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Challenges facing the development of new nuclear capacity in South Africa

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Abstract

South Africa currently (2022) hosts two nuclear reactor facilities, the electricity generating Koeberg nuclear power plant, and the SAFARI - 1 reactor, which is used for medical isotope production, research, and development. With the nationwide problems of loadshedding due to a lack of operational capacity, resulting in economic decline, and the climate concerns associated with fossil fuels, the addition of nuclear capacity is an appealing concept. This dissertation details several of the challenges associated with the development of new nuclear power plants (NPPs) in South Africa, from the availability of nuclear fuel and technical expertise to environmental, political, and economic issues. These challenges were explored in both national and international spheres, drawing on case studies from around the world. The long-term operation of the existing nuclear capacity was considered, alongside the viability of spent nuclear fuel re-processing in the South African context as a strategy for waste management and generation of revenue. Ultimately, political factors, and public participation and acceptance were identified as the primary challenges that have delayed the deployment of NPPs, which need to be addressed by the government when developing a rigid national nuclear energy policy to sustain South Africa's economy both for current and future generations.

Key Words:

Nuclear, energy, proliferation, reprocessing, economy, public participation, public perspective, public acceptance, politics, policy, regulation.

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Dissertation outline

This dissertation is divided into seven sections.

Chapter 1 introduces the document and research outline. It does so by highlighting the bases under which the research was initiated and conducted. In addition, the objective, aim, methodology and rationale of the research are provided in this chapter.

Chapter 2 provides a review of South Africa's natural resources and introduces the nuclear power plants in the country.

Chapter 3 introduces various sources of energy in the country, nuclear energy generation, spent nuclear fuel (SNF) management including reprocessing strategies such as PUREX, Pyro-Processing and Advanced Fuel Cycle Initiative (AFCI).

Chapter 4 introduces the Long-Term Operation (LTO) of nuclear power plants. A closer look at Koeberg and SAFARI – 1 nuclear facility is taken with an intent to establish how South African nuclear power plants are operating. Aspects such as human resources management strategies, aging management programmes, safety culture and the viability of Periodic Safety Reviews (PSRs) are covered in this section.

Chapter 5 covers the challenges facing the development of Nuclear Power Plants in South Africa and globally. In this section, environmental, political, economic, public participation, public acceptance of nuclear deployment, policy and regulatory framework are considered. The successes in nuclear energy deployment in countries like China, Japan, and Russia are taken into context to understand these countries' approach.

In Chapter 6, the findings from the previously presented literature are consolidated, discussed in the South African context and several recommendations made to overcome the presented challenges.

Chapter 7 gives the conclusion.

Chapter 8 gives the references.

Definitions

Loadshedding – curtailing of supply in specified intervals to ensure that all customers connected to the national grid have access to electricity and that the system is protected against overloading.

Acronyms:

Acronym	Description
ACFI	Advanced Cycle Fuel Initiative
ALARA	As Low As Reasonably Achievable
AMP	Aging Management Programme
ANC	African National Congress
DA	Democratic Alliance
DEMR	Department of Energy and Mineral Resources
DGR	Deep Geological Repository
DID	Defence – in - Depth
DoE	Department of Energy
EV	Electric Vehicles
GDP	Gross Domestic Product
I&C	Instruments and Components
IAEA	International Atomic Energy Agency
ICTS	Interim Centralised Interim Storage
IMF	International Monetary Fund
INPO	Institute of Nuclear Power Operators
IRP	Integrated Resource Plan
KNPP	Koeberg Nuclear Power Plant
LCOE	Levelised Cost of Energy
LOCA	Loss Of Coolant Accident
LTO	Long term operation
MEI	Maximally Exposed Individual
NECSA	South African Nuclear Energy Commission Corporation
NLT	Non – Linear Threshold
NNP	Nuclear Power Plant
NNR	National Nuclear Regulator
NOU	Nuclear Operating Unit
PSR	Periodic Safety Review
PWR	Pressurised Water Reactor
RVA	Reactor Vessel Assembly
SADC	Southern African Development Community
SALTO	Safety Aspects of Long-Term Operation
SCRAM	Safety Control Rod - Axe Man
SMR	Small Modular Reactors
SNF	Spent Nuclear Fuel
WAN	World Nuclear Association
WANO	World Association of Nuclear Operators
WWF	Worldwide Fund for Nature

1. Introduction

As of 2023, South Africa hosts several nuclear facilities that are used for a variety of applications. One of the well-known nuclear facilities in South Africa is Koeberg Nuclear Power Plant (NPP) which is in the Western Cape and committed to civilian power production. In addition, other nuclear facilities involved in research and producing medical isotopes, such as iThemba Labs in the Western Cape and SAFARI-1 in Gauteng also exist. The country's persistent inadequate power generation capacity, which in turn causes significant economic, social, and political setbacks, together with the environmental concerns associated with the use of fossil fuels, position the idea of nuclear capacity expansion as an appealing avenue to explore.

The deployment of nuclear energy facilities both in South Africa and internationally is challenged by delays (Mostly above 10 years) if not cancellations. These delays and cancellations are attributed to political, economic, policy and regulatory framework, public perception, public participation, public acceptance, the law, environmental, and proliferation factors. These factors are exacerbated by trust in the government, academic stratification, and the failing economy of the country (Wang *et al*, 2020; Ahmed *et al*, 2020; Alzahrani *et al*, 2023; Zimmermann and Keles, 2023).

The most critical factors that lead to the delay or cancelation of nuclear energy technologies are politics, policy, law, and the regulatory framework. This happens primarily when the political climate sees frequent changes in cabinet members due to corruption scandals, maladministration and 'weak policy strategic objectives' resulting in policy shift from nuclear energy deployment towards other sources of energy. In addition, because of corruption, the law and regulatory framework become contributing factors towards the delay or cancelation of nuclear energy projects (Woo *et al*, 2020; Kessides, 2014; van Wyk, 2021)

Other factors such as the economy, environmental, proliferation risks and the international community also contribute towards the delay and cancelation of nuclear energy projects. South Africa is currently experiencing economic retardation leading to poor incentives in financial institutions like the International Monetary Fund (IMF) and the World Bank to lend money to South Africa (van Wyk, 2021). In addition, Environmental and proliferation risks as well as the international community have a potential to hinder nuclear energy deployment while ensuring nuclear safety globally (Minacca & Locatelli, 2020).

Case studies from Russia and China as third world countries were analysed to establish the approach and policy implementation strategies leading to their success beyond the Three Mile Island, Fukushima and Hiroshima accidents such as the construction of Fujiani, Liaonin, Guangdong and Zhejiang NPPs currently underway China (Lin and Xie, 2022; Wang *et al*, 2020). In addition, Japanese case studies were analysed to deduce how government successfully addressed political and public acceptance aspects of nuclear deployment. Furthermore, Koeberg and SAFARI – 1 Long Term Operation (LTOs) were analysed to establish South Africa's potential to develop, deploy and operate nuclear power plants (NOU, 2022).

While South Africa's traceable record in nuclear facility operations is renowned, several obstacles hinder the full deployment of new nuclear energy technologies in the country. These obstacles range from negative public perception and a wavering political and legal landscape to economic decline and the nation's standing in the international community. If South Africa wants to bolster its nuclear capacity amidst these challenges, it is vital that it addresses these issues, advocating for transparency, fostering public trust, and aligning its nuclear ambition with global safety standards, thus presenting a more viable path towards achieving its nuclear energy goals.

1.1 Research questions

The aim of this dissertation is to address the following questions and bring into attention those aspects that significantly challenge the deployment of new nuclear power plants in South Africa.

1. *Why is South Africa lagging in the deployment of nuclear energy?*
2. *Does South Africa have enough uranium resources to sustain an additional nuclear fleet?*
3. *Has South Africa developed adequate skills to operate additional nuclear plants?*
4. *How does politics, policy and the regulatory framework affect the deployment of nuclear technologies?*
5. *How does the economy affect the deployment of nuclear technology?*
6. *How does public perspective and participation affect the deployment of new nuclear technology?*
7. *What challenges face the development of new nuclear facilities in South Africa?*
8. *What would need to change to accelerate the development of new nuclear capacity?*

1.2 Problem statement

Since the commissioning of Koeberg Nuclear Power Plant in 1984, South Africa has not constructed and commissioned new nuclear power plants for civil applications. Despite the nuclear energy project initiation in 2010, to date no construction is taking place to ensure that the proposed nuclear power facility is deployed to the National Power Grid.

1.3 Research rationale

Although several studies have been done to establish the feasibility of deploying new nuclear power plants in South Africa, none of the studies has covered the factors hindering the deployment of these technologies to date. This research then highlights the challenges faced internationally, how the challenges were overcome and how these challenges relate to South Africa. In addition, the dissertation highlights the various factors such as economic, socio-political, environmental, technical and policy aspects associated with the deployment of new nuclear facilities.

1.4 Aim

The aim of this dissertation is to deduce the factors influencing the deployment of new nuclear power facilities for civil applications in South Africa.

1.5 Objectives

- Deduce if South Africa has enough uranium resources to sustain new nuclear power plants.
- Establish if South Africa has adequate operating experience to operate new nuclear power plants
- Establish the challenges hindering the deployment of new nuclear power plants in South Africa
- Provide policy recommendations towards the deployment of new nuclear facilities in South Africa

1.6 Relevance of the research

This research is relevant in a sense that it seeks to establish why South Africa has not been able to deploy new nuclear power plants despite having shown interest in acquiring such plants. In addition, the research

shall contribute towards establishing the gaps in the current nuclear energy policy and provide recommendations thereof.

1.7 Methodology

This dissertation employs a qualitative method to deduce the impact of various aspects towards the deployment of new nuclear energy projects. The thesis shall look at the conclusions drawn from countries that have successfully deployed nuclear energy projects. These include Russia, Japan and China. These countries were selected because they are third world countries therefore falling into the same category as South Africa. Japan on the other hand, was chosen because its nuclear energy policy was developed immediately after the Sino-Japanese war with Japan's economy being at a very poor state.

In addition, the dissertation looks at South Africa's ability to operate new nuclear power plants. This is done by looking at South Africa's performance during the operation of Koeberg NPP, SAFARI - 1 and Ithemba Labs. Again, South Africa's application for an LTO forms the basis for the benchmarking of operational skills set, collaboration with international organisations and expects as well as the effectiveness of internal organisation.

Lastly, the various factors are linked to the international and national environment to deduce which aspects in the spectrum significantly hinder the deployment of new nuclear power plants in South Africa.

2. Electricity generation in South Africa

Chapter 2 provides the background in the electricity needs of the country. The natural resources available in the country are discussed. In addition, this chapter highlights the electrical energy generation contributions per energy resource. The challenge facing the extraction of uranium are highlighted. Lastly, this chapter highlights the nuclear facilities in the country and their purpose.

The electricity generation in South Africa is the engine that propels the South African economy. Most of the economy driving sectors such as agriculture, mining, construction, and services depend on the electricity available in the country. The population growth influences the amount of electricity consumed. These parameters set out several factors such as the need for new jobs, innovation, infrastructure expansion and academic development.

As the above factors increase, so does the need for electricity. The increase in electricity demand forces the country to find innovative ways to supply electricity as it was observed in 2008 where South Africa promoted the installation of solar panels for households and other properties. The inability of the electrical utility to supply power continuously in 2008 has seen the emergence of numerous innovations aimed at resolving the power crisis in the country (Monyei and Adewumi, 2023).

Various sources of energy were evaluated both in large and small scale within the South African context. Although some of the features that resulted in the power constraints were inherent to the political system of the country, planning for electrical generation has seen major improvements to see the development of a power system that will meet the electricity demands of today and that of the future generations (van Wyk, 2021).

The current energy mix plan, which is based in the DoE (2019), is faced with a lot of challenges with economic and political challenges being the most dominant. The fluctuating changes in the political structure and decision makers in the country influence how the energy mix plan is implemented. The energy mix designed to address the energy demand for the period until 2030 has seen its implementation being opposed by politicians from diverse political arenas, therefore, largely give the policy makers difficulties in determining a suitable energy mix.

The IRP (2010) energy mix drive to produce 14 GW of electrical power from nuclear energy by 2035 has seen objections both from the public and political parties. The objections were based on environmental concerns and financial viability. On one hand, renewable energies received enormous support due to lower impact on the environment and quick implementation.

On the other hand, the financial implications and intermittency of renewable energies led to a court interdict that prevented Eskom from signing more contracts between 2016 to 2017 (wwf, 2017; Todd & McCauley, 2021). Recently, Eskom has signed the contract for 27 Independent Power Producers (IPPs) projects. These IPPs are currently facing another wave of court appeals by labor unions who foresee an increase in job losses and high tariffs arising from the use of renewables (Todd & McCauley, 2021).

Eskom, being a state-owned electrical utility under NECSA and regulated by NNR, has its objectives set out by the government. Eskom's primary mandate is to provide electrical energy to South Africa in a manner that is cost effective and sustainable. Eskom's objectives include budget spending, determining project priorities as well as long term goals. The goals are set by both the minister of enterprises together with the minister of electricity. The government policy is the main driver of Eskom's activities. The government

policy is however, influenced by external organisations such as the world bank, Moody's and IMF (Minnaar, 2020).

The new cabinet's approach has given nuclear energy players a huge blow and demise with no rigorous prospects, further highlighting the impact of policy makers in the technical fields as these decisions influence mostly not only the technologies to be used but also the pace at which the technologies are implemented (Kessides, 2014; van Wyk, 2021). Despite the numerous uncertainties shadowing the energy mix plan such as the regulatory aspects, economic, supply constraints, political influence and technological changes, a concise energy mix plan for the country must be pursued to the best extent possible.

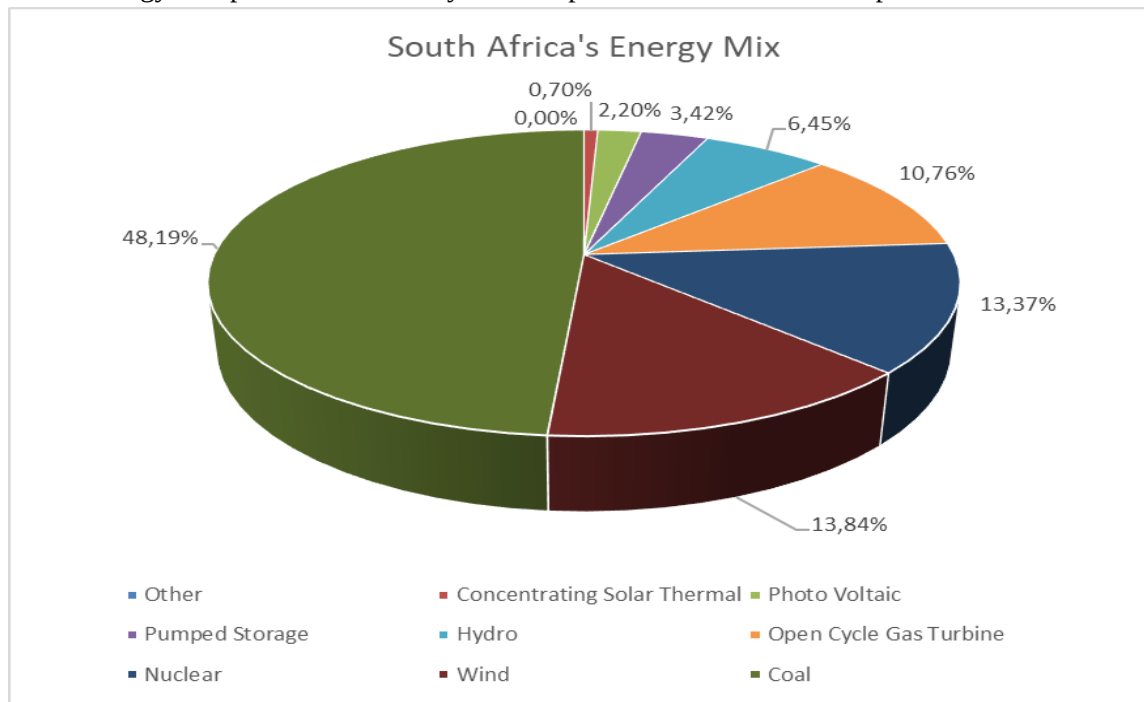


Figure 1: South Africa's natural resources (Delta Natural Resources, 2017)

According to *Figure 1*, nuclear fuel and wind shall compete for the same amount of electricity to be generated by 2030, that is, 13.37% and 13.84% respectively. With the future of renewables at stake, it is highly probable that nuclear energy shall gain more momentum to support the deficiencies resulting from a drop in wind energy or its intermittency. The chart also shows that coal shall continue to be the most dominant component of the energy mix. This may still be true bearing in mind that coal is the cheapest type of fuel and that technology changes are currently underway addressing the carbon emission challenges (Todd & McCauley, 2021).

While the sensitivity surrounding the intermittency and lack of storage facilities for renewables cannot be discarded, it remains to the technology developers to ensure that such storages are developed and are cost effective. In the current energy mix plan, such provision is not in the scope although it should be noted that when effective technologies emerge, the energy mix plan could be revised to explore such avenues. In fact, South Africa, together with the World Bank are implementing a high-capacity battery storage system to store electrical energy when available and make it usable during unfavorable weather conditions (WWF, 2017; DoE, 2019).

New discoveries of gas reserves especially in the Karoo may add flexibility in the energy mix plan. The four identified areas in the country with gas reserves can be exploited through different technologies. The extraction of gas poses challenges due to the technologies used and the scarce water resources necessary to

support fracking. This has raised environmental concerns and proper analysis and public participation needs to be done before such projects are realized (Delta Natural Resources, 2017).

Although South Africa has a diverse range of sources of energy, they all face similar challenges. The current public participation process takes too long to finalise. The process has a lot of departments with authority over the same project but in different classifications. In addition, regulatory and socio-economic aspects are not well defined which further inhibit the success of such projects (Kessides, 2014; WWF, 2017). A typical example is the challenges facing the granting of a license to construct a coal-fired power plant at Lephalale where the granting of the environmental authorization was set aside on the grounds of climate change considerations (de Boer *et al*, 2022).

2.1 Challenges facing the exploration of nuclear energy resources in South Africa

The exploration of natural resources for electrical energy generation in South Africa is faced with several challenges most of which end up in court. The court cases against the applicants range from environmental concerns for nuclear power plants, resource scarcity such as water for fracking in the Karoo and global warming in the case of Eskom coal power stations in Mpumalanga. What is paramount in these applications for authorization review is the time elapsing while following the licensing processes which is about 24 months, see Appendix C (van Wyk, 2021; Vondracek *et al*, 2020).

Kessides (2014) points out that the major challenge facing the development of nuclear power is the associated capital cost. For this, Kessides (2014) and Minacca & Locatelli (2020) propose Small Modular Reactors (SMRs). SMRs have low capital cost, and least development time and deployable in remote areas where grid infrastructure is not yet fully developed. This is particularly prevalent in the remote areas of South Africa especially in villages far from the major towns and reticulation networks found in the Kwa-Zulu Natal and Eastern Cape Provinces. Typical villages identified in the Eastern Cape for small grids are Dumsi and Mbandana where small sealed SMRs with low power output at ranges between 40 to 50 MW could play a very significant role (Kessides, 2014).

Kessides (2014) views large nuclear power plants as unsuitable for most African countries. This is true to countries with smaller power demands and those with undeveloped transmission and distribution infrastructure. For South Africa, where baseload demand is significant and transmission infrastructure is sufficient, larger power plants could play a significant role.

According to Kessides (2014), nuclear energy delivers electricity in bulk with low carbon emissions, reliably and without intermittency. Kessides (2014) also claims that the mentioned factors could resolve the power crisis facing African countries. This is true especially in the case of South Africa where economic losses due to loadshedding amount to about 2% of the GDP in Africa. Although the electricity dependency in the SADC region is crucial to retain continuity of electricity supply, none of the countries in the region has enough capacity to meet at least its own electricity demand (DoE, 2019). In such a case, an installation of larger nuclear power plants could play a significant role not only to South Africa but also to the SADC region (DoE, 2019).

However, Kessides' (2014) argument that SMRs are scalable, suppresses the need for larger nuclear power plants when development costs and experience are considered. This approach enables the installation of incremental SMRs therefore enabling the country to optimize its current financial ability.

Hayes (2022) claims that the very foundations of renewable energy were traditionally formulated with the inclusion of nuclear energy for network stability. Hayes (2022) further claims that any energy source that is

deemed viable must be sustainable, affordable, have a small environmental footprint and be able to replace the fluid energy transportation sector. This claim is in line with the current drive by European and Western states to transform the transportation sector from fossil fuels to electrical energy for which nuclear energy could play a significant role. Such a move requires reliable sources of energy and a stable grid that will ensure that Electric Vehicles’ (EVs) charging stations are always readily available and operational in the designated locations.

As crucial as it is, nuclear energy has radioactivity as a byproduct. However, during normal operation radiological exposure is minimal. Hayes (2022) claims that in the USA for example, the exposure to radioactivity through medical applications is higher compared to that due to nuclear power generation as shown in figure 2.

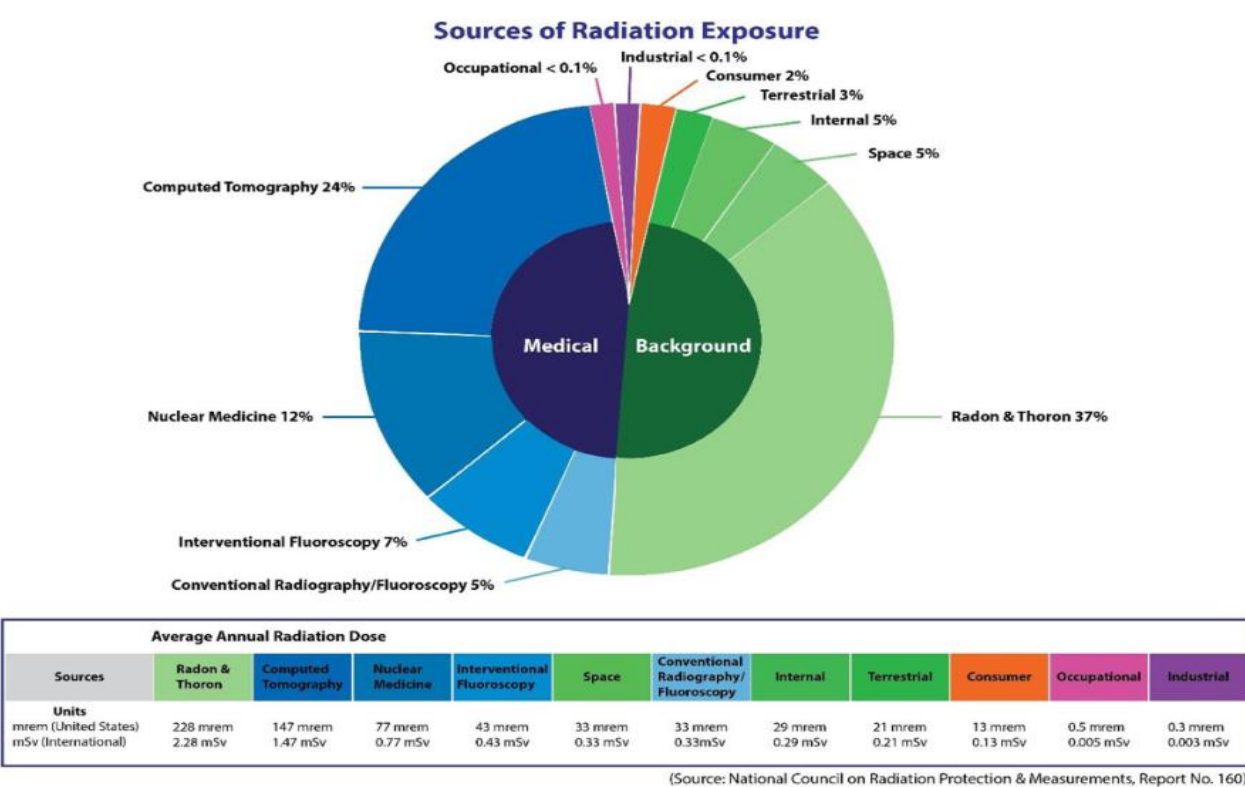


Figure 2: Sources of radiation exposure (Hayes, 2022)

From Figure 2, it can be noticed that the radiological exposure is significantly attributed to background at 37% and medical radiation at more than 50%. However, the above quantification makes no mention of the exposure during accidents which is currently the focus in nuclear power plant risks. Although the above analysis depicts a healthy radiological exposure to the society during normal plant operation, during accidents the radiological release increases to about 40 mSv in approximately 20 km as observed during the Fukushima accident. This value is above the worldwide 20 mSv regulatory exposure limit (van Wyk, 2021; WNA, 2023; Oishi et al, 2021).

Radiological risk management can be attributed to several methods designed to ensure that radioactive levels are kept low during nuclear power plant operations. Some of the applied methods include the Non-Linear Threshold (NLT) method, As Low As Reasonably Achievable (ALARA), biological design specifications and alternative models for low radiation exposure risks (Hayes, 2022).

According to Hayes (2022), relocating people to free them from radiological exposure may result in greater consequences than the exposure itself. Therefore, if such a relocation of masses is necessary, it must be done in such a way that those who are not flexible enough to move between places are moved with proper care. In areas like Cape Town, moving most people away from the radiological centers may pose a greater challenge. Such a move, however, can be facilitated by a proper analysis of ambient conditions, which would help to determine the direction and speed at which the masses must be moved at a given time as per the emergency evacuation plan.

In addition to ALARA, Hayes (2022) claims that humans are designed to habituate in an environment where background radiation is unavoidable. To support this claim, Hayes (2022) argues that potassium, an element necessary for human system functioning, exposes humans to radiation at about 0.1 mSv. Again, this is in line with the fact that humans are exposed to radiation from various sources (including natural) as shown in in *Figure 2*. To be noted, is the threshold model which attests that a reasonable radiation exposure is necessary to place a human body in an ambient which it was designed for. No radiogenic effects are expected until the radiation exceeds a threshold of 100 mSv.

Hayes (2022) argues that different places in the universe have different radiation levels owing to the existence of uranium and radon in some parts of the world. He further adds that some natural exposures are above 100 mSv and the referred populations in the area may be able to handle the radiation. Although due to reduced numbers, studies to affirm that natural radiation up to 250 mSv are safe for humans have not been conducted. Such a study could be so beneficial in the South African context in areas where uranium resources are naturally abundant, and no mining extraction is currently being executed (Karoo region).

2.2 Risk of nuclear accidents

The risk of nuclear accidents plays a significant role in determining how well a particular society or community accepts the development of nuclear power plants. Some notable accidents that have gone remarkably well noticed in history are the Three Mile Island (TMI), Chernobyl and Fukushima. As a result, probabilistic safety techniques derived primarily from the core meltdown at TMI, were incorporated into the core design to ensure that radioactive release is detected and prevented long in advance therefore preventing the risk of radioactive release.

The development of events in nuclear operations has been found to be slow but progressive as observed from the Three Mile Island where the sequence of events leading to a catastrophic failure exceeded 2 hours (Geduld, 2017). The Chernobyl, TMI and Fukushima accidents having been described as the worst-case scenarios, have seen a significant number of deaths emanating from suicides associated with the knowledge of radiological contamination.

2.3 Politics in the South African nuclear landscape

Politics is another factor that influences the deployment of nuclear energy technologies. Shivamba (2017) pointed out the Democratic Alliance's (DA) claim that the African National Congress (ANC) halts mining activities without disclosing any legitimate reasons. According to Shivamba (2017), the ANC government halted the mining activities because none of its members ought to benefit from these activities. The author is then prompted to marry corruption with politics as contributing risks inhibiting the deployment of mining activities in the country. Similarly, the claim is analogous to the Zuma's administration corruption scandals associated with nuclear technology deployment as inhibiting factors observed by van Wyk (2022).

The political challenges that led to the termination of the uranium enrichment program encompasses aspects like domestic politics, international politics, and national security. Domestically, the former South African president (P.W.de Klerk) initiated the nuclear disarmament in possible fear of the prospects of the revolutionary movement (ANC, black led organization) to gain power. Internationally, trade sanctions and sport activities may have influenced the need for nuclear disarmament. In addition, national security deliberations projected less risk owing to the fall of the communist regimes like the Soviet Union which had posed a greater national security risk to South Africa (World101, 2023, Albright, 1994).

2.4 South Africa's nuclear facilities

In July 1984, South Africa commissioned into service Koeberg Nuclear power plant that is in the Western Cape in the Atlantic Ocean coast with a generation capacity of 1800MW of electricity into the grid. Koeberg Nuclear Power Plant (KNPP) (which has 99 sister plants around the world; UK, US and France) was designed and built clandestinely by Electricidade de France (EDF), at the time when South Africa was under sanctions because of the apartheid regime that was not acceptable globally. Since its commissioning, Koeberg has operated safely and currently contributing about 4% of the electricity generation in South Africa (DoE, 2019).

KNPP was designed to operate for 40 years with two (Koeberg – 1 and Koeberg – 2) Pressurised Water Reactor vessels (PWR) capable of delivering 900MW of electricity each and it is expected to complete its established design life in July 2024 (Kessides, 2014).

In addition to Koeberg, in 1956, South Africa put into service the SAFARI-1 (PWR) nuclear power plant. SAFARI – 1 was designed for research purposes but was later converted to an isotope production nuclear facility with the capacity to produce ⁹⁹Mo isotopes used in cancer treatment (NECSA, 2014; NOU, 2022).

Furthermore, measurements to determine core and in-core rigging parameters and other activities associated with reactor beam tubes are conducted at SAFARI-1. The activities include measurements to determine beam characteristics, pool side facility where neutron transmutation, material modification and production of medical and other isotopes are done. Again, irradiation of samples for neutron activation analysis and measurements to determine pool side facility characteristics and parameters are carried out at SAFARI - 1 (NOU, 2022; NECSA, 2014).

South Africa is currently facing loadshedding due to decreased electricity generating capacity (58GW installed capacity with 20GW losses) because of the aging generating fleet, population growth and insufficient investment in electricity generation. The current government is then faced with a few options, such as extending the life span of KNPP by 20 more years beyond 2024, maintaining the existing fleet and investing the deployment of new generation plants (Thinus and Rix, 2021; NOU, 2022).

The life span extension, termed Long - Term Operation (LTO), is a practice adopted worldwide in nuclear power generation and it seeks to optimize the life span of the Nuclear Power Plant (NPP). In 2010 and 2012, Koeberg and SAFARI – 1 NPPs respectively, initiated the LTO process. This process is conducted in conjunction with the National Nuclear Regulator (NNR), National Energy Commission of South Africa (NECSA), International Atomic Energy Agency (IAEA) and other stakeholders through Safety Aspects of Long-Term Operation (SALTO) missions where evaluations for the granting of an LTO were done. Various modifications are underway at KNPP and SAFARI - 1 to ascertain that the LTOs are granted beyond 2024 for the case of Koeberg and until 2030 for SAFARI – 1 (NOU, 2022).

2.5 Key points

Chapter 1 highlights aspects critical to the development of nuclear energy facilities in South Africa. First, South Africa is currently experiencing electrical energy generation challenges that required a robust approach to resolve. Nuclear energy can be a solution to this challenge. Second, chapter 1 highlights that South Africa has enough uranium resources that can be exploited for electrical energy generation. Third, the challenges associated with the deployment of nuclear energy include politics, public participation and acceptance of nuclear technologies, fear of nuclear accidents emanating from the accidents such as TMI, Chernobyl and Fukushima.

However, South Africa has operated 3 NPPs since 1956 and has a proven record of safe operation. The LTOs conducted both for KNPP and SAFARI-1 show that Eskom has skills, resources and experience necessary to build and operate new nuclear facilities in collaboration with other organisations such as the international community, NNR and others.

3. Nuclear Power Generation

This chapter highlights the generation of electricity through nuclear energy, covering the processes involved in nuclear energy generation such as uranium extraction, uranium enrichment, packaging of uranium into pellets, life cycle of nuclear fuel in a PWR, management of spent nuclear fuel and NPP LTO.

3.1 Nuclear power reactors

Nuclear power reactors are nuclear power generating units consisting of a reactor core, reactor fuel, reactor vessel, moderator, control rods, coolant, steam generator and a containment vessel. The reactor enables nuclear chain reactions to take place and heat production thereafter. The heat produced is used to generate steam, which is further used to drive the turbines therefore generating electricity. External control systems also form part of the power plant, and they are responsible for the safe operation of the plant such as bringing the reactor to its operating parameters in case of a deviation (Bradley, 2017).

At start up, a neutron flux is generated into the reactor core to induce a chain reaction. The flux interacts with the fuel and the rate and nature of interaction depends in the type of materials, geometry of the reactor vessel and the energy spectrum of the nuclear material. Control rods are then used to ramp up the power until it reaches desired levels. At the operating level, when the reactor reaches criticality, neutron poisons like xenon and samarium production are at equilibrium along with neutron absorption therefore maintaining constant power production (Geduld, 2017).

Nuclear reactors can be classified according to their cooling mechanisms. In this classification the Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), Pressurized Heavy Water Reactors (PHWRs), Advanced Gas Cooled Reactors (AGRs), Light Water Graphite –Moderated Reactors (RBMKs), Advanced Reactors and Fast Neutron Reactors (FNRs) are found. Other classifications include Small Modular Reactors (SMRs), Pebble Bed Modular Reactors (PBMRs), and large reactors when size is used to classify nuclear reactors.

A typical PWR is shown in *Figure 3*.

A Pressurized Water Reactor (PWR)

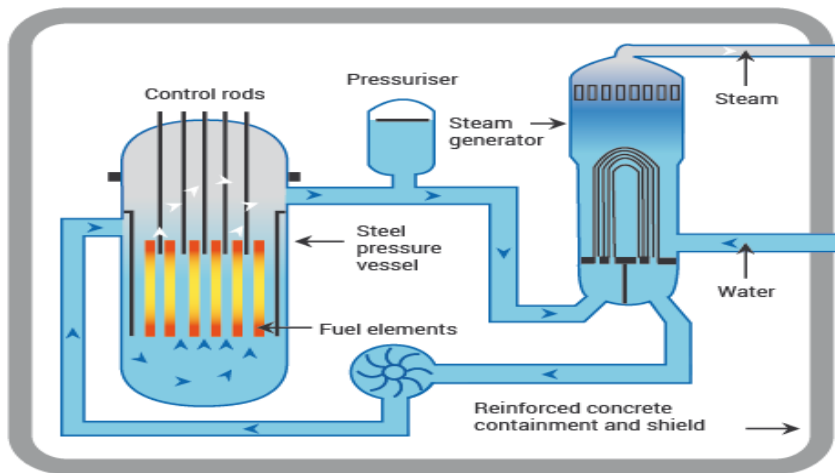


Figure 3: Typical PWR design (WNA, 2016)

The design, construction, commissioning, operation and decommissioning of nuclear power plants is encompassed in the Vienna convention in nuclear safety which was adopted by South Africa in 1994 and ratified in 1996 and came into force in 1997 (IAEA, 2017). The aspects covered by the convention are binding to the member states and contribute to various applications in the life span of a nuclear facility. The convention is primarily concerned with the containment of radioactive material in nuclear facilities (World Nuclear Association, 2016).

The defence - in - depth (DID) principle covers fundamental safety functions such as core cooling, reactivity control and radioactive confinement. This concept encourages a multi-layer design approach where if one protective system fails, the next protective system in the layer will react. The DID concept achieves its objectives through the compensation for both human and component failure, averting damage to the plant and barriers and protection of humans and the environment. To achieve this, high quality designs that incorporate fundamental safety functions, surveillance of the plant during operation, defined postulated accidents, operating experience, ambient conditions such as fires, temperature changes, flooding and landslides and providing redundant safety systems are employed (NNR, 2019).

The DID approach puts emphases on the five levels given in *Table 1* with several strategies including deterministic and probabilistic designs with probabilistic safety assessments, deterministic estimates with an improvement of DID approach.

DiD level	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting, and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident management
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

Table 1: Defence in depth levels (NOU, 2022)

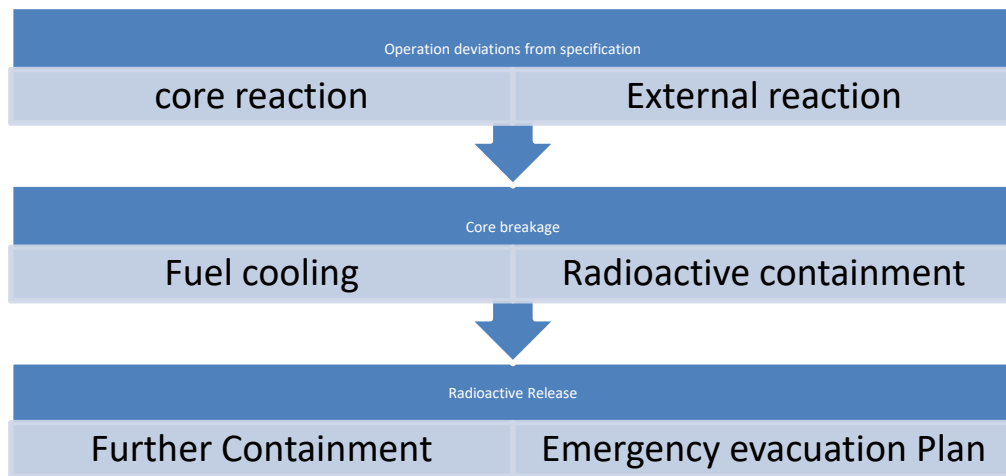


Figure 4: Hierarchy of protective layers of the defence –in - depth principle

As seen from Figure 4, the reactor core is the first protective layer that forms the radiological barrier to prevent the release of radioactive nuclei. The design of the reactor core should take into account all operating parameters such as temperature and pressure. The walls of the reactor core must have good tensile strength to resist deformation at high temperatures and rupture at high pressures (Barret *et al*, 2012).

External (secondary) reaction systems such as protection systems, cooling, containment and emergency evacuation plans as shown in Figure 4 only become useful once the core exhibits abnormal operation. Despite being secondary systems, they ensure the safety of people and the environment (Barret *et al*, 2012).

The reactor core must be able to return the system to normal when a deviation occurs. If the reactor core fails to control itself, then the protection systems together with human input must react and put in extra functions such as reactivity control to bring the reactor to its operating limits (Barret *et al*, 2012).

The control of accidents within the design bases is enshrined in Level 3. In this level, the evolution of events such as those postulated is resolved through safety engineered features. Active and passive safety systems are used together with the design and operating procedures to maintain the effectiveness of the barriers. The provision of redundant safety systems, prevention of common mode failure, automation of safety and operational features to minimise human error, testing and qualification of systems, components and structures are used to minimise the impact of accidents (NNR, 2012).

The design should also make provision for the assessment of possible radioactive doses and the provision of such information to be available to both the NPP operator and the regulatory body together with the local authorities to ensure that offsite emergency preparedness is effective in all relevant stakeholders. The regulatory body (NNR in South Africa) and the license holder are mandated in this level to provide advice to the local authorities (NNR, 2019).

Once construction is completed, testing and commissioning processes can begin to ascertain the conformance of all operational and safety systems and to provide bases for the development of commissioning test documents. In this stage, plant system specifications and manuals constitute the reference material (Paul *et al*, 2011). Phase I commissioning should provide preliminary tests and controls or start up functions which do not interact with the reactor core. Phase II aims at both hot and cold tests of the reactor coolant and other secondary systems before the reactor is loaded (Paul *et al*, 2011). The initial start-up test programme is composed of Phase III that focuses on core loading, cold and pre-critical tests as well as an initial run up for initial plant operation.

The operation procedure validation test is done during commissioning and through a simulation by a computer code. Innovative concepts are tested through the first of a kind test using specific approaches and equipment (Paul *et al*, 2011). The initial start-up test programme is done during the actual operating conditions. This test is meant to demonstrate that the plant operation during steady state and transient conditions is within design specifications. In addition, the test checks for compliance with safety criteria, test the adequacy of postulated hypothesis for safety analysis and that operating rules are properly integrated to the plant (Paul *et al*, 2011).

Again, the start-up tests should show that the plant can generate the required power within the design specifications and provide measured data to be used as a reference in the operating life of the plant. Other tests such as the initial core loading, pre-critical tests, initial criticality and escalation to 50% of full power and eventually the escalation to full power should be done during initial start-up (Paul *et al*, 2011, IAEA, 2014). In addition, qualification tests such as tests before Loss of Coolant Accidents (LOCA) must be done as per specification detailing the thermodynamic, chemical and irradiation conditions (IAEA, 2011).

In addition, Valentine & Sovacool (2010) proposed six factors that are conducive for the development of nuclear power plants as envisaged in Japan and South Korea. These are:

- *“Strong state involvement in guiding economic development;*
- *Centralization of national energy policy making and planning;*
- *Campaigns to link technological progress with national revitalization;*
- *Influence of technocratic ideology on policy decisions;*
- *Subordination of challenges to political authority, and*
- *Low levels of civic activism”.*

3.2 Safety of nuclear power plants

To meet the safety requirements of a NPP as stipulated by the convention in nuclear safety, certain requirements must be met. These include the classification of the safety functions of a NPP such as the assessment of different reference transients, incidents, accidents, and their frequencies. In addition, it should be indicated as to whether these safety functions occur in the controlled state where the temporary heat removal is possible using steam generators with stable core coolant. The assessment must also ensure that

radioactivity released is minimal and that the shutdown state where the core is subcritical, and the heat removal are within tolerable radioactivity release limits (IAEA, 2011).

Reactivity control shall be used to retain plant criticality using control rods or borated water injection systems. The reactivity control shall be done such that it prevents at all costs, the meltdown of the reactor core. This may include the use of sudden drop of control rods (SCRAM) to cease the reactivity in the reactor core. The reactivity control must be automatic with provision for manual operation (IAEA, 2011).

From the above, it can be deduced that the design of a nuclear power plant encompasses the physical design aspects, the operational aspects as well as the safety aspects of the power plant. These aspects coexist in a complex platform where the chain of incidences from the initiating event to the actual accident require continuous assessment, monitoring and prompt action.

3.3 Uranium fuel

The four identified uranium deposits in South Africa are located in the Witwatersrand, Springbok, Namaqualand and the Karoo. This uranium is deposited in various forms for example, the Witwatersrand uranium are quartz pebble conglomerates enclosed in an area of about 30 000km², constituting about 84% of South Africa's Uranium deposits (Kenan, 2014).

The Karoo uranium is sandstone hosted and only constitutes 4% of the country's uranium deposits while the Springbok uranium is coal hosted and amounts to 12% of the country's uranium deposits, and the Namaqualand is surficial-hosted deposits of uranium constituting of 1% of the country's uranium (Kenan, 2014).

The mined uranium is processed locally to produce uranium oxide (U₃O₈) which is then exported. During 2016, South Africa was producing about 500tU with prospects to increase the production to 700tU in 2018 and 1000tU by 2020 (Kenan, 2016). South Africa had embarked in nuclear fuel enrichment and fabrication in 1988, had its own nuclear fuel in the Koeberg reactor in 1991. However, South Africa terminated the uranium enrichment and fabrication in 1995 due to political and economic reasons. The termination of uranium enrichment led South Africa to total dependency in other countries for enriched uranium (Krivanek, 2020).

Uranium deposits are currently accessed through three methods. The first and most preferred is the open pit mining, which is feasible when the uranium ore is at a depth less than 150m. Open pit mining provides several advantages including open air space, which provides natural ventilation. The main disadvantage of open pit mining is its large footprint necessary to enable machinery movement and stabilising the soil. Another method used for uranium extraction is the underground mining, which is mostly preferred when the uranium deposit cannot be extracted economically through open pit mining. The advantage of underground mining is that it enables large amounts of uranium to be extracted (Osmanlioglu, 2022).

Some major disadvantages of underground mining include poor ventilation leading to the accumulation of dust and gases such as those from the machinery, which pose health risks to the workers. In addition, underground mining poses the danger of contamination to local aquifers and its remediation being expensive and takes longer to achieve. The third uranium extraction method is the in – situ - leach mining in which uranium is dissolved and pumped out. In - situ – leaching uses drilling of wells and submerged pumps to extract the solution composed of water and uranium in a lixiviate solution. The disadvantage of this process

is the contamination of local aquifers, which necessitates continuous monitoring through the surrounding check wells (Osmanlioglu, 2022).

3.4 Prospects of uranium mining in South Africa

Anglo-Gold Ashanti holds uranium mining operations in the Vaal region with reasonably assured resources of 39 466 tU. The Sibanye Gold mining focused in the Randfontein area with an objective to extract surface gold and uranium resources. In addition, Sibanye Gold Ltd also has operations for uranium and gold extraction in Driefontein in the Witwatersrand and in the Free State province. Other companies like Mintails Mining South Africa (Pty) announced its liquidation for gold and uranium mining operations in Krugersdorp (IAEA, 2020).

With South Africa having participated in the extraction of uranium since 1952, it should be expected that South Africa has a vast amount of experience in uranium extraction for both domestic and exportation in the international market. Although the uranium production declined from 6000 tU in the 1980s to 308 tU by 2018, it should be noted that South Africa has been producing uranium since then. The decline may have contributed to the skills decline in the uranium extraction industry but with prospects for re-invigoration when necessary (IAEA, 2020).

According to the IAEA, South Africa has not abandoned its ambitions of uranium extraction since there are ongoing extraction activities around the country with the Dominion Reef mines and the Karoo deposits considered as prospects for future uranium exploration. South Africa has a potential to extract, process, enrich and use uranium in its PWRs, an approach that could bolster the integrity of the South African economy and provide independence in South Africa's nuclear energy fleet management (de Boer *et al*, 2022).

According to the IAEA (2020), most companies that had applied for uranium mining licenses had concluded their feasibility studies and investigations. Although the studies showed positive results for uranium extraction with other minerals, these companies opted not to go ahead with the mining. Some of the companies cited financial constraints and economic viability while others deferred the mining process to 2018 due to the lengthy application process (IAEA, 2020). It is worth also noting van Wyk's (2021) supposition that the mining companies that were expected to extract uranium in the Karoo were somehow linked to the Zuma administration. This made it difficult for these companies to continue with their operations when Zuma lost his presidency.

According to the DEMR (2022), several barriers affect the extraction of uranium resources in South Africa. These include a time frame for exploration rights, multiplicity of rights, inactive prospecting rights, refusal of access to private land, unintended ramifications of the first come first serve principle, incongruent policies and legislation, blurred instruments of transformation, financial and investment, and research and development barriers. The DEMR proposes several interventions to address the stated barriers.

To address these challenges, DEMR (2022) proposes interventions such as the development of an efficient and transparent system, prioritising licensing using a cohesive multi-disciplinary approach, provision of a one - stop for information necessary to enable smooth process flow, use research and development to disseminate necessary skills, develop an uninterrupted and continuous investment plan, assignment of powers to the DEMR minister to expropriate land for extraction and economic reasons and pose time limitations (one months) for the processing of appeals and rejections.

3.5 Uranium fuel production

After the mining process has been completed, the uranium ore is crushed and treated chemically to separate the uranium from the rest of the elements. Through the separation process, ore is crushed, ground and leached then added to a sulphuric acid leaching solution. After grinding, the ore is mixed with water to form slurry, which is then pumped into tanks where it is mixed with agitators. The agitators remove uranium oxide and non-uranium gangue material by exploiting the slurry's physical properties. In addition, radiometric sorting is also used to improve the ore grade if necessary, depending in the initial quality or the slurry (Kim, 2018).

The enrichment of uranium is followed by fuel fabrication where the properties of the SNF are characterised and the fuel management requirements that encompass cooling, reprocessing and disposal are integrated in the design of the fuel elements. UF_6 cannot be used directly in nuclear power reactors since it has neither high mechanical strength nor the ability to withstand high temperatures and pressures. Therefore, it is necessary for the UF_6 to be converted into UO_2 which is then heated at temperatures above 1400°C so that it can achieve high density and stability (Ulmer-Scholle, 2018).

The UO_2 rods are packed to form pellets of specific dimensions (radius and length of the cylinder) that satisfy both the geometric and material buckling requirements and then placed in fuel rods which have high mechanical strength and temperature coefficients. These rods are then assembled into the reactor core where nuclear fission takes place (Ulmer-Scholle, 2018).

For applications in PWRs, the fuel is enriched with ^{235}U to about 5% and packaged into pellets. In the PWR, the enriched uranium interacts with neutrons through the fission process. The total energy produced in the PWR can be estimated using $E = N \times f \times \Phi = m \times f \times Av/M$ and consequently the power by dividing by time. In this equation, E is the total energy, N is the number of fissions, f is the number of fissile material and, Φ is the neutron flux, m is the mass, A is the atomic number, v is the velocity and M is the molar mass.

When designing the fuel rods, the designer must ensure that the material used (mostly ceramic) meets the operating and abnormal temperatures to cater for the cladding integrity, oxidation and hydrogen generation limits in the core (Ulmer-Scholle, 2018). The thermodynamic properties of the cladding must be such that the heat difference between the inner and outer cladding is maintained to ensure that there is a heat gradient enabling the removal of heat from the cladding (Ulmer-Scholle, 2018).

After reactor shut down, residual heat amounting to about 7% of the operating power is still generated for less than 24 hours. The remaining residual heat must be removed from the fuel for a period of about 10-30 years while the fuel is cooling. The fuel cladding design must be such that the cladding properties are not lost in waters at the depth of about 6m and 50°C temperatures. The cladding must further be designed to survive dry storage conditions where temperatures are low by inhibiting cladding creep rupture and mechanical strength degradation. Furthermore, the cladding design must enable the separation of the cladding from the fuel pellets through specific separation processes such as chemical or thermodynamic processes (Ulmer-Scholle, 2018; Shama *et al*, 2021).

3.6 Fuel life cycle in a NPP

The life span of fuel in a PWR reactor is currently estimated to be between 18 and 24 months. During this time, the fuel element, fuel rod, neutron flux and the coolant interact thermodynamically at very high temperatures. Typically, the temperature rises to 1307°C in the fuel element, between 500 and 2000°C for the fuel pin measured radially and 377°C for the moderator. The heat transferred from the fuel elements is affected by the geometry of the fuel design, the distribution of the neutron flux, coolant flow conditions and cladding properties (Moreira *et al*, 2022; Hussein, 2020; Zakir *et al*, 2019).

Waste management is another concern arising mostly from the characteristics of spent nuclear fuel. These characteristics include radioactivity, risk of explosion, handling challenges and possible release of radioactive material to the environment. The environmental impact of nuclear operations is very severe if an accident does occur as has been observed in the Chernobyl accident where about 200 000km² of land were contaminated with radio cesium (IAEA, 2006).

The nuclear fuel cycle can be categorised as either open cycle or closed cycle. The open cycle strategy does not consider the recovery of residual uranium that remains in the fuel after nuclear power production. In a sense, this cycle is much cheaper as it does not entail the reprocessing of the SNF which would rather necessitate the handling of irradiated uranium. After the spent fuel has been removed from the reactor, it is taken to a temporary storage where it is allowed to cool. This may take a period between 10 to 30 years and thereafter the spent nuclear fuel may be transported to a final geological repository for disposal (IAEA, 2011).

The closed cycle includes all the steps up to the cooling period. However, after cooling, the SNF is taken to a reprocessing facility where the fuel will be separated from the cladding and uranium extracted through chemical processes. After reprocessing, High-Level Waste (HLW) is vitrified and stored in a natural Deep Geological Repository (DGR). The extracted uranium, in a form of UO₂, is then recycled and sent to the fuel fabrication stage and then back to the nuclear power plant (IAEA, 2011).

3.7 Characteristics of SNF

The extractability of various nuclei is important in SNF volume reduction especially when disposal in DGRs is considered. In a sense, reprocessing may reduce the volume of SNF to 0.5 m³ of high and intermediate waste and 1.4m³ of low and very low-level waste for every tone of SNF translating to very low transportation and storage costs of SNF waste (Khalil *et al*, 2004).

The fission products released during fission can be categorised into fissile material and non-fissile material. In addition, the fission products can be categorised as short time lived, medium lived and long lived. The short-lived isotopes will decay about four years after the reactor shutdown. The medium term lived fission products such as ¹³⁷Cs and ⁹⁰St undergo beta or gamma decay in a period of about 30 years (Baisden *et al*, n.d).

Of the three identified groups, the long-lived fission products are of greater concern since they can take decades to decay. Again, the SNF can be categorised in terms of the energy released, half-life and composition. In terms of energy released, SNF can be classified as High-Level Waste (HLW), Intermediate Level Waste (ILW) and Low-Level Waste (LLW). Furthermore, SNF can be categorised as major, minor and heavy actinides (Baisden *et al*, n.d).

HLW is a form of highly radioactive nuclear waste generated in NPPs and nuclear weapons production, which has a high concentration of fission products in which the temperature may increase significantly following radioactivity. This form of waste is also produced during reprocessing in a liquid form, and it generates significant amounts of heat. Intermediate Level Waste (ILW) is generated from activities undertaken in the nuclear plants and constitutes 7% of the spent nuclear fuel volume and 4% of radioactivity and they are disposed by burial in DGRs. These include gloves, tools, defective reactor components, redundant fuel casing and other radiated material from reprocessing plants. ILW may be solidified, untreated or partially treated then kept on site or transported to special locations (Baisden *et al*, n.d).

LLW is materials that get contaminated by radiation during nuclear operations both in civil and military facilities. These materials are common materials such as paper, tools, protective clothing and others as well as materials that contain low levels of radiation as classified by the regulations. This type of waste can be disposed with minimal protection using the principle of delay to decay, or dilute to disperse. Again, the volume of LLW can be minimised through the compaction of the material before disposal near surface with no restrictions depending in the level of radioactivity (Baisden *et al*, n.d).

Long-lived fission products (LLFP) have half-lives ranging from 30 years to a couple of millions of years. Most of these decay by β^- to their stable state. Khalil *et al* (2004) identified the transmutation characteristics of LLFPs such as ^{99}Tc and ^{129}I . There are six nuclides transmutable in both fast and thermal reactors. These are neodymium, technetium, palladium, iodine, cesium and samarium. Their transmutability makes them a target for reactor-based transmutations.

Actinides are all the elements in which the extra electron enters the $5f^{\text{th}}$ orbital of $(n-2)^{\text{th}}$ main shell and they all have the same physical and chemical properties. Actinides are also heavy radioactive metals with no stable isotopes and can be classified as major, minor and heavy actinides. The difference in stability between oxidation states for various actinides enables the separation of uranium and plutonium from various actinides therefore facilitating reprocessing.

Plutonium, in its fifth distinct oxidation states forms part of major actinides depending in the medium of acidity. Plutonium in the oxidation state is unstable and can undergo disproportion only in its oxidation states +IV and +V. For nuclear fuel treatment, the disproportion plays a greater role in enabling separation to be done in an acidic medium with a high concentration of protons. In an aqueous solution, plutonium cannot be reduced to its metallic form using an electrode made of noble metal since the redox potential has a strong negative value relative to the reduction potential of water. Plutonium is pyrophoric in its metallic form citing that it requires a lot of oxygen hence difficulty with extraction (Robert & Pradel, 2008).

The distinct feature of neptunium is its stability in oxidation state +IV which is contrary to uranium which is unstable in oxidation state +IV. Neptunium in oxidation states IV and V exhibits a complex redox behavior close to that of NO and NO₂ and nitrous acid, making it difficult to extract (Robert & Pradel, 2008).

Americium is highly unstable in oxidation state +IV due to disproportionation in the formation of Am (III, IV). Am absorbs alpha radiation forcing it to reduce its oxidation states. In an aqueous solution, Cm exhibits two oxidation states (+III, +IV). Due to the high values of the redox potentials, curium exhibits a low stability in state +IV therefore preventing extraction through redox reactions (Robert & Pradel, 2008). The heavy actinides, californium and berkelium are more stable in oxidation states +III although they may also occur in state +IV. Nobelium is more stable in oxidation state +II while lawrencium is only accessible and stable in oxidation state +III hence it can be separated from uranium and plutonium (Robert & Pradel, 2008).

3.8 Global nuclear waste management strategies

As new nuclear power plants come online and the existing ones continue producing spent nuclear fuel, it is evident that the spent nuclear fuel inventories are increasing. This necessitates a definite spent fuel management system with well-defined strategies and processes. Currently, the most adopted strategy for spent fuel management is a direct disposal strategy.

The current scientific and engineering concept for spent nuclear fuel disposal is deep geological facilities. In this strategy, the spent nuclear fuel is first vitrified, encapsulated in copper and iron canisters where the iron provides mechanical strength, and the copper provides radiation shield. The canisters are then placed in deep multi-barrier geological repositories. The first barrier is the canister through solid fuel pellets and fuel rod cladding followed by a multi-barrier canister system and other clay-based materials and the actual geological formation providing the ultimate shielding (Sinnathamby *et al*, 2017).

Lim (2016) supposes three strategies currently employed worldwide to manage SNF. The first two strategies; open cycle and closed loop cycle have been discussed. The third strategy proposed by Lim (2016) is the wait and see strategy. This strategy involves the storage of the SNF in the nuclear facility to cool down then transport it to a long-term storage facility where the SNF will be stored for a long time while waiting for technological developments that will provide solutions to the management of SNF. Lim (2016) further poses a multilateral approach towards the management of SNF.

In this approach, Lim (2016) supposes that countries and organizations could come together to devise SNF management strategies. This approach could improve the security and safety of SNF since most countries that have SNF in pools are prone to natural disasters and terrorist attacks. This notion is not far from van Wyk (2021)'s concern in the armed robberies at Pelindaba site. In addition, such a multilateral approach could enhance transparency, reduce the risk of plutonium accumulation, and consequently reduce the risk of proliferation. Another advantage pointed out by Lim (2016) is the simplicity associated with the management of a single SNF management facility rather than managing facilities scattered around the world.

When responding to the questions associated with multilateral storages, Lim (2016) considered the conglomerate of East Asian countries in relation to the "123 agreements" signed with the USA. An international SNF management strategy and an international plutonium storage facility could be helpful. Several organizations including the Organization for Economic Cooperation and Development (OECD), IAEA and the Radioactive Waste Management Committee (RWMC) are significant stakeholders that embarked in research to determine the viability of such multilateral SNF management and plutonium storage facilities.

Although the USA has been developing an internationally integrated and inclusive SNF management strategy, other countries like Russia had a different approach in the management of SNF including importing the SNF from countries producing nuclear energy without a closed cycle (Lim, 2016). The approach by Russia shows the diverse approaches countries may have towards SNF and its use in that such an ownership would provide Russia with the ability to produce weapons grade plutonium therefore contributing towards proliferation.

To effectively implement the international SNF management strategy, various organizations engaged in research such as Pangea Resources, Golder Associates and Swiss Radioactive Waste Management in Nagra and concluded that Southern Africa, Argentina, Western China and Australia were the most suitable candidates to harbor SNF. This proposal could not come without challenges due to the perceived safety and security aspects of SNF. Public acceptance would pose a greater challenge in such a proposal especially

from the communities closer to the identified sites (Alzahrani *et al*, 2020). Lim (2016) also argues that although this approach is attractive, the “not in my backyard principle” could come into force in various communities chosen to participate in the international SNF management strategy with SNF facilities to be developed in their proximity (Lim, 2016; Alzahrani *et al*, 2022).

Lim (2016) claims that a European Repository Development Organization (ERDO) that included 14 countries, was formed in 2009 to facilitate the development of a shared storage for SNF and that every member state to ERDO ought to develop and maintain its own national policies for the effective management of shared SNF facilities. However, the challenge facing the implementation of the ERDO programme is that the countries that are still members of ERDO either have limited nuclear facilities or have no nuclear facilities at all. In addition, these member countries are also part of the ‘123’ agreement with the USA. This means that these countries’ independence in decision making relating to SNF management must be made in consensus with the USA therefore making it difficult to house the shared SNF storage and developing related policies (Woo *et al*, 2020).

One of the major challenges facing East Asian countries in relation to SNF management is the acquisition of licenses citing that such an acquisition has become difficult. With stockpiles of SNF amassing and with DGRs being developed, the proliferation risk amounts which can be observed from Japan’s failure to disclose the 2013-2014 plutonium quantities may exacerbate the challenge (Lim, 2016). This failure speaks to the failure in security systems requiring disclosure of the accountancy of SNF material. China’s dissatisfaction in the matter resonates the political issues associated with SNF echoed by both van Wyk (2021) and Woo *et al* (2020).

A strong opposition to multilateral SNF storage in Mongolia indicated a significant turn in the multilateral approach for SNF. Diplomatic means to implement shared repositories, domestic factors associated with the public acceptance, economic and financial aspects significantly have a potential to impede the success of the development of shared DGRs (Lim, 2016). Such a failure can be partly attributed to the lack of formal organizations vested with the development of shared DGRs. Several proposals such as taking SNF to the USA were brought to the table without success probably owing to the lack of driving organizations or even trust in the host country (Lim, 2016).

Lim (2016) suggested that the Asia-Pacific countries are more diverse with respect to their economic development, demographic sizes, socio-political systems and history. This diversity poses a challenge in that trust between countries in relation to the safe storage and use of SNF is nonexistent if not limited. This makes it difficult for Asia-Pacific countries to reach consensus in matters related to a shared DGR. Lim (2016) further argues that a shared DGR would pose significant challenges if the SNF volumes are very large to be managed collectively. The Asia-Pacific countries have different policies in relation to SNF management and interaction with the international community. This makes it difficult for these countries to coordinate or consolidate their SNF management policies.

The South African SNF is currently stored on site in the KNPP. NECSA is currently responsible for the management of spent nuclear fuel emanating from Koeberg which is currently stored in pools as well as in casks at Koeberg NPP. In 2009, South Africa has embarked on research to initiate reprocessing of spent nuclear fuel to which the MOX – fuel could be exported but the idea submerged (Damveld *et al*, n.d).

In 2008, the minister of minerals and energy stated that South Africa would investigate the possibilities of building a reprocessing facility while sending fuel for reprocessing in other countries in the meantime (DoE, 2008). Damveld *et al* (n.d) claims that South Africa would need a high-level waste management site by

2070 and that three sites would need to be identified with environmental assessments to be done individually. The negotiations for such sites were expected to surface in 2015 with the National Nuclear Regulator (NNR).

The total spent fuel produced at Koeberg up to 2022 is given in *Table 2* below.

	Dry storage casks	Spent fuel pool Unit 1	Spent fuel pool Unit 2	Total spent fuel assemblies
Quantity of fuel assemblies	336	1 229	1 116	2 681

Table 2: Koeberg SNF up to 2022 (NOU, 2022)

3.9 Spent nuclear fuel reprocessing

The objective of reprocessing is to extract, through chemical means the components of the SNF that can be re-used for power generation or other applications such as in medicine. Currently, France, India, the United Kingdom and Russia are the only countries that have declared operational reprocessing facilities. Reprocessing plants are very few in the world owing to the cost associated with it and more important, the environmental and proliferation concerns (Percebois, 2003). A global reprocessing and storage facility has been proposed and Australia is the target country. However, the feasibility of reprocessing in South Africa still needs to be investigated (Penalunga *et al*, 2017).

Reprocessing is a sequence of mechanical and chemical processes through which spent nuclear fuel (SNF) is processed to exploit the energy stored in it and reduce the volume of HLW. These processes must be well established from the time the fuel reaches the NPP until the fuel is reprocessed. The SNF from a PWR consists of about 96% ^{238}U , 1% of ^{235}U and 2% of plutonium. The reprocessing strategies seek to extract uranium and plutonium from the SNF so that it can be re-enriched and re-used in the nuclear power production process (Penalunga *et al*, 2017).

For effective reprocessing, the twice- through (closed) cycle which involves the transportation (after the cooling period) of the SNF from the NPP to a reprocessing facility is employed. In this strategy, uranium and plutonium are separated from minor actinides and other fission products using Plutonium and Uranium Redox Extraction (PUREX). Since uranium constitutes 96% of the SNF from PWRs, the minor actinides and other fission products only form about 4% of high-level waste. The high-level waste is reduced by 80% and the radiotoxicity is reduced by 90% after reprocessing (Penalunga *et al*, 2017).

The plutonium component is recycled into Mixed Oxide (MOX) which is suitable for use in nuclear reactors. Fast Breeder Reactors are more suitable for the use of reprocessed MOX fuel since they enable the fission process to take place using fast neutrons which have very high energies. In addition, FBRs do not necessarily require the separation of plutonium from uranium therefore reducing the proliferation risk (Penalunga *et al*, 2017).

The recovered uranium, though highly radioactive, can be re-enriched in special plants at a higher cost than the enrichment of natural uranium. The challenge here is that both the MOX and re-enriched uranium are currently stored due to radioactivity and lack of special facilities. The fear is that un-radiated uranium entering the NPP can be exposed to radioactive contamination (Penalunga *et al*, 2017).

3.9.1 PUREX reprocessing

Using the PUREX process, the extraction of Pu and U through Redox reaction can be explored first as it is known to be the most reprocessing mature technology in the world (Penalonga *et al*, 2017). In this process, only Pu and U are extracted using nitric acid and minor actinides and fission products remain in the acid which gets vitrified (transformed into glass) and stored in universal canisters suitable for deep underground storage (Penalonga *et al*, 2017). The extracted U and Pu are then recycled into fresh or MOX nuclear fuel that can be re-used (See Appendix A).

The improved PUREX process (Extended PUREX) involves the additional separation of neptunium and technetium through the tributyl phosphate (TBP) purification cycle. In addition, minor actinides such as Am and Cm are also recovered using the DIAMEX-SANEX, TRUEX-SPEAK and NEXT processes. Am and Cm can be further separated using the DIAMIDE process if necessary (Penalonga *et al*, 2017).

A development of reactors with a potential to use reprocessed fuel is necessary. If South Africa cannot use the processed fuel, the fuel can be sold to utilities with appropriate facilities for reprocessed fuel. Reprocessing can reduce the HLW inventory together with other LLW inventory significantly such that the transportation cost, storage and disposal of SNF could be minimized.

3.9.2 Pyro-processing

According to Woo *et al* (2020), a sustainable nuclear power plant must overcome the challenges posed by astronomical capital costs, detrimental radioactive waste and proliferation risks. To address the radioactive waste challenges, Woo *et al* (2020) proposes a closed loop approach with pyro-processing (electro-chemical extraction method) being the most prevalent strategic solution for radioactive waste management. Woo *et al* (2020) cited that pyro-processing is more proliferation resistant compared to PUREX reprocessing simply because the PUREX strategy produces pure Pu, which is more viable for the creation of weapons. Pyro-processing produces depleted uranium and trans-uranics for which Pu, the main element, is less attractive for proliferation with the unavailability of water also contributing significantly to the simplicity of handling the SNF since the risk of criticality is averted (no thermalisation) (Woo *et al*, 2020).

In addition, Woo *et al* (2020) claims that pyro-processing reduces the amount of nuclear material needed during power production. To support that, Woo *et al* (2020) argues that in a closed cycle only about 50% of the nuclear material is needed to generate the power that would rather be produced in an open cycle. This in turn would mean that the amount of SNF to be handled is reduced in a closed cycle therefore minimising the resources necessary for such handling. With this benefit, comes the reduction in enrichment capacity needed and the proliferation risk associated with the use of nuclear power facilities.

Woo *et al* (2020) also evaluated the proliferation risk in conjunction with nuclear material handling especially diversion possibilities. Without heat generation, the SNF can be easily enriched to proliferation grade. The two main aspects covered by Woo *et al* (2020) are the probability of detecting the misuse of pyro-processing special nuclear material and policy recommendations that would assist in ensuring a safe use of pyro-processing.

Woo *et al* (2020) cited the Pacific Northwest National Report in pyro-processing which claims that pyro-processing has significant challenges most of which emanate from the fact that the world has not yet managed a commercial pyro-processing plant with a capacity above 1000MTU making current safeguard approaches in relation to pyro-processing conceptual. In addition, Woo *et al* (2020) claims that the nuclear

material accounting would be more difficult because of high temperatures during electro-refining. Woo *et al* (2020) then poses extensive video surveillance, verification of the stability of plutonium in relation to curium and homogeneity verification of materials with high destructive assay methods as necessary to further understand the principles that could underpin the success of pyro-processing.

Woo *et al* (2020) then concluded that a combination of NaI gamma ray detection to detect the deviated plutonium, nuclear magnetic resonance (NMR) for material accountancy and a neutron detection system to safeguard plutonium and uranium when pyro - processing is employed. Woo *et al* (2020), does however, acknowledge that despite the proliferation resistance of pyro-processing, an addition of a covert PUREX step in the pyro-processing system could result in a proliferation risk (Woo *et al*, 2020). This risk would be as a result of numerous failures in the pyro-processing system such as material handling, barrier credibility, forging of documents, failure in monitoring systems, personnel involvement and handling issues (Woo *et al*, 2020).

3.9.3 Advanced fuel cycle initiative (AFCI)

Dixon *et al* (2005) claims that the Advanced Fuel Cycle Initiative (AFCI) is a strategy that seeks to explore the extraction of nuclear energy through the development of technologies that enable efficient disposal of SNF and HLW while recovering most energy content from the SNF in conjunction with generation IV nuclear energy systems and designs that are more proliferation resistant. By so doing, the SNF inventories around the world would be reduced therefore the requirements for DGR systems would be minimal. In addition to the open cycle and limited cycle fuel management strategies, Dixon *et al* (2005) proposes a limited cycle strategy where the Trans-Uranic (TRU) elements will be recycled continuously and that no TRU should be taken to the DGR. The 4th strategy is the sustained recycle strategy where fission reactions would be used continuously to sustain the reactions in FBRs. This fourth strategy involves the recycling of depleted uranium. Dixon *et al* (2005) presents 4 basic objectives to achieve the AFCI needs with 3 identical questions asked per objective;

- What is the meaning of the objective?
- What strategies work for this objective and
- What are the key separation challenges to that particular objective?

3.9.3.1 Meaning of the objective

Dixon *et al* (2005) argues that the first objective seeks to reduce the environmental burden posed by nuclear energy production by employing more efficient disposal of waste material strategies. In this objective, it is proposed that uranium be recycled into new fuel or disposed in non-geologic ways while the TRUs can be extracted, recycled and converted into fission products with heat extracted therefore storage therefore posing shorter-term disposal problems.

The second objective involves improving the proliferation resistance using improved technologies for SNF management. Dixon *et al* (2005) claims that countries with low nuclear capabilities could benefit from the use of AFCI strategies in that the technologies needed in nuclear power generation could be supplied by those countries with high nuclear power capabilities. Dixon *et al* (2005) further argues that physical and monitoring strategies could improve the security of nuclear material by increasing the time required to divert material and decrease the detection time.

The third objective is aimed at increasing the efficiency of the nuclear power generating systems to ensure that all recoverable energy in SNF and Uranium is extracted, and that uranium resources usage are extended. Dixon *et al* (2005) argues that if new power plants that use depleted uranium are employed, nuclear energy resources could replace fossil fuels for the next 1000 years. The efficiency in nuclear power generation can be done by considering strategies like the AFCI where heat is extracted for further use from the SNF, the SNF is recycled to remove uranium and make new fuel and plutonium and other TRUs are used in FBRs.

The fourth objective seeks to improve fuel cycle management, improve safety performance while improving fuel cycle economics. The first intention of the fourth strategy is to make the production of nuclear energy more economical as better technologies emerge and better DGR strategies are developed. Dixon *et al* (2005) argues that such developments as in the Yucca Mountain will reduce the cost of nuclear power generation with fast reactors guaranteeing the practicality of sustained recycling while on the other hand giving uncertainty in relation to the cost penalty. Fast reactors are more preferred when generating power from SNF since they can accommodate fast neutrons, which are more prevalent in U^{238} reactions.

3.9.3.2 Working strategy

The second question is related to the strategies that work. This is critical to ensure that the employed strategies will yield expected results with regards to sustainability, safety, economics and development when the AFCI strategy is used. The conversion of TRUs into fuel creates an opportunity to reduce the waiting time for TRUs to decay from millennia to a few centuries. While waiting, the TRUs can be converted into fuel and reused in Fast Reactors. The proliferation resistance can be achieved through four main objects; first, material theft could be curbed with advanced security monitoring systems and integrity of barriers preventing unauthorised access to nuclear material.

Safeguards by design will reduce clandestine diversion from declared facilities through improved designs and monitoring technologies. Furthermore, AFCI would employ reprocessing strategies that are less attractive to weapons proliferation compared to the conventional PUREX strategies. Lastly, AFCI may improve the inhibition of abrogation from nations intending to pursue proliferation objectives through improved security and use of technologies that require periodic checks and inspections to ensure that nations are compliant with the Non-Proliferation Treaty.

The AFCI strategy also minimises the transportation of the materials necessary for proliferation since these materials would have been recycled and reused in Fast Reactors. Through Extended refuelling and maintenance intervals such as 5 to 10 years, the incentive to wait for that opportunity fades with time therefore making AFCI a better proliferation resistant option. In addition, the strong security measures associated with reloading would require precise modules to be part of the maintenance therefore preventing material diversion (Dixon *et al*, 2005).

3.9.3.3 Separation challenges

The third question deals with the separation challenges experienced through recycling. During separation, the residual uranium can be separated and converted into fuel for re-use in fast reactors. In addition, plutonium is also separated from the SNF together with at least one TRU element preferably Np due to its simplicity for extraction with Pu. Another challenge is to make technologies that are tamper proof prohibiting both access and diversion of nuclear material. The primary challenges

associated with the separation process is the technologies necessary to extract 99% of the TRUs. Another challenge is reducing the disposed TRUs by a factor of 100 and also reducing the longer-lived radiation dose by a factor of 10 (Dixon *et al*, 2005).

3.10 Key points

This chapter has highlighted the various types of nuclear reactors. Among these, KNPP uses a PWR design. For the safety of the NPP, the DID approach plays a significant role in ensuring that radioactive release is prevented. In cases where the release occurs, the DID specify measures to be taken to reduce the consequences thereof. In addition, various tests are conducted in the NPP before it is put into service. The commissioning is meant to ensure that all design specifications and parameters are met.

Uranium is abundantly available in South Africa especially in the Witwatersrand, Springbok, Namaqualand and the Karoo regions. Uranium extraction is done through open pit mining, in Situ leaching and underground mining. The extracted uranium is then processed to form slurry which is then mixed with agitated to remove UO₂. The UO₂ is then enriched to about 5% and packaged into fuel pellets.

Once the pellets have been fabricated, the pellets are packed into fuel rods then used in the NPPs. The life of nuclear fuel in the NPP is currently between 18 and 36 months. During this time, nuclear fission takes place therefore enabling the production of energy. Once the fuel has been used, it is removed from the reactor and stored on site between 10-30 year for cooling.

Various SNF management strategies are explored worldwide. The SNF can be stored in a Geological repository, or it can be reprocessed and re-used in NPPs. One of the most dominant reprocessing processes is the PUREX process. During the PUREX process, HLW, ILW, LLW are produced. In addition, heavy and minor actinides are also found in SNF. It should be noted that after reprocessing, the SNF inventory is reduced both high level waste and radiotoxicity significantly.

KNPP currently holds SNF amounting to 2681 tonnes. The SNF is currently stored on site at Koeberg. South Africa is currently adopting the wait and see strategy. This is based in the hope that the international community will devise better solutions for SNF management.

4. Long term operation (LTO) of existing nuclear power plants

Chapter 3 discusses the premises for the granting of an LTO. The importance and contributions from both internal and international organisations are discussed. The SALTO seminar reviews as well as the roles played by organisations like the WANO and INPO are also discussed.

Lastly, the SALTO reviews based in the KNPP, SAFARI – 1 and global experiences are discussed. From the SALTO reviews, KNPP performance and safety culture are considered. In addition, the aging management plan is discussed to deduce South Africa's experience in operating NPPs.

4.1 Long term operation

Havel & Krivanek (2016) puts forward a need to comply with IAEA safety standards and best international practices as guides provided to ensure the safety of a NPP whose life is being extended. In addition, Havel & Krivanek (2016) claims that SALTO peer review is available to nuclear operators that are member states of the IAEA with the intent to extend the life of their NPPs. Seminars such as Pre-SALTO mission, SALTO mission and follow up SALTO missions that are designed to focus on the review of aging management programmes are necessary for LTO. The seminars identify aspects related to programmes, processes and management issues (Havel & Krivanek , 2016).

According to Havel & Krivanek (2016) the SALTO reviews cover:

“A. Organization and functions, current licensing basis (CLB), configuration/modification management;

B. Scoping and screening and plant programmes relevant to LTO;

C. Ageing management review, review of ageing management programmes and revalidation of time limited ageing analyses for mechanical components;

D. Ageing management review, review of ageing management programmes and revalidation of time limited ageing analyses for electrical and I&C components;

E. Ageing management review, review of ageing management programmes and revalidation of time limited ageing analyses for civil structures;

F. Human resources, competence and knowledge management for LTO (optional area) ”.

During the SALTO missions, an LTO module is included which seeks to address the integrity of the plant process and programmes to hold safe operation beyond the design life base (Havel, 2016). The outcomes of the SALTO peer review include aspects of safety that are critical to LTO where improvements are needed. In addition, Havel & Krivanek (2016) claims that the findings from various NPP that seek to do an LTO, are common worldwide and the lessons learnt can be applied in other NPPs.

Furthermore, an OSART (Operational Safety Review Team) mission that identifies issues that occur in NPPs is conducted. Findings and recommendations from the reviews are categorized appropriately and that attention can be generalized to those that exhibit commonalities in a significant amount of NPPs (Havel & Krivanek, 2016).

Pre-SALTO and SALTO missions.

No.	Plant	Mission type	Year
1	Paks	Pre-SALTO	2005
2	Paks	Pre-SALTO	2006
3	Paks	Pre-SALTO	2006
4	Paks	Pre-SALTO	2007
5	Paks	Pre-SALTO	2008
6	Paks	Pre-SALTO	2008
7	Karachi	Pre-SALTO	2007
8	South Ukraine	Pre-SALTO	2007
9	Kori 1	SALTO	2007
10	Dukovany	Pre-SALTO	2008
11	Borssele	Pre-SALTO	2009
12	Koeberg	Pre-SALTO	2011
13	Paks	SALTO	2011
14	Borssele	SALTO	2012
15	Wolsong 1	SALTO	2012
16	Tihange 1	Pre-SALTO	2012
17	Armenian 2	Pre-SALTO	2013
18	Angra 1	Pre-SALTO	2013
19	Ringhals 1&2	Pre-SALTO	2014
20	Dukovany	SALTO	2014
21	Tihange 1	SALTO	2015
22	Laguna Verde	Pre-SALTO	2015

Table 3: SALTO missions in various plants around the world (Havel & Krivanek, 2016)

Table 3 shows the Pre-SALTO and SALTO missions conducted between 2011 and 2015 for which Koeberg NPP took part. In the above NPPs, Hayes (2016) claims that not all aspects were reviewed in all plants. For example, human resources, competence and knowledge review were only reviewed in 5 plants out of the 22 plants sampled.

In three missions of the 15 samples, it was found that LTO specific regulatory requirements are either not available or too general. 20% of the plants sampled show that the decision on LTO has been adopted but organizational actions related to the LTO have not been established or implemented. In some plants (about 33% of the 15 samples), Havel & Krivanek (2016) claims that the LTO is not clearly defined and established. This leads to problems such as lack of strategy to implement the LTO, definition and allocation of tasks to staff. These challenges may lead to grey areas contributing towards unclear task execution, responsibilities delegation and clearly defined organizational structure. Also, 33% of the sampled plants show that the LTO has been established but there are no actions to ensure its implementation.

Havel & Krivanek (2016) concluded that in about 20% of the sampled plants, pre-SALTO reviews identified deficiencies with the final safety analysis report and current licensing basis document. In addition, scoping and screening methodologies used do address appropriately non-safety measures which, when they fail may have detrimental consequences in the safety of the NPP were inconsistent. Again, some screening and methodologies used do not cover active components adequately, which may hinder the safety of the NPP. Havel & Krivanek (2016) also added that in many plants prompt evaluation of programmes relevant to LTO are not conducted as necessary with the correct scope. These challenges do not assure that the NPP can be operated safely beyond its established operational time base.

Other aspects that Havel & Krivanek (2016) considered is the aging management review, review of aging management programmes and revalidation of time limited aging analysis for mechanical components. In

some plants, about 20% of the deficiencies were attributed to the scoping and screening, inadequate operating experience and Aging Management Programmes (AMPs). In a few plants, codes and standards are not applied consistently and proactive obsolescence aging management programmes are not yet operational.

Furthermore, the aging of Electrical I & C components with environmental monitoring lagging, incomplete or missing, not revalidated environmental qualification. This aspect is of utmost importance in that it may accelerate the degradation of electrical components rendering them ineffective when needed for safety functions. The SALTO mission also found that in some plants, the civil structures were not adequately monitored to ensure effective and safe operation for the granting of an LTO. In many plants the aging management review was not performed while in some plants, the aging management review was not done timeously or comprehensively to facilitate LTO.

Katona *et al* (2011) on the other hand provides the various tests performed to ensure a safe LTO. *Katona et al* (2011)'s research covers Time Limited Aging Analysis (TLAA). In *Katona et al* (2011)'s research, only aspects associated with the LTO are brought into consideration but not necessarily the validation of the inputs since those would be different from the ones employed at Koeberg NPP. Such an approach will give insight in the technical aspects to be considered when a time limit aging analysis is performed.

Katona et al (2011)'s examination focused on the reactor pressure vessel, steam generators, pressurized vessels, cases of the main circulating pumps and the main gate valves, other pipes, heat exchangers and valves in class 1 & 2. In the pressure vessel analysis, *Katona et al* (2011) also included pressurized thermal shock, new pressure temperature curves which would help in determining heat up and cool down temperatures of the reactor vessel. In addition, thermal stratification was analyzed to deduce the LTO between 50 and 60 years. *Katona et al* (2011), proposes, if necessary, the modification of in-service inspections, testing and maintenance on site to allow for proper operation during the extended period.

The American Standard for Mechanical Engineers (ASME), Boiler and Pressure Vessel Code (BPVC) Section III has been used by *Katona et al* (2011) to evaluate and validate the reconstitution of the TLAA and strength verification. This application brings to relevance the manufactures national and industrial standards, technical specifications, rules related to material construction and welding and quality assurance as identified in the passport (document containing as build measurements and test results of the plant obtained during installation) and relevant for LTO.

Katona et al (2011) considered the aging effects on the wall thickness as one of the significant factors that would help determine if a NPP meets the criteria for LTO. For Paks NPP, the designed wall thickness was to survive up to 30 years. *Katona et al* (2011) claims that the wall design thickness for 60 years should be twice that of 30 years. In comparison, the same conclusion could be drawn for Koeberg NPP although it was designed to operate for 40 years.

Besides the ASME BPVC III, other standards such as the PNAE-G7-002-86 can also be applied. In addition, the "Unified Procedure for Lifetime Assessment of Components and Piping in WWER NPPs", which is a framework of the European Commission, can be used to perform time limited aging analysis. *Katona et al* (2011) claims that the material used to fabricate WWER – 440/213 that are prone to fatigue are carbon, low alloy steels and stainless steels. Fatigue, which is defined as a basic degradation mechanism that affects NPP components in various plants, can be analysed using fatigue curves during the reconstitution of TLAA's.

Katona et al (2011) claims that NPPs operate without repair of cracks detected with advanced fatigue detection processes, which means that if an LTO is not to be considered, the operation of a NPP could meet its design establishment time expectations. However, to extend the time expectancy of the NPP, defects that

may arise due to fatigue must be deduced or analysis should be done to ensure that there are no prospects of cracks emanating from fatigues. In addition, Katona *et al* (2011) argues that the cumulative utilization factor (UCF) equal 1 eliminates the possibility of fatigue cracks in areas where the analysis was done.

The cumulative utilization factor greater than 1 enables the management of cracks due to degradation that are not included in the TLAA. The requirement is that there should be no cracks that are detected in the joining cross sections when nondestructive material test is done (Katona, 2010) and that if $CUF \leq 1$ is not achievable during the test, a crack propagation test must be performed. Katona *et al* (2011) proposes that a brittle fracture test be performed for all critical cross sections of the equipment. This is to deduce that the carbon steel of the component does not exceed the assumed lowest temperature for the equipment pressure test at the end of the LTO and during transients occurring during normal operation or accidents.

According to Katona *et al* (2011), effects caused by thermal stratification were not required initially but current regulations make it necessary to establish them before an LTO is granted. In addition, during modeling, the speed of estimated high temperature change while considering the specifying of the distribution of linear and parabolic temperature changes as contributing to the health of the components must be analysed.

The pressurized thermal shock was identified by Katona *et al* (2011) to be the most critical lifetime limiting event in the reactor pressure vessel (RPV) citing studies done by the Hungarian experts. Other aspects such as neutron irradiation damage, thermal aging and low cycle fatigue decrease the fracture toughness of the RPV. The neutron irradiation causes a significant damage near the core where the neutron fluence is significant therefore making the area prone to brittle crack initiation and propagation than in other parts of the RPV.

Katona *et al* (2011) points out 7 deterministic Pressure Thermal Shock (PTS) analysis required during a TLAA's reconstitution and critical for LTO granting. These are the selection of thermo-hydraulic transients, performance of thermo-hydraulic analysis, reactor physical calculations, evaluation of results of reactor dosimetry, evaluation of aging structural material, calculation of temperature, deformation, stress field and fracture mechanics and the evaluation of integrity criteria. In addition, the PTS is more persistent in the RPV close to the core due to high irradiation neutron concentration in this area. Katona *et al* (2011) then proposed that pressure thermal shock test be performed in the area near the reactor core.

In addition to SALTO seminars, other initiatives such as the The World Association of Nuclear Operators (WANO) and Institute of IPNO assist in creating nuclear safety culture. WANO is one of the organisations vested with the safety of NPPs. WANO focusses in the registration and review of events in NPPs. By so doing, WANO supposes that organisations the recurrence of deviations resulting in accidents can be prevented. In addition, WANO seeks to create a learning culture by promoting the sharing of registered events (Berglund, 2020). WANO's approach bears resemblance to SALTO missions in that they both focus in reviewing incidents and promote the sharing of information.

Burglund (2020) considered knowledge, leadership and critical thinking as some of the aspects prevalent in a nuclear safety culture. WANO plays a significant role in the promotion of a Corrective Action Plan (CAP). This plan is derived from the culture of information sharing where, if a deviation from normal operation occurs, it is considered to be a best practice to share it with the rest of the nuclear organisations worldwide as observed from the Japanese Fukushima case.

WANO considers a culture of compliance with prospects to question those in authority. This approach emanated from the observed Japanese culture of compliance with no challenge to those in authority. The lack of questioning may lead to deviations that could have rather been prevented. Again, the culture of

questioning enables employees to deal with unexpected eventualities by promoting constructive discussions (Berglund, 2020).

China for example, is affiliated with WANO and through the years, it has been established that China's reactors design is more reliable. In addition, WANO has established that China's safety operation is commendable. The benchmarking of China's nuclear performance with regards to safety, including safety culture, is done with international role players. It is important to note that because of the benchmarking, China's weaknesses were brought to light which may enable China to learn and improve its safety culture (Lam et al, 2022).

The Institute of Nuclear Power Operations (INPO) Reviews is another stakeholder in the nuclear industry. The INPO was created in the USA and was meant to be the interface between the nuclear industry and the nuclear regulator. INPO assist in the development of organisational approaches towards safety in the nuclear industry. INPO does so by conducting external safety reviews for NPPs around the World. These safety reviews enable INPO to formulate organisational guidelines that promote nuclear safety (Schobel et al, 2022; Lam et al, 2022).

4.2 The granting of an LTO and its requirements

4.2.1 Koeberg nuclear power plant LTO

Eskom has requested a variation to Koeberg NIL - 01 to extend the NPP beyond its initial design by 20 years from July 2024 to 31 July 2044. Koeberg has submitted a request for extension, referred to as Long Term Operation (LTO) (NOU, 2022). According to the NOU (2022), Koeberg's safety file shows that Koeberg NPP can be operated safely for 60 years. In addition, the safety case shows that KNPP has no undue radiological risk, health or environmental event that can compromise the safe operation of the NPP.

The conclusion drawn from 1150 safety requirements obtained during periodic safety reviews concluded that continued operation of KNPP and consequently the granting of an LTO is supported by NNR. Through the periodic safety review (PSR), it was deduced that the public risk exposure is less than 3% for the public and less than 20% for workers, a factor considerably lower than the exposure to individuals to road accidents (NOU, 2022). According to the NOU (2022), Koeberg invited the IAEA to assist in SALTO missions to identify and align precarious aspects of the NPP that may hinder its safe operation beyond LTO.

The intention of the SALTO missions at Koeberg were to determine the completeness and effectiveness of the aging management programmes. This is in line with Havel & Krivanek's (2016) observation that most recommendations arising from SALTO missions from various plants do as well apply to most NPP owing to several commonalities with the design and the standards applied during design, construction and operation. Aging programme management is one of the aspects identified by Havel & Krivanek (2016) as being one of the aspects that most NPPs have no clear management processes therefore causing difficulties in the granting of the LTO owing to the absence of relevant information.

Through the subscription to the IAEA, NNR can apply and maintain international standards that enhance the safety of KNPP. The significance of the alignment of Koeberg with the international community is that through peer reviews, seminars and investigations, KNPP can learn and adapt to the risks associated with the operation of NPP. Other aspects concerning aging management programmes related to nuclear material accounting and deviation need to be considered (NOU, 2022).

NOU (2022) claims that the radiological exposure to the public and workers is less than 1% of the prescribed limit of 20 mSv. The effective radiological exposure limits for workers worldwide are 100 mSv for a period

of 5 year, 20 mSv taken on average for 3 years and 50 mSv for a one-year exposure (Shubayr et al, 2021). In addition, NOU (2022) also confirmed that the radiation levels are kept as low as reasonably achievable (ALARA) and below regulatory limits at KNPP.

The periodic safety review (PSR) which details the findings of KNPP, established that the radiological release to the environment around Koeberg is far less than prescribed and that people around Koeberg are exposed to radiations less than that released naturally therefore concluding that the health effects due to radiation from KNPP are very low.

According to NOU (2022), Koeberg NPP has a robust human resources management strategy. This strategy encompasses human resources processes and training facilities to ensure staff adequacy, competency that encompasses highly skilled contractors while recruitment processes ensure new entrants to the NPP. The robustness of Koeberg NPP human resources strategy may be another aspect that enables Koeberg to provide adequate training, knowledge management and staff development in line with international standards.

In addition to the robust human resources strategy, NOU (2022) claims that Eskom has committed itself to ensuring that adequate financial resources. These financial resources shall support KNPP through the LTO including its decommissioning and rehabilitation of the land and managing the environmental impact due to NPP operations. It is important to note that Koeberg NPP has a nuclear safety culture review every 3 years (2014, 2016 and 2019). Through these reviews, it was concluded that the KNPP safety culture is acceptable, compliant with international standards and capable of enabling a safe operation of KNPP once an LTO is granted (NOU, 2022).

An LTO application to the NNR is supported by a safety case that exhibits a periodic safety review. The periodic safety review for the KNPP LTO started in 2010 NOU (2022). This periodic safety review covers 14 critical aspects necessary to determine gaps with the international, national and regulatory safety requirements given in Table 4 (NOU, 2022).

Subject area	Number	Safety factor title
Plant	SF-1	Plant design
	SF-2	Actual condition of SSCs
	SF-3	Equipment qualification
	SF-4	Ageing
Safety analysis	SF-5	Deterministic safety analysis
	SF-6	Probabilistic safety assessment
	SF-7	Hazard analysis
Performance and operating experience (OE) feedback	SF-8	Safety performance
	SF-9	Use of experience from other plants and research findings
Management	SF-10	Organisation, the management systems, and safety culture
	SF-11	Procedures
	SF-12	Human factors
	SF-13	Emergency planning
Environment	SF-14	Radiological impact on the environment

Table 4: Safety factors reviewed during the Koeberg periodic safety review PSR (NOU, 2022)

The sharing of operational experiences in the global perspective provides insight on aspects experienced by other nuclear operators. For example, in the USA, one of the requirements for an LTO was the replacement of the reactor pressure vessels. Although the replacement was successful, the NPP suffered significant tube damage that rendered the NPP not operable indefinitely. Since this has been brought to

the attention of KNPP, it would be of utmost importance to establish the factors that led to such a damage and consider whether such a replacement is necessary for the case of Koeberg.

According to NOU (2022), the requirements for the support of application for the granting of an LTO as per R.266 and NNR regulations are as follows:

“

- *Site-specific characterisation*
- *Risks to safety, health, and the environment*
- *An assessment of plant design adequacy for LTO*
- *An assessment of the actual condition of SSCs*
- *The outcome of an IAEA support mission on safety aspects of long-term operation focusing on ageing management*
- *The outcome of the most recent periodic safety review (PSR), which is conducted on a 10-yearly basis and was submitted to the NNR in June 2022*
- *The impact of LTO on the following programmes:*
 - *Radiation protection arrangements and effectiveness*
 - *Nuclear security*
 - *Emergency planning*
 - *Radioactive waste management*
- *Organisational provisions for LTO such as management systems, knowledge management, human resources and staff competency, finance, and external support organisations*
- *The adequacy of Koeberg's nuclear safety culture”*

To ensure a safe NPP, NNR provides oversight for compliance and enforces such compliance to Koeberg through audits, routine inspections, non-routine inspections, review of routine reports and occurrence reports. This oversight, inter alia, is performed in line with international standards, norms and regulations to ensure uniformity with the IAEA and other international bodies. The actions that NNR can institute depend on the findings and include issuing of written warnings, penalties, curtailing operations, suspending the authorisation or as the last resort, withdraw the license to ensure that the safety of the NPP is not compromised (NOU, 2022).

According to NOU (2022), the studies done in relation to site suitability for an LTO concluded that there were no disqualifying findings that could render the site not suitable for an LTO. These studies included terrestrial phenomenon such as geological, geotechnical, hydrological, and meteorological characteristics, effects of climate change, population growth and distribution as this affects the emergency preparedness and accident response.

The land and adjacent sea use which may affect radiological kinetics, transportation, industrial and military facilities were found to be compliant. The radiological impact in the environment and humans has also been considered. These studies were done in association with the Fukushima incident as well as the most relevant information about the site, most recent regulations and analysis method (NOU, 2022).

The long-term operation of Koeberg NPP takes into account the following risks:

- Nuclear safety risks limits
 - The PSR conducted in the past few years at Koeberg showed that the NPP Safety Probabilistic Analysis (SPA) (method used to identify and quantify risks) concluded that Koeberg complied with the principal safety criteria (which sets maximum risk to fatalities to 1×10^{-5} and as low as reasonably practicable). An effective risk management criterion implemented at Koeberg ensured that operational activities do not negatively affect the principal safety criteria (NOU, 2022).

- The defence in depth approach devised by the USNRC requires that NPPs be designed and operated in a manner that prevents radiological release to the environment. According to NNR (2019), Koeberg meets this criterion in that no accident that can occur at Koeberg that could lead to a radioactive release without provision to timeous remedial action that will prevent a release. Through the PSR, it was established that the defence in depth systems employed at Koeberg NPP are adequate both for current operations and LTO.
- Koeberg has plans and procedures to return the plant to a safe condition in case of an accident. These plans cater for earthquakes occurring as far as 8km from the plant and that measure 7 in the Richter scale and a tsunami with a wave height of 8m. such procedures and plans are done in accordance with international and national standards covering a range of abnormal accident conditions arising in the NPP. The plans and accident management procedures also form part of the DID design.

In the wake of the Fukushima accident, Koeberg implemented several improvements to the plant to ensure its safe operation for “design extension conditions”. Mobile diesel generators, mobile pumps to supply water to areas such as the SNF storage, mobile equipment to clear debris, autocatalytic recombiners to reduce the risk of hydrogen explosion (NOU, 2022) were introduced. Again, these improvements are in line with global experiences and the SALTO mission recommendations combined with the experience from various experts and peer reviews. Noting that KNPP has about 99 sisters around the world, related experiences should be available and relevant.

Although neutrons do not cause ionisation, when interacting with matter they can give rise to the gamma, beta and alpha rays which can be stopped only by thick masses of water, concrete and paraffin. This is because concrete, water and paraffin have high attenuation for the referred radiation particles above (NOU, 2022; Khali et al, 2023).

In relation to radiological protection, NOU (2022) claims that the approach to it is consistent all over the world and that the International Commission in Radiological Protection (ICRP) supposes that any exposure above the natural radiation should be kept As Low As Reasonably Achievable (ALARA). This is done through three fundamental principles like justification, optimisation and dose limits. Koeberg on the other hand, has radiological release quantities far below the expected minimum (less than 1 mSv).

The radiological exposure impact to the public has occupational exposure, medical exposure and public exposure as the main contributing factors. The exposure can be attributed to a number of radiation sources as shown in the Figure 5 below.

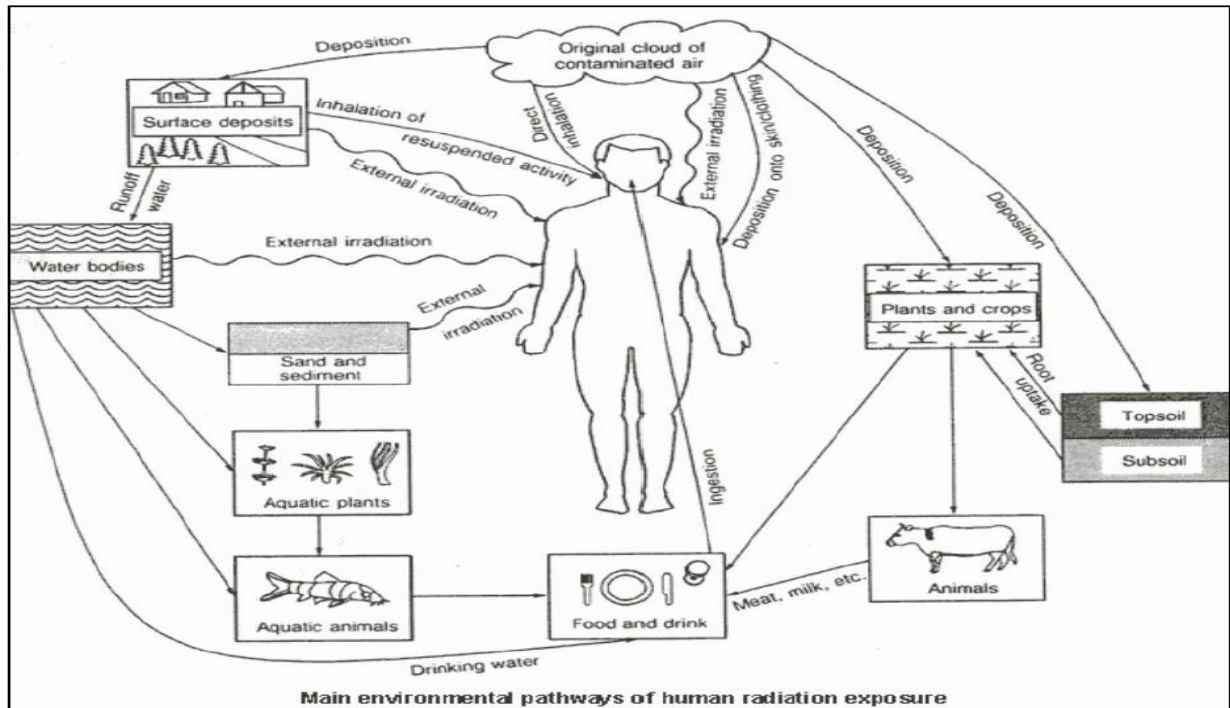


Figure 5: Radiological exposure pathways (NOU, 2022)

Figure 5 shows that various sources of radiation contribute towards the exposure to the public as also discussed by Kong *et al* (2017). In addition, like any NPP, Koeberg releases effluents both in the liquid and gaseous states which are limited to regulatory limits in conjunction with annual authorised discharge quantities (AADQs) as prescribed by NNR (NOU, 2022).

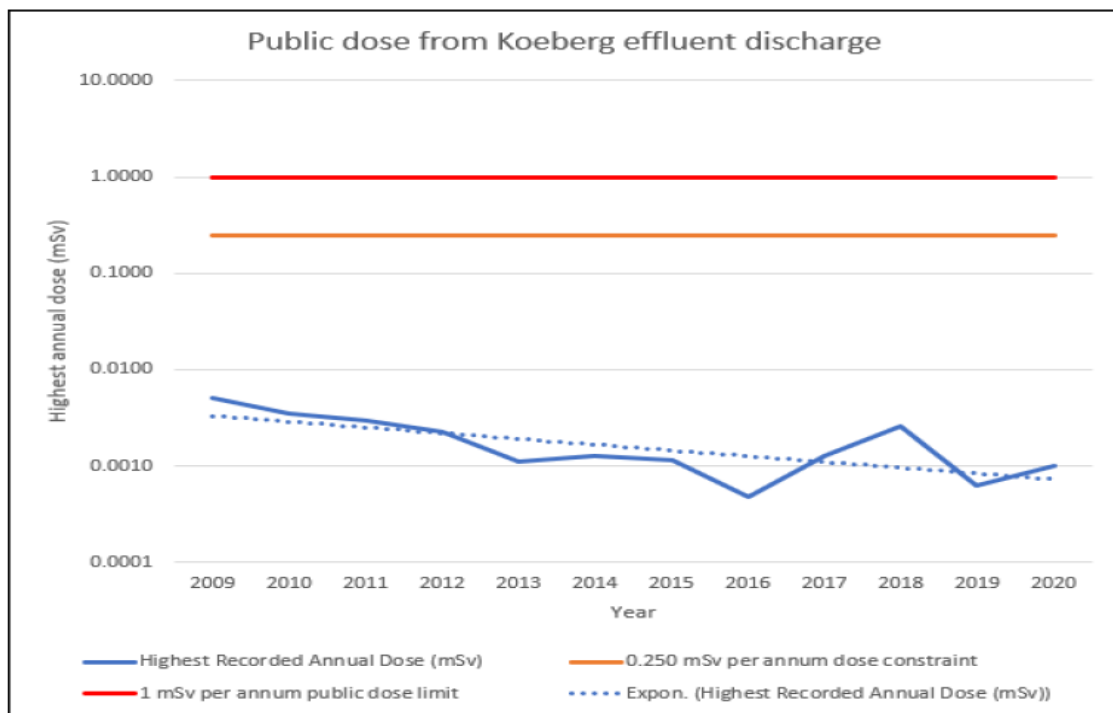


Figure 6: Public exposure because of Koeberg NPP operations (NOU, 2022)

The NOU (2022) claims that the granting of an LTO to Koeberg will not result in a significant exposure to the workers. NOU argues that radiation workers are issued with personal protective equipment, which enables the monitoring of radiation they are exposed to. In addition, a few interventions such as limited time spent near radiation source, proximity to the source and the shielding material thickness are employed to ensure that the workers are minimally exposed to radiation. Workers at Koeberg are exposed to radiation doses of about 17 mSv per annum as recorded in 2021, which is less than 20 mSv prescribed by NNR for workers.

Figure 7 shows that from 2009 until 2020, the workers radiation exposure has been less than 20 mSv per annum. The maximum stipulated radiation dose of 100 mSv for 5 years has not been exceeded at Koeberg. Therefore, there is no incentive warranting halting the LTO for Koeberg NPP to carry on operating beyond 2024 based on worker radiological exposure.

Several activities at Koeberg NPP affect the environment. These activities include the refurbishment of the NPP to cater for the LTO. This exercise is done in accordance with the Koeberg PSR therefore enabling a stringent monitoring of radioactive effluents release to the environment. In addition, the aging plant contributes towards the risk of environmental degradation through possible systems leaks such as civil structures, radioactive effluent treatment structures and those structures that form a barrier between the radioactive material and the environment.

Bioaccumulation is another aspect that affect the environment. Plants and animals ingest radioactive material through various forms and releasing the material to the environment (NOU, 2022). Koeberg has a radioactive accumulation program that monitors such a release to the environment. The prospective radiological release to the environment is about 0.094 mSv compared to permissible levels of 0.24 mSv per annum. In addition, a land use review has given no evidence that the radiological exposure to the environment will increase due to population dynamics.

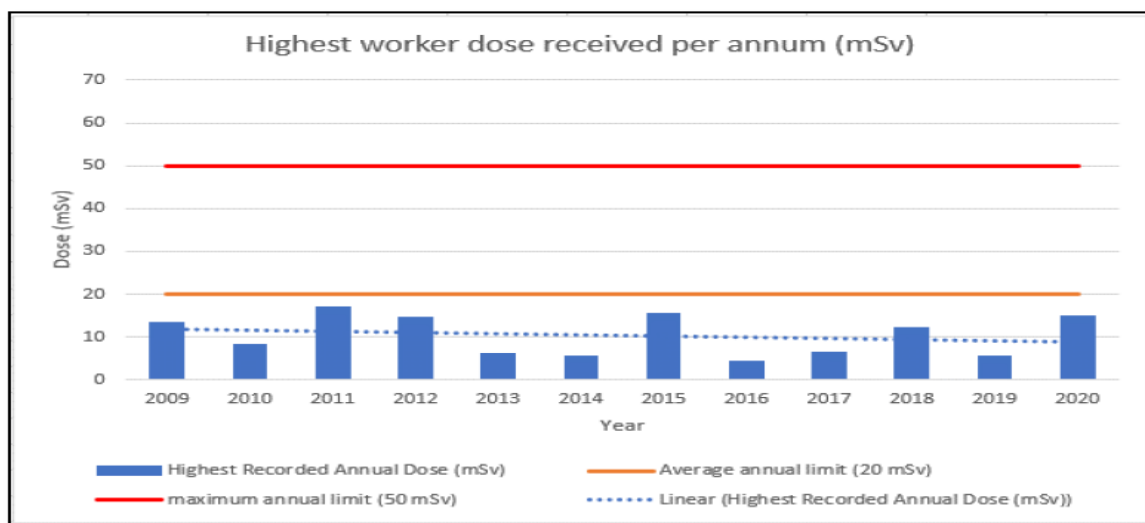


Figure 7: Highest worker dose received per annum at Koeberg (NOU, 2022)

The emergency preparedness plan was reviewed during the PSR and it was found to be more reliable and consistent for the granting of an LTO. This plan has been discussed with the local municipalities and has been reviewed, audited and assessed to ensure that it remains within the regulatory framework. Again, the plan provides enough capacity for execution during emergency situations arising from Koeberg NPP operations as per NOU (2022).

According to NOU (2022), Koeberg is mandated by international norms to retain a sustainable human resources strategy that ensures that Eskom has adequate, skilled and well-qualified personnel. The strategy includes the sourcing of well-experienced contractors both for normal plant operation and

beyond LTO. Furthermore, Koeberg contributed significantly to the skills development and that it provided, seeks to continue providing and managing knowledge and competency of staff in the NOU.

Both Havel & Krivanek (2016) and Katona *et al* (2011) defined culture as the driving force enabling a safe operation of an NPP. These authors echoed the importance of a good safety culture, which NOU claims that it is reviewed annually and assessed three yearly using *INPO 12-012*. The *INPO 12-012* is used to determine the culture's effectiveness and do necessary modifications to align with relevant regulations. A safe nuclear safety culture has 10 categories grouped into three factors as per Table 5 that are required during licence bases and beyond LTO.

Traits of a healthy nuclear safety culture (INPO 12-012)	
Individual commitments to safety	Personal accountability Questioning attitude Effective safety communication
Management commitment to safety	Respectful work environment Leadership safety values and actions Decision-making
Management systems	Continuous learning Problem identification Environment for raising concerns Work processes

Table 5: Aspects of a healthy nuclear safety culture (NOU, 2022)

Furthermore, Koeberg has a radioactive waste management strategy, which is covered by a number of regulations such as the Nuclear Energy Act 46 of 1999, National Nuclear Regulatory act 47 of 1999, Radioactive Waste Disposal Institute Act 53 of 2008 and the NEMA act 107 of 1998 that must be satisfied beyond LTO. Eskom's responsibility in relation to radioactive waste management entails the provision of necessary financial resources, technical and administrative management of radioactive waste as stipulated in the NIL 01 (variation 19) on handling of radioactive nuclear waste (NOU, 2022).

To ensure that radioactive exposure is ALARA, the principle of delay and decay, concentrate and contain and dilute and disperse is applied at Koeberg before the waste is taken to the disposal site and the radionuclide inventory is recorded and tracked thereafter.

The South African regulations on SNF management permits that radioactive material be stored on site for a period of 100 years and then encapsulated and stored in a deep geological repository which currently, the National Radiological Waste Disposal Institute seeks to establish. Currently, Koeberg provides an Interim Centralised Transient Storage (ICTS) on site capable of handling the spent nuclear fuel it generates. The management of SNF at Koeberg complies with the Vaalputs nuclear waste disposal criteria. The criteria cover radiological, mechanical, physical and biological characteristics of the waste. These include the size, dimensions and weight of the package to ensure a safe transportation and disposal both for now and beyond LTO (NOU, 2022).

A decommissioning plan will be provided by Koeberg to NNR prior to decommissioning as per the NIL 01 licence and must prove that enough human and financial resources are available for the decommissioning activity. The decommissioning plan shall include radiological decontamination and rehabilitation of the land. The radioactive waste produced shall be transported and handled as per the

IAEA transportation requirements, which cover in addition, methods of containment of radioactive content, shielding and control of external dose rate beyond LTO (NOU, 2022).

4.2.2 SAFARI-1 nuclear power plant

Havel & Krivanek (2016) noted that in most plants, human resources strategy was not consistently implemented or not available and added that in some plants, the allocated staff was inadequate for the extension of the LTO. This claim seems to be applicable to SAFARI-1 NPP when noting Havel & Krivanek (2016)'s claim that some activities could not be accomplished due to understaffing. Havel & Krivanek (2016) argued that in some plants, AMPs were in place together with the action plans, but no action has been taken to execute the required actions. Such a claim is consistent with D'Arcy *et al* (2011)'s observation at SAFARI - 1 where scheduled activities could not be performed due to under staffing.

D'Arcy *et al* (2011) claims that an AMP which complies with the International Organisation for Standardisation (ISO) systems together with IAEA safety standards was developed in 2010 to ensure continued reliable reactor operation. The AMP identified aspects for implementation over a period of 5 years, the identification of 18 management projects, 38 development and upgrade projects, and 24 maintenance projects. This means that the alignment of ISO and IAEA systems brought about significant changes to the NPP management approach. These changes somehow support the notion that SALTO mission recommendations can be applied in various plants and make easier the transition of an NPP to LTO.

As stipulated above, the conditions of the licence cover most aspects which are considered during an LTO. It is also imperative to note that SAFARI - 1, although slightly distinct in nature, D'Arcy *et al* (2011) claims that it shares some properties with HFR NPP in the Netherlands and OPAL in Australia. In relation to Havel & Krivanek (2016)'s claim that the recommendations made by the SALTO missions are applicable to most NPPs, it can be concluded that the lessons learnt from HFR and OPAL NPPs can be applied at SAFARI - 1 although such recommendations would still require site-specific considerations.

One positive aspect pointed out by D'Arcy *et al* (2011) is knowledge maintenance and transfer. According to D'Arcy *et al* (2011), a personnel culture change was necessary to migrate from research and development to commercial isotope production together with the changes in the operation cycles. This observation is in line with Havel & Krivanek (2016)'s finding although Havel & Krivanek (2016)'s point was based in a few plants where knowledge maintenance and transfer was inadequate to ensure safe operation of an NPP for an extended period especially when LTO is considered.

The conditions of the license for SAFARI - 1 require that the maintenance of the plant be done within specified intervals prescribed in the maintenance schedule and by a competent and suitably qualified and experienced person appointed for the relevant activities. According to D'Arcy *et al* (2011), the SAFARI - 1 maintenance programme lists schedules, parts of the plant to be maintained and assigns responsibilities to individuals who will execute the maintenance. A planning meeting is held prior to the shutdown with maintenance and other staff and users to schedule all activities to be performed as per the maintenance plan. NNR provides regular surveillances therefore facilitating the transition to LTO.

A post shutdown meeting is held with senior management and other senior engineering staff to review various reports obtained during maintenance to ensure compliance with Operating Technical Specification (OTS), Maintenance Shutdown Plan (MSP) and OLC. What is important to note is that despite the staff shortage mentioned by D'Arcy *et al* (2011), the wealth of knowledge that the existing staff exhibits is put into use effectively to execute functions that would rather be difficult with less staff. This, however, does not compensate for the need of adequate human resources since even with well-

experienced staff; human fatigue may hinder the success of the maintenance shutdown plan therefore affecting the level of confidence on the granting of an LTO.

Among the various aging mechanisms identified by D'Arcy *et al* (2011), fatigue, temperature surges, corrosion, radiation and changes in legislation were also identified. However, a detailed study to identify the fatigue levels and tests to be performed were not investigate. It is crucial to note that together with mechanical displacement, material disposition, fire resulting in effects of heat, smoke and reactive gases as well as time dependent phenomenon are performed through the aging management programme at SAFARI - 1. These could help in establishing the credibility of the operation of the NPP beyond LTO.

According to D'Arcy *et al* (2011), once the aging Structure, Systems and Components (SSC) has been selected and the aging mechanism identified, a prioritisation task is carried out using a mathematical model. The models help determine the remedial action necessary, characterised as replace, refurbish, redesign or maintain. A prioritisation factor is identified which helps in resource allocation and scheduling purposes. This ties up, to some extent with staff availability, knowledge transfer and maintenance as observed through SALTO missions to be of significant challenge in some NPPs therefore challenging the granting of an LTO.

The physical security as described by D'Arcy *et al* (2011) support the requirements for the issuing of the NIL-02, a condition required for the drafting of an LTO. Physical security of the SAFARI - 1 NPP has been strengthened with a security fence. Building parameter doors have been hardened to make unauthorised access difficult, cameras were installed to monitor various parts of the plant, inner building walls have been further hardened to cater for LEU to be received. Again, the building security has been improved to comply with *INFCIRC/225/Rev.5* requirements.

In 2021, NECSA authorised an In-Service Inspection requirements specification for the SAFARI - 1 reactor assembly. The purpose of the specification is to outline the inspection requirements for the SAFARI - 1 reactor vessel assembly. The inspection covers welds on high stress areas, responsibilities of parties involved in the inspection, ultrasonic testing to cover any cracks, weld thickness and measurements of defect size in reactor vessel assembly as well as qualifications of personnel, procedures, responsibilities and test methods and deliverables necessary for a thorough inspection of the reactor vessel assembly. The in-service specification could help determine if SAFARI – 1 can be granted an LTO (NECSA, 2021).

The allocation of responsibilities is vested in several departments such as the reactor engineering department which ensures that all documentation supplied by the service provider meets the SAFARI - 1 requirements. The engineering department also facilitates access to the Reactor Vessel Assembly (RVA) (Figure 8) for the service provider and assesses and review the scope of work performed by the service provider. Another department is the reactor operations department which is responsible for ensuring that the RVA is ready to be handed to the service provider through decontamination of the RVA and help with the crane to the service provider as well as ensuring that power and compressed air is available (NECSA, 2021).

The quality department is responsible for the verification of personnel qualifications and the validation of documentation and inspection methods to be used. The radiation protection office ensures that radiation limits are not exceeded, and that continuous invigilation is provided to the service provider when necessary as well as issuing the radiation permit. Lastly, the service provider who renders services required in the reactor vessel assembly through an agreed contract and ultimately the SAFARI - 1 Snr Manager who signs off the inspections and outcomes reported by the service provider (D'Arcy *et al*, 2011).

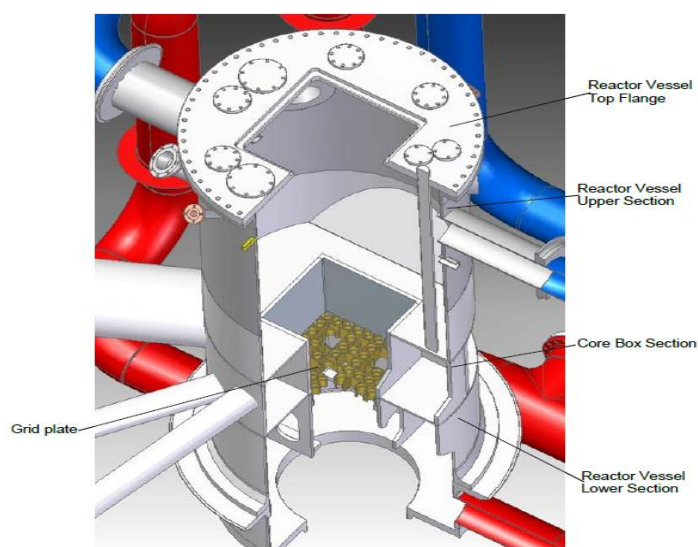


Figure 8: Characteristics of the reactor vessel (NECSA, 2021)

Finally, the regulator also oversees that any changes in the regulations governing NPPs are delivered to the NPP operator and that measures are put in place to conform to such regulations. This was observed from both Katona et al (2011) through equipment fatigue analysis and by Havel & Krivanek (2016) through SALTO missions done to evaluate 15 NPPs around the world. The SALTO missions focussed on document review and discussions with staff and creating a platform for the staff to interact with the experts in the nuclear field. This platform may play a significant role both in identifying the culture of the NPP and determining aspects that need consideration which may be challenges experienced by staff during the inspections.

4.3 Key points

The LTO reviews conducted at KNPP, and SAFARI - 1 have provided insight in the aspects critical for the extension of a life span of a NPP. Some of the aspects such as human resources strategy and the aging management programme are designed to ensure that the NPP can function effectively beyond its design base. Both NPPs have complied with various SALTO reviews.

From the reviews, it can be concluded that South Africa has adequate skills base in the nuclear industry. In addition, the culture of learning and knowledge management shows that KNPP can continuously enable personnel to learn and adapt to the changing technologies. The human resources strategy is so prudent in that it enables personnel consultations and collaborations both locally and abroad. Through the gained knowledge and experience, South Africa can design and construct its own nuclear power plants for civil applications. This can be done in collaboration with experts and other organisations around the world, sourcing of appropriate skills and learning from India's nuclear development path.

The aging management review may provide basis for understanding the behaviour of various components and systems in the NPP during operation. This, combined with the test results obtained during initial testing, could provide basis for specific component development locally. In addition, the various tests performed during testing can be used to determine the life span of NPPs currently in design therefore introducing the necessary design bases for longer operating times for NPPs.

5. Aspects affecting the deployment of new NPPs

This chapter discusses the various aspects influencing the deployment of new NPPs in worldwide then link these aspects to the South African context. The country's resources and technical expertise form the bases for a rigorous nuclear energy policy. Although there are vast classifications of resources, in this case focus is given to human resources. South Africa's natural resources including uranium were discussed in chapter 1.

Proliferation challenges as envisaged domestically and internationally are also taken into consideration. Various organisations and states with interest in proliferation as well as the associated treaties and responses to various pressures are discussed. In addition, the role of nuclear states in hindering the deployment of new NPPs is also discussed.

Other aspects discussed in this chapter are the economic challenges and how these challenges impact the deployment of nuclear technologies. In this category, nuclear energy deployment strategies such as SMRs and large scale are discussed in the context of economic viability in association with time and grid potential.

In addition, politics, public participation and acceptance, and environmental challenges that affect the deployment of new NPP technology deployment are discussed. In this case, cases drawn from Russia, Japan and China are taken into consideration. Public participation approaches are discussed and various political challenges are highlighted. Environmental challenges as well as the role of the impact of legislature and judiciary are also highlighted.

5.1 Resources and technical expertise

Kessides (2014) claims that lack of technical expertise in the nuclear industry in the African countries contribute to the challenges of developing nuclear power plants. In the case of South Africa, such lack of expertise is attributed to scavenging of resources by developed countries such as UAE (Dubai), France and Canada and internal staff movements and aging.

With Africa operating only one nuclear power plant, it is evident that skills shortage cannot be ignored especially in the development, construction and testing of nuclear facilities. Kessides (2014) also claims that the maintenance culture is almost non-existent in African countries. Although this argument cannot be disproved, the author notes that in the case of Koeberg and SAFARI – 1 maintenance is done in accordance with NNR requirements as discussed in the LTO section. It is essential though, for the African continent to introduce such a culture through acquiring, training and retaining competent engineers and other personnel that will drive the African nuclear arsenal.

In the United States, it has been estimated that approximately 65 nuclear engineers, 42 nuclear operators, and 31 nuclear technicians are needed for the operation of a single nuclear reactor (Kessides, 2014). These numbers are significant and may be unattainable in the current skills platform in Africa. The envisaged skills include, as claimed by Kessides (2014): “*radioactivity and its sources; radiation health effects; radiation protection methods and regulations; measuring of radiation; exposure and contamination control; handling of radioactive wastes; establishment of radiation protection programs; releases and emergency response; procedural and regulatory compliance; workers' safety; configuration management; and a questioning attitude*”. The aspects encompassed in this claim are by far achievable in the South African context and KNPP can act as a breeding field to develop and train engineers, technicians, artisans and other staff members necessary for the safe operation of NPPs.

In addition to sending people abroad for training, Kessides (2014) argue that a country can outsource the operations and maintenance to the developer of the NPP or an external body with extensive experience in NPP operation and maintenance. This argument holds ground in enabling the country to bring in experts who will in turn train the local people on NPP operation and maintenance.

Van Wyk (2021) cites IAEA's acknowledgement of the lack of technical expertise in the country and proposes that South Africa develops and implement human resources strategies from high school level. This could increase the number of engineering graduates and develop training facilities for artisans in areas relevant to the nuclear industry. The notion is in line with the SALTO mission findings that saw Koeberg applauded for human resources strategy while having to develop a sustainable skill base due to loss of staff to other NPPs.

The contribution towards skills development from an NPP harboured by the country arises from the minimal cost of travelling and accommodation for potential candidates, availability of a large pool of human resources to be trained from the local communities and the familiarity of the community with NPPs therefore minimising the stigma associated with its rejection.

The NECSA academy and the nuclear operator pipeline project are some of the initiatives that seek to address the skills shortage in the nuclear field in South Africa. This skills shortage is also alluded to by D'Arcy *et al* (2011) who proposes that effective knowledge management has seen SAFARI – 1 being able to adapt despite the lack of adequate human resources. In addition to the above projects, Rosatom aspired to provide training in the nuclear field to South African personnel (van Wyk, 2021).

Van Wyk (2021) viewed budget constraints as one of the factors decelerating the development of nuclear energy. Van Wyk (2021) argues that between 2018 and 2019 nuclear energy was allocated a budget of \$75Mil which is by far less for the realisation of nuclear development in the country. The budget allocated for 2020-2023 is insufficient for Request for Information (RFI) necessary for nuclear development. This claim aligns with the government's slow strategy in nuclear technology implying that the government policy does not support a rigorous nuclear development policy. In the contrary, it can be argued that the government's policy is more inclined towards the development of renewable energies such as solar and wind.

Van Wyk (2021) points out that aging infrastructure is one of the aspects affecting the South African nuclear fleet. Koeberg's LTO is meant to be extended for the next 20 years after its life span elapses while SAFARI - 1 will be extended up to 2030 or beyond depending in the success of the engineering investigations. In addition, van Wyk (2021) questions the safety aspects of South African nuclear facilities arguing that three attempted armed robberies took place at Pelindaba between 2007 and 2012.

5.2 Proliferation challenges

Currently, the Non-Proliferation Treaty (NPT) of 1968 is the guiding treaty that enables countries to use nuclear energy peacefully worldwide. Proliferation may be described as either concrete proliferation or supportive proliferation. Concrete proliferation involves more in-depth transfer of knowledge and technology related to nuclear power and fuel cycle, which are correlated for the civilian and military use of nuclear energy (Lim, 2016).

The fear of proliferation is noted by Lim (2016) who points out that many countries have shown interest to develop nuclear power technologies but safety and security as well as project mismanagement are of concern since most interested countries scored low in aspects related to safe use of nuclear energy.

The ban on nuclear explosives test is an extension of the NPT that seeks to ensure that nuclear energy is not used to create weapons of mass destruction (WMD). The acquisition of WMD is prohibited under the UNSCR 1540 for non-state actors. In the South African context, Lim's (2016) claim can be alluded to the level of corruption in the state where, for self-enrichment, individuals may divert nuclear material from use in the NPP for sale in non-state organisations. Lack of adequate border security measures may compromise the NPT by enabling the movement of nuclear material between South Africa and neighbouring countries then to other countries around the globe.

Supportive technological cooperation involves sharing of information about nuclear related aspects and training thereof. South Africa engages in both aspects of proliferation citing that it is a user and operator of nuclear power plants.

When evaluating a country's potential to consider nuclear proliferation, Kim *et al* (2022) looked at “the ratification of the Additional Protocol (AP), completion of the UN Security Council Resolution (UNSCR) 1540 requirements and the ratification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT)” as well as traditional non-proliferation norms such as NPT, IAEA, and NSG memberships” (Lim 2016). The question in the South African context would be how well vested South Africa is in the above aspects is.

In addition to the above aspects, Lim (2016) studied the geographical separation between supplier countries and client states to deduce whether proximity plays a significant role in promoting concrete nuclear cooperation, which may result in proliferation risks. Lim's (2016) study concluded that economic capacity (also influenced by proximity) plays a significant role in determining whether a country undergoes a concrete nuclear cooperation or not. Lim (2016) ties trade cooperation between supplier and client states as a motivation to concrete nuclear cooperation. This notion would seek to excuse South Africa from the concrete cooperation in relation to BRICS; however, strategic imperatives between BRICS members may influence such decisions (van Wyk, 2021).

To the larger extent, Lim (2016) claims that countries with common enemies are more likely to undergo concrete cooperation. In his comparison, Lim (2016) deduced that even with ratifications, countries with common enemies are more likely to undergo concrete cooperation. But this means that the risk of proliferation increases with the proximity of a non-nuclear state to nuclear states, economic prowess and military security both as a country or in trans-national platform.

5.3 Economic challenges

The prospects of developing nuclear power technologies can be viewed in a number of contexts or perspectives. Nuclear power plants can be seen as economic enablers in which the lower tariffs associated with electrical power consumption promote economic development and investments. Valentine & Sovacol (2010) argues that dominant economic priorities can enable the development of nuclear power technologies and that Japan saw the introduction of nuclear power technology as one of the economic positive drivers and invested heavily in it.

Stewart & Shirvan (2022) claims that the most fundamental problem facing the development of nuclear power plants is the associated cost and that in the past 15 years, the cost of NPP development has doubled. Stewart & Shirvan (2022) also added that the cost escalation is attributed to mismanagement and complex designs meant to cover various safety aspects and environmental concerns. An exception is pointed out to four NPPs built in Japan between 1990 and 2000 that were completed within 4 years and under budget.

According to Stewart & Shirvan (2022), SMRs can contribute significantly to the nuclear technological deployment for reasons discussed by Kessides (2014). Stewart & Shirvan (2022) however, argues that the cost of SMR technology is not necessarily less than that of large scale NPP. Stewart & Shirvan (2022) cited that the cost of the IRIS SMR was about 5% higher than a generic large reactor. In addition, Stewart & Shirvan (2022) cited that SMAT (Korean SMR) costed about 4 times the cost of a larger reactor (APR1400). Therefore, in his estimation, Stewart & Shirvan (2022) separated modularisation from the NPP design arguing that modularisation can be done in plant systems during design.

Stewart & Shirvan (2022) also points out that estimating the cost of SMRs is far more difficult because various estimators used different methods, for which some information was deemed to be confidential

and that creates a wide range of variables undetected from other models therefore creating a high level of uncertainty in the cost estimation of NPPs. One cost estimation model estimated an SMR (300MWe) deployment to 45% less than a large scale NPP. To reduce the uncertainty due to various methods, Stewart & Shirvan (2022) used the Energy Economics Data Base (EEDB) method to estimate the cost of an SMR.

The EEDB method is applicable to LWR designs and it establishes a consistent set of assumptions to quantify deriving cost factors for selected designs. This work distinguishes itself from its predecessors in its detailed bottom-up approach using best engineering-based judgment and practices to capture the intrinsic features of SMR designs, including factory production, learning rates, passive safety, simplified electrical and piping while quantifying the lack of economy of scale in a holistic framework (Stewart & Shirvan, 2022).

Stewart & Shirvan (2022) used the Economy of scale, modularisation, plant design and megaprojects risk to deduce the cost estimate of an SMR using the EEDB method but did not include the construction schedule. According to Stewart & Shirvan (2022), the EEDB model consists of construction services, engineering & home office services and field supervision & field office services, factory equipment cost, site labour hours, site labour cost, and site material cost.

Modularisation is a costing method that combines various components and systems into modules that could be easy to transport and install on site as modules in the estimation. This simplifies the burden of single component installation and therefore reducing time since modules can be built in the factory and transported as modules. Stewart & Shirvan (2022) claims that modularity may reduce construction time by nearly 26% through enabling bulk of the work to create modules to be optimised in the factory therefore saving on labour on site consequently reducing the cost of deployment. This approach could prove to be fruitful in South Africa since most of the intense construction work can be done in the factory therefore reducing the need for prolonged labour during construction which is a significant problem for South Africa due to lack of skilled personnel for specific tasks.

According to Stewart & Shirvan (2022), benchmarking pinpoints the trends in the costing but does not validate or show the effectiveness of the model. Again, Stewart & Shirvan (2022) claims that for the first of a kind (FOAK) NPP, a project should incur an escalation of 59% if a new construction method is used and 78% escalation if a project experiences regulatory challenges. The regulatory challenge could play a significant role in escalating the construction cost in the South African environment since regulation is faced with lack of expertise and coordination as well as unclear regulating processes.

In addition, various countries have different labour rates which could significantly influence the cost of a NPP. Although this labour comparison was deduced between the USA and China, its relevance to the South African arena cannot be dismissed since the labour market in South Africa is vibrant and mostly labour union orientated just as the USA is (Stewart & Shirvan, 2022).

The development of a NPP project spans a number of cycles from the mining of uranium through the various interim stages such as milling, enrichment, fuel fabrication, fuel management, reprocessing, disposal and the management of the disposal facility. According to Bunn *et al* (2003), the cost of reprocessing cannot be defined in isolation. Bunn *et al* (2003) claims that if reprocessing costs were to be determined in isolation, the costs that the nuclear license holder may have to pay will omit aspects of the SNF cycle that are relevant to reprocessing.

Bunn *et al* (2003)'s claim is consistent with both closed and open fuel cycles in that it filters the cost of reprocessing into the total cost of a NPP project. The inclusion claimed by Bunn is necessary to ensure that all costs such as those related to technological applications, environmental protection, siting and regulation are incorporated in the project. During reprocessing, the recovered fuel will go through a recycling process therefore adding to the cost of the fuel cycle while if reprocessing is omitted, the extra steps associated with reprocessing should be subtracted from the project costs.

Bunn *et al* (2003) identified the “break-even method of cost estimation” as the method at which the cost of reprocessing equals the cost of direct disposal of SNF. This concept is critical in determining the most viable solution depending on the deviation of the cycle from the break-even price. In the proposal for break-even prices, Bunn *et al* (2003) included the cost of the geological repository, fabrication, interim storage, enrichment, burn up, method of enrichment, discount rate, price of uranium, conversion and premiums for various processes.

Another method used in the estimation of a nuclear power plant costing is the levelised cost of energy (LCOE). This method considers the total amount of electricity that the NPP is expected to produce and project it to the present term. This cost also takes into account the return on investment, which is not covered by the break-even method. When analysing the cost of reprocessing, it is imperative to look at the composition of the reprocessing (closed cycle) strategy and that of open cycle fuel management strategy. **Error! Reference source not found.** shows the flow diagram of the two strategies. The open cycle strategy on the left-hand side shows a flow diagram of the fuel life cycle in a nuclear power plant. The closed cycle on the right-hand side of **Error! Reference source not found.** shows additional steps necessary before the fuel can be re-used.

5.4 Politics

Kessides (2014) argues that Africa's power crisis is as a result of institutional and government failure. Kessides (2014) attributed the power calamity to misguided public policies, ineffective management and political interference, lack of stable policy environment and the failure to effectively utilise the country's natural energy resources. Kessides (2014)' claim of political interference is prevalent in the South African context especially in the nuclear sector where the development of nuclear facilities has been halted in 2017 owing to political instability in the country. The change in government cabinet has the potential to shift the policy of the country with regards to the implementation of the energy mix plan. This conclusion is drawn from the change in the IRP (2010) objectives to increase nuclear power capacity by 9.6 GW by 2030 to the mere consideration on nuclear power plant application in the IRP 2019 energy mix with no prospects to its development.

Van Wyk (2021) argues that governance poses a potential to inhibit nuclear technology deployment primarily through poor performance. For example, the department of energy failed to submit its financial report for two consecutive years therefore avoiding accountability. In addition, the Department of Mineral Resources and Energy (DMRE) scored below 60% performance between 2014 and 2019 with a declining trend resulting in a performance below 32% in 2018-2019. Van Wyk (2021) claims that due to poor governance, NECSA has operated at a significant loss of about R95Bn. Such a loss combined with poor performance in delivering its mandate, NECSA has undermined its responsibilities and thus significantly contribute towards the failure of various aspects of the New Nuclear Build Programme (van Wyk, 2021).

Van Wyk (2021) highlighted a sequence of political events that contributed towards the failure in the deployment of nuclear technologies in South Africa. First, van Wyk (2021) points out that the Mbeki administration had initiated a nuclear programme with prospects for success. However, the change from the Mbeki to the Motlante administration owing to the political turmoil in the ruling party (ANC) led

to the loss in momentum in the nuclear build programme. Second, as Motlante was gaining momentum, he was replaced by Zuma who had strong ambitions in nuclear technology. However, Zuma's ambitions were shadowed by corruption scandals that saw him resign, after having approved a fleet of 9000MWe from nuclear.

Another player in the nuclear power use is the international community. Although state sovereignty minimises the influence of one state on another, it can be argued that with matters related to weapons of mass destruction a number of nuclear states take such matters with greater attention. This can be observed from the intervention by the USA, China and Russia in states like Iran that are still in the path to develop nuclear weapons. Van Wyk (2021) claims that President Obama took interest in the South African Highly Enriched Uranium (HEU) left by the apartheid government.

Lim (2016) claims that countries with a common enemy (which can be both current and historical) may undertake a concrete nuclear cooperation owing to the joint abilities to face the enemy when circumstances become conducive. This aspect is evident in the prospects of Russia and China that jointly consider the USA as the common enemy and as such vow to maintain full military, diplomatic and socio-economic cooperation.

Concrete cooperation manifests itself in the South African context, although not at a significant scale, under military challenges, South Africa may choose to align with Russia due to historical participation of Russia in the struggle against apartheid. Again, concrete nuclear cooperation can be deduced as existent between Russia and South Africa looking plainly on the fact that South Africa had awarded Russia the development of nuclear power plant in South Africa. Although such cooperation faded due to internal politics and corruption, the author does not dismiss its existence.

Other aspects such as democracy and a military pact of defence play a significant role in the concrete cooperation between states (Lim, 2016). Although this claim may be true in other aspects of cooperation between South Africa and other democratic states, South Africa's alliances do not seem to be derived from democratic values but rather on mutual benefit between states.

The author does not neglect that other aspects such as common policy could further simplify concrete nuclear cooperation although the challenge of opposition on conflict occasions may render other countries reluctant to undergo concrete nuclear cooperation with South Africa. This can be seen through USA's disapproval to support South Africa in developing nuclear weapons and developing rigid ties with Russia.

Lim (2016) also claims that strategic considerations contribute towards the concrete nuclear cooperation between states. This is an amicable claim depicting the core foundations of concrete cooperation in that countries sharing the same strategic objectives such as Russia and China in the military perspective develop and share technological objectives. Lim's (2016) claim can be associated with the strategic objectives shared by Brazil, Russia, India, China and South Africa (BRICS) countries although at this point only economic objectives seem to be pursued.

According to van Wyk (2021), Obama hoped that the former South African President (Zuma) could announce that South Africa would dispose of all its HEU. However, the former president (Zuma) did not announce that it would destroy its HEU in 2014 because of the ambitions to align South Africa with BRICS membership and deployment of nuclear power facilities in SA. Again, joining BRICS may have led to the contestation of the South African drive to develop nuclear facilities by Western countries who would rather deprive both Russia and China of the opportunity to collaborate with South Africa in matters related to nuclear power both for peaceful and military applications (van Wyk, 2021).

The US president, Jimmy Carter, announced in 1977 that the United States would no longer commercially reprocess plutonium produced in the USA and that reprocessing and recycling were not necessary to sustain a viable and economic nuclear program (Woo *et al*, 2020). Woo *et al* (2020) claims that the US president was more concerned with the risk of proliferation more than other matters. This

can be observed through the number of agreements that the US subsequently signed with countries like Australia, Republic of Korea and others, which required prior consent for uranium enrichment resulting from these agreements. The Republic of Korea suffers enormous pressure from the reprocessing perspective owing to the need to obtain consensus from the US.

Woo *et al* (2020) claims that in 2015, the USA denied giving the Republic of Korea a go ahead to develop pyro-processing abilities. The factors cited in the refusal included the idea that it may be too easy to convert a pyro-processing system into a proliferation system and that pyro-processing would simply reduce the quantities required for long term storage but that it does not resolve the storage issues completely. Although these findings are plausible, the author concludes, with a high degree of confidence that the Republic of Korea has surrendered some of its sovereignty to the USA, a factor beneficial especially if cooperation in security aspects is guaranteed while on the other hand hindering the deployment of a pyro-processing facility in the Republic of Korea.

Woo *et al* (2020)'s claim on the Republic of Korea's reprocessing challenges due to international politics echo the South African experience in relation to President Zuma's encounter with the expectations of the USA's former president Obama that South Africa should destroy its HEU. This aspect challenges the state's ability to develop nuclear facilities without hindrance from the international community. Woo *et al* (2020)'s observations in the Republic of Korea challenge the very ideals of cooperation therefore leading states to undertake nuclear programmes in secrecy such as those undertaken by the apartheid government and the current Iranian nuclear weapons programme (Kerr, 2022).

5.5 Public participation

The public participation process is aimed at obtaining information about the proposed site that may not be available to the NPP applicant and should enable interaction between the applicant and the surrounding communities where specific aspects of the site and their relevance to the project are identified and possible alternatives explored (Yamashita, 2021).

In the South African context, public participation exhibits a number of challenges. These can be categorised as political challenges, societal, economic, law and academic challenges. Scott (2009) claims that the internationally identified public participation models such as the pure representative model, basic model, realism and elite models of public participation are ineffective in the South African context. Scott (2009) then proposes a four-layer public participation model for South Africa as shown in Figure 9.

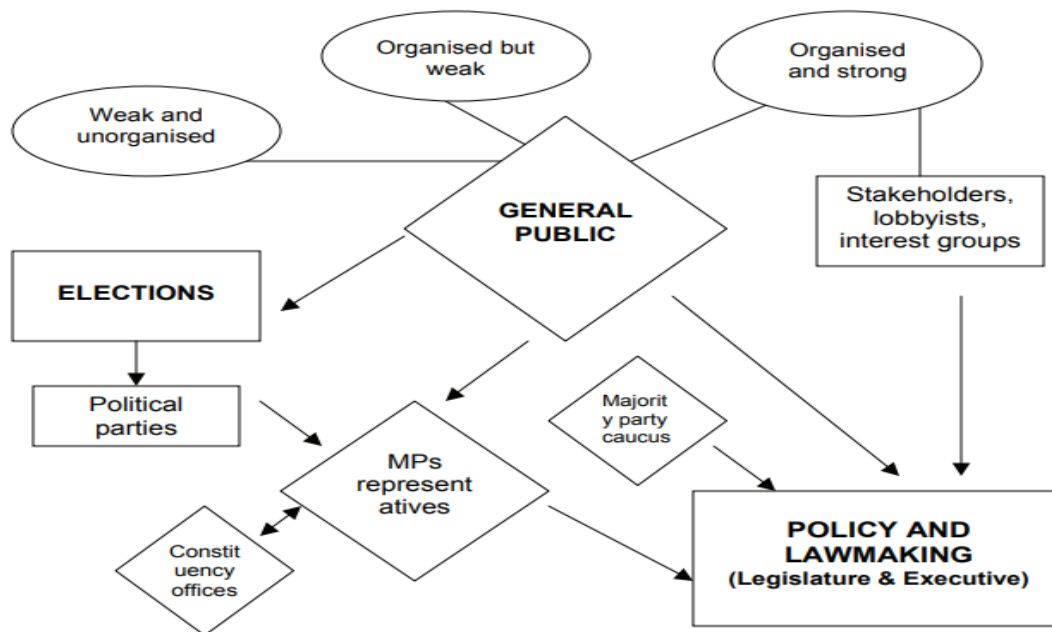


Figure 9: A perceived ideal public participation model for South Africa (Scott, 2009)

The ineffectiveness of the above-stipulated model rises from the societal inequalities primarily due to the apartheid legacy. These inequalities can be observed in a stretch of age spans in the society. The classification of residential status either as Suburb, township or village resemble a unique context in South Africa that physically defines the state of academic life, social stratification, political affiliation and communication capabilities (Scott, 2009).

Economic influence hampers the participation process by depriving those infringed from participating primarily due to lack of access to information, unfamiliarity with the public participation process, travel costs associated with the participation process and the detailed scope of activities enshrined in the project at hand as well as the basic understanding of the technicalities of the project (Shivamba, 2017).

The political climate in South Africa favours the minority affiliated to certain political parties while leaving behind the majority with no political affiliation at all and the voice of the political party becomes the voice of the majority in critical aspects of the society, exhibiting minimal engagement therefore hindering the effectiveness of the public participation process (Scott, 2009).

The available legislative framework which is only known and understood by the minute elite literates influences positively the public participation process. This is however, undermined by the diverse nature of socio-economic challenges that hinder its implementation. The oversight of the legislative framework requires skills and commitment to serve South Africa but other barriers such as the country's financial status and economic empowerment projects necessitating the employment of candidates on racial bases undermine the integrity of the public participation process.

The weaknesses identified by Scott (2009) in the South African public participation process can widely be supported by the numerous court cases facing nuclear installation applicants. These include the case by Earth Life Africa in 2017 where the court had to set aside the determinations that led to the granting of an environmental authorisation for NPP development (IAEA, 2017).

5.6 Public acceptance of nuclear power generation

Public acceptance is the fundamental principle that embroils a successful implementation of the government's policy in any public domain. What complicates the implementation of nuclear assets development is the physical characteristics in a sense that no NPP can be built behind the public eye because a NPP is built with an interaction with the public (Woo *et al*, 2020).

Zhou & Dai (2020) studied the communications media that permit public acceptance of NPP installations and operation. Zhou & Dai (2020) investigated how people make decisions and proposed both systematic and heuristic decision-making. Systemic decision making is when people are highly motivated and capable of making a judgement depending on the nature of the issue at hand and the explanations provided and heuristic decision making is where people make decisions by putting trust on experts and majority acceptance of the issue in question (Zhou & Dai, 2020).

Zhou & Dai (2020)'s study concluded that people with knowledge of nuclear power made decisions on the basis of their knowledge of energy efficiency and nuclear energy risks while those with no nuclear power knowledge made decisions on the basis of trust on nuclear power operation. The question that arises from Zhou & Dai (2020)'s study in the South African context is *“then which knowledge should be disseminated to those with nuclear knowledge, those who are illiterate but with nuclear energy knowledge and those who are completely illiterate”*.

Zhou & Dai (2020) proposes scientific knowledge education, station visiting, community building and national strategy advertising as effective means by which the Chinese government disseminated information to the public. Zhou & Dai (2020) pointed out that scientific education involves educative activities aimed at nuclear power through various means such as lectures, brochures and others.

This method is best suited to target people with nuclear knowledge who will be able to process the information and make decisions based on the merits of the current technological developments, strategic safety imperatives and weight of other available components of the energy mix. In addition, this approach favours more organisational structures where people can easily be gathered for a conference and whereby participation will be objective citing that the people would have the capability to individually analyse the information and make decisions (Zhou & Dai, 2020).

Station visiting is one of the most effective ways to engage the public in that communities could have direct access to the power station therefore increase the level of understanding. This approach could increase the level of nuclear power generation awareness in the communities and provide a direct interaction between the community and the nuclear power operators to engage and exchange information crucial to enhance public acceptance of nuclear installations or deployment (Woo *et al*, 2020). In addition, station visit could breach the literacy gap by enabling the community to have a traditional and generic dialog on nuclear power generation including profound safety aspects and how they are addressed in a non-technical language (Zhou & Dai, 2020).

Zhou & Dai (2020) proposes that during community building, nuclear power operators could engage with local people through arts performances, introducing nuclear scholarships, nuclear energy competitions and providing free medical check-ups. Coupled with appropriate media information dissemination strategies, this approach could significantly improve public access to information related to nuclear energy. In the South African context, this approach could include the involvement of environmentalists and other interest groups who could engage meaningfully in the dissemination of nuclear information once all legal structures have reached consensus in the deployment of NPPs.

Creating a national strategy that will be advertised and communicated effectively to the public could be a meaningful way of gaining public acceptance of NPP deployment (Zhou & Dai, 2020). However, the strategy will only be widely acceptable if the public can innately find it profound that the deployment will be of importance both to the current and future generations. Again, it is paramount for the public to be targeted as per their academic, influential and motivational strata. This stratification fully supports

Zhou & Dai (2020)'s claim that people will make decisions on nuclear power based on their level of knowledge with those with little or no knowledge following mass acceptance and trust while those with nuclear knowledge will decide on the bases of their assessment of the information at hand.

Zhou & Dai (2020) has identified public acceptance as a concept distinct from public perception. He argues that public acceptance involves the public's alignment with the deployment of nuclear technologies and perception being the general view of the public, which may not necessarily imply acceptance of deployment. According to Kessides (2014), sophisticated systems that are designed, constructed and operated according to very rigid standards could satisfy the public's demand for superior nuclear safety. This approach is in line with the NECSA requirements for the development, construction and operation of nuclear facilities. First, the attainment of a high nuclear safety culture is a staggered approach that involves public participation and regulatory authorities.

Risk perception is an important determining factor when it comes to public acceptance of nuclear power especially when coupled with low literacy levels (Zhou & Dai, 2020). This is true because the public is not aware even of the safety measures applied in NPPs hence their knowledge of nuclear power is limited to significant consequences both to the environment and human life (van Wyk, 2021).

With this perceived risk, the affected community is unlikely to accept the installation of nuclear power plants even though scientifically a radioactive leak is necessary to ignite diseases. Therefore, given that the South African community has little knowledge on nuclear power generation and safety principles surrounding nuclear generation, they are unlikely to accept nuclear technology deployment unless the government embarks in a mass information dissemination (Woo *et al*, 2020; van Wyk, 2021).

In his design of the model, Zhou & Dai (2020) stratified the samples into age, educational level, income and gender. Although this section does not cover the credibility of the samples, it does take from the model those aspects that could provide guidance in developing a communications model for the South African context. Other aspects not entailed in the model are ethnicity, migration and political affiliation.

Shivamba (2017) argued that during mining public consultations, the knowledge discrepancy between the experts and the community is so significant that the public has no detailed knowledge of the technicalities of the mining activities. Shivamba (2017) brings forth the notion of limited education or no education at all in the side of the participating communities. This observation is in line with Zhou & Dai (2020)'s proposal that the public participation method should include educational stratification and the four communications strategies married to the correct strata to enable the public to effectively engage with the experts.

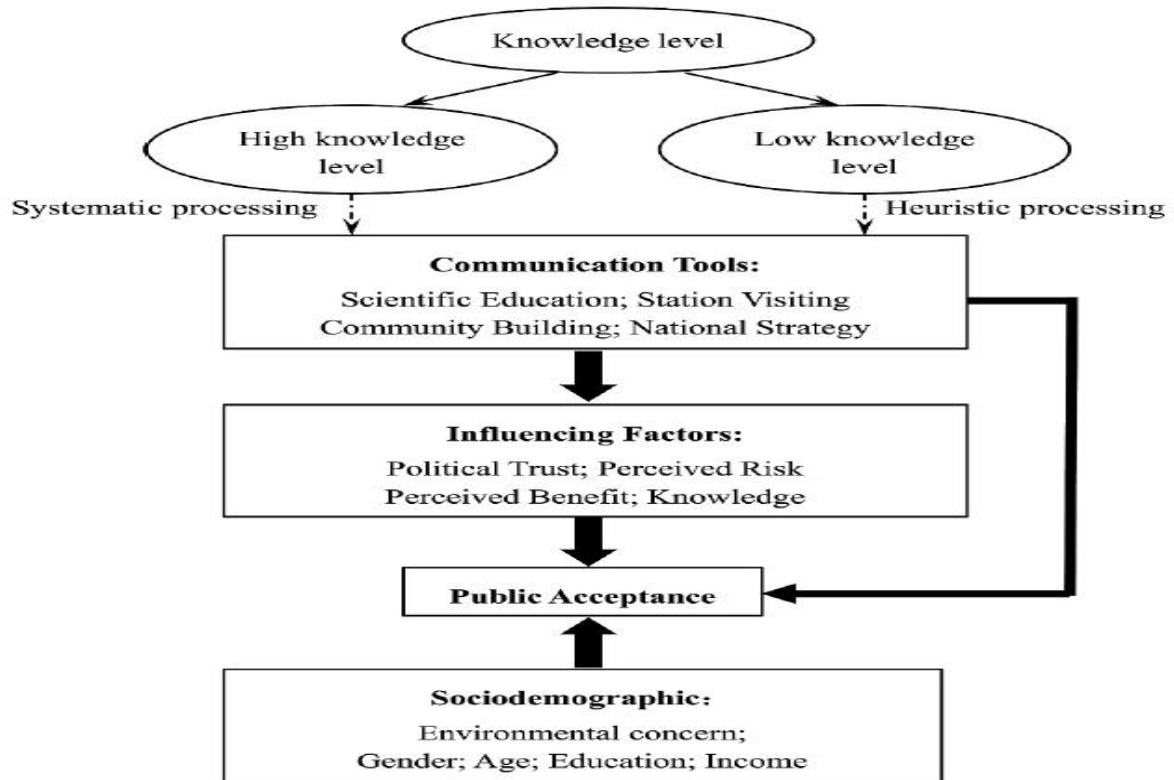


Figure 10: The role of communication tools in public acceptance formulation (Zhou & Dai, 2020)

In his study, Zhou & Dai (2020) concluded that the scientific education model encouraged those with low knowledge level of nuclear power to accept its deployment. This means that, somehow, either the population with low knowledge of nuclear power become acquainted with the benefits of nuclear energy or effective risk perception in that their fear of illusive risk is minimised (Zhou & Dai, 2020).

In his stratification of knowledge, Zhou & Dai (2020) found that scientific education played a significant role in enabling public acceptance of nuclear energy deployment for those who attended the scientific education programs. Zhou & Dai (2020) further claims that public acceptance is more observed in people with less knowledge of nuclear power but who have been to scientific education.

When doing station visiting analysis, Zhou & Dai (2020) came to conclude that people with less knowledge of nuclear power come to an understanding and elimination of perceived nuclear risks. Such an elimination reduces the barriers towards public acceptance of nuclear power to those with more knowledge of nuclear power. This works in favour of public acceptance because those with more knowledge can now make a more scientific judgement with their knowledge basis therefore increasing the level of acceptance.

In addition, Zhou & Dai (2020) claims that those with less knowledge of nuclear energy would gain more insight during a station visit and therefore contributing towards their decision-making. The acceptance is born of the benefits that nuclear technology deployment may bring and so, this perception largely supports the benefits understanding than the risk perception.

According to Zhou & Dai (2020), community building contributes significantly towards increasing the level of acceptance of nuclear power technologies in people with less knowledge of nuclear energy. The acceptance is linked to the political trust as shown in Figure 10. Inferred to the South African political arena, this aspect is crucial since the political structures are by far detached from the communities they

serve. Therefore, community building could encourage a direct participation between the communities and local government.

Furthermore, the political trust established through community building could inherit the minimisation of perceived risk and a notion of collectiveness between the government and the community. Zhou & Dai (2020) also claims that the reciprocal relationship established could create trust to the local government and further enable an existence of communication channels through which community concerns could be raised and responded to, with transparency and accountability.

The effects of national strategy echo a number of platforms that drive public acceptance for both the less knowledgeable and more knowledgeable individuals. In Zhou & Dai (2020)'s model, for people with less knowledge, the national strategy triggers the political trust and reduction in perceived risk. This enhances public acceptance of the adoption of nuclear technologies since the community rests the safe operation of nuclear plants to probably a familiar institution vested with their safety interests and on benefits that will be realised through the development of nuclear energy. For people with high level of nuclear energy knowledge, the advertisement of nuclear strategy encourages political trust, improved perceived risk, benefit, and knowledge of deployed nuclear plants (Zhou & Dai, 2020).

Since the implementation of the communication instruments should not be discriminative in nature, in the South African context, a broader approach that follows the scientific education strategy should take precedence (Woo *et al*, 2020). This strategy shall lay the foundations for the understanding of nuclear technology in which the national strategic imperatives will be introduced to the communities.

Zhou & Dai (2020) investigated the effectiveness of the instruments of communication towards public acceptance of nuclear technology deployment. Sugyawan & Managi (2019) on the other hand, investigated how trust issues influenced public acceptance of nuclear power technology deployment in Indonesia and deduced that nuclear power authorities and local governments are the key players that positively influence the acceptance of nuclear power technology development. Sugyawan & Managi (2019) cites the perception of nuclear energy as high-risk technology associated with radioactive hazards, nuclear accidents and proliferation (nuclear weapons) and disregard to public engagement leading to public distrust. Sugyawan & Managi (2019)'s study includes two additional aspects that influence public acceptance of nuclear power technology. These aspects are stakeholder background and interests.

Sugyawan & Managi (2019) claims that trust vested in the nuclear energy authorities as well as the central and local government play a significant role in promoting acceptance of nuclear technology deployment. This claim is in line with Zhou & Dai (2020)'s conclusion based on the communication instruments that seek the enablement of strategic communication, station visiting and community building which ensures that there is an engagement between the public and other authorities such as the government and nuclear installation operators.

Sugyawan & Managi (2019) introduces another dimension in the acceptance of nuclear technology being the public acceptance and community acceptance of the technology. He argues that public acceptance is an aggregate acceptance nationwide even by stakeholders who may not suffer the consequences of such a technology. Sugyawan & Managi (2019) adds that community acceptance concerns that community which will be impacted directly by nuclear technological acquisition. This distinction is paramount to the South African context where people in other areas may not be affected by events in the vicinity of the NPP installation.

The additional dimension posed by Sugyawan & Managi (2019) in the decision-making process puts into perspective the sense of locality, knowledge base as influential in the decision-making process. This perspective aligns with Zhou & Dai (2020)'s observation in the response of various knowledge groups in decision making towards acceptance of nuclear technology. Sugyawan & Managi (2019) claims that sociodemographic characteristics such as age, gender, social class and psychological factors

such as the level of trust and knowledge of the nuclear technology determine the net perception of nuclear risk.

This claim exhibits a diverse approach to risk perception especially in South Africa where the lower class tends to be the least literate therefore having little knowledge of nuclear associated risks (Shivamba, 2017). This can increase the negative attitude towards nuclear energy since the analysis of the risk is limited. Zhou & Dai (2020)'s approach to communication instruments could play a vital role in mending the negative approach towards a comprehensive national strategy owned by the majority of the citizens. In addition, Sugyawan & Managi (2019) and Alzahrani *et al* (2020) see contextual factors such as technology, spatial proximity to the NPP and public engagement as influential components towards the perception of the risk of nuclear technology.

According to van Wyk (2021), the South African community knew little about nuclear energy and related technologies. Van Wyk (2021) argues that 40 % of the participants in the NECSA survey were undecided as to whether nuclear technology should be deployed in the country or not. It is alarming to note that NECSA reported that only 23% of the participants has a positive view and approved the installation of nuclear facilities while 42 % of the participants did not know if South Africa should construct new nuclear power plants.

Gu *et al* (2020) claims that public acceptance of risk technologies is based in three factors such as trust in government, risk and benefit perception. Gu *et al* (2020)'s research focused in determining whether perception taking influenced public acceptance towards nuclear energy in China. Gu *et al* (2020)'s analysis was based in a sample of 933 samples taken in China. The research provides insight in an individual's acceptance of nuclear technology when taken out of normal routine, how energy policy affects acceptance and the implications of government policy in developing nuclear technologies.

According to Gu *et al* (2020) the Chinese government has strong ambitions to develop 58GW of nuclear power by 2020 for which, by May 2020, 45 GW were in operation while 12.5 GW were under construction. The total GW energy envisaged for 2020 is about what has been achieved. Such a success merits a thorough analysis both in the government's attitude towards nuclear energy, financial resources as well as the public acceptance.

The introduction or development of science popularisation activities such as Popular Science Activities on Green Nuclear with videos such as the Chinese Nuclear, Nuclear Power, Road to a Carbon Free Future are some of the interventions that contributed towards the success of the nuclear deployment projects in China (Gu *et al*, 2020). In addition, Gu *et al* (2020) claims that the Chinese government and other nuclear organisations set up an online column that enabled the interaction with the public with an objective to promote the government's nuclear ambitions. The inclusion of the local government and mandating it with the facilitation of information sharing with the public, creation of communications channels enabling the public to actively participate in aspects of their concern.

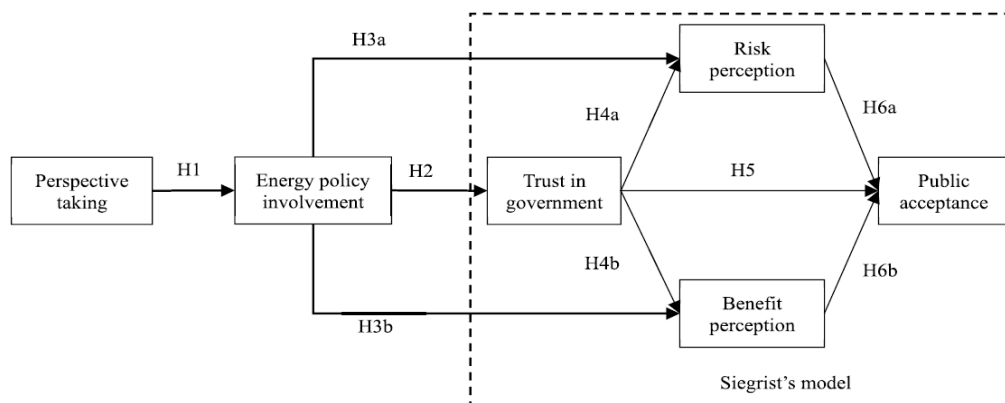


Figure 11: Perspective-taking model (Gu *et al*, 2020)

Gu *et al* (2020)'s model in perspective taking (*Figure 11*) shows how perspective taking influences public acceptance of NPPs. From the energy policy, depending on how information is disseminated to the public, trust in government can be achieved. In the South African context, this trust may be based in the operational efficiency of the NPP citing that for decades, KNPP operated without significant incidents. However, in other spheres such as corruption and maladministration, the South African government would significantly underscore owing to various scandals associated with two South African presidents and lack of accountability and poor performance in various government departments as noted by van Wyk (2021).

According to Gu *et al* (2020) individuals process information in relation to their motives. This means that individuals are most likely to access information that they deem important for them and can use it for decision making depending in the individual's motivational traits. In addition, to effectively process the information, the individuals need to make the target information a need, make it part of their values and interests. Gu *et al* (2020) supposes that highly motivated individuals take serious environmental issues as part of their decision making therefore becoming aware of environmental policies becomes their objective.

Gu *et al* (2020) claims that individuals with high motivation will access information related to the government's policy in nuclear development therefore develop a trust in government with positive expectations and consequently believe that the government seeks to minimise carbon emissions through the use of nuclear technologies that exhibit high efficiency. Gu *et al* (2020) argues that the individuals trust that the government will improve health and safety through research and development while improving radiation and emergency response to safeguard the communities affected is crucial. Gu *et al* (2020) concluded that trust in government is related to risk perception, which can either contribute towards benefit perception therefore facilitating public acceptance.

Gu *et al* (2020) supports the introduction of perspective taking in early childhood to facilitate public acceptance of nuclear technologies. This posits van Wyk (2021)'s notion that the Zuma administration did seek to introduce nuclear energy knowledge in the high school level. This aspect is paramount in enabling future generations to make informed decisions in relation to nuclear technologies with consensus in the risks they pose, environmental consequences and economic benefits as observed in Japan. This approach could bring the general mass to at least minimum knowledge in relation to nuclear technologies, economic opportunities presented by such, including uranium mining, enrichment and possible commercial exports while bearing in mind the risks brought about, such as conflicts and proliferation potentials that may undermine the safe use of nuclear energy in South Africa.

5.7 Environmental impact of SNF or nuclear accidents

According to Kessides (2014) nuclear energy has a well-established technology that has no carbon emissions or other climate relevant emissions. This is a very significant concept that removes the danger imposed to the ozone layer by emissions causing ozone layer depletion. In addition to its no carbon emission, nuclear energy can be produced in bulk and incrementally in a scale suitable for a particular grid.

Nuclear fuel has substances that are toxic to humans and the environment and should be kept safe from accidents or theft. Theft and security concerns cannot be excluded from the African continent given the currently unmanageable insurgency in countries like Mozambique where economic beneficiation from natural resources sparked a series of killings, ongoing conflicts in Mali, insurgency in Ghana and Congo. In these occasions, the theft of nuclear material may result in the release of radioactive material that can pose danger to the environment. Kessides (2014) claim that the consequences of a nuclear plant failure, especially radioactive release, has currently no technological match to alleviate or treat.

According to Kong *et al* (2017), Korean regulatory authorities categorise radioactive release into liquid and gaseous material under normal NPP operation. The authorities further regulate the effluents through the monitoring of the radioactive release and the dose to which the members of the public are exposed. According to Kong *et al* (2017), the members of the public should not be exposed to more than 1 mSv of radiation per year under normal NPP operation. Kong *et al* (2017) further claims that the regulatory authorities seek to keep the radiation in unrestricted areas to ALARA during the normal operation of a NPP.

Kong *et al* (2017) estimates the dose to the public as estimated from the unrestricted boundary as the sum of the doses of all reactor units at the given site. In the case of Koeberg for example, this would mean the sum of the doses of the two-900MW units at the unrestricted boundary. Kong *et al* (2017) cites KDOSE 60 as an effective program that can be effectively used to estimate the radiation exposure to the members of the public. KDOSE 60 focuses on liquid (LIQ), gas (GAS) and atmospheric diffusion parameters (XQDQWQ) for estimating the maximum dose to which the Maximally Exposed Individual (MEI) has been exposed to in a given population.

Although this document does not seek to analyse the effectiveness nor the appropriateness of the use of KDOSE 60, its outcomes are taken to help analyse what the radiological impact of a NPP such as Koeberg to the public and the environment is. These could in turn inform the basis for which public fear of nuclear power plants is routed and possible mitigation factors as opposed to general knowledge of radioactive release (Kong *et al*, 2017). In addition, if the outcomes of such information can be shared with the public through community building (a strategy proposed by Zhou & Dai, 2020), could acquaint the public with the safe operation of nuclear power plants.

Kong *et al* (2017) claims that the fission of tramp uranium, leak from failed fuel rods, diffusion of intact radioactive fuel rods, activation of radioactive material in the reactor cooling water and corrosion of activated material are the main sources of the radioactive effluents being estimated using the KDOSE 60 program. The dispersion forms stated above may be applicable to Koeberg NPP which disposes its cooling water in the Atlantic Ocean.

Kong *et al* (2017) also claims that the radioactive release for a site with a HPWR had 5 times more radioactive release compared to other sites. Kong *et al* (2017) attributed the increase in effluents to the use of heavy water, which releases tritium through neutron capture by deuterium. In addition, Kong *et al* (2006) affirms that 95% of the contribution in effluents is because of tritium in both liquid and gaseous states. This escalation is not expected in the context of Koeberg since it is a PWR NPP.

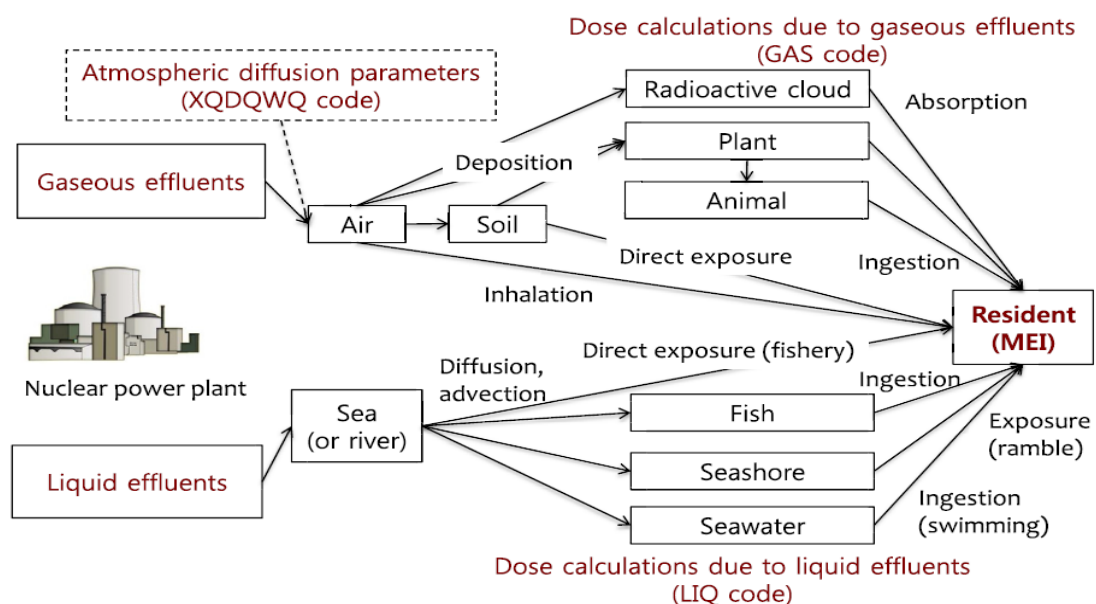


Figure 12: Maximum radiation exposure for an individual (Kong *et al*, 2017)

Figure 12 shows how effluents migrate from the NPP through the rivers, sea, air, soil and through living organisms such as plants and animals until the effluents reach human beings. In the case of South Africa, radioactive effluents from KNPP would either enter the sea through cooling and directly into the air. This has a significant impact in the Cape region where the consumed fish is from the sea presumably within a 100km coastline. The various fish captured in Cape Town such as snoek, hake, salmon and others may somehow be exposed to radioactive material emanating from Koeberg NPP.

The combination of the various sources of effluents linked to the KNPP may raise the effluents significantly for an individual residing in the Cape Coastal area. In the Korean context, radioactive release is estimated annually to determine the public dose to which the population around the NPP is exposed. Korean NPP operators use four models to estimate the total exposure of the population around a NPP.

These are the real measurements of the effluents to the environment during normal plant operation, which is the direct indication of how much radioactive material is present in the environment. Dispersion and dilution of radioactive material in the environment give an indication of how the effluents interact with the environment to facilitate its migration. Inclusion of models that encompass how effluents contaminate plants, animals and soil put into context the effluents consumption by humans. A bio kinetic model is one of the models that analyse the human intake and how the human metabolism interacts with the effluents during processing. The conclusion from this model and *Figure 12* is that the individuals living around the KNPP would be the most exposed therefore having a high dose 0.001 mSv of radioactive effluents as shown in *figure 8* (NOU, 2022; Kong et al, 2017; Maree, 2009).

5.8 Crime as a challenge in nuclear energy deployment

The unauthorised access to the nuclear site places the plant at risk. If the robbery was aimed at the nuclear material, either internal or external parties to South Africa have a motive necessitating such material or a possible intent to develop nuclear weapons is imminent. If the robbery was a general criminal act, then the nuclear facilities physical barriers need to be strengthened to ensure that no access to radiological material is possible. In addition, regardless of the intentions of the robbers, the security measures for nuclear facilities in South Africa need to be improved probably as envisaged in the regulations in physical protective measures for nuclear facilities under development (van Wyk, 2021).

5.9 Public opinion as a challenge towards nuclear energy deployment

Furthermore, van Wyk (2021) sees public opinion as another factor holding back the development of nuclear facilities in South Africa. Despite the fact that the South African community is less knowledgeable in relation to nuclear activities, various organisations and individuals do hold the government to account by challenging the legalities of the development of nuclear facilities. So far, 31 individuals and organisations made presentations to the court and 38 requests to make oral submissions in relation with the draft IRP. Again, civil societies such as Save Bantamsklip, Thyspunt alliance, Earthlife Africa Johannesburg and SAFCEI had reasonable influence in inhibiting the development of nuclear facilities through successful court cases and community contestations to nuclear projects.

5.10 Key points

Human resources and technical skills are crucial for design, construction and commissioning of a new NPP. These further determine the success of a new NPP projects. Van Wyk (2021) highlighted skills shortage in the nuclear industry in South Africa. Although this is true, KNPP continuously embark in training, recruitment and maintenance of personnel with technical skills. In addition, KNPP has provided South Africa if a base set of skills and personnel in the operation of NPPs. With this in mind, the author concludes that South Africa has a potential to design, construct and commission new NPPs.

Other challenges such as proliferation can be mitigated through collaboration with the international community and implementation of proliferation resistant technologies. In addition, proliferation drivers such as supportive cooperation and concrete cooperation between South Africa and other states can be mitigated through transparency and inclusion of the international stakeholders. The relationship between Russia and South Africa for example, may pose a threat to Western countries. The significant threat is the alignment of South Africa militarily with the BRICS countries. South Africa's ratification of the AP protocol, NPT and other protocols surrounding nuclear energy could be used to initiate discussions around peaceful uses of nuclear energy (Lim, 2016).

The impact of national politics in nuclear deployment is concerning. Political regimes seem to follow policies developed in accordance with the governing party's motion with public misconception taken as the bases for policy formulation. South Africa needs to develop a nuclear policy for the country that can be implemented by any regime. The Japanese approach in this regard can shed light on how the changes in cabinet officials facilitate the continuation of the policy.

Environmental challenges are a concern both to policy makers and the judiciary. More important, is the impact of nuclear activities in the environment. For an effective socio-economic development, a balance must be attained through research and development that will guide, with high success prospects, the deployment of nuclear energy.

In addition, public acceptance of nuclear energy is more associated with the environmental impact, safety and corruption related aspects. The public find itself in a state of disproportionate in that the government has not, up to so far been able to demonstrate the extent to which nuclear energy is necessary. For example, there is no indication that the government is promoting nuclear technology as an imperative necessity for socio-economic development and to improve the livelihood of South Africans.

From this chapter, the author concludes that although several challenges face the deployment of nuclear technology, politics is the major hinderance. The manifestation of politics covers spheres such as corruption, political instability, inability to provide policy continuity beyond cabinet tenure, inadequate financial planning and lack of resolution strategy to resolve court cases. Furthermore, the government's inability to induce effective communication strategies that can promote nuclear technology is another indication of political challenges. Lastly, it could be beneficial to south Africa if political barriers can be analysed and solutions devised to enable the deployment of nuclear technology.

6. Discussion

In this chapter, the findings from the previously presented literature are consolidated, discussed in the South African context and several recommendations made to overcome the presented challenges. The mining of South Africa's uranium resources and the prospects of a self-sustained nuclear industry are discussed. The policy and regulatory aspects are discussed in the context of enabling nuclear energy deployment.

This chapter also highlights and give recommendations on aspects associated with political challenges and how various stakeholders could positively contribute towards the deployment of new NPPs for civil application. The impact of crime and lack of trust in the government are also considered. communications strategies that could improve public participation also discussed. Other strategies linked to policy as a driving force towards the deployment of new NPPs are taken into consideration.

6.1 Uranium resources

The resources currently available at the disposal of the Department of Energy include fossil fuels, uranium, wind, solar and other forms of energy. Nuclear energy (with 400892 tU of uranium) is tempting to pursue. In the cases of Japan, China and Indonesia nuclear energy was proposed and pursued as the economic driving source of energy (Valentine & Sovacool, 2010; Kenen, 2014). Based on this research, an ambitious nuclear energy-based economy is proposed for a period of at least 40 years for South Africa, while using other sources of energy to complement nuclear energy. During this time, various technologies such as pyro-processing and AFCI could be developed through research and development that could seek to maximise the amount of energy that uranium provides at the country's disposal.

With the long history of uranium extraction, processing, enrichment, use in PWRs and reprocessing, South Africa is at an advantage of developing a full uranium usage cycle (closed cycle). With more than 200 mines, South Africa has enough mining skills to ensure industrial mining capabilities to sustain the country's uranium needs. Although South Africa's uranium resources (400892 tU) cannot support an infinite number of PWRs, the available resources are enough to power South Africa for more than 750 years if reprocessing is not taken into consideration (DEMR, 2022).

Once the primary uranium resources have been depleted, South Africa can use the reprocessing strategies discussed in chapter 2 to fabricate nuclear fuel from the SNF. With the use of AFCI strategy, one can argue that the uranium resources available in South Africa could last double the estimated time to 1500 years (Dixon *et al* (2005). During the reprocessing process, South Africa could develop more matured nuclear technologies that could optimise further the use of uranium resources like China and Russia, therefore increasing the time to depletion of uranium resources (Kessides, 2014).

Despite the financial and policy challenges facing the mining industry with respect to uranium extraction as identified by Stewart & Shirvan (2022), a rigorous energy policy is necessary. The policy could facilitate the allocation of funding to mining entities and allow flexibility with regards to uranium private mining while vesting the safety and security of uranium in the regulatory bodies such as the IAEA and NNR. The regulatory bodies could then ensure that the funding and uranium resources are not diverted from the intended peaceful use for civil applications.

The challenges facing the South African mining industry concerning uranium extraction can be alleviated through collaboration with various stakeholders especially in aspects associated with the policy and regulatory framework. Once an exporter of about 6000 tU in the 1980s, currently South Africa only exports about 308 tU with an expectation to increase the export to 600tU by 2020. The exportation of uranium resources must take into account the resources available in relation to population and economic growth to ensure that SA retains enough uranium for its own consumption.

In addition, the lack of sufficient investment in uranium mining can be addressed through a national strategy, which could seek to promote nuclear energy as an economy driving force therefore enabling the government to allocate reasonable funding for the development of nuclear mining resources. Other challenges such as access to private land and conflicting legislation and the first come first serve principle could be addressed through a nuclear energy policy designed to limit access denial and promote a potential based principle for uranium resources access to support the national strategy (DEMR, 2022).

6.2 Policy and regulatory framework

Policy is one of the most important aspects driving both national and international interests of a country. The national policy of a country determines how national resources are utilised to satisfy the interests of the country. With regard to nuclear energy, the South African government needs to develop a rigorous policy driven by a national strategy in the deployment of nuclear energy. The policy should cover the mobilisation of various resources necessary for the success of a nuclear energy programme such as the natural uranium resources, human resources, financial resources and regulatory bodies, and align these with the national strategic objectives including education, labour and health.

The nuclear energy policy should be shielded from the volatility of the political system such that changes in government agents and political parties would have no impact on the policy. The Japanese approach where officials were replaced without affecting the energy policy can be adopted in South Africa. This could address the delays in nuclear energy deployment associated with the political instability in the country. In a sense, the changes in the political climate that influence the energy policy depletes financial resources by halting, if not discarding the work done by the previous state officials therefore necessitating rework and more time. The elapsed time has significant implications in the implementation of the new energy policy in that technology and economic status of the country may have changed resulting in possible rework and additional expenditure (van Wyk, 2021).

The regulatory framework of the country should be such that the various state agents and nuclear energy role players develop a common goal, which is the success of the nuclear energy deployment. This can be done through the removal of red tapes in government agents vested with the authority to enable aspects such as licensing in the case of the department of environmental and water management. Other regulatory bodies such as NNR, NECSA, IAEA and other international organisations must ensure an effective regulatory environment with the deployment of nuclear energy as their priority as enshrined in the rigorous national nuclear energy policy. In addition, other regulatory structures associated with land use must develop policies that facilitate the deployment of nuclear energy (DEMR, 2022).

The national energy policy strategy must identify aspects such as court cases, which may contribute towards the delay of nuclear energy deployment and actively collaborate with affected parties during the planning phase. Regulatory bodies such as NNR and NECSA should actively engage communities to disseminate aspects relevant to nuclear deployment and to some extent, promote the national energy policy. In conjunction with NEMA regulations, the department of environmental affairs must collaborate with NECSA and NNR to establish the feasibility of a particular site for a nuclear plant installation (NOU, 2022).

Again, the international community must be engaged both at the political and technical level to establish aspects that may hinder the deployment of nuclear energy in South Africa. The engagement should be conducted through or with a number of organisations such as the IAEA and World Association of Nuclear Operators (WANO). This engagement should cover aspects associated with the safety of the intended nuclear energy deployment and proliferation risks, bearing in mind aspects such as the concrete nuclear cooperation between South Africa and other countries such as Russia, China, USA, Germany and France (Woo et al, 2020).

Although South Africa is not party to the '123' agreement with the USA, it is imperative for the South African government to look at aspects entailed in this agreement to establish the basis of the disagreement with nuclear power countries and establish conditions favourable, if possible, to the deployment of nuclear energy for civil applications (Woo *et al*, 2020). When evaluating a country's potential to consider nuclear proliferation, Kim *et al* (2022) looked at the ratification of the Additional Protocol (AP), completion of the UN Security Council Resolution (UNSCR) 1540 requirements and the ratification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) as well as traditional non-proliferation norms such as NPT, IAEA, and NSG memberships. South Africa became a member of the AP in 2002 (IAEA, 2022), UNSCR 1540 in 2004, ratified the CTBT in March 1999, the NPT in 1999 and the IAEA in Jul 1991 as well as the Nuclear Supplier Group (NSG) in 1995.

Woo *et al* (2020) proposed a number of policies to enable the effectiveness of nuclear non-proliferation. First, Woo *et al* (2020) argued that nuclear safeguards agreements such as those with the IAEA and other international organisations could mitigate the risk of proliferation. In addition, states with nuclear ambitions could develop policies for financial resources required to develop the safeguards necessary for the success of pyro-processing.

Policies promoting cooperation between allied countries could be developed in South Africa with the aim of enabling allied countries to be observers of the nuclear material therefore creating a barrier that could prevent material diversion. Lastly, sanctions could be developed to ensure that countries in which nuclear material diversion is observed are unable to trade or make economic gains that could enable them to make nuclear weapons. In addition, limitations in material associated with nuclear weapons could be posed therefore preventing such countries from developing nuclear weapons.

6.3 Economy

With regards to nuclear technology deployment, the South African government gives less credit to its funding. Stewart & Shirvan (2022) and Van Wyk (2021) observed that the funding allocation for nuclear energy clearly aligns with the IAEA's report on why uranium mining operations have been significantly hampered by funding and economic viability.

However, this approach is more policy based rather than the ground technicalities such as corruption, crime and financial constraints, even though the budgetary constraints are a reality. Adding on this, the National Financial Planning has not put a significant budget in the long-term national plan for the execution of nuclear energy projects such that the budget does not cover the cost of a Request for Information (RFI) giving a clear indication that the current (1990-2023) South African government does not drive a rigorous nuclear energy policy (van Wyk, 2021).

Similarly, the economic estimation methods applied worldwide highlight that economic factors contribute to the deployment of nuclear facilities in the society, while some scholars consider public acceptance and participation, policy, and politics to take precedence (Zhou & Dai, 2020). In the South African case, some non-governmental organizations like Earth Life Africa contested the project implementation testifying that the government did not execute the public participation in a regular manner; the politicians took up corruption acts, as well as the shortage of funds. After trial, the court suspended the Thuyspet nuclear power plant project, fearing impact in climate change and the lack of public consultation and participation (van Wyk, 2021).

In the past few years South Africa's economy saw a significant rise in downgrades although from Nov 2022, Moody's projected a positive economic outlook. It is important to highlight that the global economy does pose a challenge to South Africa's ability to attract investors. Another finding shows that the government is able to invest significant amounts of money into renewable energies. With this in mind, it is true that economic implications are not the primary factors challenging the deployment of new nuclear technologies in South Africa (de Boer *et al*, 2022).

Stewart & Shirvan (2022) introduced unit timing in the construction schedule arguing that it is a shortened construction schedule that allows the modular units to be deployed timeously in relation to demand growth. China used environmental protection and energy needs for economic development as driving policies to achieve the deployment of nuclear technologies (Woo et al, 2020). This view or approach can find a significant application in the South African context where the current electricity demand is uncertain due to poor economic growth coupled with loadshedding. The timeous modular deployment could find its relevance in localised networks as discussed for some regions of the Eastern Cape and Kwa-Zulu Natal.

6.4 Human resources and technical expertise

The credibility of South Africa's experience in nuclear energy is known both nationally and in the international community with more than 30 years of operation and maintenance of PWRs as KNPP operation started in 1984 (NOU, 2022). In this period the country gained vast experience in nuclear operation, safety culture and aging management programmes, this knowledge enabled the government to decide in the extension of the life span of its nuclear power plant by 20 more years.

Considering the human resource capability and the experience, the country is capable to build new PWRs, and ensure successful implementation, missing only political willingness and favourable public acceptance. In addition, the South African nuclear operator has communication both with the local regulatory authority (NNR) and the IAEA. This communication is ensuring that experience learned from Koeberg's sister plants is transferred to South Africa. In addition, through information sharing, South African engineers could gain knowledge from experts in the nuclear field and use it in the development of new nuclear power plants inside the country or cooperative programs around the world.

In addition, SALTO missions highlighted that South Africa has adequate human resources strategy, which encompasses training new staff, use of external resources and employment of technically competent staff through advertising of vacancies. This means that South Africa has a potential to develop a human resources strategy capable of handling the needs of a new fleet of nuclear power plants in the long term (NOU, 2022). In addition, if South Africa deploys SMRs as the nuclear technology of choice, then fewer human resources could be required due to operational and maintenance simplicity of SMRs. Therefore, based on NOU (2022) on the SA human resources and their technical skills, there are no grounds to dispute that South Africa has a potential to develop and deploy new nuclear power plant facilities.

It is essential to note that the design and construction of nuclear power plants in India was achieved locally through continuous maintenance and refurbishment of the NPP owned by India and that the skills acquired has given India confidence to embark in safe nuclear facility design, construction and operation (Penalonga *et al*, 2017; Kessides, 2017; Ramana, 2009). This means that the South African can learn from India's approach together with cooperation with the international community. In addition, the design and manufacturing of components for nuclear applications can be achieved locally through the same process.

The South African nuclear energy sector staffing is hampered by the movement of experienced staff to high paying regions such as the United Arab Emirates (UAE), Canada and Australia. In addition, local staff movement also affects the availability of staff in the nuclear energy sector. To address this, KNPP employs a human resources strategy characterized by knowledge transfer and management, training and development, outsourcing of services to external organizations with training prospects and advertising of vacant positions (NOU, 2022).

Havel & Krivanek (2016) presuppose that prior to the renewal of a license for LTO, it is imperative that the review of various aspects of the NPP be done. Such a review should marry the prospects of the technical applications of the NPP such as designs, standards and procedures, operating with associated

human resources aspects such as staffing, knowledge management and transfer as well as human resources strategy that is effective in ensuring the operation of the NPP beyond its established life span.

6.5 Future of nuclear energy extraction

In the South African context, the AFCI strategy could play a significant role in resolving the storage challenges of SNF in the longer period. The fuel currently stored at Koeberg NPP could be recycled, the uranium recovered and converted to new fuel, which could be used in fast reactors. The major challenge in the South African context is the development of fast reactors which may take longer, face financial challenges and technical skills associated with the development of such facilities. This could be overcome through build and maintain programmes, outsourcing of some activities as pointed out by Havel & Krivanek (2016) and intensive skills training which may take longer to ascertain the readiness of the country to operate Fast Reactors.

It is worth noting that with the current loadshedding challenges, public rejection of nuclear energy may see a decline depending on how much the government projects the viability of nuclear power plants in the country. The diversion of material requires significant attention as discussed by van Wyk (2021) in that whether the elements of crime resulted in the armed robbery at Pelindaba or it is the act of terrorism, both aspects desire a closer analysis and a significant and rigid stance from the government in relation to nuclear sites security.

Pyro-processing and AFCI strategies are future envisaged strategies to which only ideas and studies are being performed at this point. Having noted that the PUREX process exhibits proliferation risks, this strategy is not advisable for the South African context. Pyro-processing on the other hand, is worth exploring but the challenges are more of a technical viability nature than logistical making it hard for South Africa to adopt it. For the AFCI, South Africa could play a significant role in the research and development of this strategy through partnership with countries interested in AFCI to acquire skills and contribute towards the development of this strategy to remedy the challenges that may face the future of nuclear technology while increasing access to nuclear power production.

6.6 Political factors

Valentine & Sovacool (2010), claimed that one of the effective strategies in mitigating political nuclear challenges in Japan is to develop a sustainable nuclear energy policy in which the government resignation strategy allows the new decision-maker (current official responsible) to shift public focus from the presiding officer to the resigned individual. Although the South African government does not have a long-term strategic plan, in practice the implementation has been similar to Japan, such as the resignation of the Minister of Health and the minister of foreign affairs but who still hold office in other facets of the government or the ruling party.

As the South African resignation strategy is not designed for long-term implementation of nuclear energy policy, the SA government members who are nominated do not maintain the vision and implementation of the previous officer's nuclear policy. Because of this, the community have been rejecting the implementation arguing that to invest on it is to give chance to the officers to steal public resources, supporting themselves on the previous experiences. To address this short fall, a strategic imperative with the organisational drive and clear goals such that the subsequent replacement official would still drive the objectives of the policy is required. Contrary to the mentioned Japanese approach, it is of the opinion of the author that the nuclear energy policy in South Africa came to a total collapse

when the president was impeached, and the presiding officers aligned the energy mix policy with the public perception rather than with the government objectives.

Media diversification and control can play a major role in ensuring that the public does not hinder the implementation of nuclear energy technologies. According to Valentine & Sovacool (2010) and Woo *et al* (2020), Japan had control over the media during the development of its nuclear arsenal. This entailed creating ministerial officials in the media fraternity who could pass filtered information to the public. In addition to insulating the nuclear power factors from the public, ministerial media advocated for the positive aspects of nuclear power generation therefore minimising the opposition towards nuclear technology acquisition.

In the current South African media platform, where thorough transparency and independence is a subject of the day, ministerial media diversification and control may be a contentious issue. This contention would be attributed to the existence of various non-governmental organisations who lobby on behalf of the public.

To the contrary, the South African media can be nurtured to positively contribute towards the development of nuclear technology by advocating, with the involvement of nuclear energy experts and the government officials to depict those aspects of the nuclear energy that render the technology unacceptable to the public. Although the Japanese experience may be different from the South African context on historical and racial dynamics, an attempt to foster public support towards economic emancipation through cheap nuclear energy may prove to be fruitful in the long run (Kessides, 2014).

A rigorous nuclear energy plan may be crucial in promoting public acceptance of NPP. The South Korean's approach involved a plan to revitalise the peasant's economy while the second plan focused on the country's ambitions to develop nuclear power plants by quantifying, within reasonable parameters the amount of NPP to be built.

The synonymy between Japan and South Korea shows that the main drive towards these plans were economic development and energy security, which in the context, South Africa suffers the same fate although with large coal reserves which are of great debate due to environmental consequences. Both Japan and South Korea saw nuclear power as a means to uplift their economies and derived policies that supported these technologies. It should, remarkably be noted that today, both Japan and South Korea have better economies in the world owing to their ability to drive such energy policies despite the challenges associated with their development (Woo *et al*, 2020).

The model employed by both Japan and South Korea to develop their nuclear power plant denotes an autocratic regime where public participation and transparency are limited. This approach would not be fruitful in the South African context owing to the participation by various NGOs and diverse general public perceptions. Coupled with illiteracy in the public, the model could require a total transformation to transparency. The transformation can be done together with the exploitation of the objective media with the perception to deduce positive solutions to nuclear power technological developments (Zhou & Dai, 2020).

The role played by the media could include the promotion of debates in the public sphere and the attainment of experts in a form of dialogue through various social media platforms. The author is of the opinion that the current objections towards nuclear energy development in South Africa both in a form of public inputs or through court cases are based in negating the acquisition of NPPs rather than a common goal to ascertain nuclear safety. This can be observed from the cases by Earth Life Africa and

others who advocate primarily for the suspension of nuclear energy rather than addressing such aspects that may result in harm to the environment and its inhabitants (Zhou & Dai, 2020).

The challenges facing the deployment of nuclear technologies in South Africa have already been faced by other countries. The experiences gained by countries like Russia, China and Japan who managed to overcome public resistance towards nuclear energy can be a learning platform for South Africa. Most prominent, is a need to develop a national policy driven by the national development plan, which does not lose its credibility when political officers change office (Woo *et al*, 2020).

In Japan, where the change in political officers did not affect the deployment of nuclear energy, the national strategy was built with the motor that sees nuclear energy as a primary economic driver for the development of Japan. South Africa, with a high rate of unemployment and loadshedding ravaging the country, the use of nuclear energy to create bases for economic development is a factor that could signal a new direction in the country's development (Woo *et al*, 2020).

However, the notion of nuclear powerhouse in South Africa could spark concerns from the international community especially if a closed loop fuel cycle is to be considered. In addition, internal political organisations may contest such a move arguing the financial status and readiness of the country to host a significant fleet of nuclear power plants. The contestation could be quenched using SMRs with low capital and short period for development and deployment coupled with the strong motivation to eradicate poverty, improve economic outlook and social wellbeing of South African citizens (Kessides, 2014; Minacca & Locatelli, 2020).

The various contesting organisations focussing on corruption and other aspects that are not critical to the safety of nuclear power plants could rather be responded to through the development of policies that enable the safeguard of state funds. In addition, the creation or use of a possible independent body to oversee and account for the use of such state funds with continuous oversight to ensure that funds are used for intended purposes can be employed.

Although van Wyk (2021) has not discussed the political turmoil owing to various regions with conflicting interests, it is obvious from the list of interested parties that both Western and Asia-Pacific countries with conflicting interests were involved in the pool of stakeholders acquired by Zuma. Zuma's preference of the Russian firms to build NPPs in South Africa may have been attributed to the ANC stakeholder beneficiation claimed by Shivamba (2017).

Therefore, the author concluded that the South African political environment does pose a significant challenge towards the deployment of nuclear power plants. The political challenge is so complex that it incorporates other aspects such as crime, political instability, contestation from various political parties, involvement of courts in case of court cases challenging nuclear energy policies with political motives, political officers with no trust in one another and ultimately, the inability of the government to develop a nuclear energy policy insulated from political manifestations but resilient to all negative forces (Shivamba, 2017; Lim, 2016). Detailed research in the effects of the South African political sphere in nuclear technology deployment could shed light in the nature of political forces and how they inhibit nuclear energy deployment in South Africa.

6.7 Environmental issues

The National Environmental Management Act (NEMA act 47 of 1998), requires that the environment be protected from harm and that if harm does occur, actions to remedy the harm be taken. In the Koeberg's application for LTO, it was concluded that Koeberg's LTO cannot be denied on the bases of environmental consequences since through all annual monitoring activities, Koeberg has no radiological effluent release that compromise the NNR requirements.

In addition, Koeberg's nuclear waste disposal is in line with NNR and the international regulation for nuclear waste management. Furthermore, such nuclear waste management strategies comply with the Vaalputs requirements. The experience gained from Koeberg nuclear waste management can be transferred to the new nuclear power plants that can be deployed in South Africa to ensure compliance with environmental regulations (van Wyk, 2020).

Furthermore, the cooperation with the international community could enable Koeberg staff to share environmental experiences with experts from around the world and the lessons learnt transferred to the new plants. The initially identified sites such as Thyspunt, could undergo rigorous evaluations to determine whether environmental management strategies implemented at Koeberg could be improved and adapted to site specific conditions (NOU, 2022).

Court cases associated with environmental concerns such as Earth Life Africa do pose a challenge to the deployment of nuclear technology (IAEA, 2017). The challenge is born from the intentions of the challenging organisations and the subsequent rulings. The researcher then questions whether the court determinations should be of a halting nature or to serve as a safeguard where aspects not covered in the feasibility studies should be taken into consideration and corrective measures be employed. However, the current environmentalists' cases did not bring about proposals on how to remedy their findings or enable the respondent to find solutions to the challenges while allowing the project to continue. In contrary, the Chinese and Russian authorities succeeded in deploying nuclear technologies through rigorous consultation and inclusion of aspects raised by the communities in the project scope (Woo *et al*, 2020).

Through the South Africa's environmental management strategies, it can be concluded that the development of nuclear power plants in South Africa cannot be halted by lack of sufficient nuclear material management strategies but by organisations that seem to be lacking an incentive in the prosperity of nuclear technology development combined with the court's strategy which did not enable a cost benefit analysis to determine the consequences of the decision in the long term (Loadshedding is one of the consequences) (NOU, 2022). Therefore, through experience gained at Koeberg and interaction with the international nuclear operators and regulators, South Africa is better positioned to deploy new nuclear power technologies.

Not neglecting the importance of such reviews, stringent measures must be put in place to ensure that the appeal and review processes are expedited and reasonable timelines are adhered to together with the legislative and governing authorities (van Wyk, 2020). This will ensure that utilities are able to develop assets at minimal cost while conjuring all perceived safety aspects into a more diverse conglomerate solution. This in turn will facilitate the planning, design, licensing and construction of nuclear power plant facilities in the country.

6.8 Public perspective, participation and acceptance

The Japanese approach towards public acceptance of nuclear technologies sheds light on how governments can influence the deployment of nuclear technologies. First, the communication between government and the public is crucial. The Japanese government used its officials to communicate positive information in relation to nuclear energy. Japan put economic development and saving the environment as the primary objectives for the deployment of nuclear energy. This approach, when coupled with the communications strategies as envisaged by Zhou & Dai (2020) (scientific education, station visiting, national strategy and community building) could play a significant role in South Africa.

One of the advantages that South Africa has is an independent media, which, when used through carefully planned programmes could facilitate public academic stratification. This stratification could enable a smooth flow of information from both national and international experts directly to the public. When experts who worked at Koeberg are brought to the community, they could ease the negative safety perception of nuclear energy through discussions covering advanced nuclear power plant

protection features. In addition, the experts could explain in non-technical terms how Koeberg stabilises the network and therefore contribute to the economy of the country (Woo *et al*, 2020).

Another important factor that could sway the public perception in the positive direction could be the sharing of the best practices acknowledged by SALTO missions in one of South Africa's nuclear power plants. If the sharing of the findings could be discussed in the South African radio and television stations together with nuclear energy as a "National economic enabling strategy", the public participation could be significant and various aspects that currently hinder the deployment uncovered and dealt with without having to face court cases (Zhou & Dai, 2020; Ahmed *et al*, 2020).

Van Wyk (2021) claimed that the South African public has no trust in the current government noting that the lack of trust emanates from the information released to the public by the government in relation to its nuclear ambitions. Although South Africans could trust the nuclear operator, the government corruption scandals could be the leading factors towards the challenge of deploying nuclear technologies (Gu *et al*, 2020). The operator could do well in maintaining the notion of nuclear safety to the public but trust in the government to effectively see the success of the nuclear power plants projects could be minute owing to various tender mismanagement associated with the findings in the state capture making government's ability to execute mega projects questionable (van Wyk, 2021; Woo *et al*, 2020).

The vast consensus in the level of illiteracy or discrepancy in knowledge levels in the country presupposes another dimension affecting the public participation process and consequently the public acceptance of nuclear technologies in South Africa. The author then questions whether the approach to introduce nuclear energy concepts at high school level could be adequate to enable the South African community to understand the technical aspects of nuclear technologies. Another dimension would then be for the government to educate the country in aspects that have a direct impact in the usage of energy resources of the country so that the public can understand why certain policies are made and provide meaningful contribution towards the implementation of the policies (Gu *et al*, 2020).

The educational mechanism could then take into account all energy resources available in South Africa including its pros and cons, the available technologies with their maturity levels, and the educational strata of a particular group. This exercise could seem to be costly, however, with the current media platforms the dissemination of such information to both young and adult South Africans could be much cheaper than thought (van Wyk, 2017).

The proposed nuclear sites in Bantamsklip, southeast of Pearly Beach and Thyspunt near Cape St Francis in Eastern Cape exhibit significant differences from those studied in China in that ethnicity, chieftaincy and population dynamics were not taken into consideration for the Chinese study (Zhou & Dai, 2020).

Despite the setbacks identified, Zhou & Dai (2020)'s studies suggest that the strategic communications constructs can manifest themselves as valuable tools towards the dissemination of nuclear power information when contextually applied to the right audience. Scientific education could play a significant role to disseminate information to those with little knowledge of nuclear power technologies with applications relatively relevant in the South African context when Cape Town is considered due to the existence of Koeberg NPP and the communities in the surroundings meeting the conditions entailed in Zhou & Dai (2020)'s study such as age, income levels, education levels and gender.

The risk perception associated with nuclear technologies can be improved through proper communication in technological developments and the safety aspects put in place worldwide and in consultation with the IAEA. In addition, various international organisations whose participation in nuclear technology deployment contributes towards public acceptance can be considered. Aspects such as physical security, deployment of the South African National Defence Force (SANDF) to protect nuclear power plants, integration of SALTO missions in the public domain, effective communications

channels, rigorous training and participation of the local communities in the skills development programmes, frequent access to nuclear facilities by the public are likely to project a positive image in relation to risk perception of nuclear technology.

The stigma associated with radio-phobia may be attributed to the basic nature of humans since even educated people could disapprove nuclear development projects based in tribal motion, therefore ascertaining that the fear of nuclear energy does not necessarily have to be factual but based in the experiences of the said tribe or in general, the perceptions of a particular tribe (Hayes, 2022). Hayes (2022) gives the analogy of the political tolerance in certain tribes, which is more lenient towards the tribe than the potential of other political parties.

The author then concludes that public perspective in South Africa in relation to nuclear energy deployment is more negative and that this negativity is as a result of a weak drive from the government to align the public with the nuclear energy policy.

In addition, the author is of the opinion that public participation is hindered by aspects such as academic stratification, economic challenges and poor communication strategies in relation to nuclear energy with the lower academic strata having little or no knowledge of nuclear energy and related technologies (Zhou & Dai, 2020). Lastly, public acceptance of nuclear energy technologies in South Africa necessitates public education on nuclear energy resources followed by a mass mobilization to support the national strategy coupled with a rigorous policy that could see coherence in all government sectors such as the legislature, executive and the judiciary.

6.9 Key points

South Africa has a vast amount of uranium resources that could sustain the country's electricity needs for approximately 750 years without reprocessing and 1500 years when reprocessing is taken into consideration. With experience in mining, enrichment and reprocessing, South Africa have the necessary skills and Knowledge to introduce new NPPs in the grid. Challenges associated with corruption and proliferation may be addressed using controlled entities such as the NNR, NECSA, IAEA and others, vested with the authority and necessary control measures.

Policy and regulatory framework have a potential to hinder the deployment of new NPPs. To avert this challenge, the country needs to have a common goal based in the development of a national energy policy. The policy should take into consideration the South African community (Public, judiciary, NPP operators and the political structures and institutions) and international role players and demonstrate strong measures towards non-proliferation.

Economic and human resources challenges are somehow intertwined. It is therefore, imperative that the National Financial Planning takes into account the economic prospects that can be brought about by nuclear technology. In addition, the planning should ensure that financial resources are available to incentivize and promote staff and skills retention. Furthermore, nuclear energy related activities can be outsourced with conditions to ensure that local people gain adequate skills to develop and operate NPPs.

The deployment of new NPPs can be staggered through the use of SMRs to allow for economic viability as while meeting the current demand. The fact that SMRs can be deployed in modules and as needed and afforded, it makes it an attractive option which can enable South Africa to eventually have a nuclear fleet that can sustain South Africa's economy and electricity demand.

The most interesting aspect is the public motivation that can be gained when nuclear energy is promoted as a country's policy aimed at eradicating poverty and bolster economic growth. Japan and China have done remarkably well in using this strategy. The author is also of the opinion that a patriotic policy that can retain skilled engineers is necessary. The policy can be built as a component of the nuclear energy policy but with emphases in the future of our country and future generations. For an example, a communication strategy that could state "Our nuclear, our economy and our development is our responsibility".

The political climate of the country significantly determines the success of new NPP deployment. The various political regimes in South Africa (from 1994 to 2023), had different approaches towards nuclear energy. Some regimes such as the Zuma administration had strong ambitions in nuclear energy while other regimes like the Ramaphosa administration inclined towards renewable energy. The author concludes that the downfall of South Africa's regime changes is that there seem to be no drive to materialize the policies initiated by other administrations. Lessons from Japan could shed light in overcoming this challenge.

The state needs to develop communications strategies that will engage the public meaningfully. The strategies should address public perception, public participation, environmental conservation as well as media diversification and control. The South African media can be conditioned to project the possible gains that can be derived from nuclear energy, advocate for poverty alleviation and promotion of research and development in various aspects that nuclear can contribute.

The essence of chapter 5 is that the state needs to develop a rigorous nuclear energy policy. This policy needs to take into consideration nuclear resources in the country. In addition, the policy must create a patriotic sentiment among South Africans through the implementation of various communications strategies as discussed by Woo et al (2020), Zhou & Dai, 2020 and Valentine & Sovacool (2010). Again, the policy should be insulated from political regimes or cabinet officials. Furthermore, the policy should enable the judiciary to make decisions that promote the deployment of nuclear energy without compromising safety and environmental consequences. The judiciary can be empowered by the legislature to enable role players to seek reasonable solutions to nuclear energy challenges.

7. Conclusion

This dissertation investigated the challenges facing the development of new nuclear facilities in South Africa. The research on how Russia, China and Japan managed to develop a significant fleet of nuclear facilities was analysed. Natural and human resources, skills availability and knowledge management including LTO and SALTO missions together with the contribution of the international community in the operation of nuclear facilities in general and in South Africa (Koeberg and SAFARI - 1 NPPs) were considered. Furthermore, the impact of public participation, public perspective and acceptance of nuclear technology as well as politics, policy and regulatory framework were investigated and comparisons drawn from international level and in the South African context.

South Africa's declared uranium resources are found in the Witwatersrand, Randfontein, and Karoo and Namakwa regions. According to (DEMR, 2022), these resources can sustain the SA energy sector needs for the next 750 years at least. With the application of reprocessing strategies such as AFCI and controlled exports, the country's resources can last up to 1500 years and the issues associated with DGRs could be reduced as well. Therefore, SA has enough uranium resources to meet its long-term energy needs.

The research presented a number of nuclear energy technologies that South Africa can explore for deployment. To a greater extent, SMRs seem to be the most economically viable technology to follow given their modularity, simplicity, cost effectiveness and shorter deployment time. Therefore, it could be beneficial for South Africa to consider this technology especially when considering the country's economic situation. Again, the fact that a staggered approach can be used to eventually achieve the size of the desired nuclear power plant with the required capacity in the long run makes this technology more attractive.

South Africa has an effective human resources strategy characterised by competitive skills, knowledge management and adequate human resources with a possibility to outsource activities, employ experts, train staff and collaborate with the international community. This strategy is effective for a safe execution of new nuclear plant designs, construction and safe operation of NPPs as observed in the Indian approach and concluded through PSRs and Salto missions held for SAFARI – 1 and KNPPs LTOs (Ramana, 2009; NOU, 2022; Woo *et al*, 2020).

The SA political climate challenges the deployment of new nuclear technology policies by providing a platform for the public's lack of trust to flourish due to corruption, maladministration, poor performance and lack of accountability in government cabinets resulting in public protests and court challenges that lead to project delays and cancellation (Shivamba, 2017; van Wyk, 2013; De Boer *et al*, 2020).

Again, public perspective, participation and acceptance of nuclear technologies is categorised by a wide gap in the academic strata, with many people having little knowledge of nuclear energy resulting in the lack of informed decision making in aspects related to nuclear energy. This lack of nuclear energy knowledge could be cabbed by community building, station visiting, national strategy and scientific education combined with an effective public participation model (Shivamba, 2017; Woo *et al*, 2020; Zhou & Dai, 2020).

The volatility of the South African and international economies together with the environmental issues and regulatory framework contribute towards the challenges facing the deployment of new nuclear power plants in South Africa. However, the author is of the opinion that these challenges are not significant citing that funding is allocated to other sources of energy such as wind and solar therefore concluding that economic viability is not a deciding factor leading to the delay or cancellation of nuclear energy projects in South Africa.

The author concludes that politics and public acceptance are the main obstacles hindering the deployment of nuclear energy facilities in SA and further proposes detailed research in the effects of changing political officers in nuclear energy technology deployment. In addition, the author proposes a

development of a rigorous nuclear energy policy totally insulated from the political aspects of the country as applied in Japan (Valentine & Sovacool, 2010) such that nuclear energy projects initiated by one official could be completed by the newly appointed official in cases where officials swap positions. Furthermore, the policy should cover the instruments of communication such as ‘nuclear energy strategy’ designed to sustain economic development, induce a culture of nuclear energy acceptance and, in the long-term bridge the gap in the academic strata therefore facilitating knowledge acquisition for the betterment of the South African community.

The author acknowledges the following limitations to the document:

- Public perception has not been evaluated through questionnaires in the South African context
- Influence of South African academic stratification was not investigated
- Consultation with nuclear energy experts was not conducted
- Ethnicity and tribalism were not considered

8. References

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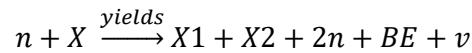
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9. Appendices

Appendix A: Nuclear fission

Worldwide, nuclear energy is extracted through nuclear fission. This is the process whereby a neutron is used to bombard a nucleus therefore releasing binding energy, two daughter nuclei, two neutrons and a neutrino. These neutrons are thermalized and further undergo successive fission reactions. The total number of successful fission reactions determine the total amount of energy released for a specific mass of nuclear material. The difference between the initial mass and the final mass of the fission process, called mass defect, is associated with the energy produced when one nucleus collides with a neutron (Aschman, 2017).

The binding energy, given by $\Delta E = \Delta mc^2$ released in one fission is estimated to be 200MeV and the aggregate sum can give the amount of energy released when more than one nucleus collide with neutrons.



In the above equation, n is the neutron, X is a fissile nucleus, BE is the binding energy and ν is a neutrino. During a nuclear fission, typically two or three neutrons are released. These neutrons are released as fast neutrons with energies greater than 1MeV and a life span of 10ms and get thermalized through interaction with the cooling medium to reach thermal velocities (2200m/s) and further induce fission reactions (Aschman, 2017).

The total power generated through a nuclear reaction for a given mass of fissile nuclei can be determined by calculating the total number of fissile nuclei with their fission cross sections, the number of thermal neutrons capable of inducing fission in the case of thermal reactors, and fast neutrons in the case of fast breeder reactors (Aschman, 2017).

Fissile materials are the type of nuclear elements that are ready to undergo nuclear fission when bombarded with a neutron. This includes isotopes of uranium and plutonium (^{233}U , ^{235}U , ^{239}Pu and ^{241}Pu). Some nuclear elements, however, may not be readily available to undergo nuclear fission but can be transmuted to other material that can undergo fission like thorium ^{232}Th and uranium ^{238}U , which are considered fertile (Aschman, 2017).

Uranium is obtained through mining extraction in nature. It is available in soil, rocks, plants, animals, and human beings and has three naturally occurring isotopes. These are ^{238}U which constitutes 99% with a half-life of about 4.5 billion years, ^{235}U which constitutes 0.7% with a half-life of about 700 million years and ^{234}U which forms 0.01% of the total uranium with about 25000 years half-life. Once processed, uranium constitutes of 3-5% of ^{235}U with an atomic number of 92 amu and its radioactivity increases when used in power generation in (USA DoE, 2001).

Due to its high fission cross section, about 590 barns, ^{235}U is mostly preferred for power generation both in military and civil applications. ^{235}U fission is mostly effective through thermal neutrons, which have lower velocities typically 2200m/s and an energy of 0.0025eV as shown in *Figure 13* (Aschman, 2017).

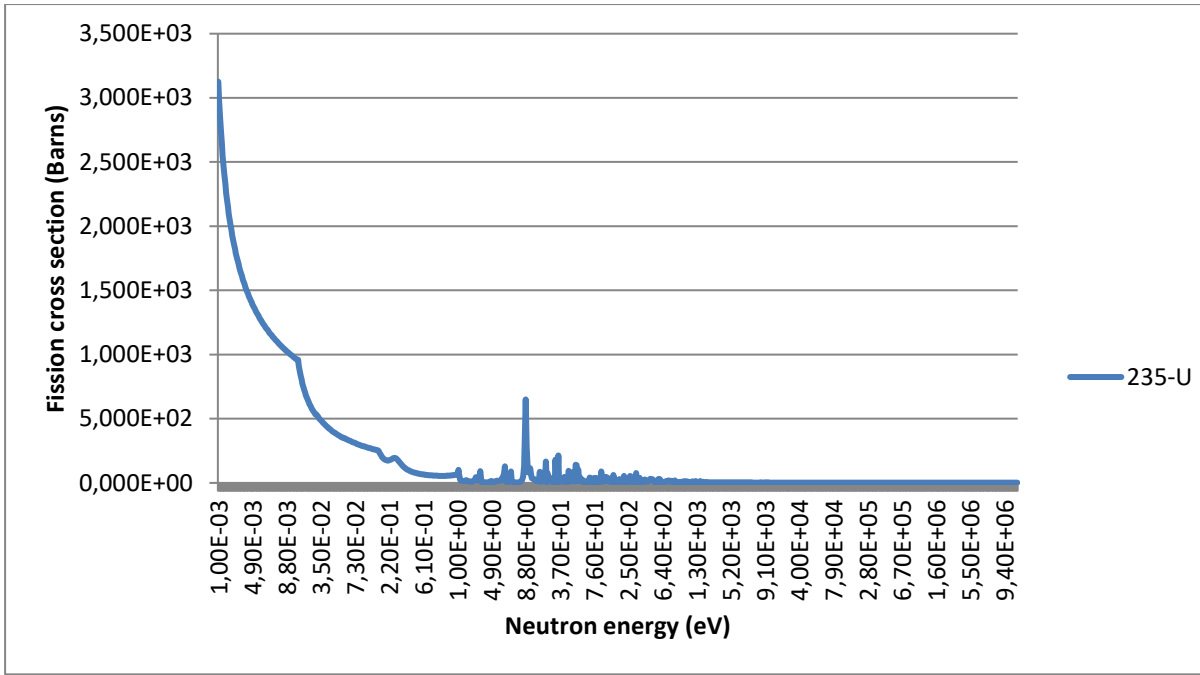


Figure 13: Fission cross section of ^{235}U (Adapted from Young et al, 2006)

^{238}U has a high absorption cross section for fast neutrons and high energy spectrums at the range of 10-100MeV. Although this isotope is largely available in the U^{3}O^{8} solution, its use is limited by the difficulties faced with the control of fast neutrons in the earlier generations of Pressurized Water Reactors (PWRs). Fast breeder reactors (Generation IV) however, operate within the ranges of fast neutrons therefore bringing into context the use of ^{238}U in nuclear power generation.

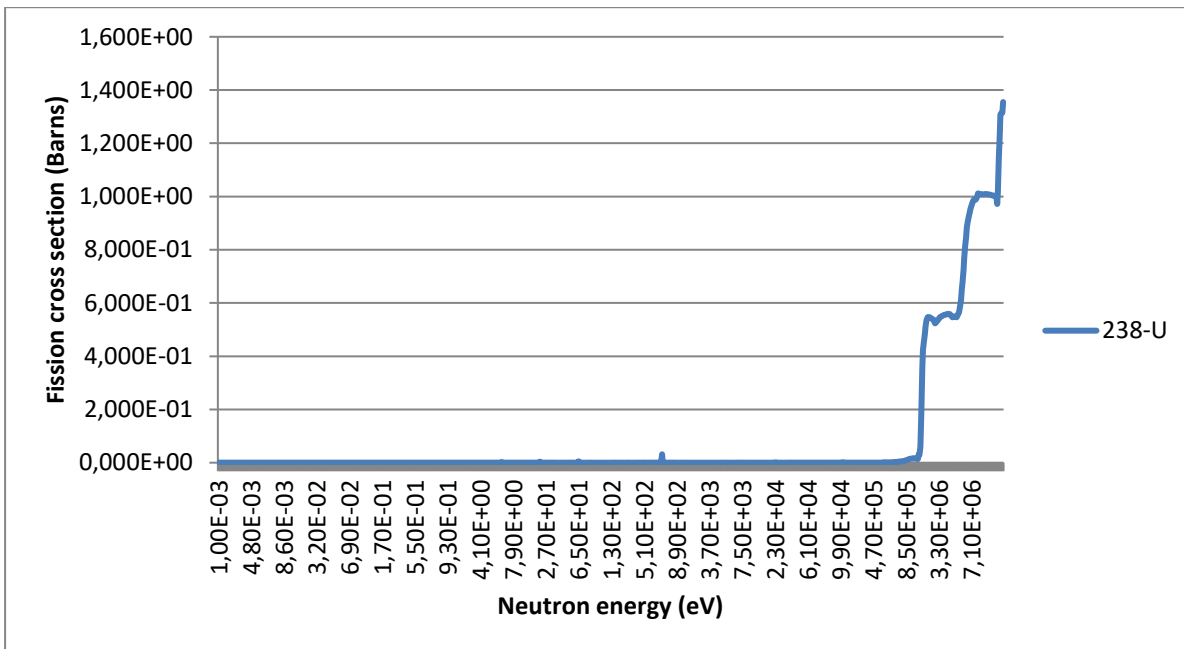


Figure 14: Fission cross section of ^{238}U , (Adapted from Young et al, 2006)

From Figure 14, the fission cross section of ^{238}U is higher in the fast neutron region between 1 and 100MeV. In this region, ^{238}U will capture a neutron and transmute to ^{239}U or ^{239}Np . The fission cross section however, decreases with the energies in the ranges below 100eV. The advantage of high energy fission cross section

is that neutrons do not need to be thermalized since they are induced with the prompt neutron energies and velocities (Nusbaum, 2011). The challenge with fast neutron induced fission is controlling the startup of the reactor as well as ramping the power since fast neutrons do not provide enough time to control fission. At thermal energies, ^{238}U has very low fission cross section, which makes it difficult to use it as fuel in thermal neutron reactors or pressurized water reactors (PWRs) (Nusbaum, 2011).

Since Spent Nuclear Fuel (SNF) constitutes 96% of ^{238}U , reprocessing with an objective of using ^{238}U as fuel in PWRs is not recommended since it has a low fission cross section for thermal neutrons. However, ^{238}U transmutes into ^{241}Pu , which is fissile and usable in PWRs. In addition, reprocessing enables the extraction of ^{238}U from SNF and make it available for Fast Breeder Reactors (FBRs) which operate well with fast neutrons (Nussbaum, 2011). *Figure 16* shows the formation of plutonium.

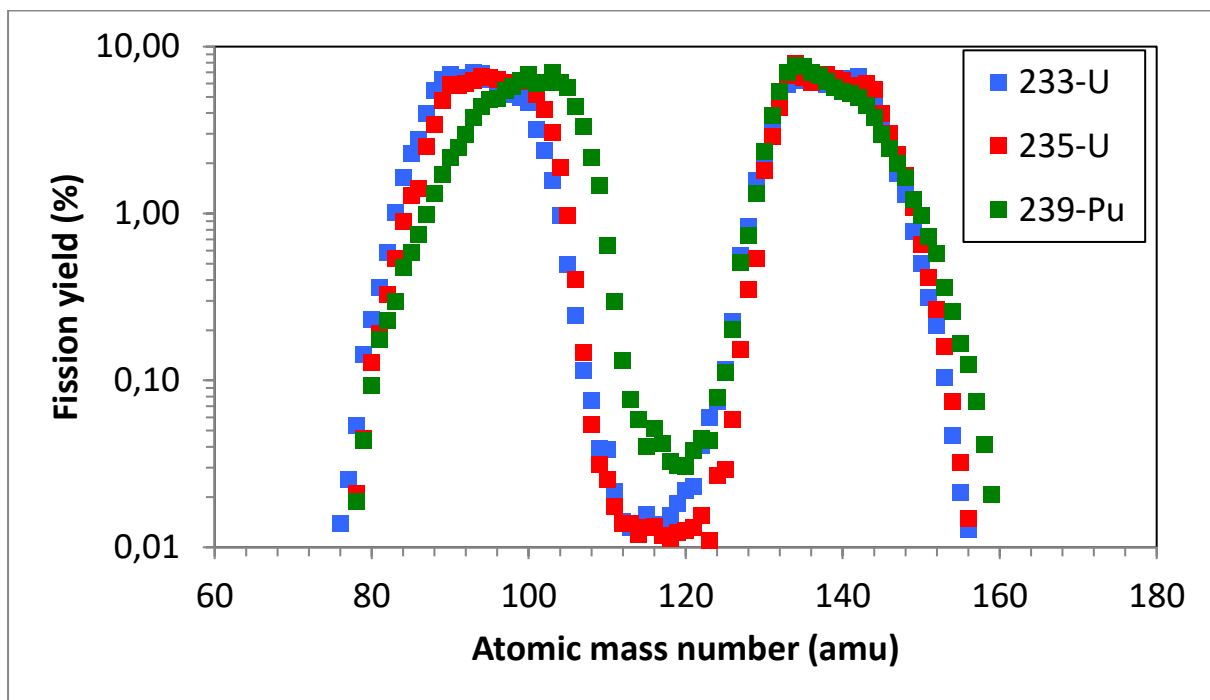


Figure 15: ^{235}U , ^{233}U and ^{239}Pu fission products (Katakura, 2011)

The fission products can be derived from the mass yield curve for the thermal neutron fission for ^{235}U shown in *Figure 15*. The graph shows that ^{235}U will yield fission products with atomic masses between 70 and 120 amu. These are the light nuclei such as Kr with maximum fission yield of about 800%. In addition, ^{235}U has a high yield cross section at mass numbers between 120 and 150. These are heavy nuclides such as Cs and Tc also with a maximum yield of about 800% (Katakura, 2011).

Among the set of the fission products released, some are stable while some decay within seconds, minutes, hours, days or years. Some fission products like plutonium add integrity to the fuel while others like xenon reduce the number of thermal neutrons available for fission therefore affecting the sustainability of the chain reaction (Katakura, 2011).

Formation of Plutonium through neutron absorption

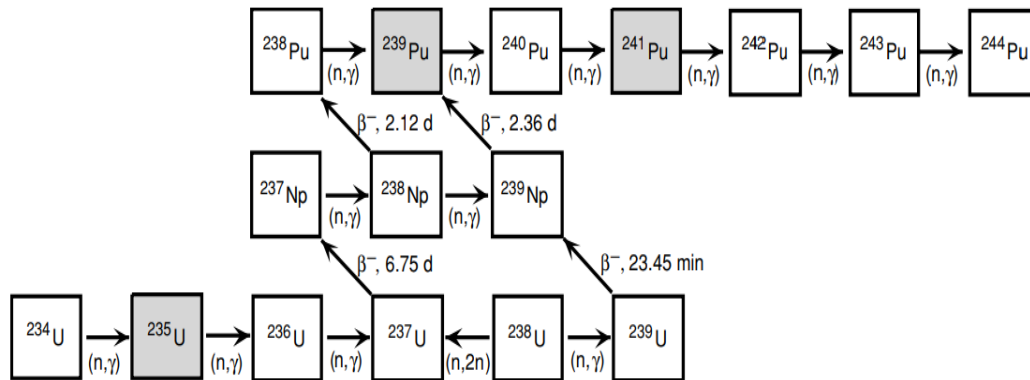


Figure 16: Formation of plutonium through neutron absorption (Clark et al, n.d))

According to Leinetti (2015), thorium is a radioactive material that is abundantly (about 0.0006%) found in nature but can also be produced synthetically in the laboratory in a form of ^{232}Th . The three known isotopes of thorium are ^{232}Th , ^{230}Th and ^{228}Th (USA DoE, 2017). Since thorium cannot generate energy directly when bombarded with a neutron, it is allowed to transmute into ^{233}U which is fissile. ^{233}U is then recovered from the irradiated thorium after cooling off through chemical separation in a nuclear reprocessing plant. Like plutonium, ^{233}U can be used for both weapons production and nuclear power generation in the civil space (Nusbaum, 2011).

Appendix B: Reprocessing of spent nuclear fuel

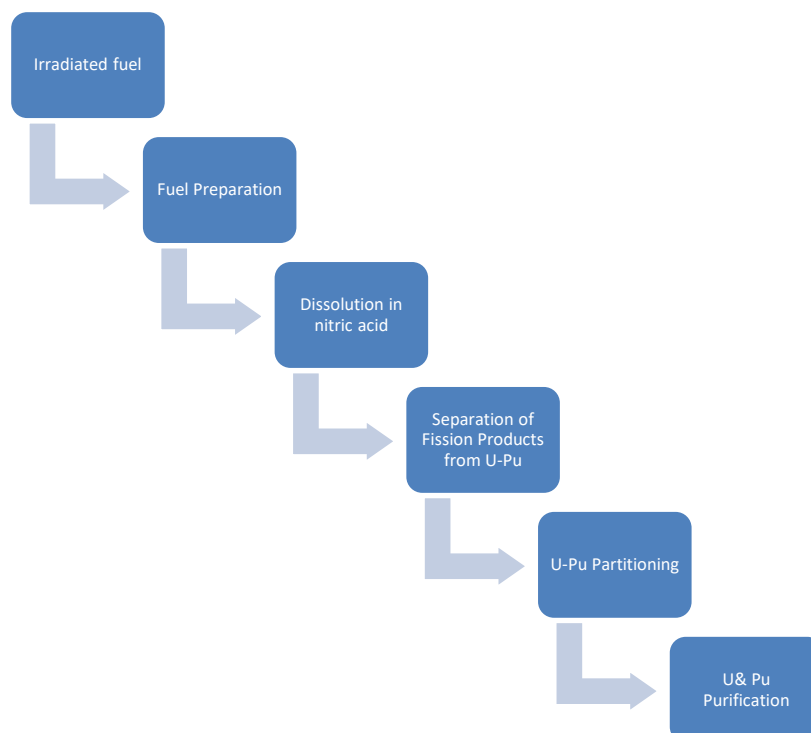


Figure 17: SNF cooling (USA DoE, 1993)

Before reprocessing begins, spent nuclear fuel must be separated from the cladding, bonding agents, mechanical supports, spacers, coolant flow directors, moderators, and fissionable – atom diluents to reduce the heat flux of the spent nuclear fuel. For most reprocessing plants, the separation is done through mechanical techniques although older techniques such as sawing, extrusion, rolling, milling and hydraulic expansion also exist (USA DoE, 1993).

After the fuel has been separated from the unnecessary material as stated above, the nuclear spent fuel is then deposited in the batch dissolver as classified according to the separation method or shape (Geometry for criticality) of vessel. A container designed to be operated and maintained remotely that is corrosion resistant, critically safe, easily loaded with fuel and dissolvent, readily accessible for removal of cladding and gaseous waste and which must operate within stringent ambient conditions as well is used (USA DoE, 1993).

Spent Nuclear Fuel dissolution in nitric acid

Jubin (2009) claims that the conversion of solid fuel into an aqueous chemical suitable for spent nuclear fuel separation steps is the primary purpose of either the dissolution process, which can be categorised as *batch*, or *continuous process*. In the batch process, the sheared fuel is placed in a perforated metal basket immersed into hot nitric acid to dissolve the spent nuclear fuel, leaving only the hulls at the end of the dissolution process and insoluble fuel that can be treated and disposed of (Jubin, 2009).

Another method is the *continuous process* where uranium, plutonium, minor actinides, and fission products are reacted with nitric acid for solubility, which will complete the separation of the fuel from the cladding and other supporting materials. To achieve the desired separation, the properties of the extractant must control both the organic and aqueous distribution coefficients, which are a function of temperature. The flow rates must be varied to be such that criticality is not reached by compromising the buckling of the nuclear fuel through material fluctuations (Jubin, n.d).

Dissolution process

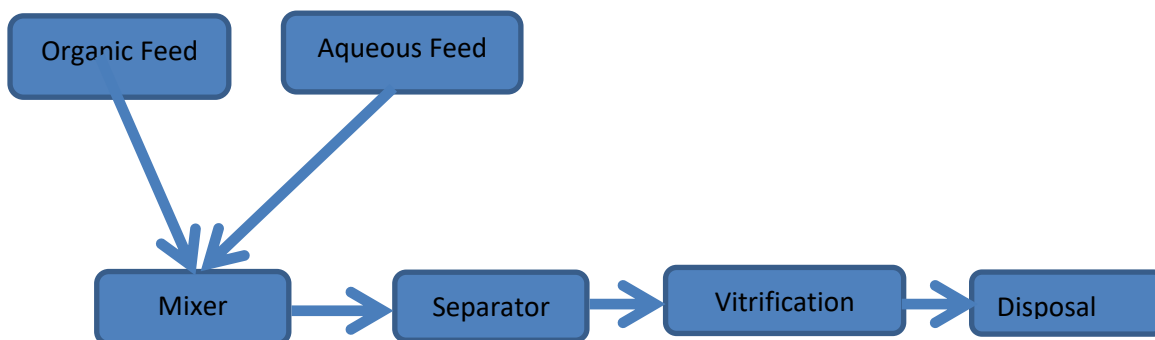


Figure 18: Dissolution process (Jubin, n.d)

Separation of uranium from plutonium

Once the extraction of uranium is complete, the UO_3 obtained goes through a reduction stage to UO_2 where reduction using hydrogen in a counter – current process is done. Once this stage is complete, UO_2 goes through two different technologies where UO_2 is converted to UF_4 through a wet process in which UO_2 is allowed to interact with aqueous hydrofluoric acid to produce UF_4 . UO_2 is allowed to react with gaseous Hydro-fluoride (HF) to produce UF_4 and smaller quantities of HF that can be recovered in a form of dilute hydro-fluoride (DHF).

The UF_4 obtained from the hydrofluorination stage is then taken through the fluorination stage where it is allowed to react with fluorine to form UF_6 through a fluidized bed reactor with an inert bed in the separator (Figure 18). In this stage, small residual quantities of UF_6 , F_2 and HF are released as by products and recovered using potassium hydroxide and they are precipitated as CaF which is non-radioactive and can be recycled within the plant (IAEA).

Plutonium purification follows the same process as that for uranium purification as above but in a different oxidation state (IV and V). The outcome of the plutonium purification process is PuO_2 , which can then be used for nuclear power generation for civil applications.

Vitrification

Vitrification, in nuclear engineering, is defined as the process by which liquid spent nuclear fuel is solidified and made immobile by storing it in glass or ceramic material. First, the liquid is evaporated and then denitrated or calcinated to form a calcined product which takes a granular or solid form. The granular calcines are then exposed to additives and melted to form a glass or ceramic product and then stored temporarily while awaiting DGR availability (USA DoE, 2012).

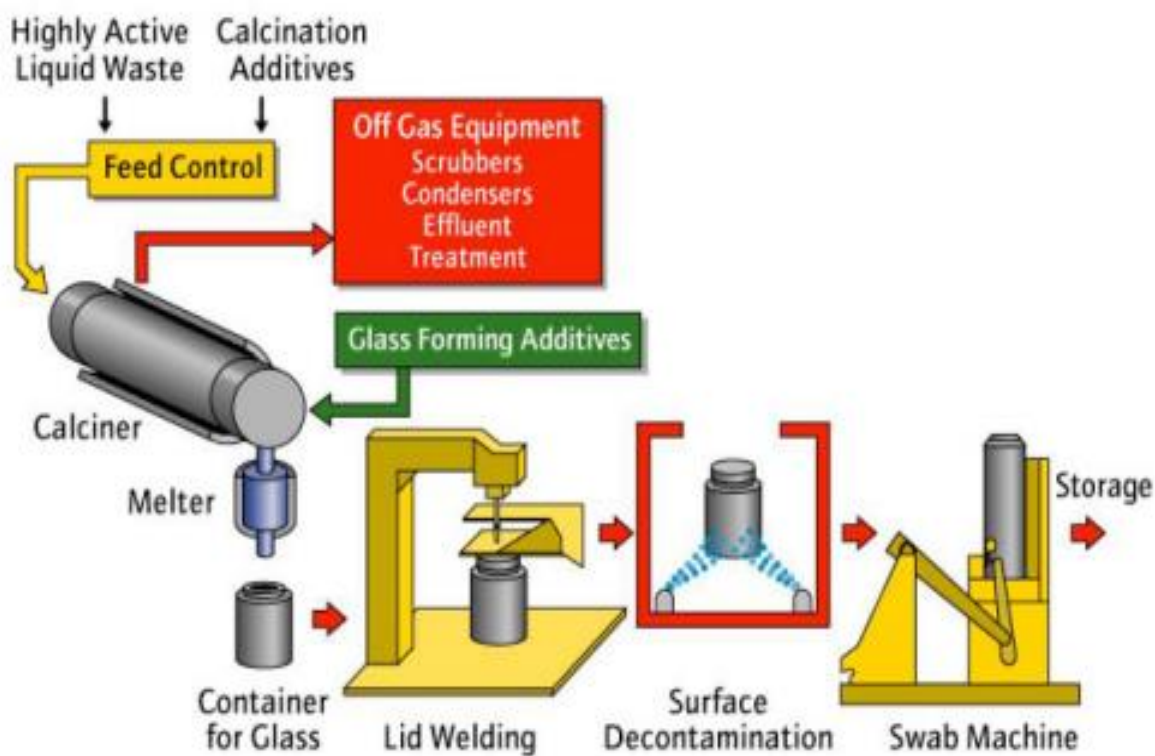


Figure 19: High level waste vitrification process (Harrison, 2014)

The spent nuclear fuel can also be vitrified by taking it through an absorption process where high temperature (1000°C) treatment will take place to form a ceramic material (USA DoE, 2012). In the Vitrification process, off gas treatment systems shown in red in Figure 19 which contain some carryover of fine products and particulates must trap all radioactive carryover and ensure that the release of gases to the environment is within acceptable limits (USA DoE, 2012, Harrison, 2013).

Modern vitrification facilities encompass a vitrification cell, operating aisles and a control room. In the vitrification cell, high activity waste slurry is concentrated by the shield vitrification cell. The

slurry is then mixed with glass formers which are then melted to form borosilicate glass that is poured in the stainless steel canisters that gets sealed and its exterior decontaminated as shown in Figure 19 to facilitate transportation (USA DoE, 2012).

Appendix C: Licensing timelines

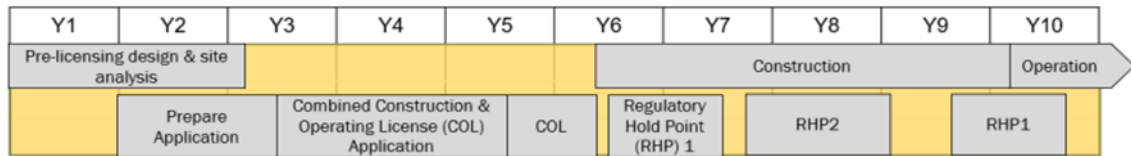


Figure 20: Average licensing timelines (Vondracek et al, 2020)

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