windridge, 2011) largely because of the way our brain perceives risks, but further exacerbated by ineffective risk communication during the critical early years of implementing a previously unknown method of power generation. Considering future reactor designs and waste disposal methods, the nuclear industry is investing copious resources to render nuclear power plants safer and more efficient than the current research even shows it to be. The problem is therefore not with the safety systems or disposal methods in use, but rather with informing and convincing the public in an effective and honest and yet persuasive manner. To this end, this study proposed the method of first informing the public of the advantages of nuclear over its alternatives, only then followed by the possible risks. This leaves them to make their own conclusion, ultimately hoping to gain their support (Lévêque, 2013; Frantal & Maly, 2017).

# CHAPTER 5: CASE STUDIES

## 5.1 Chapter introduction

To better illustrate the effectiveness of the safety systems discussed throughout the study, two simulations using different safety systems are conducted, one representing newer safety systems and the other representing older or more conventional systems. The reactors chosen for simulation purposes were pressurized water reactors (PWR), as they are the most common type currently in use. PWRs form part of what is known as light water reactors (LWR), classified as generation II. These reactors have the advantage of being economical, easy to operate, easier to control under abnormal conditions and with a fairly low chance of contaminating the environment as the primary and secondary cooling loops are completely separate from one another, which explains why they are often favoured over other types of LWRs (Shaw, 2017). The aim of the simulation is to demonstrate the advantages of using passive safety systems over active safety systems, which have also been discussed earlier. Therefore, two simulations are conducted: the first simulates a power plant incorporating newer passive safety systems; the second simulates a power plant incorporating more of the conventional active safety systems. The software used to complete these simulations was applied for and obtained directly from the IAEA. Note that although the simulated reactors will both be PWRs, the same simulator cannot be used for both simulations as the systems used for cooling the core differ from one another. Results obtained from these simulations are significant, as the increased use of passive systems could have prevented some of the major nuclear disasters of the past, such as the 2011 Fukushima accident. Clear proof that passive safety systems have more advantages than disadvantages over active safety systems would promote passive system use, preventing unnecessary nuclear disasters in the future.

## 5.2 Simulator specifications

For the simulation making use of newer passive safety systems, Advanced Passive PWR Simulator (CTI) is used (IAEA & Cassiopeia Technologies Inc., 2011). The simulator was developed using PCTRAN software by Micro- Simulation Technology of the USA. The simulator, although not replicating a specific reactor design exactly, is developed in such a way as to represent a Framatome, Westinghouse or KWU reactor design, and is essentially a generic 600 MWe two-loop pressurized water reactor with inverted U-bend steam generators and dry containment system. A modular modelling approach is used and developed in FORTRAN, consisting of basic models represented as algorithms for each type of device and process to be simulated. The different models make use of first order differential equations, and logical and algebraic relations, of which the input-output relationships and other required parameters are assigned to the models as demanded by a particular system application (Cassiopeia Technologies Inc. 2011). The simulator features are summarized in a table obtained from the user manual, and is available in Appendix A.

For the second simulation making use of more conventional active safety systems, Advanced PWR Simulator (KAERI) will be used. The simulator, although not replicating a specific reactor design exactly, is designed to be similar to the Korean Optimized Pressurized water Reactor-1000MWe-class (OPR1000) and applies nuclear technology from Combustion Engineering in the USA. The thermal-hydraulic models used by the simulator are based on two-phase conservation of mass, energy and momentum equations for each phase, relating algebraically to calculate source terms of conservation equations. The design features of the reactor represented by the simulator are summarized in a table obtained from the user manual, and is available in Appendix B (Korea Atomic Energy Research Institute, 2004).

## 5.3 PWR reactor simulation with increased use of passive safety systems

The aim of the simulation is to visually illustrate the working of the passive safety systems incorporated into the PWR simulated. The first step in doing this is to identify the passive safety systems. Figure 10 below presents the PWR passive cooling systems to be illustrated in the simulation (IAEA & Cassiopeia Technologies Inc., 2011).

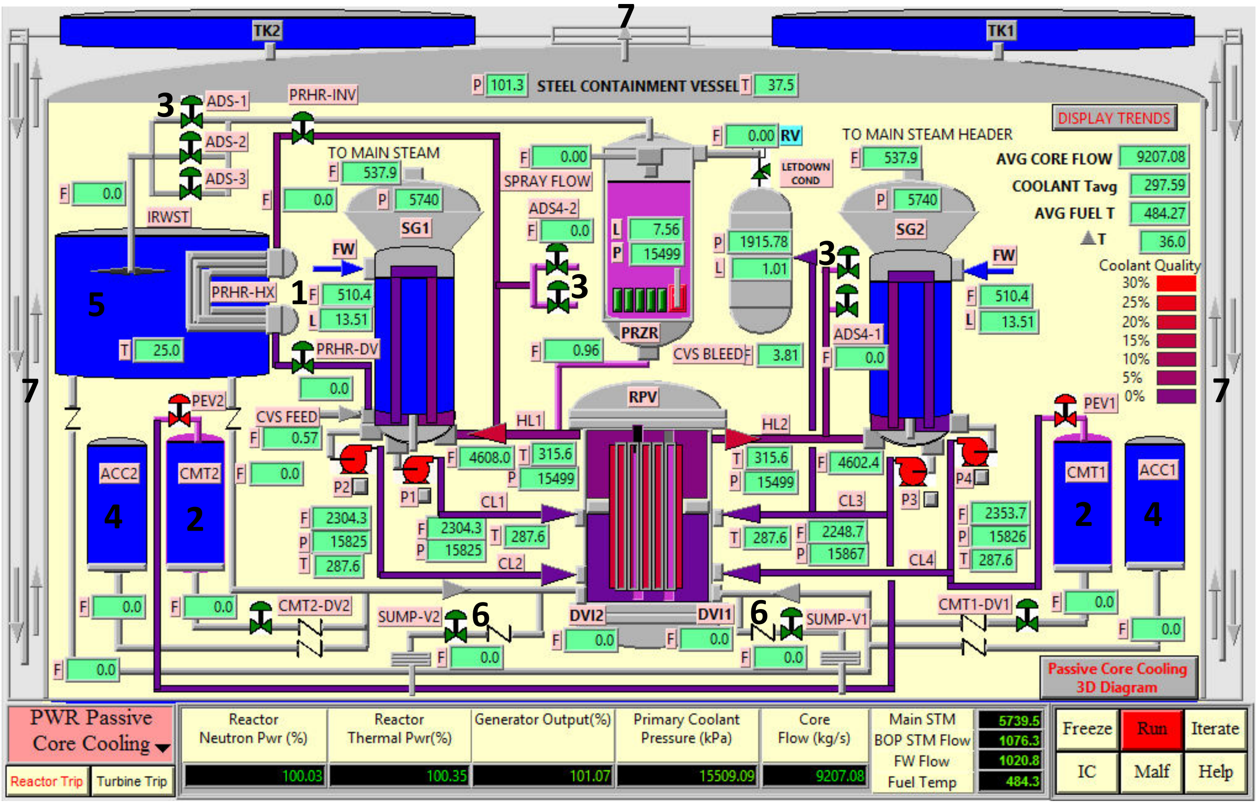



**Figure 10: Simulation 1 PWR passive safety systems**

The passive cooling systems incorporated into the above design work by means of a natural circulation processes and will therefore operate by cooling the core under extreme conditions, for example during a complete station blackout. The first passive safety system incorporated is a Passive Residual Heat Removal (PRHR) system, numbered "1" in figure 10. The PRHR system consists of a heat exchanger that runs through the water-filled In-containment Refuelling Water Storage Tank (IRWST) in a C-type formation, providing heat removal for the core. Considering the simulation screenshot in Figure 10, since heat naturally rises, hot water enters the tubes submerged in the cool IRWST from above, thus exchanging the heat from the PRHR system to the IRWST through boiling which occurs on the outside surface of the submerged tubes. The cool water exiting at the bottom is then returned to the primary core cooling loop, after which this process is repeated (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; Zou *et al.,* 2014; Nawaz *et al.,* 2016).

The second passive cooling safety system incorporated is known as a Core Make-up Tank (CMT) and is numbered "2" in Figure 10 above. This system consists of two large stainless-steel tanks filled with cold borated water. The inlet to the top of each tank is connected to one of the reactor's cold legs, while the bottom outlet is connected to the Direct Vessel Injection (DVI) line. Under normal operating conditions, the top inlet valve will be kept open, thereby keeping the tank at primary system pressure while the outlet valve at the bottom remains closed. If the primary cooling system of the core were to fail, the bottom valve of the CMT will be opened allowing the cold borated water to enter and cool the reactor core. The system is then driven by natural circulation, as the hot primary coolant from the core enters the CMT from the top, allowing the cold borated water to exit the CMT at the bottom. The natural circulation creates a loop that will continue to flow and cool the core without needing pumps. The CMT system is implemented to replace the high-pressure safety injection system found on conventional PWRs, which will be discussed later during the second simulation where this is present (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009).

The third passive safety system is known as the Automatic Depressurization System (ADS) and is numbered “3” in Figure 10 above. The ADS consist of four stages of valves that open to provide a controlled reduction in primary system pressure. The first three stages consist of valves connected to the top of the pressurizer. The opening of stage one is initiated by the CMT liquid level reaching 67.5%, followed by the timed opening of stages two and three approximately 80 seconds apart. The fourth stage of the ADS consists of two large valves connected to the ADS lines on each hot leg. The stage four valves open when the CMT liquid level drops below 20%, bringing the pressure of the primary side down to containment level. The vented gasses from valves one to three is vented into a separate line and redirected to the IRWST, where it is condensed. The stage four valves of the ADS vent directly into the containment building (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009).

The fourth passive safety system is in the form of two Accumulators (ACCs), numbered “4” in Figure 10 above. The ACC tanks on each side are filled three-quarters of the way with cold borated water and pressurized using nitrogen gas. Like the CMTs, the ACC outlets are also connected to the DVI line of the reactor, while flow is restricted under normal operating conditions using check valves. To activate the ACC, the system pressure needs to drop below the accumulator and check valve pressure, allowing the check valves to open and inject the cold borated water into the reactor via the DVI line (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009).

The fifth passive safety feature is known as the In-containment Refuelling Water Storage Tank (IRWST), marked as “5” in Figure 10 above. The IRWST consists of a large concrete tank filled with borated water and two normally closed check valves in a series at the bottom connected to the DVI system of the reactor. Under normal operating conditions, the IRWST serves as a heat sink for the PRHR system, thereby assisting in cooling the core. Like the ACC system, the IRWST valves will remain closed until the primary pressure drops below that of the IRWST and check valves. When the valves open due to low system pressure, the borated water contained in the IRWST floods the lower compartments of the reactor through the DVI system up to a level above the reactor vessel head, but not so high as to restrict the ADS-4 outlet (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009). The system is therefore able to passively monitor and cool down the core in an emergency, preventing the core from overheating and going into meltdown.

The sixth system which assists the passive safety systems mentioned above is known as the Containment Sump recirculation system. This system is responsible for establishing and maintaining the passive flow of coolant in the core to continually remove decay heat after shutdown. The system consists of two sump valves which are opened after equalization of the lower containment sump and IRWST water levels, establishing a natural circulation path. These valves are identified in Figure 10 above labelled as “6”. Natural circulation causes the low-density mixture to flow upward through the core. Steam forms and is then vented through the ADS-4 valves into the containment. This causes cool water to be drawn up from the sump lines connected to the DVI, maintaining the circulation of cool water to cool the core (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009).

The seventh passive safety system incorporated is known as the Containment and Passive Containment Cooling System (PCCS), labelled “7” in Figure 10 above. The PCCS is essentially the steel and concrete housing vessel for the Nuclear Steam Supply System (NSSS) as well as all the passive systems mentioned above. The first feature of the containment is to allow cool air to meet the outside surface of the steel vessel, achieved through ducts incorporated into the sides of the concrete containment. This allows the steel containment to remain cool by dissipating some of the heat to the outside air. The second feature is to condense the steam released into the steel containment by the ADS-4 valves discussed earlier. The steam released naturally rises to the top of the containment where it is condensed upon meeting the cooler inside of the steel containment. The steel containment manages to keep cool, as heat transferred from the steam will rise from the outside of the steal containment and escape through a vent in the top of the concrete containment structure. The heat escaping at the top will naturally draw the cool outside air in through the ducts running up the outside of the steel containment, cooling it. On the inside, the newly condensed cool water is redirected by the design of the containment back to the IRWST and containment sump, again becoming part of the passive cooling loops of the passive safety systems discussed. The third feature of the PCCS is to cool the top of the containment vessel head (of the inner steel containment) in the event of a LOCA, during which heat can build up quickly. This is achieved using large water tanks at the very top of the containment. If the steel containment heats up faster than the naturally circulating cool air can cool it, water is released and sprayed from the tanks onto the outside of the steel containment. The water is sprayed using gravity, making this a passive safety system as no pumps are required (Cassiopeia Technologies Inc., 2011; IAEA & Cassiopeia Technologies Inc., 2011; IAEA, 2009).

### 5.3.1 Simulation 1

To best demonstrate the workings of the above discussed passive safety systems, a LOCA break is chosen as the malfunction to be inserted. Simulating a LOCA will allow all the passive safety systems discussed to come into play. Simultaneously, although relatively uncommon, LOCAs are often the underlying cause of major accidents at nuclear power plants, disrupting the effective and continuous cooling of the core, which is considered one of the most important actions to keep in mind when operating a nuclear power plant. For the simulation to follow, the initial operating power of the nuclear power plant was set to 100%, as nuclear power plants usually operate close to or at 100% of their output capabilities. Figure 11 below illustrates the initial condition of the PWR to be simulated with no active malfunctions.

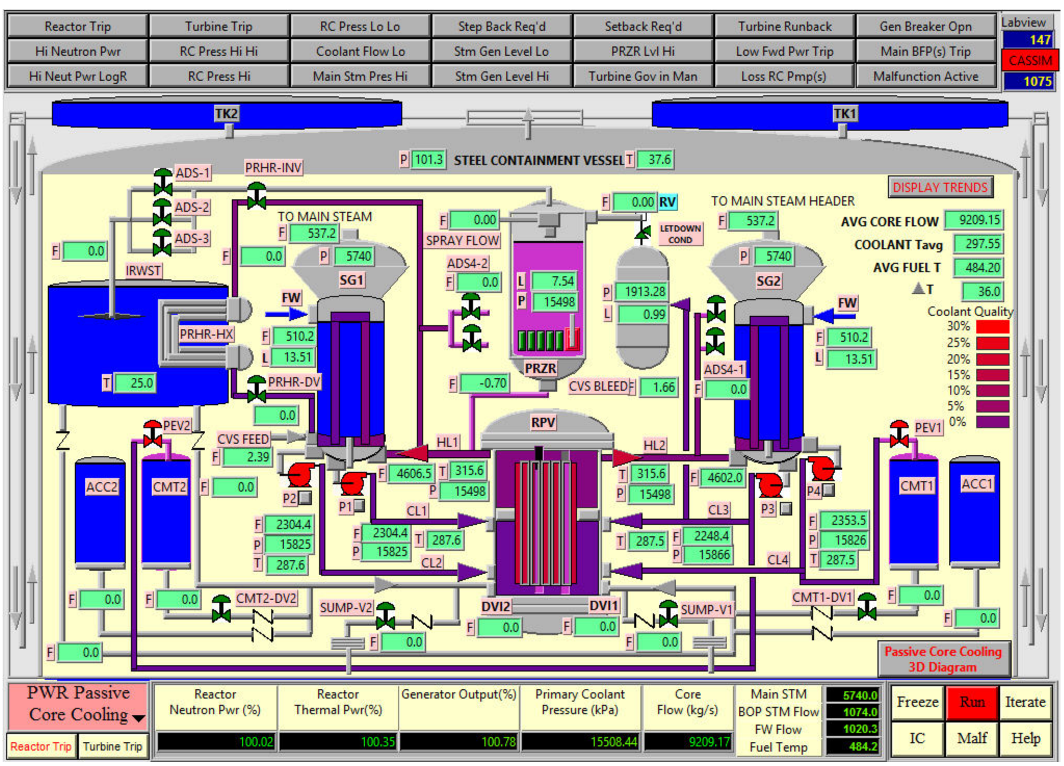



**Figure 11: Initial/baseline condition, no malfunction active**

Figure 11 illustrates the layout of the passive safety systems inside the PWR containment vessel. Additionally, the top section shows the virtual warning lights which indicate when a malfunction is active while showing what is happening to the system at any given moment. Note that the various valves and coolant pumps illustrated in Figure 11 are either green or red. Green valves and pumps indicate that the valves are closed, or that the pumps are off. Red valves and pumps indicate that they are open or on. Various blocks containing values can also be noted in Figure 11, of which the ones with an 'F', 'P' or 'T' in front are the most significant for the purposes of this simulation. Blocks with an 'F' indicate the flow rate at that particular point, while a 'P' block indicates the pressure. Blocks with a 'T' indicate the temperature.

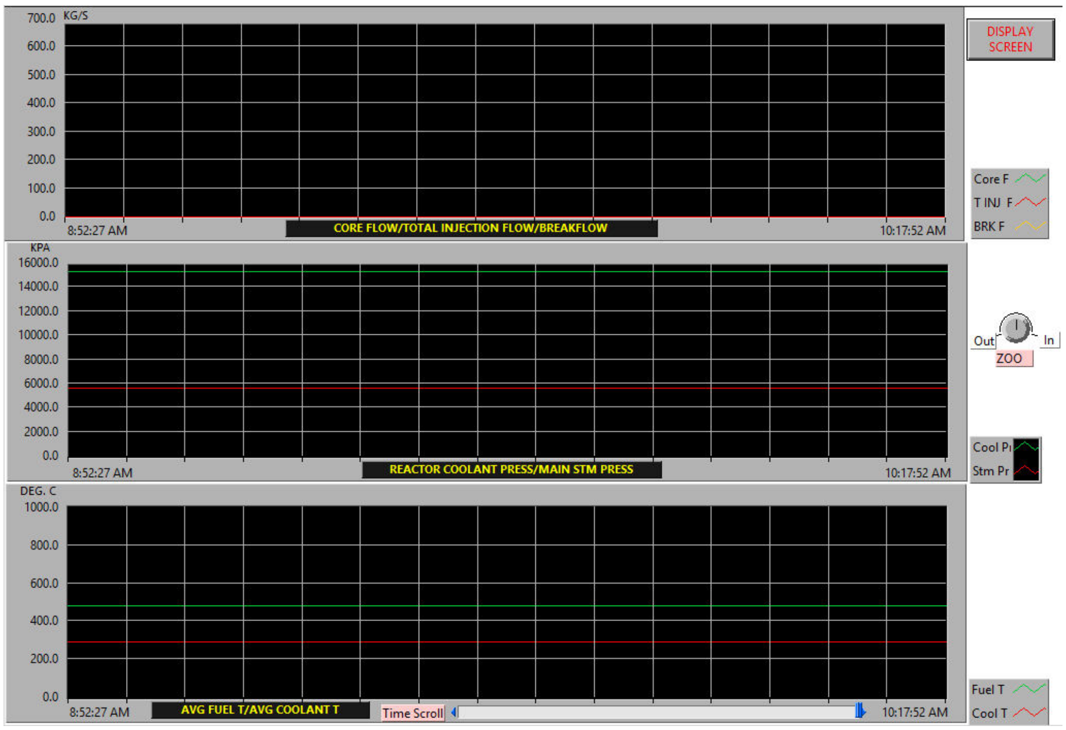



**Figure 12: Output parameter graphs, no malfunction active**

The graphs in Figure 12 are used to visually display important information and parameters also displayed on the PWR passive core cooling screen in Figure 11. The top graph represents the core flow, total injection flow as well as the break flow in green, red and yellow, respectively. The middle graph is used to represent the reactor coolant pressure and main steam pressure in green and red, respectively. Lastly, the bottom graph represents the average fuel temperature and average coolant temperature in green and red, respectively. The values displayed in the graph above represent the normal operation of the power plant, with no malfunctions active. Note that the top graph representing the flow values appears to be empty, as the core flow during normal operations illustrated by a green line is in the thousands, as read from the flow values in Figure 11, and therefore out of the graph range. As no additional coolant is injected through the DVI system, and no break in the system is active, the red and yellow lines are both at 0.  Figure 13 is also illustrates the PWR control rods and SD rods during normal operation. From Figure 13 the normal core coolant flow and average fuel temperature can be noted.

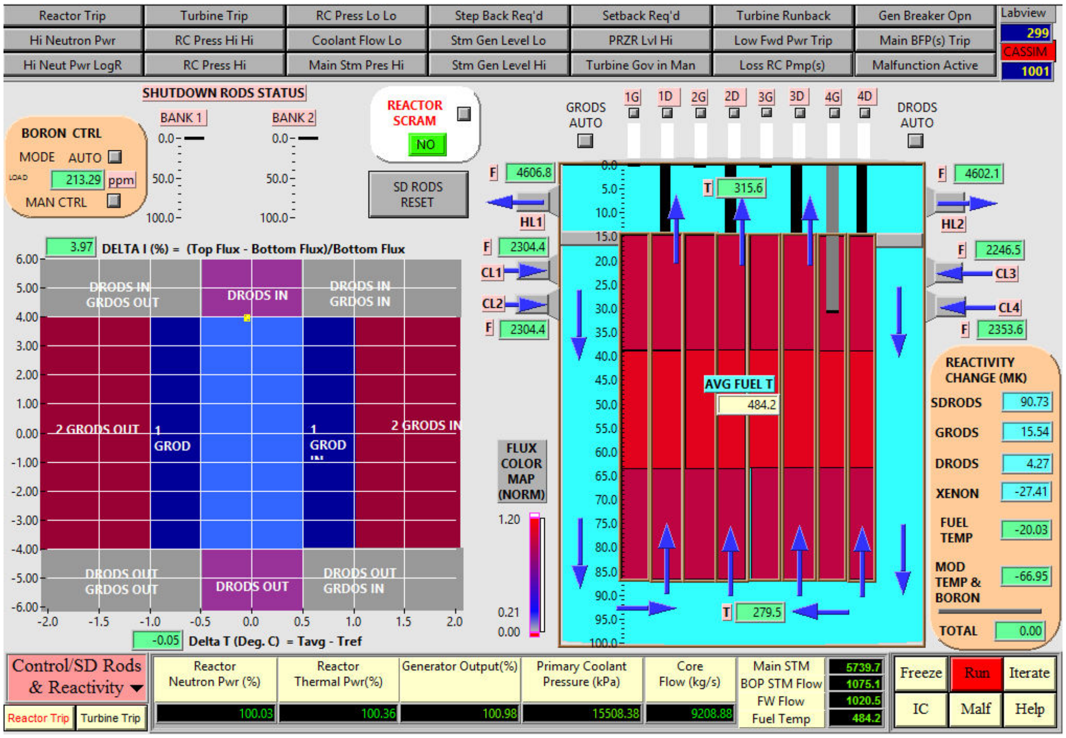



**Figure 13: PWR control and SD rods, no malfunction active**

The first step in illustrating the effectiveness of the passive core cooling systems in action would be to insert the LOCA.  Figure 14 below illustrates the simulator's malfunction screen, with the RC cold leg #4 LOCA break selected.

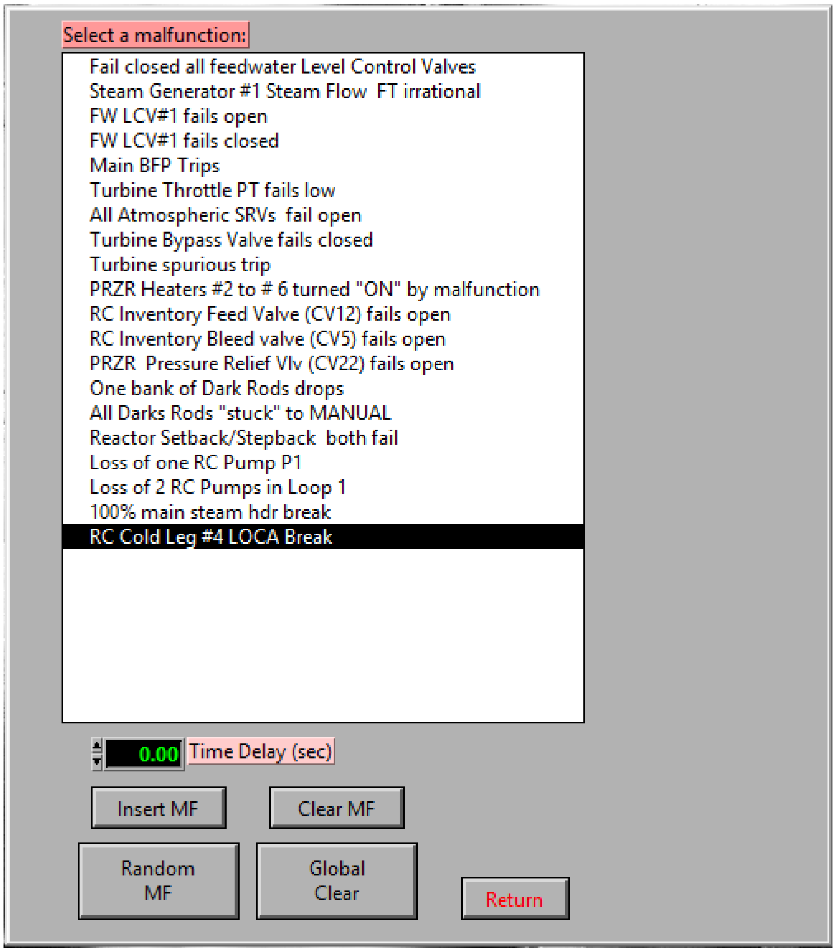



**Figure 14: Simulator malfunction screen, LOCA at CL #4 selected**

The RC Cold Leg #4 LOCA Break is selected and indicates that a break resulting in a loss of coolant to the core will be inserted on cold leg number 4, or essentially pipeline number 4 feeding cool water to the reactor vessel, at a 0 second time delay. Since there is no time delay, the malfunction active alarm was immediately activated once the malfunction became active. The LOCA inserted on cold leg 4 caused the primary system pressure and coolant levels to drop soon after, which are sensed by the pressurizer. This is noted from the graphs in Figure 17, when the core flow represented by the green line in the top graph drops significantly, and the reactor coolant pressure represented by the green line in the middle graph also drops to below the main steam pressure represented in red. The sudden drops in pressure and flow rate sensed by the pressurizer activate several alarms initiating the safety systems and procedures listed below. The following actions were noted from the simulation in the order listed, following closely one after the other.

- The reactor scrams due to a low coolant pressure trip signal.
- The steam generators are isolated by cutting the main steam and feed water.

- The reactor coolant pumps trips automatically.
- The sudden decrease in pressure initiates the PRHR passive safety system valves to open.
- The CMT outlet valves open, so the cold borated water can be injected into the core via the DVI system.
- ACC 1 and 2 start to drain, assisting in cooling the core.

The scrammed reactor is illustrated by the screenshot in Figure 15 below, taken after the above safety systems had been activated. Figure 15 shows that inserting the control rods has caused the reaction inside the reactor core to stop, decreasing the average fuel temperature by almost half. At this stage, the main core cooling pumps have also been shut down, which is why the flow rates have decreased. Also note that at cold leg number 4 (CL #4), the flow rate is negative as this is where the break is situated.

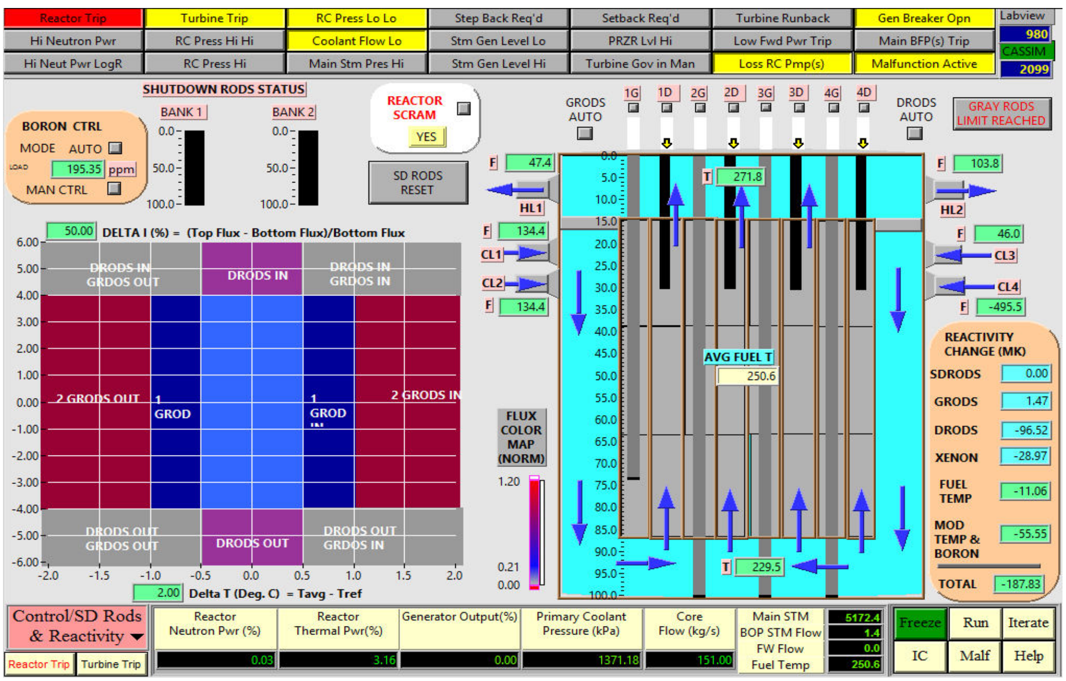



**Figure 15: Scrammed reactor after inserting the LOCA**

In Figure 16, the safety systems listed above are now active considering the positions and states of their respected valves and pumps, when compared to the normal operating conditions in Figure 11.

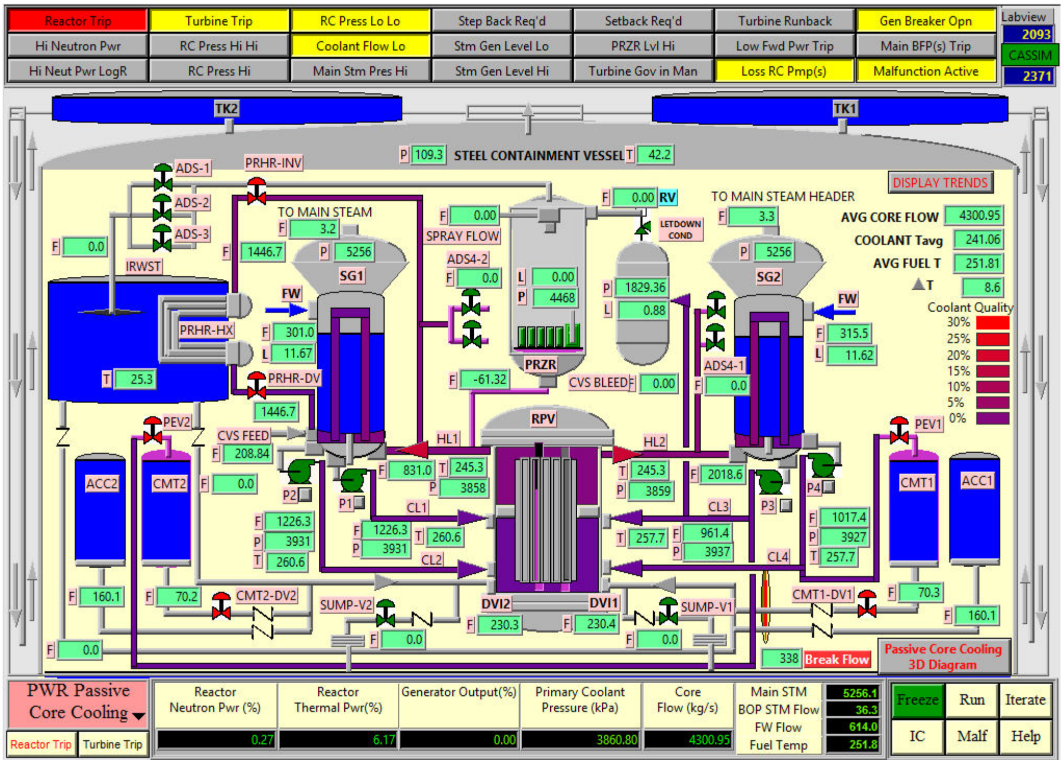


Figure 16: System screenshot, activation of first safety systems after initiation of LOCA

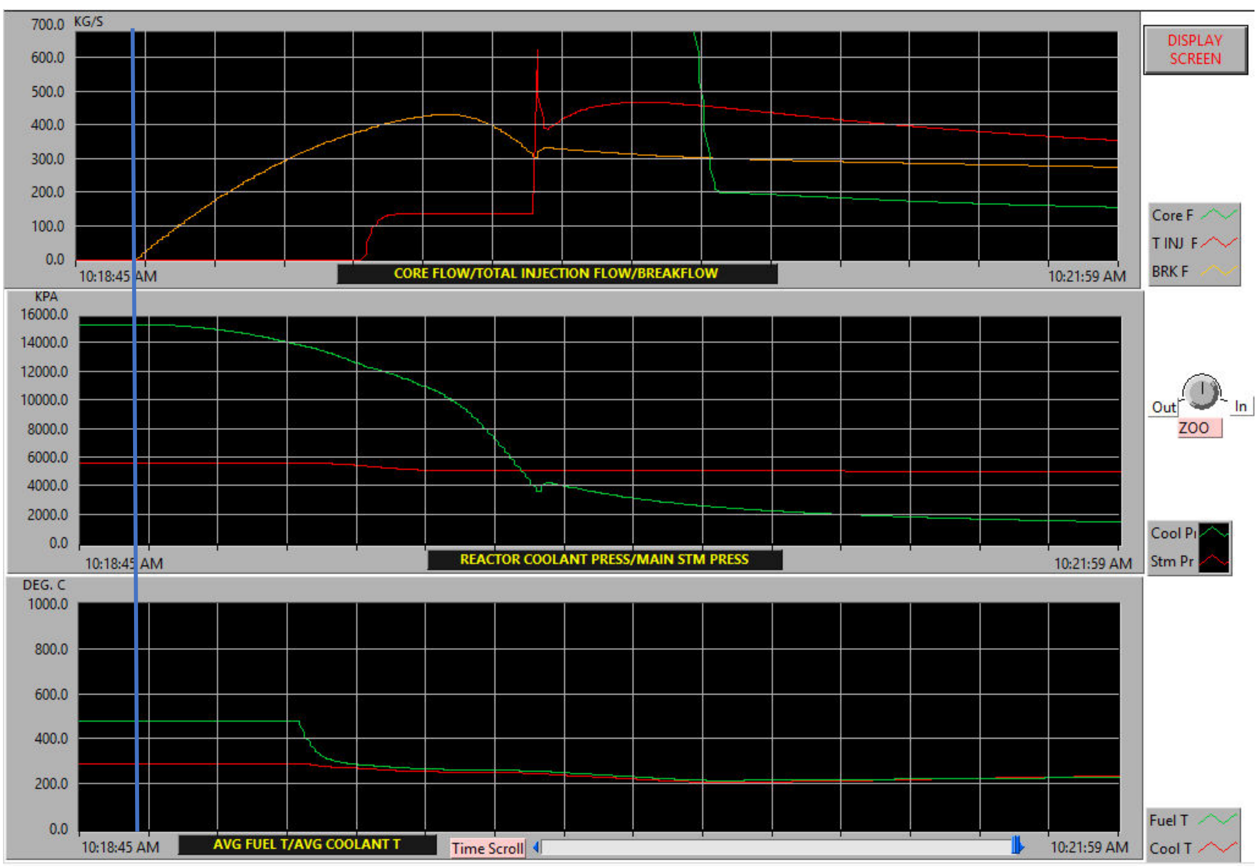


Figure 17: Graph screenshot, affect of initial initiation of LOCA

In Figure 17 above, the blue line on the left-hand side is used to illustrate the moment the LOCA was initiated. As soon as the LOCA is initiated, the break flow represented by the yellow line in the top graph begins to climb, as coolant is now escaping through the break into the containment vessel. The break in turn causes the reactor coolant pressure represented by the green line in the middle graph to start decreasing rapidly. From the initial set of actions listed earlier, it can be recalled that the first action will be for the reactor to scram, thus halting the nuclear reaction in the core causing the drop in average fuel temperature represented by the green line in the bottom graph. Next, the reactor coolant pumps are tripped, initiating the almost instantaneous opening of the CMT valves as a result of the drop in coolant pressure. The CMT then provides additional cooling to the core through the DVI system, evident from the increase in total injection flow represented by the red line in the top graph. The second even bigger spike in total injection flow is noted when the flow from the Accumulator tanks, ACC 1 and 2, is initiated. The significant drop seen in core flow represented by the green line in the top graph, illustrates the core flow rate stabilizing after the initial shutdown of the main reactor coolant pumps. After these events, the system temporarily stabilizes, allowing the coolant injection systems to work, as seen from the section in the graph following the stabilization of the core flow rate in the top graph.

As mentioned, reactor scram causes the nuclear reaction in the core to stop, thereby significantly reducing the heat produced. Scramming of the core causes the average coolant and fuel temperature to initially decrease. Although the above-mentioned passive cooling systems already initiated are aimed at cooling the core after reactor scram, the core once again began to heat up due to decay heat and the large quantity of coolant escaping into the containment vessel through the break on CL #4. The escaping coolant and increased temperature of the cooling system in turn caused the containment vessel pressure and temperature to rise. To assist in condensing the accumulating steam and building pressure in the containment vessel, the water tanks at the top of the containment started occasionally spraying water on the outside of the steel containment when pressure inside exceeded 114 kPa, until it was back down to 107 kPa, after which it stopped. This action can also be noted in Figure 18 below. It is also worth noting that the pipelines to and from the core have now turned red from the coolant heating up. The next passive safety system to activate is the ADS pressure release valves. Figure 18 below illustrates ADS-1 already open, and ADS-2 in the process of opening. The opening of ADS-1 is triggered by CMT liquid level and occurred at approximately 67.5% as specified in the operation manual, followed by the time delayed opening of ADS-2 and ADS-3 approximately 80 seconds apart as specified.

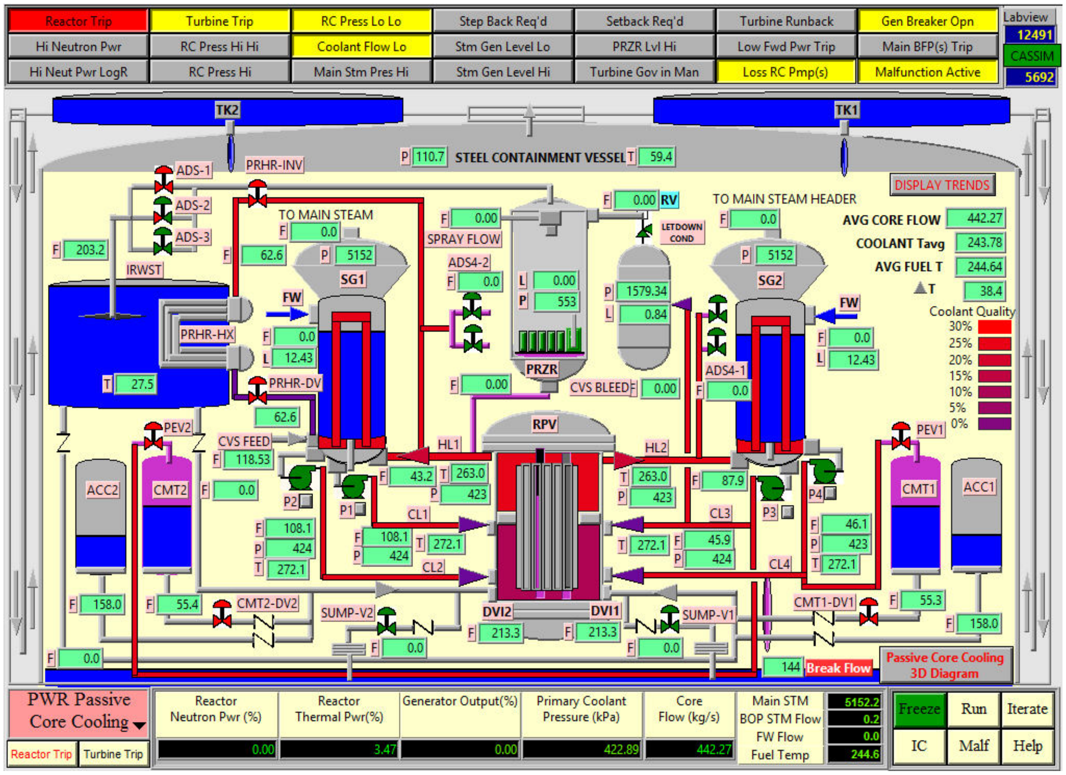


**Figure 18: System screenshot, heat build-up, activation of ADS and containment cooling systems**

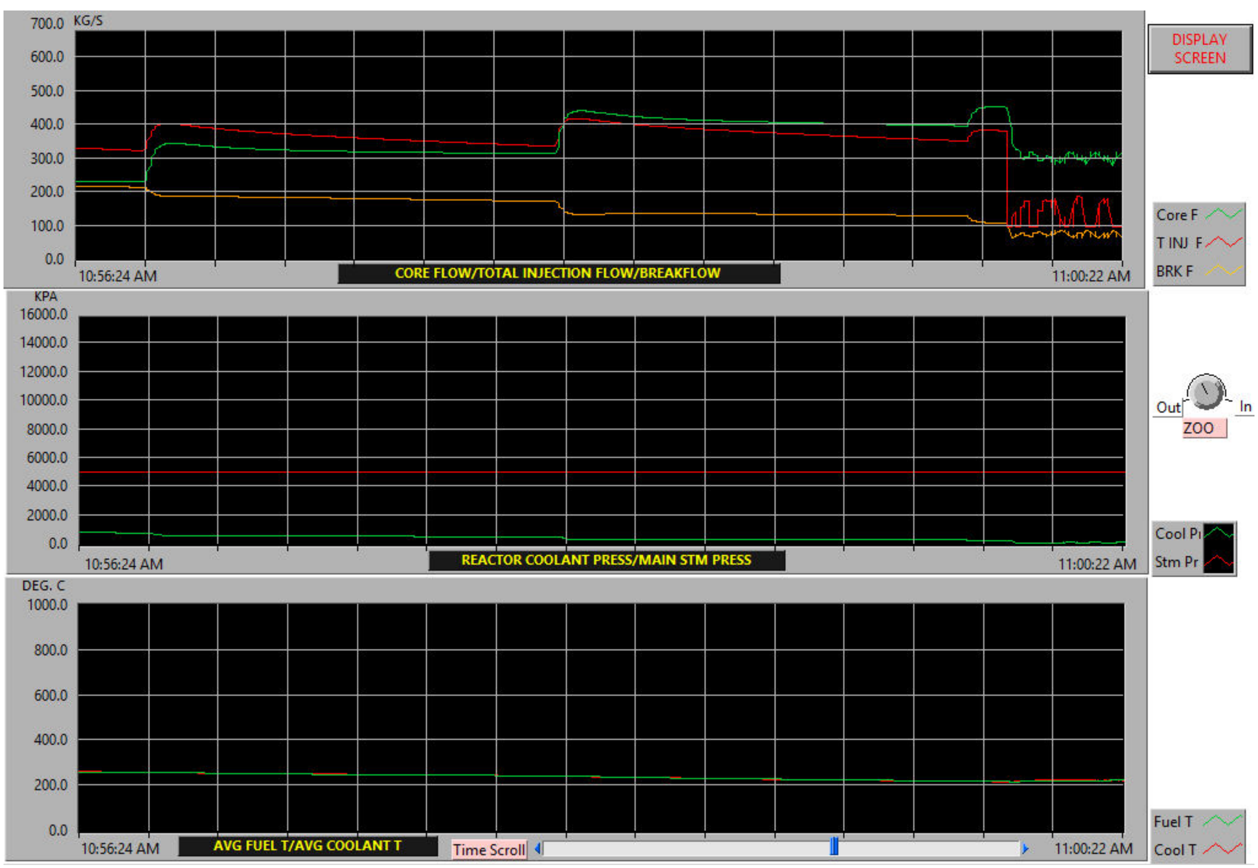



**Figure 19: Graph screenshot, ADS 1, 2 and 3 valves opening**

The effects of the first three ADS valves opening can also be identified from the graphs in Figure 19 above. Considering the top graph representing the flow values, three deviations can be noted of which the first on the far left-hand side represents the effect of ASD-1 opening. The core flow and therefore the total injection flow represented by the green and red lines respectively, fed by the ACC and CMT tanks, increase as the pressure release valve opens. Opening of the valve causes the primary system pressure to decrease, essentially lowering the resistance encountered by the flow of coolant through the DVI system, allowing water to enter the reactor pressure vessel faster. The break flow represented by the yellow line on the top graph will also decrease, as there is less pressure in the system. The opening of ADS valves three and four will therefore have the same effect of increasing core flow while decreasing the break flow, as the primary pressure continues to decrease with the opening of each additional valve. When considering the time scale of the graph at the bottom and the number of intervals between the openings of the valves, it can be calculated that they do in fact open approximately 80 seconds apart as specified in the manual. Furthermore, all flow values drop substantially shortly after the opening of ADS-3. This sudden drop is caused by the Accumulators (ACC 1 and ACC 2) emptying, and their flow becoming 0. There are varying pattern of the flow values on the graph following the opening of ASD-3 and emptying of the Accumulators; these varying flow values are caused by the IRWST, of which occasional flow has started due to the release of pressure by the ADS valves, assisting with the flow of water to the core.

The second part of the ADS system involves the opening of the fourth and final stage of larger ADS-4 valves. Opening of the ADS-4 valves is initiated by a low CMT liquid level, bringing the primary side pressure level down to that of the containment once opened. Figure 20 below illustrates the system after the ACC tanks have been emptied, and the ADS-4 valves have been opened. Note that the CMT levels are low, which initiated the opening of the ADS-4 valves. It is also worth noting that a considerable amount of coolant is starting to gather at the bottom of the containment vessel, also known as the sump, which has escaped through the CL4 break and CMT valves.

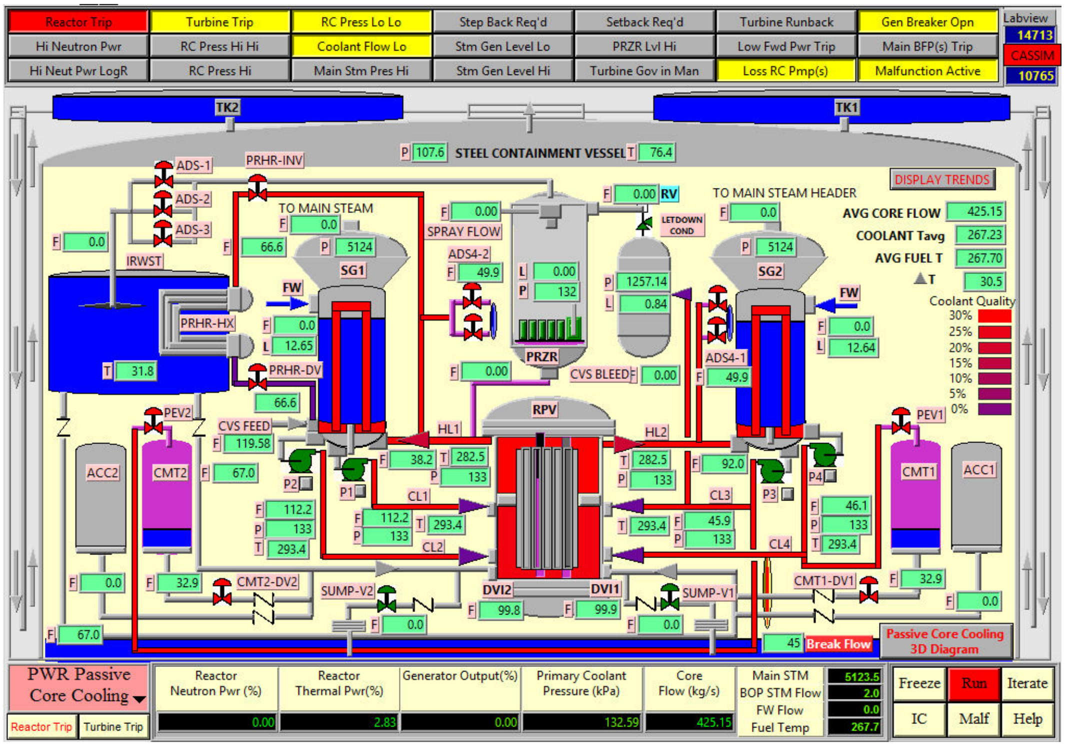



**Figure 20: System screenshot, ADS-4 valves open and ACC tanks empty**

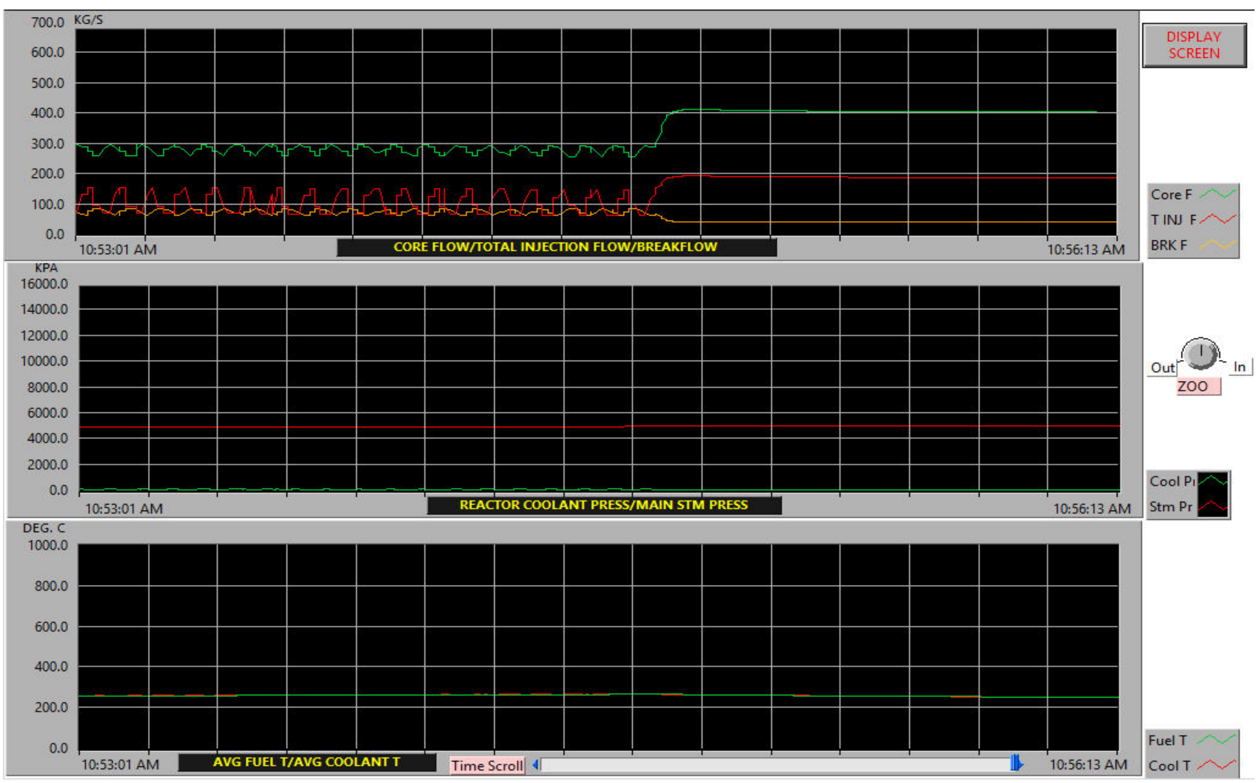



**Figure 21: Graph screenshot, ADS-4 valves opening**

The effect of the ADS-4 valves opening can be noted in the top graph of Figure 21 representing the flow values. As with ADS-1 to ADS-3, opening of the ADS-4 valves also causes the primary side pressure to decrease; however, due to the bigger size of the ADS-4 valves, the pressure now decreases to the point where it is equal to the containment pressure. This once again causes the core flow and total injection flow rates to increase, while the break flow rate decreases due to the drop in primary system pressure, evident from the top flow graph in Figure 21. It is also noted that the IRWST flow rates have now become constant due to the lower pressure, illustrated by the flow values becoming relatively constant on the graph. This is also evident when considering the IRWST flow rate during the simulation portrayed in Figure 20.

As the IRWST is aimed at removing decay heat from the core for extended periods, the system in terms of the passive safety systems stabilized. During the time to follow, these aspects were noted:

- The temperature of the upper and lower sections of the core started to decrease, causing the entire system's temperature and pressure to decrease slowly.
- Flow from CMT 1 and CMT 2 decreased substantially as they empty.
- Outside containment cooling tanks continued to spray water on the outside of the steal containment when the pressure increased.
- The IRWST continued to drain slowly.
- The flow rate from the break at CL#4 remained constant.
- The water level in the sump continued to rise slowly, ultimately reaching the bottom of the reactor pressure vessel.

The next and essentially final passive safety system to activate is the opening of the sump valves to establish long term passive sump circulation. The natural circulation through convection established by opening of the sump valves can now continue to keep the core cool, thus assisting in removing decay heat. The valves allow cool water to enter the core where it heats up and turns into steam. The steam vented mainly through the ADS-4 valves into the steel containment vessel is cooled by encountering the colder inside of the containment vessel, after which it returns to the sump. The steam released through the ADS-4 valves will also allow cool water to be drawn in at the bottom of the reactor, establishing a natural circulation loop. Sump valves 1 and 2 can be noted in the open position in Figure 22 below. It is evident how much the amount of coolant gathering in the sump has increased, as well as the liquid level of the IRWST and roof containment cooling tanks.

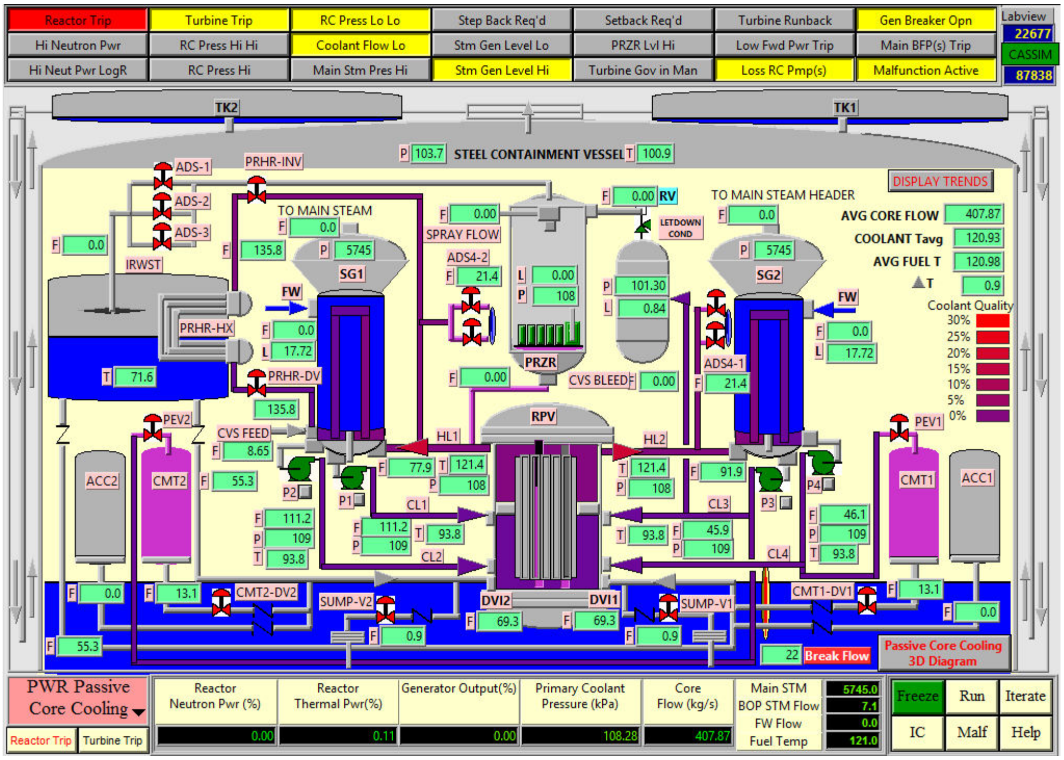



**Figure 22: System screenshot, opening of sump valves**

Lastly, Figure 23 below illustrates the containment structure after leaving the simulation to continue running for approximately 12 hours. Comparing Figure 23 below to Figure 22 above, it can be noted that the main system pressure has continued to decrease, while the sump is continuing to fill up because of the coolant being released from the IRWST. It can also be noted that the flow through sump valve 1 and 2 is slowly increasing, as the coolant level in the sump increases, while the break flow decreases. The core temperature is also continually decreasing, illustrating that the core is sufficiently cooled by the long-term passive sump cooling system. An inconstancy was noted, however, in the containment temperature. Figure 22 shows that the temperature is 100.9 0C, normal considering the temperature has slowly increased throughout the simulation. Figure 23 shows that the temperature has increased substantially to a value which cannot even be displayed by the value block or any of the graphs, while continuing to increase abnormally fast at the time when the screenshot was taken. The substantial rate at which the temperature increased was carefully monitored for a while, during which time it increased by hundreds of thousands of degrees. As none of the other values in the simulation showed similar increases or decreases, it must be assumed that this value must have grown inaccurate due to an error in the simulation code initiated when simulating a reactor for an extended period.

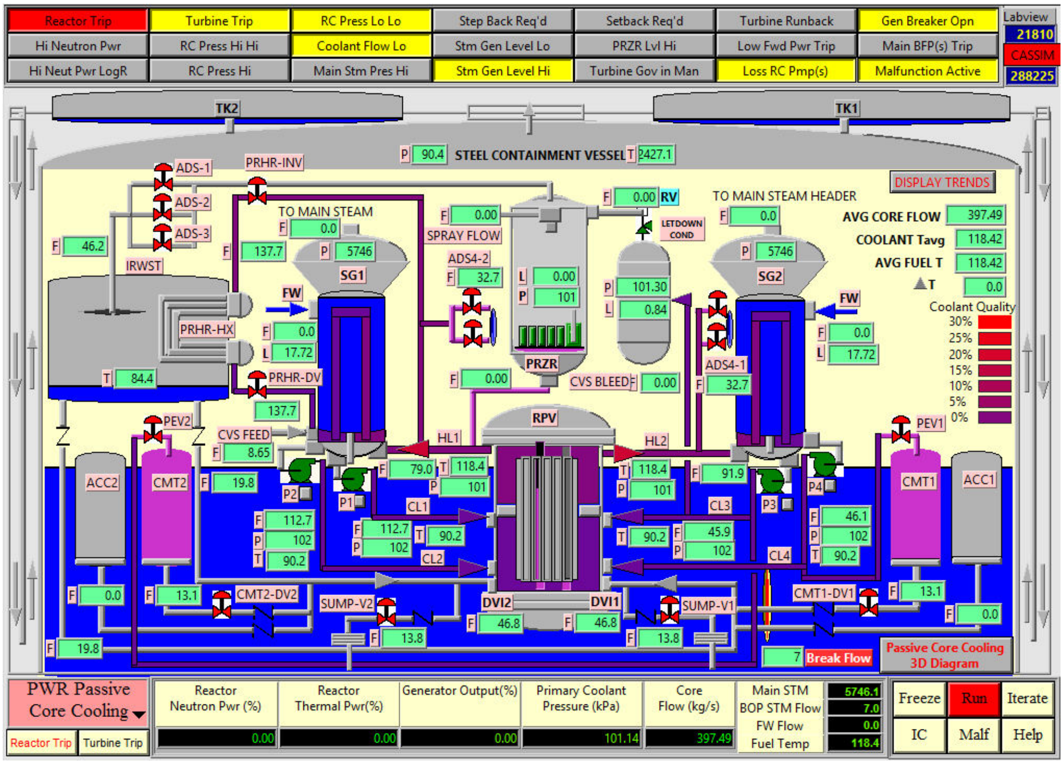



**Figure 23: System screenshot after running for approximately 12 hours**

### 5.4 PWR reactor simulation of the APR1000

The aim of the simulation is to illustrate the differences in safety features between the APR1000 and the PWR reactor from the first simulation making use of added passive safety features, even though these two reactors are technically of the same type and generation. The first step necessary is to identify the safety systems used by the APR1000, which consist of active, passive and hybrid systems.

The first, known as the Safety Injection System (SIS), or Emergency Core Cooling System, is of specific significance to this study as its main purpose is to cool the core in the event of a LOCA, which is to be studied in the simulation to follow. The aim of the SIS is to remove decay heat following reactor scram triggered by a LOCA, preventing fuel melting or alteration of the core geometry for extended periods of time. The system consists of two High Pressure Safety Injection (HPSI) pumps, as well as two Low Pressure Safety Injection (LPSI) pumps used to inject borated water directly into the RPV. These are split into two trains, or essentially two parts of the system, each consisting of two active Safety Injection Pumps (SIPs) and two passive Safety Injection Tanks (SITs) with a Fluidic Device (FD). This system is replaced by the two core make-up tanks which form part of the passive CMT safety system in the first reactor simulated (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

The second safety system briefly mentioned above is known as a Fluidic Device (FD) and essentially forms part of the SIS. The FD is a passive flow regulator to control the flow of coolant out of the SIT. To better understand the purpose of the systems, Figure 24 can be considered below.

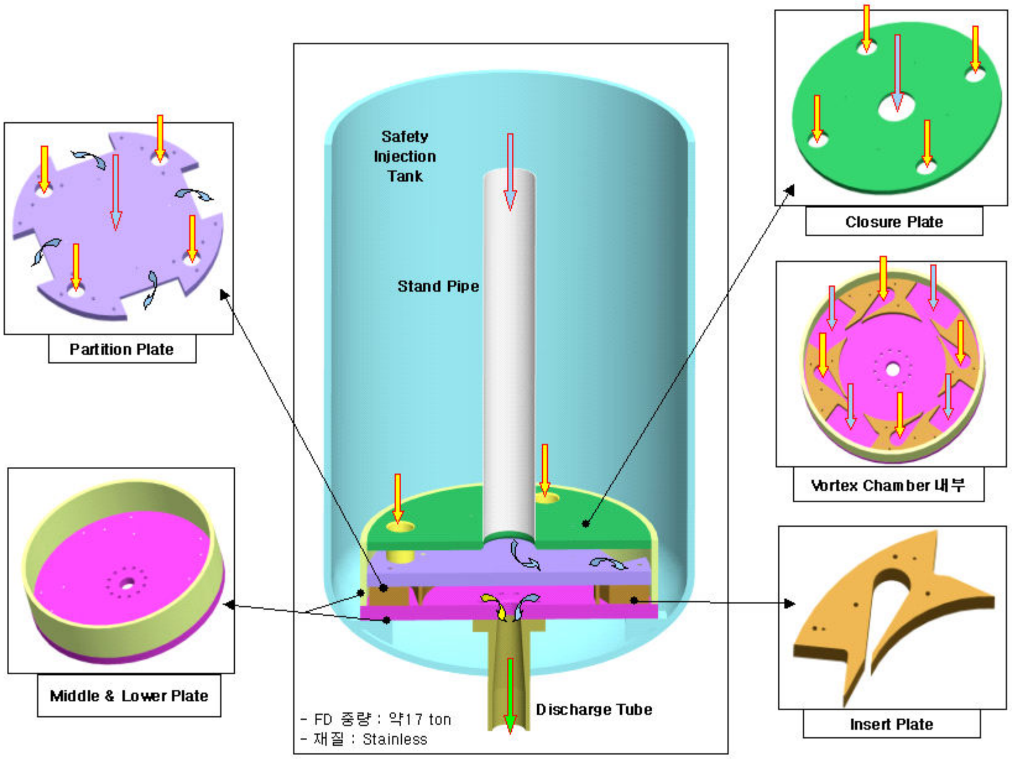



**Figure 24: Working principal of the Fluidic Device (FD) forming part of the Safety Injection System (SIS)**

Considering the diagram above, when the water level is above that of the stand pipe seen in the middle, a high flow rate is achieved due to the rectangular position of the stand pipe to the exit nozzle, as well as the low vortex resistance created by the vortex chamber at the bottom. When the water level drops below that of the stand pipe, the coolant continues to exit through the smaller holes positioned tangential to the exit nozzle, also flowing through control ports, creating a high vortex resistance and therefore a lower flow rate. This system is able to regulate the flow rate from the tanks, starting with a high initial flow, then decreasing the rate of flow as the tank empties (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

The third safety system, known as the Shutdown Cooling System (SCS), is used to cool the RCS during post shutdown conditions in conjunction with the main steam and auxiliary feed water systems. The SCS essentially consists of two independent systems, each with its own low-pressure safety injection pump for circulating coolant through the shutdown cooling heat exchanger. The SCS is activated at 176.7 0C and 28.82 kg/cm2 A, after initial dissipation of heat through the steam generators to the secondary side condenser, followed by the atmospheric dump valves. The system works as follows: after shutdown of the reactors, coolant is redirected through shutdown cooling nozzles located on the hot legs to the shutdown cooling heat exchangers using the LPSI pumps. After cooling, the coolant is returned to the reactor through four low-pressure safety injection systems located on the cold legs. The cooling rate of the system is controlled by throttle valves located on the heat exchangers. Considering the working of this system, the system can be regarded as an active cooling system (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

The forth safety system is the Auxiliary Feed Water System (AFWS) used for heat removal from the RCS in event that the main feed water system becomes unavailable. As the AFWS can supply auxiliary feed water to the SGs, it is also able to assist in minimizing leakage in the event of a steam generator tube rupture. The reliability of this system is enhanced by its design, which splits the system into two independent sub-systems: the first consists of a motor-driven pump capable of driving the system at full capacity, while the second consists of a turbine driven pump, also capable of driving the AFWS at full capacity. In addition, the AFWS has a dedicated auxiliary feed water storage tank, as well as a non-safety grade concrete storage tank, as backup for each of the system's two divisions (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

The fifth safety system is known as the Safety Depressurization and Vent System (SDVS), used in an event where pressurizer spray becomes unavailable during plant cool down to achieve cold shutdown. The system is also used as a means of rapid depressurization to initiate what is known as the 'feed and bleed' method to cool down the plant in the event of total loss of feed water. When initiating the 'feed and bleed' method, Pilot Operated Safety Relief Valves (POSRVs) assist in establishing a path for the steam to flow between the pressurizer and reactor drain tank (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

The sixth safety system is the Containment Spray System (CSS) used for cooling of the containment atmosphere, as well as for the removal of radioactive fission products from the atmosphere inside of the containment. This particular system works by spraying water into the containment's atmosphere through nozzles on spray headers in the containment dome fed from the Refuelling Water Tank (RWT). Additionally, auxiliary nozzles are located on spray headers below the operating floor to provide additional cooling from below, working in conjunction with the top nozzles to maintain containment pressure and temperature within design limits. If the RWT were to empty, the design of the system also allows for water to be sucked from the containment sump and re-circulated (KEPCO/KHNP, 2011; Korea Atomic Energy Research Institute, 2004).

### 5.4.1 Simulation 2

To effectively compare the results of this second simulation to that of the first, a small LOCA break is again chosen as the malfunction to be inserted. In doing this, the way in which the safety systems react and prevents the LOCA from escalating into a dangerous situation can be observed and compared to one another. Although different software is used for the second simulation, the break will again be inserted on one of the cold legs supplying coolant to the reactor, while the reactor is initially running at 100% capacity. As mentioned before, the reactors simulated are of the same type, with the difference being that the first makes use of additional newer passive safety systems, while the second simulation to follow makes use of overwhelmingly active safety systems. The initial state of the power plant to simulate the APR1000 reactor running at 100% with no malfunctions active can be observed in Figures 25 and 26 below.

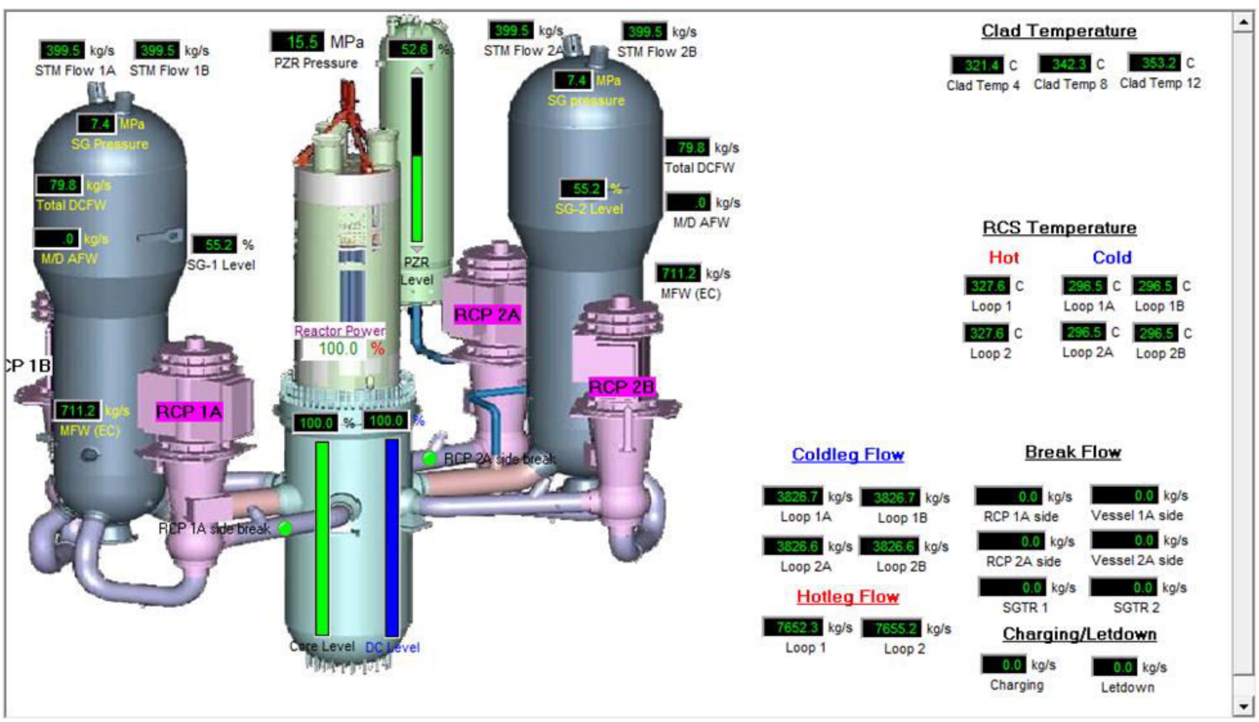



**Figure 25: Plant overview of initial/baseline condition, no malfunction active**

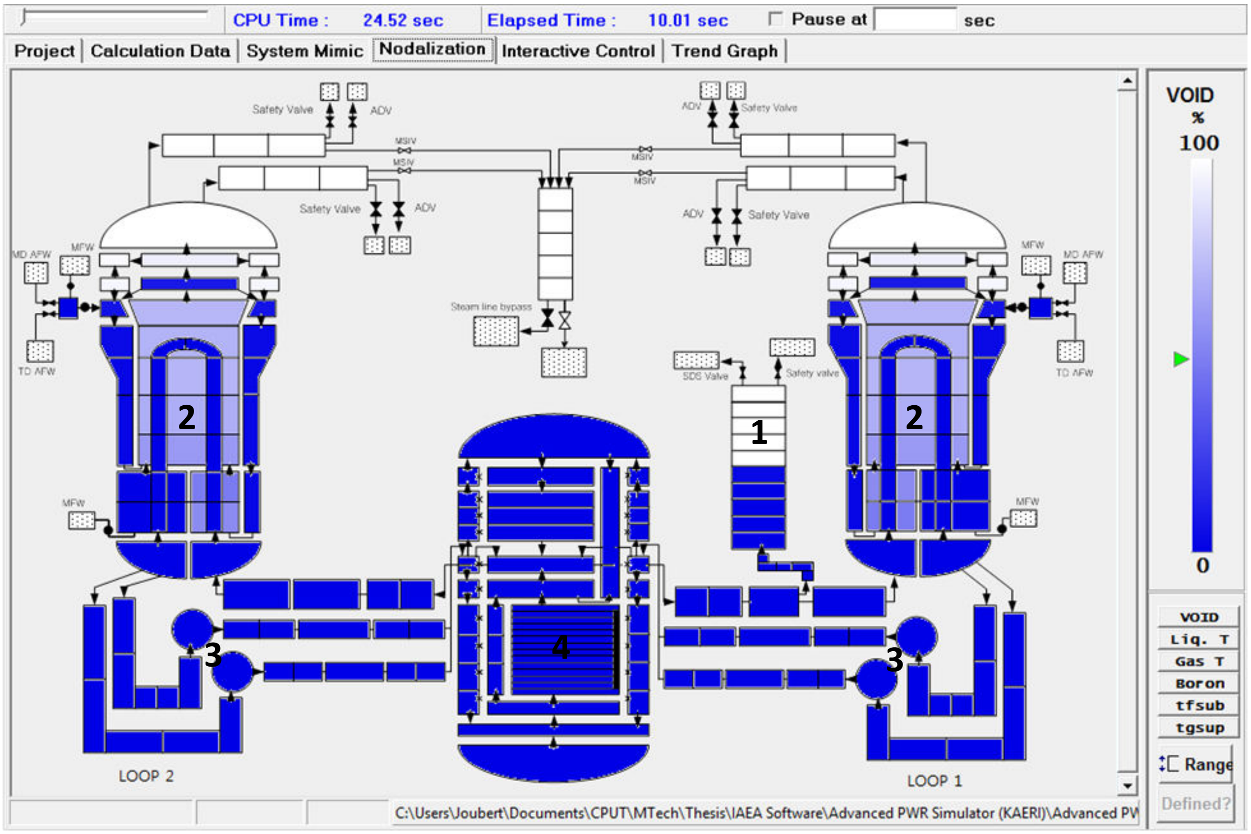



**Figure 26: Initial/baseline condition of void distribution screen, no malfunction active**

Figures 25 and 26 both represent the plant under normal operating conditions after running the simulation for approximately 10 seconds. Figure 25 is a virtual representation of the plant used for displaying important pressure, flow and temperature values. While the diagram in Figure 26 displays the same components as that of Figure 25, it visually illustrates the flow of coolant, the presence of voids, and the liquid temperature, gas temperature and other relevant information for monitoring the stability of the power plant. Considering the layout in Figure 26, the first noteworthy component is the pressurizer, labelled as '1'. The top half of the pressurizer shows as void as it is filled with steam to control the RCS pressure. The top part of the pressurizer is also the only part of the primary RCS loop that is not filled with coolant under normal operating conditions. The second parts of the system, labelled as '2', are the two steam generators (SG). As evident from Figure 26, these essentially consist of three parts: the down comer, the riser and the steam dome. The two reactor cooling pumps (RCP) on each side labelled as '3' should also be noted, making a total of four pumps used to cool the reactor under normal operating conditions. Lastly, the main component of a nuclear power plant, the reactor, can be seen labelled as '4' (Korea Atomic Energy Research Institute, 2004).

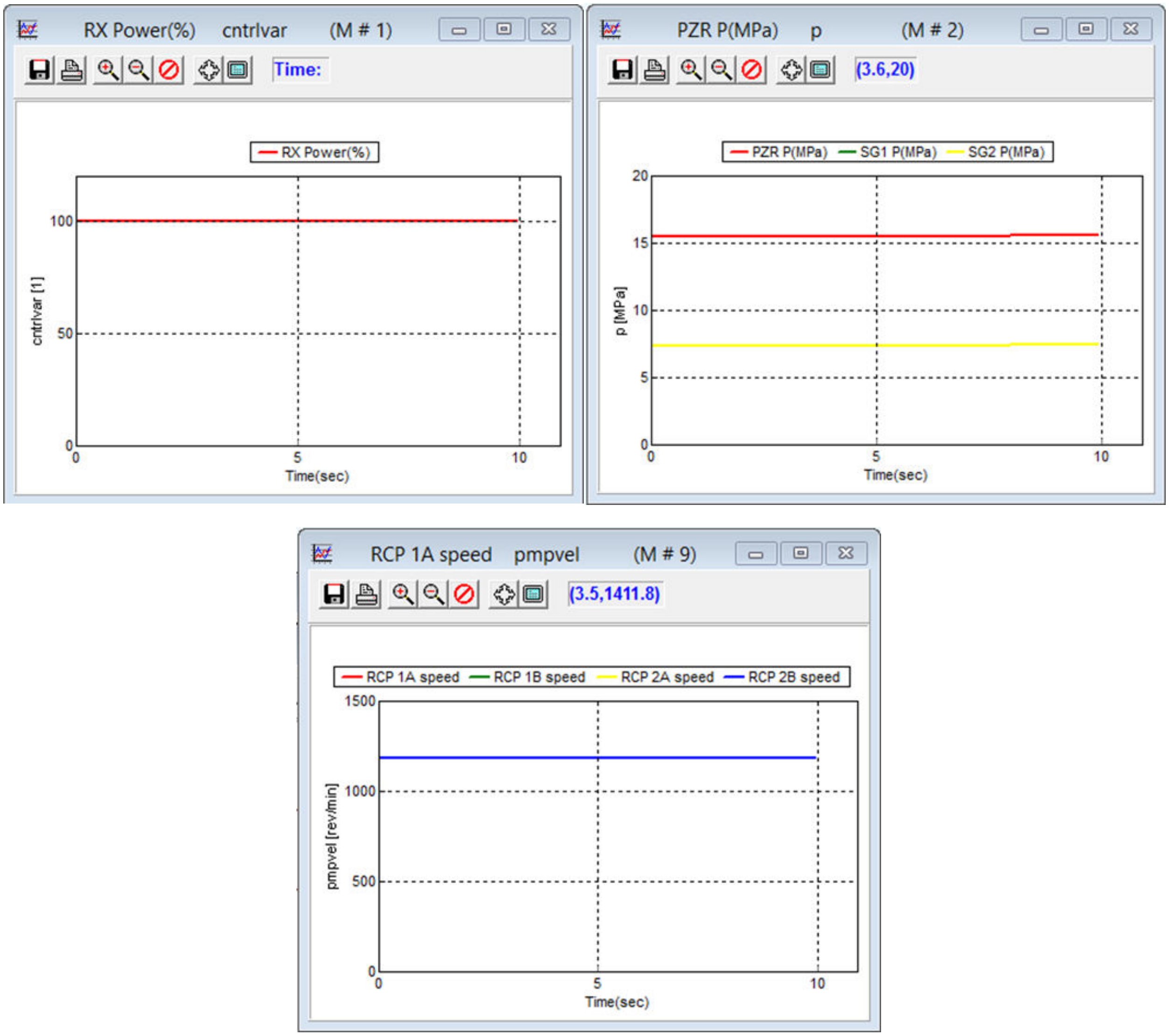



**Figure 27: Reactor power, pressurizer pressure and coolant pump speed, no malfunction active**

The graphs in Figure 27 above are among some of those used to display important information and parameters also represented in the virtual plant overview and diagrams of Figures 25 and 26, allowing changes in the plant's state and stability to be easily noted. All the graphs above represent the power plant under normal operating conditions after running the simulation for approximately 10 seconds. The top left graph in Figure 27 illustrates the reactor power, which, as mentioned earlier, is operating at 100% capacity. The top right graph in Figure 27 illustrates the pressurizer and steam generator pressure under normal operating conditions, while the bottom centre graph illustrates the reactor coolant pump speed for each of the four cooling pumps.

Under normal operating conditions with no malfunctions active, almost all values can be considered as constant.

The first step in obtaining the simulation results is to insert the LOCA. Figure 28 below illustrates the simulator's interactive control screen, with the 3% LOCA1 break activated.

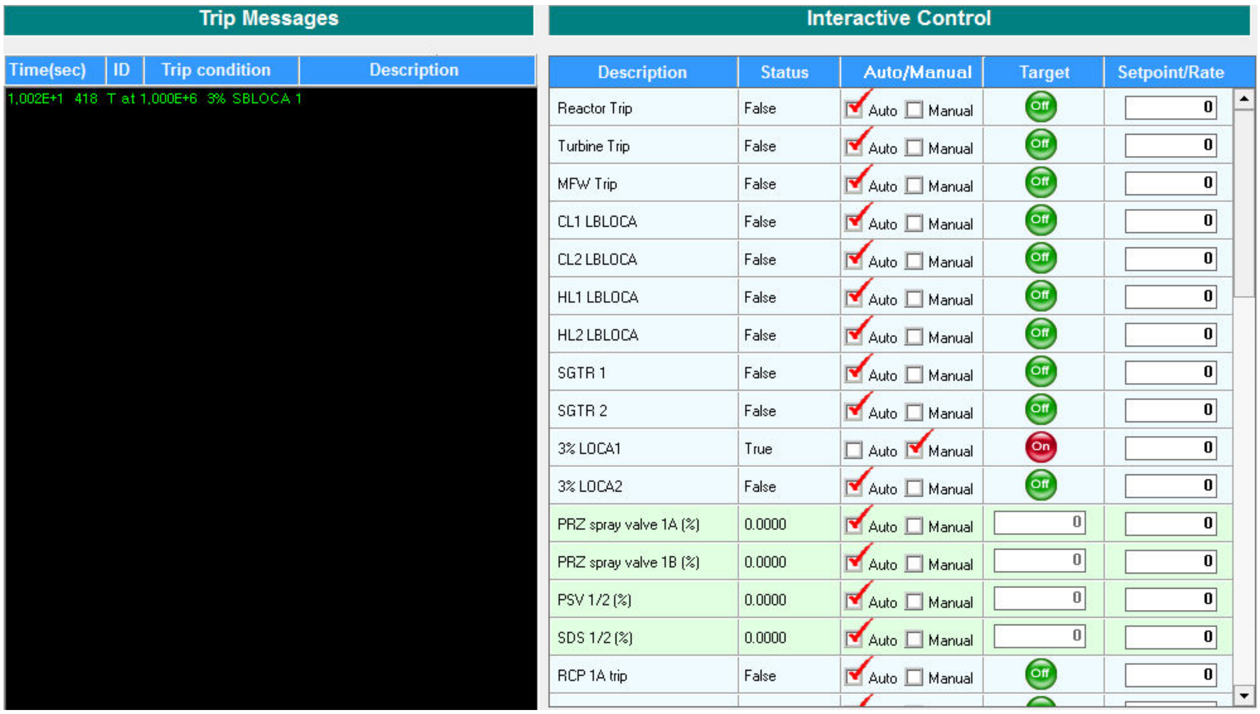



**Figure 28: Interactive control screen, 3% LOCA1 break selected**

The 3% LOCA1 break is selected and indicates that a break resulting in a 3% loss of coolant flowing through cold leg #1 to the core will be inserted at a 0 second time delay. Since there is no time delay, the malfunction immediately shows up as being active in the trip message screen to the right in Figure 28. As the simulation has already been running for 10 seconds, note that the malfunction is inserted at 10 seconds with a 0 second delay, meaning that the malfunction is active from 10 seconds onwards. The LOCA inserted on cold leg #1 caused the primary system pressure: coolant levels to begin decreasing soon after, which is sensed by the pressurizer. This is noted from the graph in Figure 29 below, where pressurizer pressure is indicated by the red line.

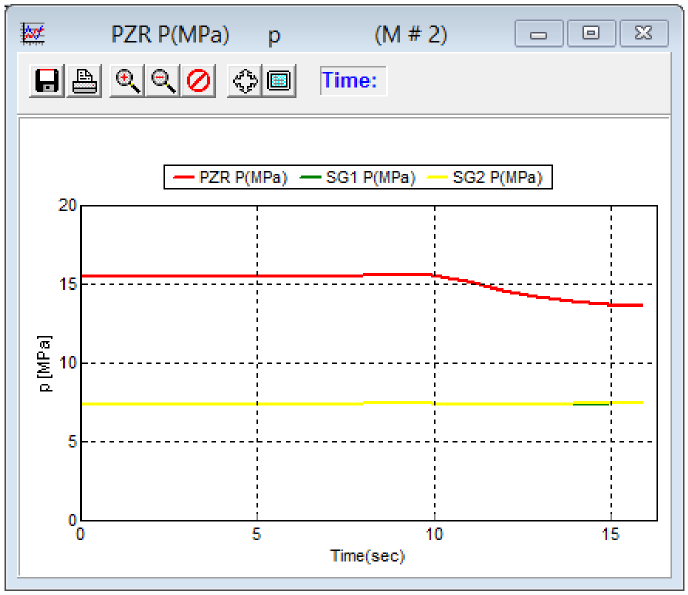



**Figure 29: Pressurizer pressure after inserting the LOCA at t=10 seconds**

The sudden drop in pressure and flow rate sensed by the pressurizer activates several alarms, instigating the safety systems and procedures listed below. The following actions were noted from the simulation, in the order listed, following closely one after the other:

- Low pressurizer pressure trip set point is reached at approximately 28 seconds.
- The reactor and turbines are tripped automatically.
- The reactor scrams approximately 2 seconds after low pressurizer pressure signal.
- This is followed by main feed water (MFW) isolation.

Considering the void distribution tab after 30 seconds, as illustrated in Figure 30 below, when compared to the initial condition illustrated in Figure 26, it can be noted that after 30 seconds the level in the pressurized is on the decrease because of coolant escaping through the LOCA. Additionally, the water level at the top of the SG has also begun to decrease.

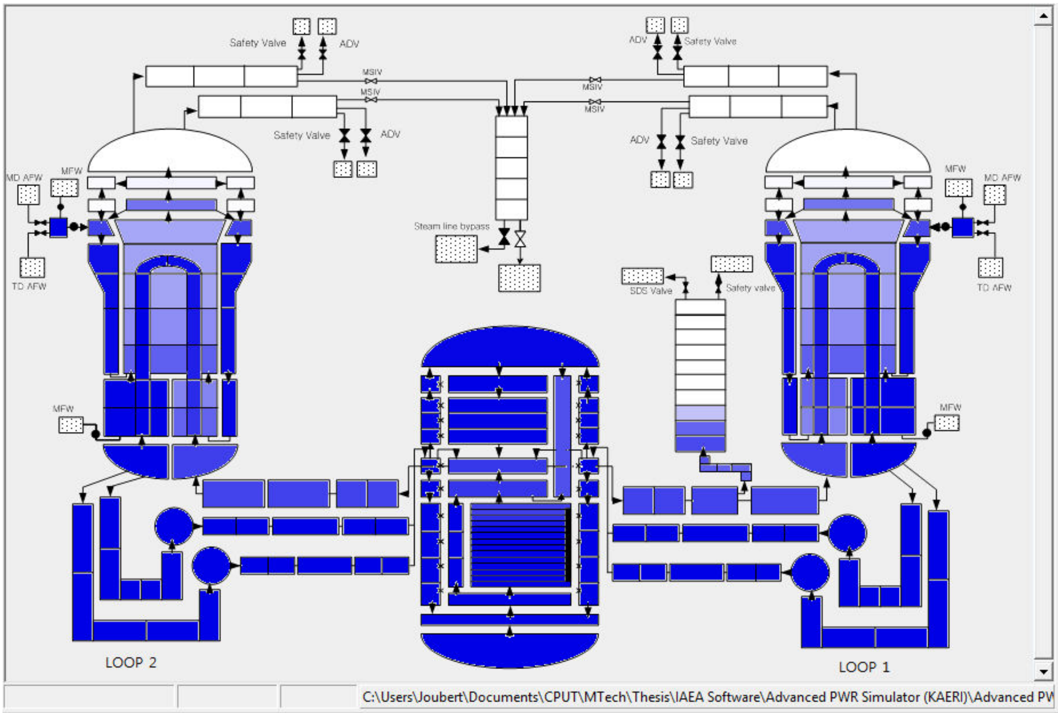



**Figure 30: Void distribution screen at t=30 seconds**

Considering the events up until t=30 seconds represented by the graphs in Figure 31 below, it can firstly be noted from the pressurizer pressure graph that as soon as the LOCA is introduced at t=10 seconds, the pressurizer pressure decreases because of the coolant now being discharged through the break. This reduction in pressure is to be expected as coolant is escaping through the break introduced on CL 1, causing the system pressure to drop. The next event can be observed from the core void distribution graph in Figure 31, illustrating voids in different sections of the core. The first void begins to form in section 12 of the reactor core at approximately t=13 seconds, at the very top part of the reactor. This void starts to form because of the pressurizer level, represented by the red line in the coolant level graph, which has now dropped to the extent that it is unable to supply enough cooling to the core. The void forming in the core can also be identified in the core level graph, as it begins to decrease from 100% at approximately t=13 seconds. Another event is noted when considering the coolant level graph at approximately 27 seconds, when a small spike in the SG pressure values occur. This spike is the result of the reactor scramming, causing the reactor power to decrease rapidly and significantly. From the coolant level graph, it can also be noted that reactor scramming has an effect on the 'SG NR(%)' level. SG NR(%) refers to the steam generator narrow range level as a percentage value. The NR value is usually measured just below the U-tube bend, as seen inside the SGs in Figure 30. Rather than simply a measured water level, the value is actually a combined measurement of the fluid density and pressure (Siniša & Grgić, 2017). It can therefore be stated in simple terms that the NR(%) value observed in the graph is essentially how close the coolant is to boiling and turning into a gas, which would occurs at a low NR(%) value.

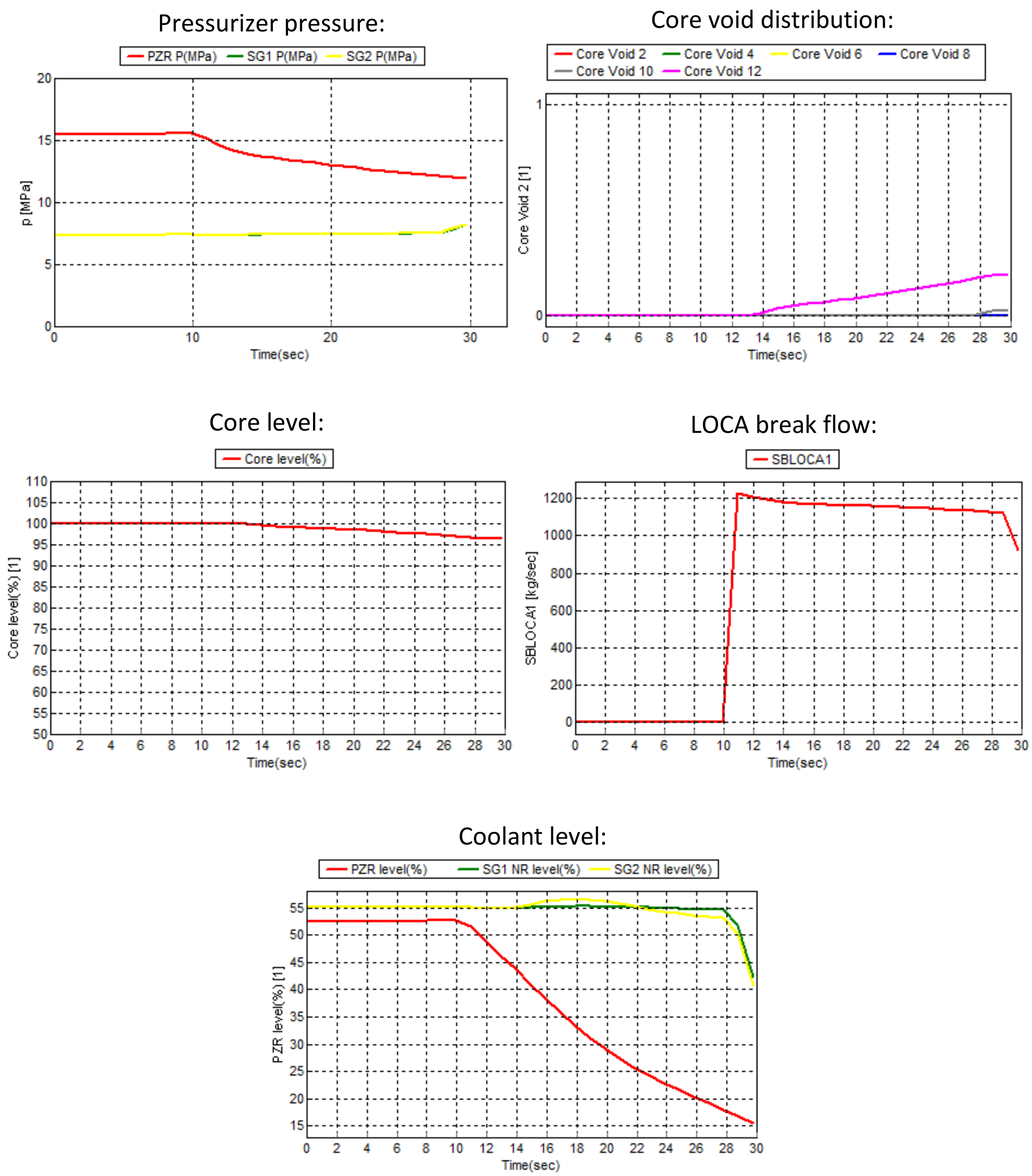



**Figure 31: Plant parameter graphs up until t=30 seconds**

Allowing the simulation to continue running onward from 30 seconds, unlike the first simulation, the reactor coolant pumps (RCPs) did not trip automatically. After consulting the reactor and software manual, it was learned that this action is not automatic given the above circumstances and the reactor setup but is rated an action reserved for the operator (Korea Atomic Energy Research Institute, 2004; KAERI, 2004). With these circumstances and knowledge acquired, the RCPs were then tripped manually at t=30 seconds, just after the reactor scrammed, as seen in Figure 32 below.


**Figure 32: Manual tripping of the RCPs at t=30 seconds**

Furthermore, Figure 32 reveals that immediately after manually tripping the four RCP's at t=30, two low flow trips were also received roughly 3 seconds later. After receiving the low flow signals, the simulation was left to run. At t=57 seconds, the safety injection system (SIS) was activated to remove reactor decay heat. Figure 33 shows that the SIS was turned on because of the low pressurizer pressure trip signal received at t=27 seconds; however, since the SIS has a 30 second delay, the SIS was initiated at t=57 seconds.

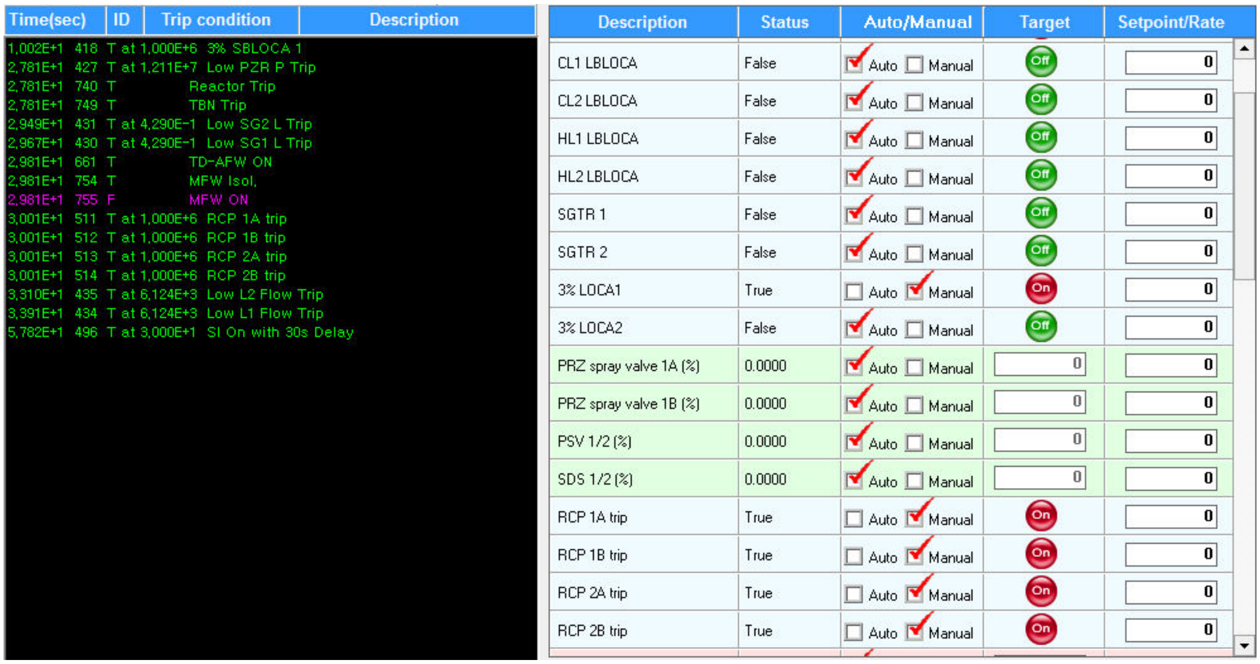



**Figure 33: Initiation of the SIS after a 30 second delay**

Continuing to observe the void distribution tab after manually tripping the RCPs, the coolant continued to drop in the pressurizer and SGs. After approximately 50 seconds, the upper part of the reactor core also became void, as well as the entire pressurizer, due to the RCS coolant escaping through the LOCA break. Considering the void distribution tab from 60 seconds onwards, after initiation of the high-pressure SIS, the coolant in the SGs appeared to have become nearly stagnant from low heat transfer between the primary and secondary sides. These events should also be noted when considering the graphs, which represent the simulation up to t=100 seconds.

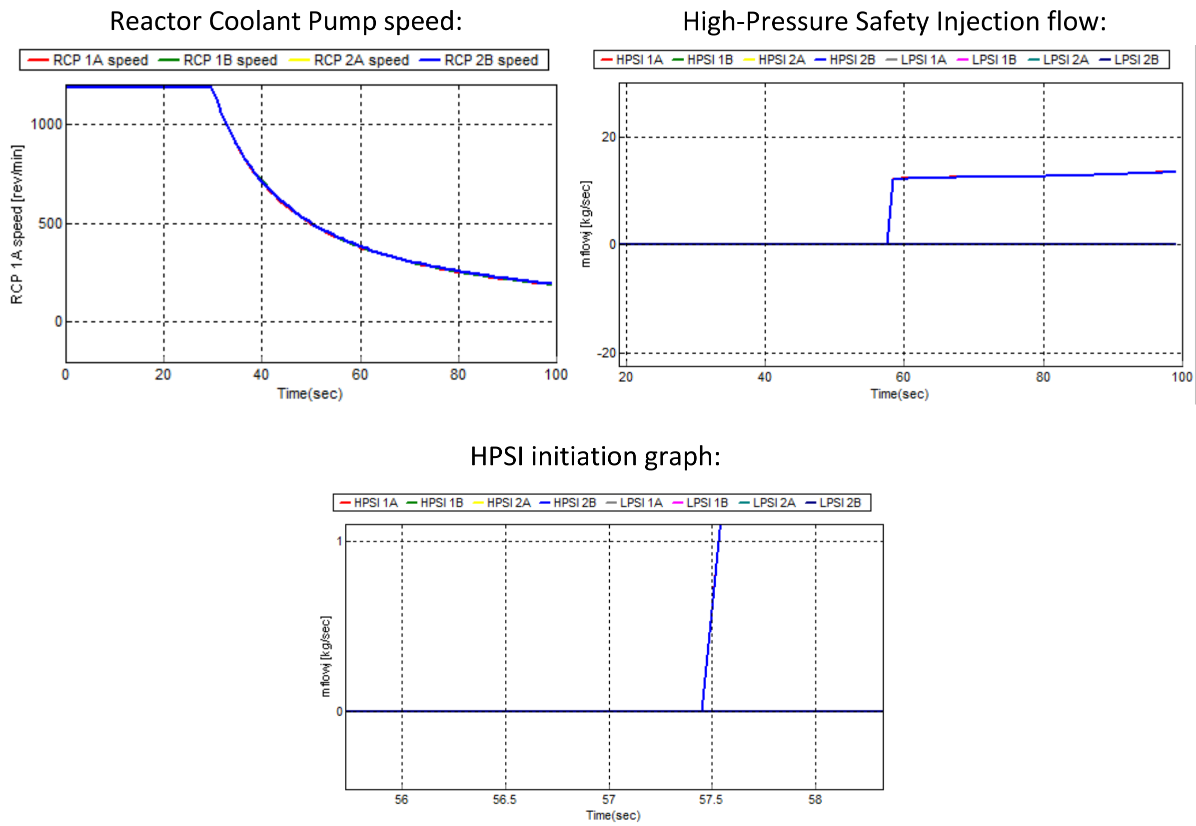



**Figure 34: Plant parameter graphs up until t=100 seconds**

Considering the Reactor Coolant Pump speed in Figure 34, it is important to note that all RCPs are tripped manually at t=30 seconds, after which their speed slowly reduces. Initiation of the HPSI system can be seen in the High-Pressure Safety Injection flow graph, with a zoomed in view of the moment it is initiated in the HPSI initiation graph. The SIS is initiated 30 seconds after receiving the low pressurizer pressure signal, as the safety injection system is automatically started with a 30 second delay. Continuing to run the simulation, the screenshot in Figure 35 was obtained after 350 seconds.

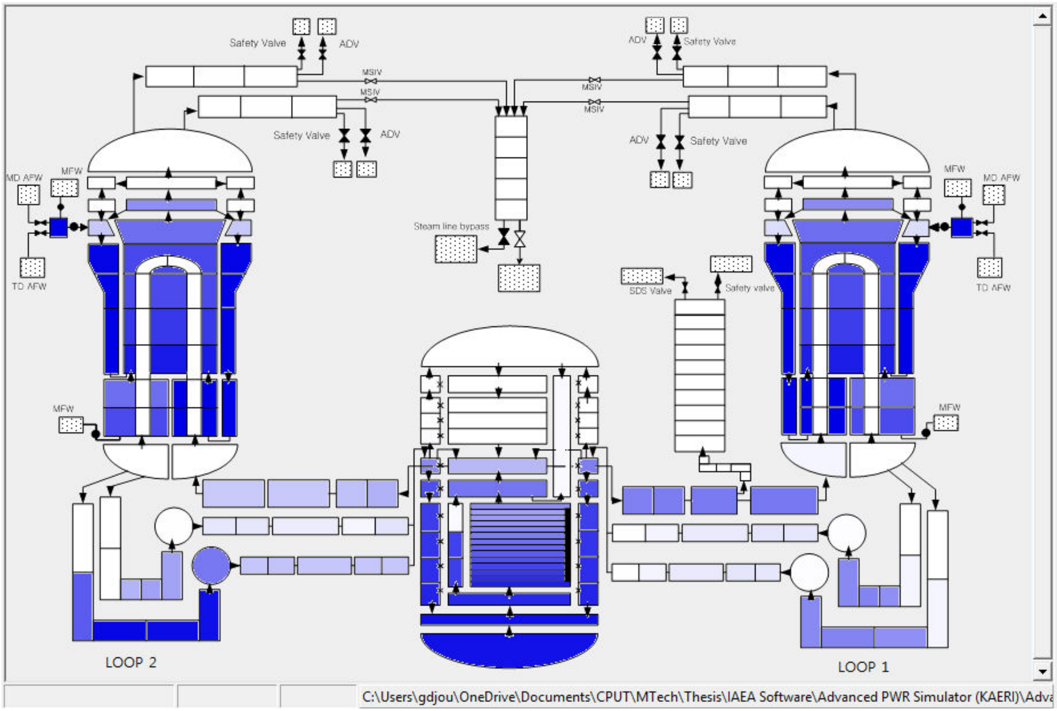



**Figure 35: Void distribution screen after 350 seconds**

Up until this point in simulation, it was observed that the coolant levels at the top of the reactor continued to drop, filling with vapour. Moreover, a void began to form in the cold legs feeding coolant to the reactor, which by 350 seconds has become almost completely void. The simulation was then continued to 400 seconds, at which time the screenshots in Figure 36 were obtained.

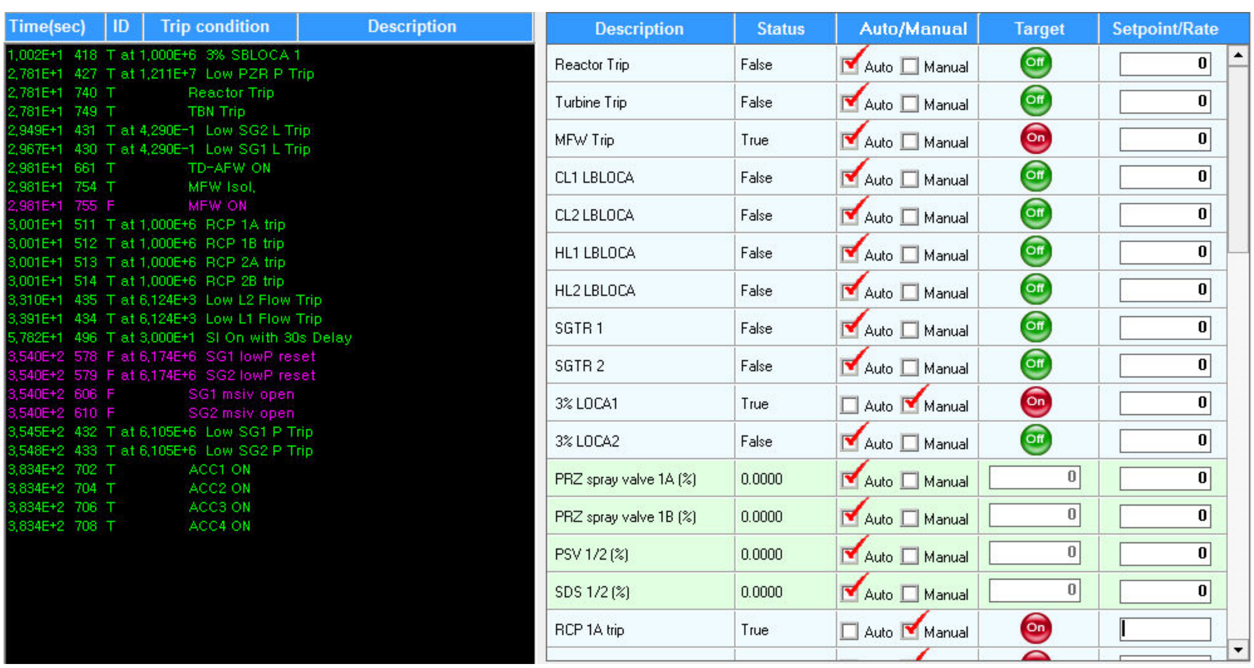



**Figure 36: MSIV open and ACC system activates**

From the trip message screen on the right-hand side of Figure 36, it should be noted that at t=354 seconds the low-pressure signal of the steam generators resets automatically, while the main steam isolation valves (MSIV) are opened automatically.  Half a second later, a low steam generator pressure trip signal is again initiated, when the 'Low SG1 P Trip' trip signal appears again.  A trip signal from SG2 also follows closely 0.3 seconds after that of SG1.  At t=383 seconds, ACC 1 to 4 is initiated to assist in cooling the reactor, filling some of the reactor voids visible in Figure 35 earlier.

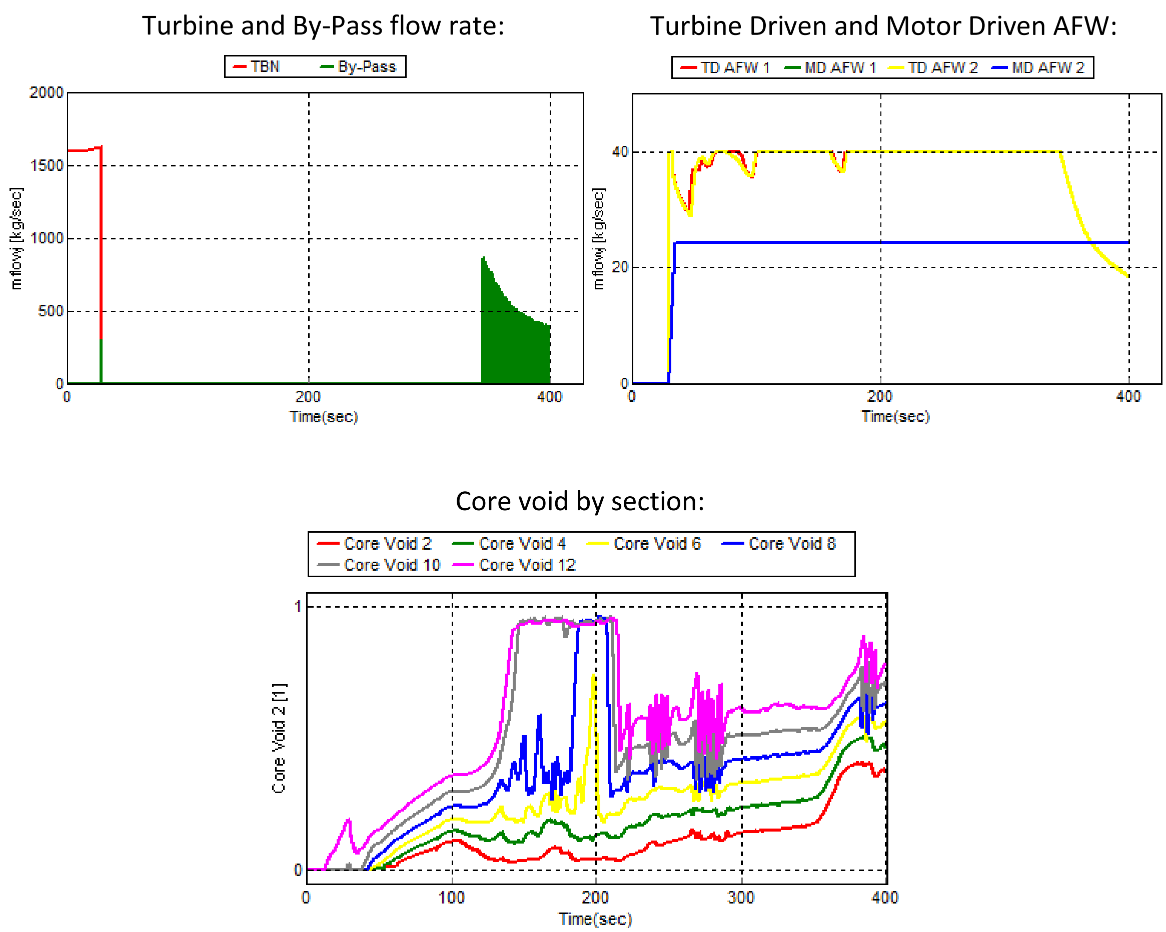



**Figure 37: Plant parameter graphs up until 400 seconds**

The plant parameter graphs in Figure 37 up until 400 seconds reveal that the opening of the main steam isolation valves (MSIV) shows up in the Turbine and By-pass flow rate graph in green, representing the turbines and steam generators by-pass flow.  Opening of the MSIV will also affect the turbine driven auxiliary feed water system, as coolant is now flowing through the by-pass, evident from the Turbine Driven and Motor Driven AFW graph in Figure 37. Considering the core void by section graph, it can be noted that the core void begins to increase rapidly.  At t=283 seconds, the ACC systems are activated, providing additional cooling to the core.  This can be seen in the core void by section graph just before 400 seconds.

The simulation was then allowed to continue until 600 seconds, at which time the plant parameter graphs in Figure 38 were obtained.

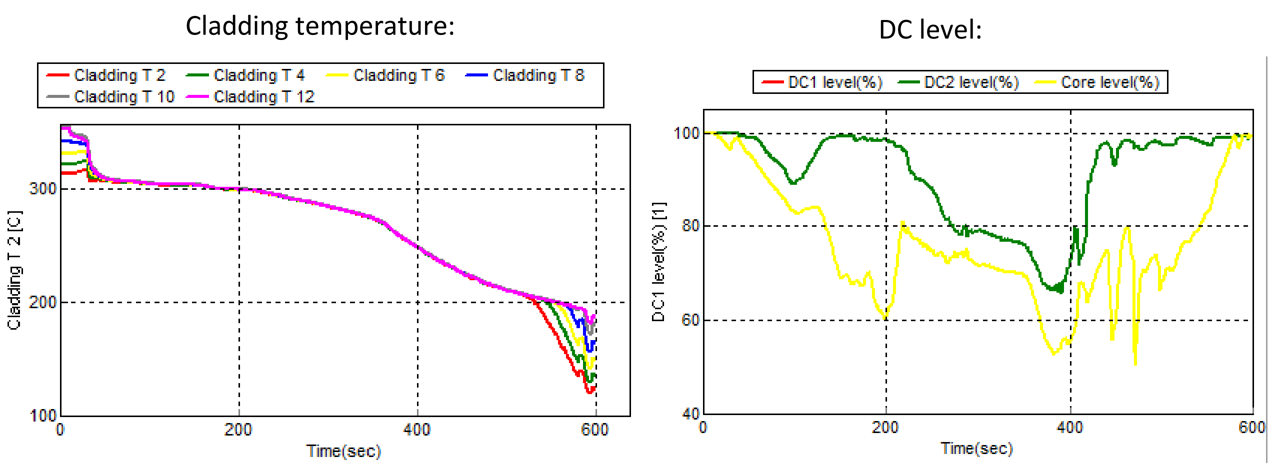



**Figure 38: Plant parameter graph from t=0 to t=600 seconds**

The cladding temperature graph in Figure 38 represents the cladding temperature from t=0 seconds to t=600 seconds. During the simulation, the cladding temperatures continued to decrease because of the primary pressure and fluid temperature decrease. The DC level graph reveals that the core and down comer (DC) collapsed level starts to recover at around t=400 seconds, when activation of the ACC system occurred. This also indicates that the core and cooling is busy recovering in such a way that the core can be continually covered by two-phase water, meaning that core heat-up will not occur. The DC level graph, therefore, essentially indicates that the system is recovering from its unstable state, to the extent where it is not in danger of progressing into meltdown.

The simulation was then left to run until it automatically aborted at t=624.82 seconds, at which time the simulation was considered finished by the software. A final void distribution screenshot can be seen in Figure 39 below.

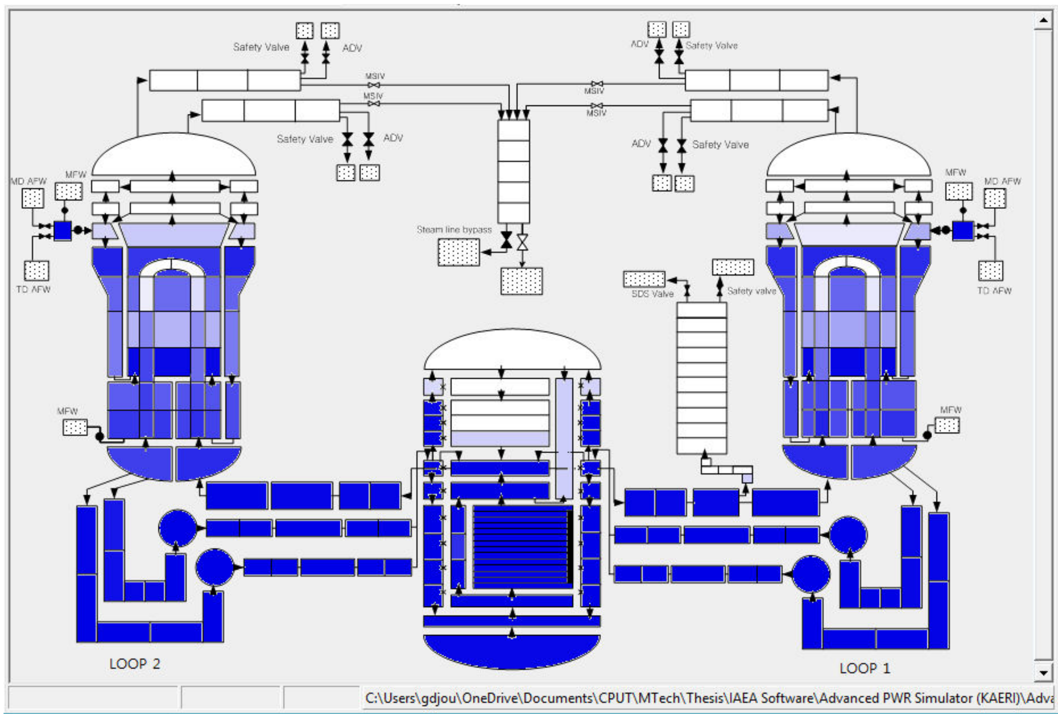



**Figure 39: Void distribution screen at t=624.82 seconds**

Comparing Figures 35 at 500 seconds to Figure 39 above, it is clear that activation of the ACC system has managed to fill the cold legs and core with the coolant necessary to sufficiently cool the core. At this point, the reactor is considered sufficiently cooled and stable, as all the necessary safety systems have activated. Because this stable state has been reached, the simulation aborted automatically, bringing an end to the simulation.

### 5.5 Chapter conclusion

During the theoretical research it was mentioned that the advances in nuclear power plant safety primarily include the automation of safety systems and protocols while replacing active safety systems with more rugged passive systems. These statements are backed up by the simulations, as it became evident that during simulation 1 making use of newer passive safety systems, actions such as shutting down the main reactor coolant pumps (RCP) occurred automatically, while this action was still required to be done manually during simulation 2. Simulation 1 also included passive core cooling systems such as the CMT, which replace the main hybrid SIS system used for emergency core cooling in simulation 2. Overall, when comparing the two systems, it was determined that the several safety systems initiated during the first simulation are much more passive in nature, often making use of parameters such as system or coolant pressure to open pressure valves, initiating the systems. Contrarily to this, simulation 2 makes use of only two main systems, often requiring electricity to initiate the systems electronically. Considering the two simulations, simulation 1 appears to be much more resilient and more capable of adapting to unforeseen circumstances because it is overwhelmingly passive, while incorporating several smaller systems. It should be noted again, however, that the systems initiated in the simulations are specifically applied to deal with a LOCA, as this is among the most feared of accidents which could potentially escalate into a dangerous situation. The safety systems activated are therefore by no means the only safety systems incorporated in these respective power plant designs.

# CHAPTER 6: RESEARCH SUMMARY AND ANALYSIS OF RESULTS

## 6.1 Chapter introduction

To achieve the goal of providing a compelling argument for the safety of nuclear power plants by investigating the advanced technological solutions and safety systems incorporated into their design, the concerns had to first be identified. By reviewing several papers throughout the study, the two predominant major concerns that came to light from the public were identified as reactor safety and waste disposal methods. The struggle for approval of this generation method is understandable, considering its origin as a method of producing plutonium for weapons production during World War II. A further distain for of this technology grew as the public began to realize that power utilities were keeping them in the dark when it comes to the workings and possible dangers of this new technology. The major loss of support for nuclear technology actually occurred in 1979 when the first catastrophic nuclear accident occurred at Three Mile Island, whereafter support plummeted (Otway, 2000).

## 6.2 Research findings

Nuclear technology, importantly including safety systems and waste disposal methods, has definitely come a long way since its early days. While accidents continued to provoke fear in the public, few realize that these events were in fact vital for learning about and developing new safety systems to improve stability and reliability. The forward movements in reactor design and safety which have occurred since the early generation I reactors can be summarized from the research in this paper as follows.

The introduction of generation II reactors reduced the need for manual operation through automation, thereby significantly reducing the possibility of human error. Generation II reactors also began to make use of passive safety systems in combination with active safety systems. This meant that the active systems could provide more precise and instantaneous protection, while the passive safety systems would be able to provide protection during extreme events. Lessons learned from accidents involving generation II reactors consequently led to the development of generation III and generation III+ reactors, which predominantly focused on the enhancement of safety through provision for even the most unlikely events, along with other improvements such as efficiency and lifespan. This led to the increased use of passive safety systems, as they have the advantage of being able to operate under even harsher conditions such as a total station blackout, while requiring no assistance from an operator. Research to further improve reactor safety, efficiency and lifespan is ongoing, evident from generation IV reactors currently in the early research and testing stages, with the aim of ultimately perfecting the process of nuclear power generation. Nevertheless, it becomes clear that the movement from generation I reactors to those currently being developed has focused on atomization and, more recently, the replacement of active safety systems with passive ones, answering to the fears of the public surrounding the possibility of another nuclear disaster. The continuous advances in reactor design and safety are made with the aim of providing protection against unforeseen and unanticipated events, which disasters of the past have shown to be the most significant threat (Goldberg & Rosner, 2011b; World Nuclear News, 2015; Bucknor *et al.,* 2017).

The second major concern most often associated with nuclear power plants is the production of nuclear waste. Contrary to the waste disposal methods used today, during the early plutonium producing days of nuclear reactors, the unprocessed waste would simply be stored in tanks or even dumped in the sea. These storage tanks and barrels, though, occasionally leaked, releasing highly radioactive material into the environment with catastrophic consequences. As with reactor safety, these past events generated misperception about the methods used today to dispose of and store the nuclear waste produced. A simple online search today will still reveal recent articles stating that the nuclear industry does not know what to do with the waste it is producing; however, considering the methods used to treat, store and dispose of the waste, this statement simply cannot be true. To address the concerns of the public, today's advanced technological solutions come in the form of not only the containment and disposal methods available, but also the strict regulations and requirements that all waste disposal methods must adhere to. These regulations and requirements are set out and provided by the IAEA and is available at the following reference (International Atomic Energy Agency, 2008).

Research revealed that the preferred present method of disposing of low and intermediate level waste, which makes up the largest percentage of the waste produced, is by casting them in cementitious materials. After casting and sealing the radioactive material in storage containers, they are thoroughly decontaminated and inspected for any leaks, whereafter they are sent for storage, mostly in underground repositories. High level wastes, on the other hand, are often first submerged in water on site at the power plant, as they continue to produce heat and therefore require cooling. The preferred disposal method includes processing the waste through calcined/drying, whereafter it is vitrified in a glass matrix and sent off for deep geological disposal. Although these are the methods most commonly used, there are also other methods available and in use, chosen based on the resources available. All disposal methods chosen *must* adhere to the strict requirements established for containment, such as that is should consist of at least three layers of containment: a primary packaging, an external container, and filling such as grout around the outer container (World-Nuclear, 2017; World Nuclear Association, 2017b; Sartori, 2013).

Although nuclear as a generation method produces among the most toxic waste of all the generation methods in use, it is important to remember that nuclear is also the only large-scale generation method taking *full responsibility* for all the waste it generates. It is felt, however, that the blinding focus on the waste produced by nuclear power plants has led to a misperception about the perceived amounts. This was backed up when assessing the total hazardous waste produced in a country such as the UK, where studies revealed that nuclear waste is only a small fraction of the total highly hazardous waste produced. The research further revealed that under normal operating conditions, coal fired power plants release approximately 100 times more radioactive material into the environment in the form of fly ash as compared to a nuclear power plant.

It can be argued that even though nuclear waste is governed by strict regulations ensuring proper management and disposal, while only being a small percentage of the total hazardous waste produced, the possibility still exists of another nuclear disaster occurring. The multiple layers of protection, in conjunction with the advanced safety systems discussed throughout this paper, all serve in preventing another nuclear accident from occurring. Even so, it is not possible to claim that all the safety systems and layers of protection will absolutely prevent a nuclear accident from ever occurring again.

The key in determining if nuclear as a generation method can be considered safe, therefore, lies in how it compares to its alternatives, which for the applications discussed earlier would be fossil fuels. It has already been established that under normal operating conditions, nuclear energy is the far better option in terms of pollution and the release of harmful elements into the environment. Another area of comparison would be the fatalities caused by each over a specified period. The period selected for a study by the NEA was from 1969 to 2000, during which the Chernobyl accident occurred, arguably the largest and most severe nuclear disaster to date. The table below illustrates the comparison between the fatalities from fossil fuels and nuclear, considering both direct and indirect or latent fatalities. Note that the table below presents a summary of the tables and information obtained throughout the research conducted in this study.

**Table 1: Fossil fuels vs. nuclear energy fatality rate summary**

| | **Total accidents** | **Immediate fatalities** | **Indirect fatalities** |
|---|---|---|---|
| **Fossil Fuels** | 2 677 | 62 623 | 8 928 000 |

| | | | |
|---|---|---|---|
| **Nuclear Energy** | 1 | 31 | 33 000 |

Based on this fairly simplified table, it can be noted that of the two methods, fossil fuel generation appears to be significantly more dangerous than nuclear. It should also be noted that the number of latent fatalities for nuclear were taken as a worst-case estimate, meaning that the fatality rate for nuclear throughout the designated time period is possibly lower than stated. In terms of fossil fuels, the largest contributor to the high fatality rate is the pollution released into the air, estimated to be responsible for 288 000 premature deaths annually, represented by the high number of indirect deaths for fossil fuels over the 31 years considered.

### 6.3 Simulation analysis and findings

To limit the severity of further nuclear disasters, the simulations in Chapter 4 illustrate the multiple safety systems and layers of protection implemented. Simulation 1 in Chapter 4 demonstrated that after the LOCA is inserted at cold leg #4, multiple safety systems are activated, each with the aim of maintaining stability of the reactor core. The safety systems discussed are limited to those activated during a LOCA, with the focus being on passive safety systems due, to the nature of the study. Simulation 1, therefore, makes use of a PWR generation II reactor, consisting of additional newer passive safety systems added on to the original design, replacing some of the original systems. Considering the events of simulation 1 from start to finish, valuable information can be gained regarding how safety systems are initiated, and at what point of time.

**Table 2: Events noted during simulation 1**

| # | Event | Purpose | Trigger | Time |
|---|---|---|---|---|
| 1. | LOCA inserted | Initiate LOCA accident | Manually inserted | 0 seconds |
| 2. | Reactor scram | Prevent core damage | Low coolant pressure trip signal | 31 seconds |
| 3. | Isolate steam generator | Prevent damage | Low steam pressure trip signal | 38 seconds |
| 4. | Coolant pumps trip | Prevent damage and limit coolant loss | Low coolant pressure trip signal | 43 seconds |
| 5. | PRHR valves open | Passive core cooling | Sudden decrease in coolant pressure | 43.5 seconds |
| 6. | CMT valves open | Passive core cooling | Sudden decrease in coolant pressure | 43.5 seconds |
| 7. | ACC activates | Passive core cooling | System pressure drop below ACC tank pressure | 75 seconds |
| 8. | Containment roof spray cooling start | Decreasing containment pressure through cooling | High containment pressure | 149 seconds |
| 9. | ADS-1 valves open | System pressure release | CMT liquid level reaches 67.5% | 353 seconds |
| 10. | ADS-2 valve open | System pressure release | Time delayed opening based on ADS-1 | 447 seconds |
| | ADS-3 valve open | System pressure release | Time delayed opening based on ADS-2 | 540 seconds |
| 11. | IRWST valve open | Passive core cooling | Drop in pressure from ADS valves opening | 549.5 seconds |
| 12. | ADS-4 valves open | System pressure release | Low CMT liquid level. | 981 seconds |
| 13. | Passive sump circulation valves open | Long term passive cooling of the core | Sump liquid level | 2 hours |

The information in Table 2 above makes evident that an important monitoring parameter is that of system pressure, as a reduction in pressure is frequently responsible for the activation of the safety systems. However, the monitoring is not only done using active systems such as electronic pressure monitors, but also through pressure activated valves working passively. These valves are forced open by pressure, in the event that the pressure on the systems side drops to below that of the safety systems side, such as in the event of a LOCA. Systems incorporating this passive method of activation include the PRHR, CMT, ACC and IRWST, rendering them capable of operating under extreme and abnormal conditions. Another noteworthy system is the passive sump circulation system as this safety system operates through natural circulation, working on the principal of heat rising, allowing the system to circulate cool water through the reactor without the need for any pumps. This system is also capable of recycling the coolant it uses, giving it the ability, theoretically anyway, to operate endlessly, or essentially until the reactor is in cold shutdown.

Simulation 2 in Chapter 4 incorporates the same type of PWR generation II reactor as that used in simulation 1, with the difference being the safety systems incorporated. The second represents a conventional design, making use of a combination of active, passive and hybrid safety systems. The same type of malfunction, namely a LOCA, was again initiated while the response of the system was monitored. A summary of the events is presented in the table below.

**Table 3 : Events noted during simulation 2**

| # | *Event* | *Purpose* | *Trigger* | *Time* |
|---|---|---|---|---|
| 1. | LOCA inserted | Initiate LOCA accident | Manually inserted | 0 seconds |
| 2. | Reactor scrams and turbines trip | Prevent core damage | Two second delay after low pressurizer pressure trip signal | 17 seconds |
| 3. | Main feed water isolation | Prevent equipment damage | Low coolant pressure | 20 seconds |
| 4. | Reactor coolant pumps trip | Prevent damage and limit coolant loss | Tripped manually | 20 seconds |
| 5. | Low coolant flow trip signal and warning | Insure enough cooling flows to cool the core | Coolant pumps trip | 23 seconds |
| 6. | High pressure safety injection system activate | Provide emergency cooling to the core | Approximately 20 second delay after receiving low coolant flow trip signal | 47 seconds |
| 7. | SG Main Steam Isolation Valve (MSIV) open | Relieve pressure on the system | SG pressure | 354 seconds |
| 8. | ACC 1-4 activates | Cooling of the RPV | Low coolant pressure | 383 seconds |

From this tabled information, it is evident that more safety systems are present and activated during simulation 1 as compared to simulation 2. The safety systems activated during simulation 1 are overwhelmingly passive and are therefore largely initiated by components such as pressure valves opening due to pressure drops. This method of initiation, though not as precise as an active system, has the additional advantage of not being dependent on an operator, computer or even electricity, ensuring its reliability. Due to the passive nature of the safety systems activated in simulation 1, it is fair to conclude that most of them will be able to operate in the event of complete station blackout. Since most of the safety systems in simulation 2 are not passive, the table in Figure 40 from the reactor manual can be applied to determine which systems will work, and which will not, in the event of a complete station blackout (Korea Atomic

Energy Research Institute, 2004). From the left, the table indicates system classification, component, function, power source and availability. Power sources capable of operating the respective components are identified with an E (Electricity), G (Gravity), S (Spring-loaded), T (Turbine), M (Manual) or A (Compressed Air), in the relevant column. The availability column at the end is used to indicate whether the system is available during a system blackout, based on its power source. An X indicates that it is not available during a station blackout, while an O indicates that it would be available. The system in simulation 1 also made use of several coolant injection systems, each independent from the other, most with their own dedicated coolant reservoir. This further decreases the likelihood of an event preventing coolant from reaching the core: if one system were to fail, another could prevent the failure from resulting in a disaster, which is part of the reason these systems are referred to as 'layers of protection'.

| System | Component | Function | Power Source* | Availability |
|---|---|---|---|---|
| Primary | Control/Scram Rod | Reactor power control | G / E | O |
| | RCP | RCS forced cooling | E | X |
| | PSV | Pressure control | S / E | O |
| | PZR heater / spray | Pressure control | E | X |
| | Charging / Letdown | PRZ level control | E | X |
| | SIP | Coolant inventory | E | X |
| | SIT | Coolant inventory | A | O |
| Secondary | MFWP/CP | SG coolant inventory | E / T | X |
| | MD- AFW | SG coolant inventory | E | X |
| | TD- AFW | SG coolant inventory | T | O |
| | SBCS | SG pressure control | A | X |
| | MSIV | SG isolation | E | X |
| | MSSV | SG pressure control | S | O |
| | ADV | SG pressure control | M / E | X |

**Figure 40: Component availability during a station blackout (Korea Atomic Energy Research Institute, 2004)**

Simulation 2 shows that there are essentially two main systems providing cooling to the core during a LOCA. The first is the high-pressure safety injection system, a hybrid safety system providing cooling by making use of pumps while relying on the low coolant flow signal as an initiation mechanism. The SIS also has a passive side, which can inject coolant by making use of the FD and safety injection tanks discussed earlier. The passive side of the SIS did not activate during simulation 2, as only a LOCA was simulated and not a complete station blackout. From the simulation, another safety system known as the ACC was also noted, activating near the end of the simulation to provide additional cooling to the rector. Although there are additional safety measures in place not activated during the simulation, such as the passive side of the SIS, backup generators and pressure relief valves, the likelihood of one of the two main systems failing catastrophically will always be more than that of the several smaller passive systems in simulation 1.

Further comparison of the simulations shows that simulation 1 ran for significantly longer than simulation 2. This can be expected, as there are more systems which are overwhelmingly passive, relying on pressure activated valves and natural convection to operate, which will naturally be slower than the active systems in simulation 2, where water is pressurized using pumps. It was noted that key parameters such as reactor pressure vessel temperature during both simulations were approximately the same, never rising much higher than 300 0C. This once again proves that although slower, the passive safety systems of simulation 1 still operate effectively, providing enough cooling to the core.

The evidence between the two simulations demonstrates that the newer passive safety systems incorporated into simulation 1 will provide a better quality of protection against unforeseen and unanticipated events. This conclusion is made as the overwhelmingly passive safety systems of simulation 1 can operate independent of operator control or external factors such as the availability of power, rendering it more reliable. The system in simulation 1 is more automated, evident from the automatic shutdown of the reactor coolant pumps in the event of a LOCA, which had to be done manually in simulation 2. The data and observations are significant as it is often not the accident initiating events for which precautions have been made in preparation for a disaster, but rather those that are unplanned for and unanticipated.

An example can again be offered when considering the Fukushima disaster, where a combination of events never thought to happen simultaneously led to an uncontrollable reactor core meltdown, exacerbated by the inability to maintain sufficient cooling to the core. One of the main contributors to the accident was the fact that the reactor, much like that used in simulation 2, required power to maintain sufficient cooling to the core. After an extremely unlikely chain of events resulted in a complete station blackout, the power plant was left with no way to sufficiently cool the core, causing the core to overheat and go into meltdown. If the passive safety systems of simulation 1 were present at the time, the chances are that the core would have avoided meltdown, as these systems would have been sufficient to maintain cooling until power were restored.

## 6.4 Recommendations for effective future risk communication

Research conducted for this thesis has assisted in demonstrating the movement of nuclear technology towards maturity in recent years in terms of increasing as a safe, reliable and controllable form of power generation, by considering the advanced technological achievements in terms of safety and waste management. The remaining challenge is therefore to find a way of effectively portraying this information to the public, re-establishing confidence in nuclear technology ability and safety. In reconciling how the human brain perceives risks with the past mistakes identified throughout the study, it is possible to formulate the key aspects for what needs to be done, and what needs to be avoided to successfully convince the public of nuclear energy's safety, thereby restoring confidence in this powerful technology. Several of these 'do's and don'ts' are listed below (Frantal & Maly, 2017; Lévêque, 2013):

- All information must be made available to the public, including the advantages as well as the risks.
- We must ensure that the public never feels uninformed or under-informed on the matter.
- When informing the public, always start by first mentioning the advantages of nuclear energy, followed by the risks.
- Never assess risk on behalf of the public.
- Allow the public to draw their own conclusion about nuclear as a suitable alternative, based on the advantages vs. the risks and the comparison to alternative forms of energy.
- Never portray that another nuclear accident is impossible; instead, rephrase that it is highly unlikely due to advanced modern safety systems in place.

The process of establishing public confidence and support in nuclear technology will take time; nevertheless, if these steps are adhered to, the outcome should be positive and beneficial.

## 6.5 Chapter conclusion

This chapter summarized the work conducted in this study. This included first identifying the primary fears and concerns surrounding nuclear technology, as well as determining where they originated from. These concerns were then addressed by evaluating the latest technological solutions, safety systems and waste disposal methods in use today, proving that the concerns are largely based on outdated knowledge and inaccurate information. This statement was then backed up by including two simulations, allowing not only the advances in power plant safety to come to light, but also to illustrate the sophistication of combined multiple safety systems at work. Lastly, this chapter concludes by proposing an effective and appropriate manner for portraying this information to the public, as knowledge gained during this study showed that a clear and effective manner of risk communication is vital for gaining support for nuclear technology.

# CHAPTER 7: CONCLUSION, RECCOMMENDATIONS AND FUTURE WORK

## 7.1 Conclusion

The study set out to identify the advanced technological solutions which will curb the negative perceptions associated with nuclear energy, and then to find the most effective way of successfully conveying this information to the public, ultimately promoting its use. In identifying the concerns surrounding nuclear energy, the study considered past nuclear disasters from which fear often stems, as well as looking at how these incidents affected public opinion about the technology in the subsequent years. It was discovered that past disasters still have a strong grip on people's opinion of this technology today, and that this is often where fears originate from. An explanation for the public fixation on these past events stemmed from how the human brain works and perceives risks, revealing that the risks of nuclear are often grossly overestimated, while the risks emanating from technologies such as fossil fuel generation are underestimated. Further contributing to the negative perceptions towards nuclear energy is the fact that the public has previously been under informed about the workings and possible dangers associated with this technology, as only limited information was made available during the early days of nuclear power. The challenge resides in successfully convincing the public that nuclear technology has come a long way since its early days, particularly through the implementation of advanced technologies and safety systems which ensure the safety of these power plants.

After identifying the concerns, the aim was to prove that nuclear power plants, and specifically nuclear reactors, are safe and that waste produced by these power plants is disposed of suitably so as to pose no risk to the environment or public. To prove the safety of these power plants, the study considered the advances made in safety and design in moving from generation I to generation II, III, III+ and IV reactors, with focus on the increased automation of newer generation reactors, reducing the probability of human error. The study also focused on the advantages of the increasing use of passive safety systems, which in recent years have become the focus of safety systems developers. The working of passive safety systems is also considered in greater detail to compare these to conventional active systems and show how the increased implementation of passive systems could have assisted in preventing past disasters, and how they are likely to protect a nuclear power plant from unforeseen circumstances in the future. This likelihood is further supported by the comparison between the two conducted simulations of a LOCA, the first making use of overwhelmingly passive safety systems, while the second representing the same type of generation II reactor, but with more conventional active systems. Results revealed how the active and passive safety systems of each work and are initiated, providing an understanding of why passive safety systems are considerably more reliable and rugged than active systems.

Other concerns surrounded the methods employed in disposing of nuclear waste; it was found that contrary to popular belief, the nuclear industry does indeed have a thorough plan for the disposal of all types of radioactive waste it produces. This involves casting LLW and ILW in cementitious materials inside storage containers, followed by a thorough decontamination and inspection for any leaks before being sent off for storage in underground repositories. HLW, which is also the smallest amount of the total waste produced, undergoes several storage, treatment and drying processes to reduce its quantity and radioactive half-life before it is vitrified in a glass matrix and sent off for deep geological disposal. The process of waste disposal further involves transporting the waste between treatment and burial sites, which has been a concern as this opens the opportunity for waste packaging to be damaged and leak radioactive material. Research, however, revealed that nuclear waste is transported in special containments, adhering to strict requirements to ensure that it can withstand any accident or rough handling which might occur. The designs of these containments have in fact been so successful, that there has never been an accident resulting in radioactive material escaping during transportation.

The focus also fell on how nuclear power generation compares to its alternative, which for producing reliable and affordable base load electricity, would be fossil fuels. It is a well-known fact that fossil fuel generation produces among the worst air pollution of all the generation methods. The research came across studies which suggest that under normal operating conditions, fossil fuel power plants release pollution in the form of fly ash, which is 100 times more radioactive than that allowed to leave a nuclear power plant without being treated. Further comparisons between fossil fuels and nuclear are made, considering the fatalities caused by each during both accident conditions and daily pollution, revealing that the overall numbers are much higher for fossil fuels largely because of the harmful air pollution it produces.

This research considered the negative perceptions surrounding nuclear technology, from its origin to the advanced technological solutions available today for curbing the fears surrounding this technology. Negativity and fears have shrouded this technology since its early days, mainly because of events and decisions made in the past. The reality is, however, that although there are possible dangers associated with this technology, nuclear can still easily compete with its alternatives in terms of both safety and reliability. The nuclear industry has admirably gone to extreme lengths, including strict safety regulations for *all* safety systems and waste disposal methods, to ensure that safety at nuclear power plants is among the highest priorities. Nuclear power generation is also the only generating industry taking *full* responsibility for all the waste is produces, showing its commitment to safety and addressing the concerns of the public. It is therefore vital to successfully inform the public of the advantages of making use of nuclear energy, as the current perception is outdated and inaccurate, meaning that this vital resource remains underexploited, and the unnecessary pollution by older forms of generation continues.

## 7.2 Study recommendations

Recommendations formulated based on this research include the following:

- Not to withhold any information about nuclear power generation and nuclear power plants, as this negatively affects support for this technology as compared to informing the public about the possible risks in a fair and effective manner.
- When providing information, always start with the advantages, followed by the possible risks.
- Informing the public on the latest technological solutions and safety systems implemented to ensure the safety of nuclear power plants, demonstrating how they compare to the older technology on which fears are based.
- Providing information on how nuclear compares to alternative generation methods such as fossil fuels, counteracting our tendency to overestimate the risks of nuclear.
- Not to conclude on the safety and advantages of nuclear energy on behalf of the public, but to leave people to draw their own conclusions based on honest and transparent information provided.

## 7.3 Future research work

1. Developing passive safety systems capable of replacing conventional active systems, doing the same functions as well, if not better, than active systems would have.
2. Informing a test group of individuals on the advanced technological solutions used in nuclear power plants, as well as possible risks, using the risk communication method delineated in this study to test its effectiveness.
3. Comparing nuclear power plant safety system behaviour and active and passive systems when inserting multiple faults, such as a LOCA and complete station blackout simultaneously.

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## APPENDIX A

Simulator features summery (Cassiopeia Technologies Inc. 2011).

| SYSTEM | SIMULATION SCOPE | DISPLAY PAGES | OPERATOR CONTROLS | MALFUNCTIONS |
|---|---|---|---|---|
| REACTOR | • neutron flux levels over a range of 0.001 to 110% full power, 6 delayed neutron groups<br>• decay heat (3 groups)<br>• all reactivity control devices - "dark" rods; "gray" rods; boron control.<br>• Xenon/Iodine poison<br>• reactor power control system<br>• reactor shutdown system | • PWR power control<br>• PWR control rods & shutdown rods<br>• PWR trip parameters | • reactor power and rate of change (input to control computer)<br>• manual control of reactivity devices - control rods and boron addition/removal<br>• reactor trip<br>• reactor setback<br>• reactor stepback | • reactor setback and stepback fail<br>• one bank of Dark control rods drop into the reactor core |
| REACTOR COOLANT | • main circuit coolant loop with four pumps, two steam generators, four equivalent "lumped" reactor coolant channels<br>• pressure and inventory control which includes pressurizer, coolant letdown condenser, charge & letdown control, and pressure relief<br>• operating range is from hot zero power to full power | • PWR reactor coolant system<br>• PWR coolant inventory & pressurizer<br>• PWR inventory control<br>• PWR pressure control | • reactor coolant pumps<br>• coolant makeup pumps<br>• pressurizer pressure control: heaters; spray; pressure relief valve<br>• pressurizer level control by regulating coolant feed & bleed flow<br>• isolation valves for coolant feed and bleed | • Pressurizer pressure relief valve fails open<br>• charging (feed) valve fails open<br>• letdown (bleed) valve fails open<br>• pressurizer heaters #2 to # 6 turned "ON" by malfunction<br>• reactor header break |
| STEAM & FEEDWATER | • steam generator dynamics, including shrink and swell effects<br>• steam supply to turbine and reheater<br>• turbine by-pass to condenser<br>• extraction steam to feed heating<br>• steam generator pressure control<br>• steam generator level control<br>• feed water system to steam generator | • PWR feedwater & extraction steam | • feed pump on/off operation<br>• steam generator level controller mode: auto or manual<br>• level control setpoint during auto operation<br>• level control valve opening during manual operation<br>• extraction steam valves opening | • all level control isolation valves fail closed<br>• one level control valve fails open<br>• one level control valve fails closed<br>• all feed pumps trip<br>• all steam safety valves open<br>• steam header break<br>• steam flow transmitter fails |

| SYSTEM | SIMULATION SCOPE | DISPLAY PAGES | OPERATOR CONTROLS | MALFUNCTIONS |
|---|---|---|---|---|
| TURBINE-GENERATOR | • simple turbine model<br>• mechanical power and generator output are proportional to steam flow<br>• speeder gear and governor valve allow synchronized and non-synchronized operation | • PWR turbine generator | • turbine trip<br>• turbine run-back<br>• turbine run-up and synchronization<br>• condenser steam discharge valves | • turbine spurious trip<br>• turbine spurious run-back |
| OVERALL UNIT | • fully dynamic interaction between all simulated systems<br>• overall unit power control with reactor leading mode or turbine leading mode<br>• unit annunciation & time trends<br>• computer control of all major system functions | • PWR plant overview<br>• PWR control loops<br>• PWR MW demand SP & steam generator pressure control (SGPC) | | |
| SAFETY SYSTEM | | • PWR passive core cooling | | |

## APPENDIX B

OPR 1000 Major design features (Korea Atomic Energy Research Institute, 2004).

| | |
|---|---|
| Thermal Output | 2825 MWt |
| Rated Electric Power | 1,000MWe |
| Design Life Time | 40years |
| Seismic design basis | SSE 0.2g, OBE 0.1g |
| Refueling Interval | 12~18months |