

**Development of a strategic decision-making model for the
South African nuclear sector**

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DECLARATION

I Jabulani Mangena solemn declare that this thesis was my own effort with the exception of support I got from individuals I have mentioned in the acknowledgement section. The utilization of an expert group was a requirement of the Analytical Hierarchy Process aspect of the model.

PREFACE

I am fascinated by how, when, why and which countries made strategic decisions to exploit and commercialise their natural resources. The fascination more is especially by those nations that do not have uranium natural resources but have been successful with their strategic objectives of localising and exporting nuclear power plant technologies. In the main, my involvement with the South African (SA) nuclear industry since 1996 and my desire to see it grow and contribute to the economic fortunes of the poor inspired me to embark on this PhD research. I initially got involved with the South African nuclear sector through the then Atomic Energy Corporation which was later renamed the South African Nuclear Energy Corporation (NECSA). NECSA, which was previously the South African Atomic Energy Board (AEB), has a colourful history that dates back to the years of its involvement in the South African nuclear warheads and the USA's Manhattan project. In the latter years, I enrolled for a Master's in Project Management at the University of Pretoria where my research there was entitled "Identifying resources required for South African nuclear new build" at the time when the country's electricity utility was considering increasing the PWR generating capacity. In 2005, I resigned from NECSA and joined the SA Pebble Bed Modular Reactor Company firstly as a contract worker. I was latter converted to a permanent employee having compiled their strategic document which was entitled "PBMR Localization Strategy." At that time, I was the PBMR Localization Manager and had an opportunity to visit S Korean nuclear supply chain entities such as Doosan that was one of foreign entities for consideration to design and manufacture the PBMR plant NSSS SSCs including the reactor vessel. In 2009, I compiled the PBMR Competitive Supplier Development Plan (CSDP) document, which focused on the localization and industrialization opportunities. I need to mention that in the aforementioned document I utilised a similar nuclear facilities life cycle approach similar to the one used in this research. I presented the aforementioned CSDP together with PBMR CEO at the SA's Department of Public Enterprises under which the PBMR Company was as a State-Owned Entity. When the PBMR closed its doors, I had a stint with the Nuclear Industry Association of South Africa (NIASA). The NIASA CEO was tremendous in supporting and commenting on my writings. At the time NIASA was fixated in preparing the nuclear industry for the Integrated Resource Plan stipulated 10 000 MW nuclear new build which was code-named nuclear-1 by the

SA electricity utility Eskom. In preparation for the new-nuclear build, the NIASA CEO and its Board tasked me to undertake a nuclear industry gap analysis. Again, I utilised the same value chain I had used when I was undertaking the PBMR localization study and the difference this time around was that I also used the SWOT analysis for the identification of the local industry gaps. A year later after submitting my NIASA studies I joined the SA Department of Public Enterprises as an Energy Director and got involved in the SA 2010 Integrated Resource Plan Department of Energy 9600MW nuclear new build working groups. I marvelled at the R&D, design engineering, manufacturing, operation and maintenance and disposal & waste management NPP and Nuclear Fuel Cycle infrastructure and competencies in the vendor countries namely Japan, France, USA, South Korea, China and Russia. As from mid-2014, I was back at NECSA managing the only ASME III “N” Stamp entity in Africa by then, hoping that it was going to blossom through the 9600MW NPP programme. Coinciding with the SA government administration changeover was the court ruling against the nuclear build implementation and the revised SA IRP energy mix, which prioritised renewables. The 9600 MW fizzled because of these factors. In essence, my participation but not witnessing the realisation SA Eskom’s nuclear-1, SA PBMR and SA Department of Energy driven 9600 MW nuclear power plant localization strategic objectives gave me an urge to develop a strategic decision-making framework or model for the SA nuclear sector.

ABSTRACT

The main objective of this research study was to develop a strategic decision-making model for the South African (SA) nuclear sector in response to lack of expansion. Since 1994, this lack of growth was marked by two failures of implementing pressurised water reactor (PWR) new builds and the third was the abandonment of the pebble bed modular reactor (PBMR) programme. Underlying and exacerbating the aforementioned stagnation are determined nuclear opponents who are vouching for variable renewables. The opponents buttress their opposition by highlighting nuclear new build cost overruns and the failure of the PBMR programme. Consequently, two specific research objectives were set and met. One was to demonstrate the reasoning behind having a model that is a combination of popular decision-making methods and SA's historical, present and possible future nuclear facilities. The other was to demonstrate how the model can be employed to identify, collect, validate, archive, retrieve and operationalise nuclear programmes factors for strategic decision-making purposes. The iterative and integrative research design resulted in a novel generic hybrid decision-making model. The model entails the Analytical Hierarchy Process (AHP), SWOT (strengths, weaknesses, opportunities, threats), PESTEL (political, economic, social, technological, environmental, legal), Life Cycle Assessment (LCA) and ten historical, present and possible future SA nuclear facilities (pressurised water reactor, small modular reactor, research reactor, uranium production, conversion, enrichment, fuel fabrication, reprocessing and recycling, spent fuel storage, spent fuel disposal). These model features demarcated the focus areas for literature review and data collection. By using the novel model's data collecting and documenting instrument, data retrieving and case study instrument, validating secondary data as it was archived in the repository and LCA phases factor quantities, having a purposively and conveniently selected nuclear sector expert team participating in factor pairwise comparisons and using the AHP Expert Choice software computed factor priority weights and consistency ratios (CRs), it was established in descending order that public acceptance, private funding and political system threats factors were three of the twenty-one threats factors with the highest potential to impede the possible resumption of the SA PBMR programme. The validity of the participants' pairwise comparison judgements was confirmed by the Consistency Ratios that were mostly <0.10 although it was also established that other similar study surveys accepted a measure <0.20 . It

was also found out that respectively, the three threats factors with highest potential to impede resonated profoundly with the informants more than likely due to (a) local anti-nuclear groupings successful court interdicts against PWR plant expansions; (b) the fact that towards its closure in 2010, the SA PBMR company failed to sign any off take agreements or to secure private funding; and (c) the fact that the SA energy debate has been transformed into a political partisan matter just like in other worldwide democracies. The use of public acceptance issues to inform nuclear new build strategic imperatives seems to be a commonality with similar international nuclear programme studies. Essentially, it was established that the model's novel extraction and listing template was also ideal for measuring the degree of how much data was collected from individual research study design demarcated nuclear facilities areas. For future studies, it is proposed that the conceptual model be used to e.g., appraise the SA energy mix technologies and to further evaluate the SA PBMR programme using already extracted and appended strengths, opportunities and weaknesses factors.

Keywords: Archiving, internal and external factors, conceptual model, retrieving, strategic decision-making, threats factors, secondary data, repository, operationalisation

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There is always a need to present one's research at credible conferences. In this regard, I had an opportunity to present the concept of my research at the same conference where my advisor presented on a related topic. For this, I will like to thank organisers of the Rosatom Technical Academy for having arranged for me to present my research concept at the Workshop for Capacity Building for Nuclear Industry: International Cooperation in Nuclear Education. At the same conference, a Professor from Bangladesh enquired about the model validation. The model's data extraction and case study instrument was partly a response to conference attendees' emphasis on the importance to validate the model. I will like to extend my gratitude to the SA Expert Team members who enhanced the validation. Prof Johan Slabber, Stephen Mosinki, Knox Msebenzi, Ayanda Myoli, Jaco van der Merwe and John Maddalena are the experts who participated in the PBMR factors pairwise comparison workshop at Pelindaba. My friend Mduduzi Moyo helped in facilitating the Pelindaba one-day Expert Team workshop. He was always there as a quantitative analysis sounding board and the fact that he also gave advice when I undertook the PBMR and NIASA SA nuclear industry studies.

I would like to thank Dr Ike Ezekoye for having taken time out of his busy nuclear industry schedule to read my dissertation drafts. His many years with the USA Westinghouse and his involvement in the AP 1000 design, training nuclear industry engineers in many countries such as in S Korea, ASME committees and PhD students were perfect ingredients for an inspiring PhD student.

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It is important for me to take note and thank the unwavering support and understanding by my family members namely Nombulelo, Lujulile, Langalibalele and Gabazile. After completing this task, I will be forever thankful.

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Definitions

An item important to safety:	Is an item that is part of a safety group and/or whose malfunction or failure could lead to radiation exposure of site personnel or members of the public (IAEA: NS-G-4.5).
Authorization:	Is the granting by a regulatory body or other governmental body of written permission for an operator to perform specified activities.
A six-day curie:	Is the measurement of the remaining radioactivity of ¹³⁷ Mo six days after it leaves the processing facility (i.e. at the end of processing - EOP). In International System (SI) Units, 1 Ci is equal to 37 Giga Becquerel.
Beneficiation:	The transformation of a mineral (or a combination of minerals) to a higher value product, which can either be consumed locally or exported. The term is used interchangeably with “value-addition”.
Fuel burn-up:	Reactor fuel burn-up is a measure of the energy produced by the fuel. High burn-up fuel generally has been in a reactor longer than low burn-up fuel and is defined as having a burn-up higher than 45,000-megawatt days per metric ton.
Gigafactories	Very large factories in this case referring to e.g. ship yards accommodating the manufacturing and assembling of a series of small modular reactors (SMRs) modules in order to drastically reduce costs during site construction.
Kärnbränslesäkerhet:	Swedish term abbreviated as KBS, which translates into English as “Nuclear Fuel Safety”
Mining Charter:	Broad-Based Socio-Economic Empowerment Charter for the Mining and Mineral Industry developed in terms of section 100 of the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002)

Right holder:	Refers to a holder of a mining right granted in terms of the Mineral and Petroleum Resources Development Act.
Targets classification:	Targets are classified as either LEU, containing less than 20% of ²³⁵ U, or HEU, which contains greater than 20% ²³⁵ U (in some cases greater than 95%).
Sustainable development:	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Acronyms

ACP:	Advanced Spent Fuel Conditioning Process
ADU	ammonium diuranate
AEB	Atomic Energy Board Republic of South Africa
AEC	Atomic Energy Corporation of South Africa
AECL	Atomic Energy of Canada Limited
AHF	Anhydrous Hydrogen Fluoride
AHP	Analytical Hierarchy Process
AMP	Ageing management programme
ANS	American Nuclear Society
ASME	American Society for Mechanical Engineers
ASN	Nuclear Safety Authority
ASSAf	Academy of Science of South Africa
ARIS	Advanced Reactors Information System
ARPANSA	Australian Radiation and Protection and Nuclear Safety Agency Act of 1998
AUC	ammonium uranyl carbonate
BEVA	Brandstof Element Vervaardigings Aanleg
BNL	Brookhaven National Laboratory
BWR	Boiling water reactor
CGNPC	China General Nuclear Power Corporation
CH ₄	Methane
CI	Consistency Index
Ci	curie
cidb	Construction Industry Development Board
CMG	Construction Management Guidelines
CNEA	National Atomic Energy Commission, Argentina
CNNC	China National Nuclear Corporation
CO ₂	Carbon di oxide
CR	Consistency Rate
CRS	Congressional Research Service
CSA	Complementary Safety Assessments
CSA	Comprehensive Safeguards Agreement
CTE	Critical Technology Elements
DACST	The South African Department of Arts, Culture, Science and Technology
DBSA	Development Bank of Southern Africa

DEA	Department of Environmental Affairs
DME	The then South African Department of Minerals and Energy
DMR	The then South African Department of Mineral Resources
DMRE	The South African Department of Mineral Resources and Energy
DoE	The then SA Department of Energy
DoD	The USA Department of Defence
DOE	USA Department of energy
DSI	Department of Science and Innovation of South Africa
DUPIC	Direct use of PWR spent fuel in CANDU
EDF	Electricité de France
EIA	Energy Information Administration
EIA	Environmental Impact Assessment
E-LCA	Environmental Life Cycle Assessment
EOP	end of processing
ETI	Energy Technologies Institute
ETO	Engineer-to-order
F-O-A-K	First-of-a-kind
GAO	United States Government Accountability Office
GE	General Electric.
GHG	Greenhouse gas
GTM	Green Tech Media
GTRI	USA DOE Global Threat Reduction Initiative
HBR	Harvard Business Review
HF	Hydrogen fluoride
HLG-MR	High-level group on the security of supply of medical radioisotopes
HSRC	Human Sciences Research Council
HTR	High Temperature Reactors
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
IFNEC-NEA	International Framework for Nuclear Energy Cooperation-Nuclear Energy Agency
IIW	International Institute of Welding
ILW	Intermediate Level Waste
IM	Industrial Manufacturing
INE	Institution of Nuclear Engineers
INEEL	Idaho National Engineering and Environmental Laboratory
INL	Idaho National Laboratory

IPE	International political economy
IRIS	International Reactor Innovative and Secure
ISFSI	Independent Spent Fuel Storage Installation
ISL	in-situ leaching
ISR	in-situ recovery
KBS	Karn Bransle Sakerhet
KEPCO	Korea Electric Power Corporation
KHNP	Korea Hydro and Nuclear Power
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCOE	Levelized Cost of Energy
LEU	low enriched uranium
LTAs	Lead Test Assemblies
LUC	levelized unit cost
MAPLE	Multipurpose Applied Physics Lattice Experiment reactor, Canada
MBR	moving bed reactor
MHI	Mitsubishi Heavy Industry
MOX	(mixed uranium oxide, UO ₂ , and plutonium oxide, PuO ₂)
MS	Management System
MSI	Management System Integration
NDP	National Development Plan
NDPs	Nuclear Decommissioning Projects and Programmes
NECSA	South African Nuclear Energy Corporation
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NEP	Nuclear Energy Policy for the Republic of South Africa
NIL	Nuclear Installation Licence
NM	Nuclear Manufacturing
NNR	National Nuclear Regulator
N-O-A-K	nth-of-a-kind
NORM	naturally occurring radioactive materials
NO _x	Nitrogen Oxides
NPS	Nuclear Power Station
NPV	Net Present Value
NRWDI	National Radioactive Waste Disposal Institute of South Africa
NSSS	Nuclear Steam Supply System

NUCOR	Nuclear Development Corporation of South Africa
NWMO	Nuclear Waste Management Organization of Canada
OEE	Overall Equipment Effectiveness
OCC	Overnight Construction Costs
OECD	Organisation for Economic Co-operation and Development
OCRWM	USA Office of Civilian Radioactive Waste Management
OTC	Once-through cycle
PBMR	Pebble Bed Modular Reactor
PESTEL	Political, economic, social, technological, environmental and legal
PET	Positron emission tomography
PhD	Doctor of Philosophy
PM	Pelindaba Manufacturing
PRC	Presidential Review Committee
PuO ₂	Plutonium (IV) Oxide
PUREX	Plutonium Uranium Extraction
PWR	Pressurized water reactor
Relap5	Reactor Excursion and Leak Analysis Programme,
RD-0034	Quality and Safety Management Requirements for Nuclear Installations
R&D	Research and Development
RG	Regulatory Guide
RID	International Rail Carriage Regulations
RR	Research Reactor
Rosatom	State Atomic Energy Corporation
SA	South African
SABS	South African Bureau of Standards
SAFARI-1	South African Fundamental Atomic Research Installation
SAIIA	The South African Institute of International Affairs
SANS	South African National Standard
SA RWMPs	The South African Radioactive Waste Management Policy and Strategy
SEA	Site Environmental Assessment
SETAC	Society for Environmental Toxicology and Chemistry
SFPI	Spent Fuel Pool Island
SHARS	Spent High Activity Radioactive Sources
SKB	Swedish Nuclear Fuel and Waste Management Company
SNPTC	State Nuclear Power Technology Corporation (China)
S-LCA	Social and Socio-economic Life Cycle Assessment

SOEs	State Owned Entities
SOx	Sulphur Oxides
SPECT	Single photon emission computed tomography
SSCs	Structures, Systems and Components
SSR	Specific Safety Requirements
STATS SA	Statistics South Africa
STUK	Radiation and Nuclear Safety Authority of Finland
SWOT	Strengths, Weaknesses, Opportunities, Threats
SWU	Separative work units
^{99m} Tc	Technetium-99m
TLAAs	Time-Limited Aging Analyses
TMI	Three Mile Island
TPM	Total Particulate Matter
TRLs	Technology readiness levels
TRR	Thermal reactor recycle
UAlx	Uranium-aluminum alloy
UCOR	Uranium Enrichment Corporation of South Africa
UFDC	Used Fuel Disposition Campaign
UNEP	United Nations Environment Programme
UNF	Used Nuclear Fuel
UNICEF	United Nations Children's Fund, is a United Nations
VRE	variable renewable energy
WACC	Weighted Average Cost of Capital
WNA	World Nuclear Association
WNN	World Nuclear News

1 Introduction

1.1 Background and Rationale

For the most part since 1994, the South African (SA) nuclear sector has been in a state of stagnation evidenced by missed nuclear new builds expansion opportunities. These missed opportunities are not in synch with the SA's Nuclear Energy Policy (2008) that envisions an “industrial and technological leadership, to secure alternative energy resources for the future, through the development of a globally competitive infrastructure and skills for the peaceful utilisation of nuclear energy and technology”. Most of the installations for the existing SA nuclear infrastructure took place before the dawn of democracy in 1994. At present, the SA nuclear sector and its stakeholders do not have a growth fostering generic strategic decision-making model or framework. A strategic decision-making model that can continuously assist SA nuclear stakeholders to anticipate challenges, assist in gathering and archiving relevant strategic factors for strategic formulation purposes can possibly minimise the SA nuclear sector's sluggishness.

The local and international emergence of cost competitive alternative energy technologies such as solar, wind and gas have exacerbated the complexities of making strategic decisions within the SA nuclear sector. Just like in other democracies e.g. USA and Germany, the SA energy debate bugged down on bipartisan politics and functionalism. Local opponents of the nuclear sector often mention nuclear power plant construction delays and cost overruns in the USA, France and Finland as a means of influencing policies and the decisions on which electricity generating technologies should be included in the Integrated Resource Plan (IRP). The SA nuclear sector is not as well prepared and organised as the renewables sector when it comes to responding to negative criticisms. From a strategic perspective, such criticisms and other challenges can be anticipated and be managed in advance i.e., if a repository of relevant data or factors is created and used for rapid responses or proactive initiatives.

Nuclear sector decision makers have to contend with impacts of past (Chernobyl and Three Mile Island) and recent (Fukushima) nuclear disasters. On the 11th of March 2011, an earthquake induced tsunami resulted in the Fukushima nuclear disaster. This disaster was given an International Nuclear Event Scale maximum level-7 which equals the Ukraine's Chernobyl. Faced with a disaster of that magnitude, Japan decided to stop the operation of its nuclear power plants thereby losing 30% of its generating capacity. The disaster gave impetus to some countries such as Germany to opt out of nuclear with others suspending their nuclear power plant build implementation. Although the Fukushima accident has directly prevented an immediate deployment of nuclear power in some countries (e.g. Germany, Switzerland and Italy), other nations (China, Emirates, Russia, India and to some extent the USA and UK) are still pursuing their programmes vigorously (Locatelli, Bingham & Mancini, 2014).

SA's pressurised water reactor (PWR) and pebble bed modular reactor (PBMR) based nuclear new builds failed to materialise despite being included in the SA IRPs. Eskom tried to implement a 20 GW PWR new build but abandoned its plans in 2011. Six years later i.e. in 2017, the SA Department of Energy (DoE) abandoned its proposed 9.6 GW nuclear new build after a court decision that ruled against the legality of the nuclear power plant vendor countries' cooperation agreements. Similarly, the SA government took a decision to stop the local development of the PBMR citing funding constraints. As in other democracies, SA decision-making on nuclear new build is constrained by multiple factors that can be political, economic, social, technological, environmental and legal. NPP new build by its nature pits proponents against opponents. As an example, such contestations can prevail in the following situations in which strategic decision makers have to answer to which, when, how, what, who and why?

- Advancing the notion that reducing greenhouse gas emissions can be enhanced by connecting both nuclear and variable renewable energies (VRE) technologies to the grid;
- Deciding on what the nuclear generating capacity should be within the energy mix;
- Deciding on which entities should be involved in the nuclear new build programme;

- Deciding which nuclear technologies should be transferred as part of the localization programme; and
- Deciding on the structure of an electricity generating and distribution entity.

Prioritisation of options becomes important considering the fact that various stakeholders within and outside nuclear sector organizations will have different expectations and influences. Those charged with charting the way forward have to be innovative so as e.g., to derive maximum value from the nuclear new build. Making decisions in the nuclear sector can be more daunting than in other sectors because the sector is involved in large and complex new builds. Hellström et al. (2013) noted that the early stages of large projects are characterised by a wide array of choices, possible directions, which successively narrow down as directions are decided, and the commitment to them escalates. Similarly, Zhou and Mi (2017) noted that compared with conventional projects, megaprojects with characteristics of multiple stakeholders, substantial investment, high degree of technological complexity and extremely long lifecycle (LC) are much more complicated systems.

1.2 Research Problem

The SA nuclear sector does not have a generic model or framework that can be used to manage factors that have a potential to enhance or impede its growth. As an example, the developed nuclear sector strategic decision-making model has the potential to bring about the following benefits or improvements for the SA nuclear sector stakeholders:

- Identify or anticipate problems and possible world class solutions well ahead of time since it is envisioned that the model will be used to continuously benchmark local nuclear sector practices against those other countries nuclear sectors;
- Enable the nuclear sector to gather information on technologies perceived to be complementary or in competition with the nuclear technologies;

- Enable policymakers, practitioners, managers and executives to have consensus on their strategic initiatives e.g. emanating from strategic sessions;
- The in advance availability of nuclear sector internal environment and external environment strategic factors (data) has a potential to enhance shortening the turnaround time and quality of solicited submissions or responses e.g. those required for finalising government energy policies; and
- Improvement on the competitiveness of nuclear sector entities since such collected and archived factors can be used for strategic positioning e.g. by virtue of having information on competitors and deciding on which foreign entities to participate or to collaborate with on nuclear related programmes.

1.2.1 Research Questions and Hypothesis

Taking into consideration the aforementioned problem and potential benefits, the research questions for this study are as follows:

- How can existing popular decision-making methods be used to develop a generic hybrid SA nuclear sector strategic decision-making model?
- How can the developed model be used to identify, collect, validate, retrieve and analyse local and international nuclear industry factors for the purposes of undertaking SA nuclear sector strategic decisions?

Based on the above questions, the research hypothesis is as follows:

The concurrent use of existing popular decision-making techniques to qualitatively and quantitatively analyse nuclear sector factors can enhance the strategic anticipation and response to the SA nuclear sector challenges and needs.

1.2.2 Research Objectives

The research study general objective is:

To develop a novel generic hybrid SA nuclear sector model that can be used for strategic decision-making.

The specific research objectives are as follows:

- To demonstrate how and why a developed SA nuclear sector strategic decision-making model should be a combination of existing popular decision-making techniques and SA's historical, present and possible future nuclear facilities.
- To demonstrate how the proposed model can be used to continuously, identify, collect, validate, archive, retrieve and operationalise SA nuclear sector factors for strategic decision-making purposes.

A mixed qualitative and quantitative approach was used for this research study by virtue of the individual attributes of the combined decision-making techniques. In this regard, the developed hybrid generic SA strategic decision-making model comprises the Analytical Hierarchy Process (AHP), SWOT, PESTEL, LCA as well as ten SA past, present and possible future nuclear facilities mainly informed by the SA Nuclear Energy Policy of 2008. Overall, for this research study there was a deliberate collection of factors around ten nuclear facilities with the intention to utilise the data for strategic decision-making using an AHP based case study.

1.3 Thesis Layout or Structure

Chapter 1 is the Introduction that entails the study rationale, problem statement, research questions and objectives.

Chapter 2 focuses on the strategic decision-making related literature review mainly focusing on existing popular methods for decision-making. The popularity and versatility of the methods is evidenced in this chapter by discussing their employment in different industry sectors i.e., both non-nuclear and nuclear.

The summary of this chapter comprises advantages and disadvantages (limitations) of individual four techniques namely; SWOT, PESTEL, AHP and LCA. The identification of the advantages partly responds to the reasoning behind having a hybrid model that takes advantage of those inherent qualities in terms of benefiting the decision-making process.

Chapter 3 is the Research Design and Methodology that delineates the following as listed:

- The model development process (research study design);
- The initial and final conceptual hierarchal hybrid models reflecting the synchronization of the four popular decision-making methods. The conceptual hierarchal hybrid models denote the superimposition of the popular techniques to the SA sector's ten historical, present and envisioned nuclear installations (pressurised water reactor, small modular reactor, research reactor, uranium production, conversion, enrichment, fuel fabrication, reprocessing and recycling, spent fuel storage, spent fuel disposal); and
- The secondary data (factors) gathering and documenting structure (repository) instrument derived from the conceptual model. The data structuring approach was used together with the UNICEF PESTEL & SWOT Factor Categorization Guide and Harvard Business Review (HBR) SWOT Analysis Guide. These two guides enabled the validation of the secondary data categorization within the repository (from sub section 3.3.1 to sub section 3.3.10). The SA and international nuclear sectors related secondary data or factors presented in the repository was collected with possible future anticipated strategic decisions on aforementioned ten nuclear facilities in mind.

The SA PBMR Case Study in Chapter 4 entails the demonstration of the utilization of the model's factor extraction and case study instrument and ultimately the operationalization of the collected secondary data in the main retrieved from the SMR's section of the repository. Hence, it was at this part of the

study in which the utilisation of repository secondary data in the repository was employed to produce primary data i.e. for purposes of strategic decision-making. Only the threats data or factors were used for the case study, leaving the appended retrieved opportunities, weaknesses and strengths data for possible future studies. Of specific importance here, was the validating of the factors using a novel extraction and listing template. The researcher undertook the validation together with the nuclear sector experts. The nuclear sector champions that participated in the Analytical Hierarchy Process (AHP) questionnaire guided pairwise comparisons were selected conveniently and purposively. The rest of the Chapter 4 presents AHP Expert Choice software computations of relative factor weights and consistency ratios (CRs) that enabled to establish that decision-makers needed to prioritise the following in descending order: public acceptance, private funding and political system as critical factors possessing the highest potential to impede the resumption of the SA PBMR R&D activities.

Chapter 5 is the overall research study conclusions that entail case study results main findings, contribution to body of knowledge, policy implications, study limitations and recommendations for possible future studies.

Chapter 6 is the Bibliography that lists all the related literature sources cited in the research study.

The last chapter is the Appendix which includes a glimpse of the international workshop at which the conceptual models were presented, the Pelindaba pairwise comparison workshop attendance register, SA PBMR case study matrix questionnaires and examples of retrieved SA PBMR related future case studies' opportunities, strengths and weaknesses factors.

2 Literature Review

2.1 Introduction

This Chapter's main thrust is the reviewing of literature on strategic decision-making and popular techniques employed. Some reviewed article briefs on what factors were considered for strategic positioning SA, S Korean and Chinese nuclear sectors are included in order to have an appreciation of three countries' growth strategies or lack of. Following this, the popular decision-making methods and examples used in different industry sectors including the nuclear sector are discussed. Specifically related writings on application areas of SWOT, PESTEL, AHP and LCA are discussed so as to make sure that the four techniques attributes are understood and to establish how their qualities can contribute to the robustness of the envisioned novel hybrid generic model. SWOT and PESTEL are very much popular e.g., with many different industry sectors' programme strategists and decision-makers. AHP is one of the multi-criteria techniques highly recommended by the IAEA and is extensively used in making decisions in nuclear and non-nuclear sectors. LCA is considered because of its utilisation on appraising different sectors' environmental issues and the fact that related sustainability assessment techniques have been derived from it with the intention to expand its use. Consequently, the advantages and disadvantages of each method are listed in this chapter's summary.

2.2 Strategic Decision Making

Policy-makers and managers are responsible for making strategic decisions whereby they have to e.g., justify that NPP installation or construction that can be implemented to support a given country's sustainable development agenda. In most cases, such decision-making is in circumstances where there are competing alternatives. According to Moody (1983), the decision may be simplistic or complex or it may relate to any of the other fields of management; however, all decisions can follow the basic closed loop shown below in Figure 2-1.

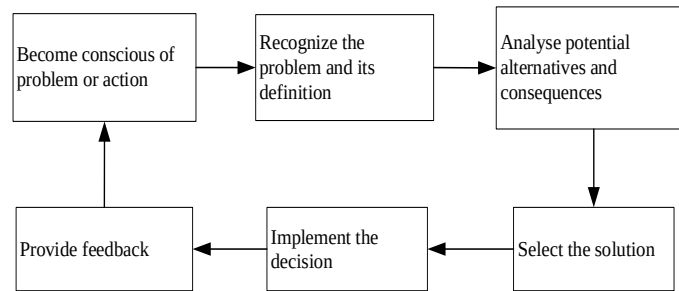


Figure 2-1: Decision-making loop
Source: Moody (1983)

Depending on a country's policies, nuclear programme strategies have to be formulated by e.g. governments and state entities, whereas in some cases jointly by the government, state entities and the private sector. The IAEA (2001) contends that some of the key reasons for writing a strategic plan are that:

- It provides a logical way to try and increase utilization;
- It provides a justification for continued operation;
- It allows for appropriate commercialization of the facility;
- It is a means to effectively manage a change in culture;
- It communicates the priorities of a facility's management and can thereby show the importance of such issues as the minimization of radioactive material releases, employee and public doses;
- It helps secure budgets, and justifies recruitment of staff and infrastructure upgrades; and
- It enables stakeholders to see the benefits and need for external support.

For South Africa and its allies, the starting of the local nuclear sector was strategic. South Africa's nuclear history began in 1944 when the allies, mistakenly thinking that uranium was very rare, briefed the South African Prime Minister, Jan Smuts, about the atomic bomb programme and asked South Africa to look for uranium in ground linked to gold mining (Kemmer & Kenny (n.d.)). Government leaders or officials in different countries with nuclear capabilities or wanting to acquire additional or for the

first time rely on prevailing circumstances in making strategic decisions. Decisions taken are responses to questions asked such as what, when, how, where, why, who, and which nuclear facilities should be built or retired? In 1961, work on the South African (SA) site of Pelindaba for the Atomic Energy Board buildings started and in 1964 uranium hexafluoride (UF₆) experiments were introduced (Venter, 2008). SA developed its civilian nuclear industry parallel to developing its nuclear military defence capabilities that it later abandoned when it signed the non-proliferation treaty in the 1990s.

Long distance moving of either coal or electricity transmission is inefficient, hence it was decided in the mid-1970s for SA to build some 1800 MWe of nuclear capacity at Koeberg near Cape Town (World Nuclear Association, 2019). In 1976, a French-based company, GDF Suez, signed a contract to build the Koeberg facility (Moore, 1987). The South African (SA) government owns and operates three nuclear reactors, namely, a research reactor SAFARI-1 and two nuclear power reactors, Koeberg 1 and Koeberg 2 (Van Wyk, 2013).

At any given time, leaders of countries or organizations wanting to embark on nuclear programmes have to make strategic decisions based on prevailing local or international circumstances. In accordance with the country-specific conditions and constraints (i.e., political imperatives, geographic situations, and population density), each country should have its own weighting approach for performing nuclear energy system assessment in a national energy strategy (Gao et al., 2018). Strategic decisions are undertaken taking into consideration past, prevailing and future conditions. According to Mudd (2014), there are numerous critical issues facing the energy and electricity sectors globally, with arguably the most important being (in no particular order):

- 1) greenhouse gas emissions released by fossil fuel sources contributing to anthropogenic climate change;

- 2) peak oil and the end of the era of cheap conventional oil;
- 3) social and environmental impacts of unconventional oil and gas extraction, such as tar sands, shale gas (and liquids) and coal seam gas;
- 4) concerns about energy security, especially ongoing supply issues and maintaining resources; and
- 5) economic competitiveness of energy sources.

The SA National Treasury Standard for Infrastructure Procurement and Delivery Management (2016) states that the critical starting point in delivering value for money through infrastructure programmes is from the onset to align such programmes with:

- strategic objectives;
- priorities;
- budgets and plans; and
- thereafter, during the planning phase, to enable defining clearly the objectives and expected outcomes, as well as parameters such as the timelines, cost and levels of uncertainty.

Deploying nuclear power plants, however, may be challenging when uncertainty in long-term electricity demand and more importantly public acceptance is also an issue for consideration (Cardin, Zhang & Nuttall, 2017). According to Valentine and Sovacool (2010), six dominant factors appear to be at the core of support for nuclear power development in each country namely:

- 1) strong state involvement in guiding economic development;
- 2) centralization of national energy policymaking and planning;
- 3) campaigns to link technological progress with national revitalization;
- 4) influence of technocratic ideology on policy decisions;
- 5) subordination of challenges to political authority; and
- 6) low levels of civic activism.

As an example, the above second factor was instrumental when in March 2008 the overseeing of energy-related issues including nuclear and the authority to lay out China's energy development strategy that previously existed in several ministries were centralised in the National Energy Commission (NEC) as part of a major reshuffle of the Chinese bureaucracy (Zhou et al., 2011).

According to The Chartered Institute of Management Accountants (CIMA), examples of analytical methods used in strategic analysis include SWOT analysis; PEST analysis; Porter's five forces analysis; four corner's analysis; value chain analysis; early warning scans; and war gaming.

2.3 PESTEL Analysis Method

The PESTEL framework or tool (Figure 2-2) analyses and monitors the macro-environmental (external environment) factors that have an impact on an organization and its results can be an input to the SWOT analysis for identifying threats and weaknesses (Professional Academy, n.d.).



Figure 2-2: PESTEL Analysis Framework

Source: <https://www.professionalacademy.com/blogs-and-advice/marketing-theories---pestel-analysis>

This PESTEL technique enables investigators to make a comprehensive appraisal of an organization since it examines wider aspects namely political, economic, social, technological, environmental and

legal. Such an approach addresses concerns raised by Lopes and Flavel (1998) who postulated that a major reason why non-financial and non-technical aspects are not considered more fully is probably the lack of analytical framework that highlights the importance of those factors, at the same time giving guidelines on how they should be incorporated. McCombie and Jefferson (2016) contended that the scientific community in general and the nuclear industry in particular, have not been very successful at responding to emotionally based public fears with rationally based science data. Likewise, Zhou and Mi (2017) observed that although researchers and practitioners have taken a great deal of trouble within the domain of megaproject social responsibility; the relevant studies are still limited and scattered.

Verbruggen, Laes and Lemmens (2014) recommended the use of a new holistic sustainability development (SD) assessment framework for nuclear fission power that uses criteria summarized below in Table 2-1 after their reviews revealed that there was a need for an extended framework for proper prior assessment of nuclear fission power's suitability for advancing sustainable development. Similarly, this research aims to develop a model that will improve the SA nuclear sector strategic decision-making processes through a holistic approach of identifying sustainability aspects.

Table 2-1: Criteria for assessing whether nuclear power can be a part of sustainable development

Dimensions	Criteria (standards on which a judgment is based). The standards are sustainability attributes to own and results to obtain by a technology.
Environmental/ecological (planet)	a) Climate change problems are relieved (mitigation and adaptation); b) Ecological resilience of the energy system's embedding environment is preserved; c) Exhaustible finite resources are managed in light of future substitutes; and d) Electricity use efficiency and deployment of renewable electricity potentials are stimulated.
Economic (prosperity)	a) All costs related to the nuclear system are identified, measured (or properly assessed), and billed to the end users of nuclear power; b) Technology evolves to higher economic efficiency: more output at reduced costs; c) Capital investments are affordable for most countries in the world; and d) The electricity supply industry that results from generation technology choices is secure and reliable, with low vulnerability.
Risks	a) Risks should be completely insurable, even catastrophic risks; b) Nuclear plant owners and operators are fully liable for risks, including long-term effects and impacts; and c) Proliferation of technologies and know-how that can be used for nuclear weaponry is limited and reduced.
Social (people)	a) Electricity bills are affordable (match the expectations of constituencies);

Dimensions	Criteria (standards on which a judgment is based). The standards are sustainability attributes to own and results to obtain by a technology.
	b) External and future costs are allocated according to the polluter pays principle and precluding d is placement of problems and risks to the poor, to developing countries, and to future generations; c) Exposure to harmful pressures is low, and proper information on safety and health impacts is available; and d) Global redistribution of access to natural resources and of economic wealth growth is stimulated.
Governance/policy (politics)	a) A global, independent agency studies nuclear power issues and choices in terms of their longevity, uncertainties, and irreversible impacts; b) Independent and accountable nuclear regulatory institutions and processes are established and monitored publicly; c) At national/regional levels, the public interest prevails over private profit, and democratic institutions prevail over technocracy; and d) At local levels, citizens can engage in debate about energy system governance and participate in the deployment of local energy systems

Source: Verbruggen, Laes & Lemmens (2014)

PESTEL complements SWOT by identifying specific relevant factors (such as economic trends, social attitudes, technological developments, etc.) that are significant for the initiative under consideration, and then SWOT classifies them as either opportunities or threats (UNICEF, 2015). As nuclear energy is highly controversial in today's society, it is important to analyse the role it plays for humanity in a multidimensional manner (Pravalie & Bandoc, 2018). PESTEL (political, economic, social, technological, environmental, legal) analysis has two basic functions for a company which are firstly that it allows identification of the environment within which the company operates and the second basic function is that it provides data and information that will enable the company to predict situations and circumstances that it might encounter in future (Yüksel, 2012). The procedure is helpful when conducting a strategic analysis of macro-environmental factors that an organization needs to take into consideration when selecting projects (Note, 2016). Since PESTEL analysis is a structured way to organize environmental factors, it is therefore suitable for analysing and mapping how the external environment affects an industry (Song, Sun & Jin, 2017). Andrei and Prisecaru (2014) employed the PESTEL analysis to identify risks that can negatively affect the implementation of the Romanian National Geological Repository (NGR) programme. Despite the ability of the PESTEL method to have a somewhat holistic structured approach, just like the SWOT technique it is not able to rank or prioritise the identified variables. The aim in this research is to take advantage of the individual techniques'

abilities namely the LCA, AHP, SWOT and PESTEL and develop a model, which will simultaneously have e.g. the ability to holistically identify relevant factors for a given nuclear sector situations, and narrow them down through ranking so as make strategic-decisions.

2.4 SWOT Analysis Method

SWOT analysis is a strategic planning method used to evaluate the Strengths, Weaknesses/Limitations, Opportunities, and Threats involved in a project or in a business venture (Seker & Ozgurler, 2012). According to UNICEF (2015), the review of the PESTEL outputs will provide the first inputs into SWOT. Jasiulewicz-Kaczmarek (2016) expounds on the four SWOT analysis elements as follows:

- Strength: A resource or capacity the organisation can use effectively to achieve its objectives;
- Weakness: A limitation, fault or defect in the organisation that will keep it from achieving objectives;
- Opportunity: Any favourable situation in the organisation's environment; and
- Threat: An unfavourable situation in the organisation's environment that is potentially damaging to its strategy.

Despite the fact that the SWOT analysis has tremendous capabilities of unravelling and dissecting businesses' internal and external factors, it lacks the ability to prioritise the identified business elements. In particular, even if the analysis is well structured, it is often subjective and a consensus about its results may be difficult to reach (Fertel, 2013). For businesses or organizations to survive, improve and succeed management planning and decision-making require information about business operations and the circumstances, which surround them, such information is the basis for business decision-making (Pickton & Wright, 1989). SWOT analysis is one of the most frequently used tools of strategic management that integrates the results of the external analysis, in which are formulated opportunities and threats, and the results of the internal analysis that describes the strengths and weaknesses

(Bartusková & Kresta 2015). Markovska, Taseska and Pop-Jordanov (2002) undertook a Macedonian energy sector SWOT analysis and found that:

- Macedonia's adoption of EU standards in energy policy and regulation as the most important achievement in the energy sector; and
- the important problems the national energy sector faces are scarce domestic resources and unfavourable energy mix, low electricity prices, a high degree of inefficiency in energy production and use, as well as insufficient institutional and human capacities.

When using the SWOT analysis Mullebeck (2015) recommended an approach in which the external factors are first examined and then proceeding to the internal ones so as to enable stronger focus on results, and identification critical threats (i.e. those that are compounded by corresponding weaknesses) and which opportunities are 'promising opportunities' (i.e. those that are matched by corresponding strengths). Figure 2-3 below is a Harvard Business Review (HBR) SWOT Analysis Tools illustration of steps 1 to 3 whereby the focus is firstly on identifying the threats and opportunities with respect to internal weaknesses and strengths.

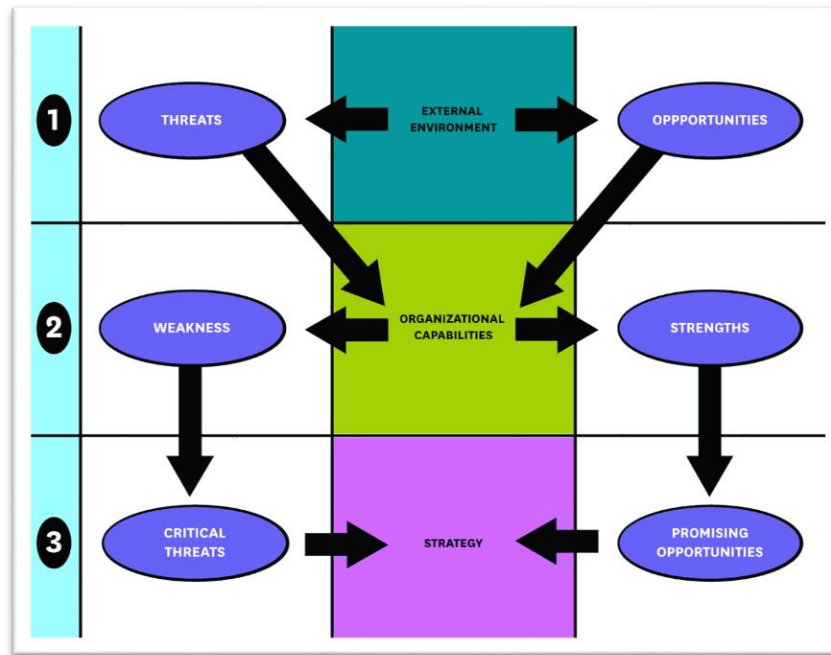


Figure 2-3: Harvard Business Review SWOT Analysis Tool

Source: <https://hbr.org/2007/03/from-swot-to-tows-answering-a-readers-strategy-question>

Lee, Lee and Oh (2007) employed the SWOT analysis to compare nuclear energy against its competitors and established the following:

- Out of the external environmental factors, electrification, the regulations for the global environments and the limited availability of fossil fuels will provide an opportunity for the nuclear energy innovation in the future;
- The changes of consumption behaviour and the liberation of the marketplace are threat factors;
- Urbanization, accelerated technological development and increased attention to the environment are either opportunity factors or threat factors i.e., depending on the innovations of nuclear technology;
- Internal factors such as ability to nuclear fuels, high energy density and little emission of greenhouse gases are strengths of nuclear power; and
- Nuclear weakness points are social situations such as the management of radioactive waste, safety and nuclear proliferation and in its structure of high capital costs.

Whereas SWOT analysis is a simple, effective, and comprehensive diagnosis of internal and external factors, which may affect an organization, each of these factors may not be easily measured (Eslamipoor & Sepehriar, 2014). This limitation can be eliminated by introducing the AHP that was specifically developed to measure tangibles and intangibles during a decision-making process. Table 2-2 below lists additional limitations of the SWOT analysis.

Table 2-2: Limitations in the use of SWOT

Inadequate definition of factors	Lack of prioritization of factors	Over-subjectivity in the generation of factors: compiler bias
Factors which appear to fit into more than one box/category Factors which do not appear to fit well into any box/category Factors described broadly: lack of specificity Lack of information to specify factors accurately	Factors which are given too much emphasis Factors which are given too little emphasis Factors which are given equal importance	Factors missed out: lack of comprehensiveness Serendipity in the generation of Factors Disagreement over factors and to which box/category they belong Factors represent opinions not fact

Source: Pickton and Wright (1998)

2.5 Life Cycle Assessment

The life cycle perspective considers all life cycle stages for products, and for organizations the complete supply or value chains, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal (UNEP/SETAC, 2011). Life cycle assessment (LCA) is a process used to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment (Lee & Koh, 2002). The nuclear industry commonly clusters NPP life cycle costs as: capital cost, operating and maintenance, fuel and decommissioning (Locatelli, Bingham & Mancini, 2014). Within the decision-making context, each organization has to solve and decide on each case depending on e.g. the size and culture of the organization, its products, the strategy, the internal systems, tools and procedures and the external drivers since there is no single solution as to how Life Cycle Assessment (LCA) can best be applied (Finkbeiner et al., 2014). Safety assessment of NPP is one driver that has necessitated life cycle assessments. Following the action plan on Nuclear Safety in response to the Fukushima disaster, the IAEA was requested to assist Member States in strengthening

and maintaining the effective management of nuclear design basis knowledge and information over the entire life cycle for licensed nuclear facilities, including design, construction, commissioning, operations, maintenance, long-term operation and decommissioning (IAEA, 2020a). Figure 2-4 below shows the life cycle of NPP as depicted by the IAEA. Similarly, Koltun, Tsykalo and Novozhilov (2018) in a description of a life cycle assessment (LCA) of a fourth generation (4G) nuclear power plant utilised the following phases of the nuclear power generation cycle:

- (a) power plant design and construction;
- (b) power plant operation,
- (c) spent fuel storage; and
- (d) back end of the cycle involving decommissioning the power plant, land reclamation, final storage (repository) of high, medium and low-level radioactive wastes (HLW, MLW and LLW) disposal.

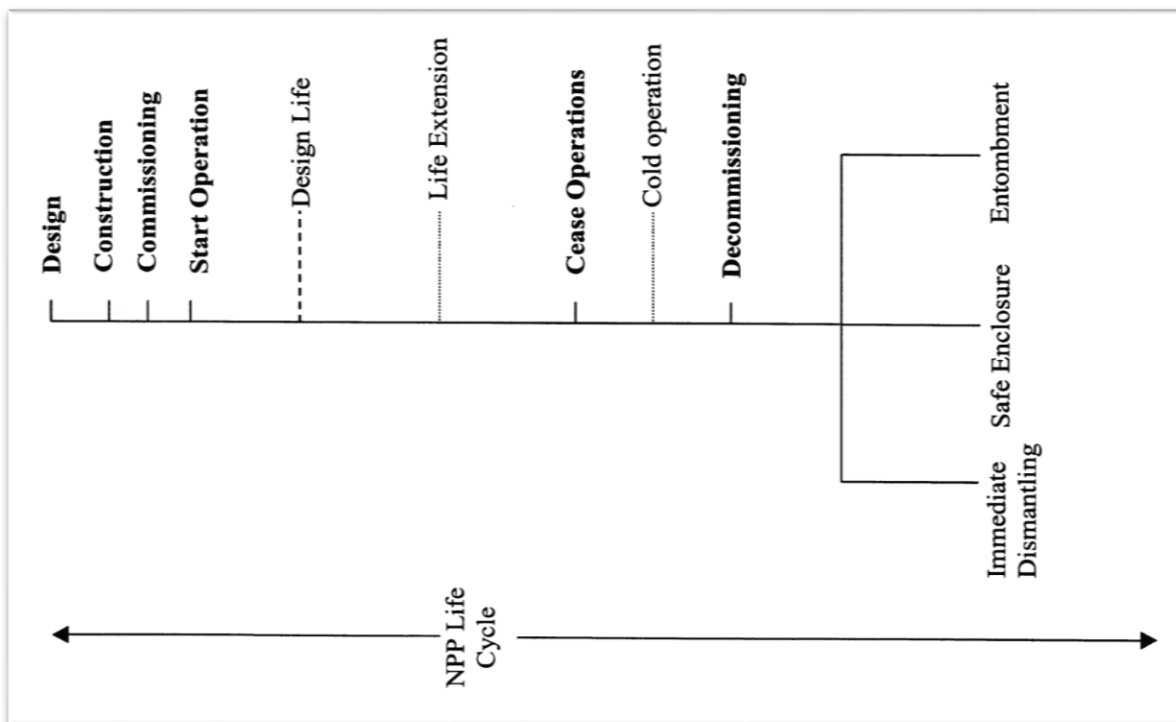


Figure 2-4: Nuclear Power Plant Life Cycle
Source: IAEA (2002c)

Pavlov (2017) stated that those responsible for creating nuclear energy strategy in any country would be concerned about the future security of supply of their stations with all the components of the nuclear fuel cycle, from natural uranium to management of spent fuel. Through the assessment of the NFC value chain, it is possible to identify relevant factors to inform the strategic decision-making process. The IAEA (2009e) states that there are eight discrete operations of the nuclear fuel cycle (uranium production, conversion, enrichment, fuel fabrication, spent fuel conditioning, spent fuel storage, spent fuel reprocessing and recycling and spent fuel disposal) and related industrial activities (production of nuclear grade zirconium, zirconium alloy tubing and production of heavy water). Since the organizations that manage the operations of these systems have limited resources and there is usually more work than can be accomplished at any one time, the proper prioritisation of work activities is essential (Weidinger, 2005).

Research & Development, engineering design, manufacturing, operation, maintenance, waste management and disposal value chain capabilities that are required for the NPPs are also relevant for the aforementioned eight discrete NFC front-end and back-end operations facilities. For example, managing the removed fuel rods constitutes the “back-end” of the LWR fuel cycle, which includes spent LWR fuel management, optional reprocessing, and high-level radioactive waste disposal (Rothwell, 2010).

On external factors, Olhager and Prajogo (2012) noted that manufacturing firms increasingly understand that gains in competitive advantage are not restricted to improvements in their internal operations but that it is also important to consider external supply chains. Likewise, Chen, Olhager and Tang (2014) contended that the perspectives on the manufacturing footprint of global firms are widening from the economic aspects and now environmental and social aspects are included as well. In response to market competition, many companies are currently strengthening their competitive positions by updating the technology used in the manufacturing process (Yusuff, Yee & Hashmi, 2001).

Fütterer et al. (2014) noted that in the European environment and even worldwide, company strategic judgements will have to consider the following:

- the potential of nuclear cogeneration ranges from making use of waste heat of existing nuclear power plants, thus increasing system efficiency; and
- the development of a specific system such as High Temperature Reactors (HTR) devoted to reliable energy supply for industrial processes.

Because it is holistic, systemic and rigorous, Life Cycle Assessment is the preferred tool when it comes to access information about potential and real impacts of products life cycle (UNEP, 2009). Application of Life Cycle Assessment to nuclear energy is important in order to decide nuclear energy policy environmental aspects (Lee & Koh, 2002). Farjana et al. (2018) used the life cycle assessment to assess the environmental impacts of uranium extraction through three different mining processes namely open-pit, underground, and in-situ leaching in Australia and concluded that e.g. that due to the higher amount of energy consumption and inorganic and organic chemical consumption, in-situ-leaching mining is more detrimental to the environment than others.

Invernizzi, Locatelli and Brookes (2017) stated that even if comparing projects in order to identify best practices and generate ideas for improvement on envisaged approach to tackle the decommissioning challenges (and due to the nuclear decommissioning projects and programmes' uniqueness), until now, benchmarking has been only partially used. According to McCombie and Jefferson (2016), life cycle analyses of energy systems are the most promising approaches to developing objective criteria that can assist future strategic decision-making, despite too little attention given to this approach by decision makers. Likewise, Poinssot et al. (2014) state that LCA (life cycle analysis) is a structured basis for deriving relevant indicators which can allow the comparison of a wide range of impacts of different energy sources. Through the utilization of the life cycle assessment technique, Karaca, Dincer and Gu (2020) established that the (global warming potentials) GWPs of employed hydrogen production

methods, namely high temperature electrolysis (HTE), conventional electrolysis (CE), 3-,4-, and 5-step Cu-Cl cycles, are 0.4768, 0.7071, 1.320, 1.201, and 1.346 kg CO₂ eq per kg of hydrogen respectively.

2.5.1 Life Cycle Sustainability Assessment

The main drivers for the scientific developments towards Life Cycle Sustainability Assessment (LCSA) are the paradigm shift from environmental protection towards sustainability and the current developments with regard to evaluation methods and tools for environmental and sustainability performance (Finkbeiner et al., 2010). More than 15 years ago, the concept of Life Cycle Sustainability Assessment (LCSA) was first addressed in literature, defining a holistic method integrating Life Cycle Assessment, Life Cycle Costing, and Social Life Cycle Assessment (Schramm, Richter & Götze, 2020). Energy-generating technologies have a long life span; for example, the lifespan of wind power is 20–25 years that of solar PV is 30 years that of fuel cell technology is 10–15 years, that of thermal power is 20–30 years, and that of nuclear power is 60 years (Lee & Yang, 2018). The consideration of life cycle cost competitiveness factors of e.g. SMRs against other technologies is a must during decision-making process. According the OECD (2013) study, PWR SMRs being developed in different countries can be competitive against large nuclear, wind, coal and gas based technologies as shown below in Figure 2-5.

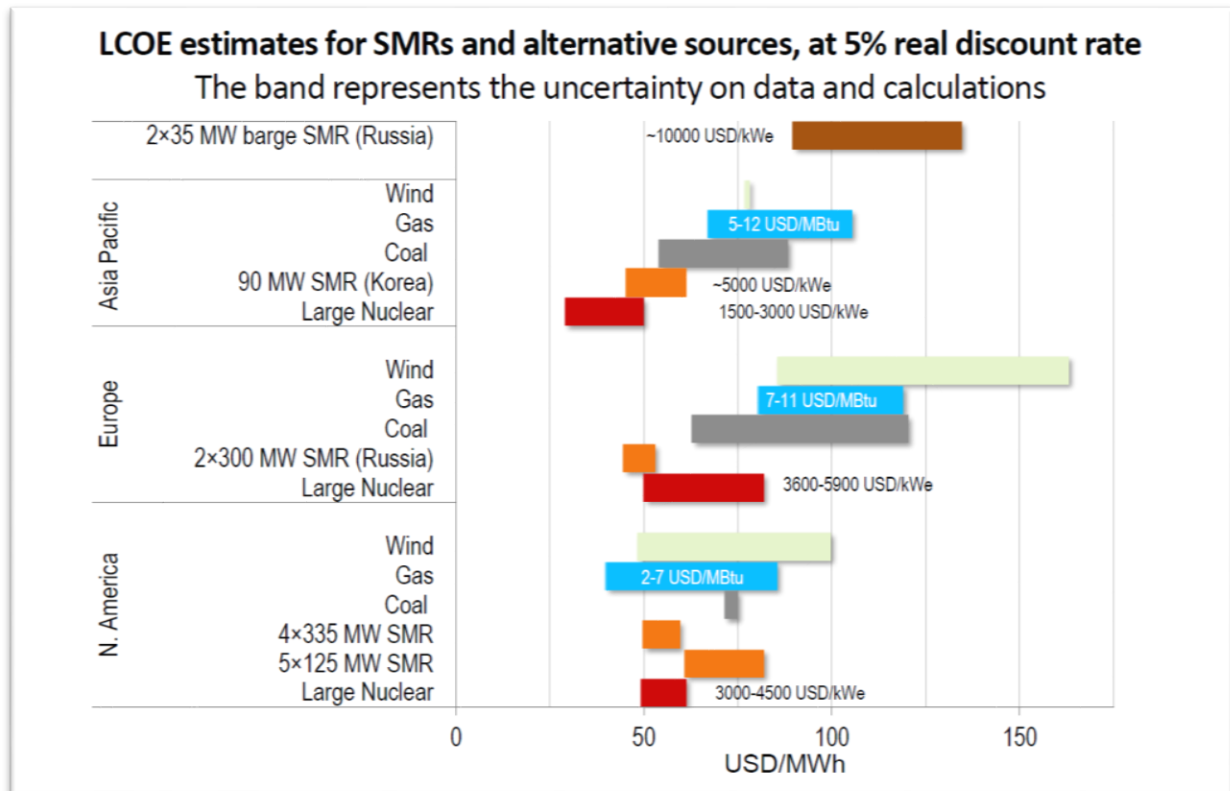


Figure 2-5: LCOE of PWR SMR due to design simplification, shorter construction time, FOAK & factory fabrication

2.6 Analytical Hierarchy Process Method

Saaty (1987) who is the creator of the Analytic Hierarchy Process (AHP), noted that this particular technique is a general theory of measurement used to derive ratio scales from both discrete and continuous paired comparisons and it consists of three main operations, including hierarchy construction, priority analysis, and consistency verification. According to Ho (2008), the AHP is a multi-criteria decision making (MCDM) technique and primarily based on the following three underlying concepts:

- structuring the decision problem as a hierarchy of goals, criteria, and alternatives;
- pairwise comparison of elements at each level of the hierarchy with respect to each criterion on the preceding level; and
- vertically synthesizing the judgments over the different levels of the hierarchy.

Roh, Choi and Chang (2019) developed a framework to compare the export competitiveness of NPP supplier countries using an AHP analysis method and arrived at the following conclusions:

- Financing Package, Demonstration of Reference Reactor, Total Capital Investment Costs, Economic Package, and Sustainability of Domestic Nuclear Industry are the most important criteria to consider during NPP export; and
- As for export competitiveness among the six supplier countries China, Russia, Korea, the United States, Japan, and France demonstrate export competitiveness in decreasing order.

The aim of constructing the hierarchy is to determine the impact of the lower level on an upper level by undertaking paired comparisons provided by the decision-maker (García-Cascales & Lamata, 2009). The AHP helps to facilitate communication within evaluators on the priorities and measurement of research results by translating evaluators' subjective judgments into quantitative terms (Shin, Yoo & Kwak, 2007). Subramanian and Ramanathan (2012) noted that the AHP is usually ideal for problems that require considerations of both quantitative and qualitative factors and its ability to consider subjective opinions of decision-makers is its main strength. Measures of inconsistency set AHP apart from other multi-criteria methods like goal programming, Multi-Attribute Utility Theory (MAUT), Conjoint analysis (CA), or Choice experiments (Alexander, 2012). Papalexandrou, Pilavachi and Chatzimouratidis (2008) stated that the use of consistency ratio to verify the consistency of pairwise comparisons minimizes errors of arbitrary subjective evaluations.

Zavadskas, Turskis and Tamosaitiene (2011) stated that there are a number of strategies (alternatives or actions) which can be ranked according to a number of criteria (criteria, aspects, or dimensions). According to the IAEA (2019), the AHP is one of the well-known MCDA methods used in comparative evaluations presented in different studies in the field of nuclear engineering. The AHP is a multi-criteria decision making (MCDM) general procedure of measurement in the sense of providing a structured and well-defined methodology to convert stakeholders' preferences to a quantitative and quantifiable

grading (Pasaoglua et al., 2018). It is a multi-attribute approach based on three principles: decomposition, measurement and synthesis (Scala, 2015). Hence Georghiou and Roessner (2000) advocate that there should be a continuous use of archival data and multivariate methods to be explored as one means of constructing analytical controls. Eliciting preferences of various components and attributes requires a series of pairwise comparisons where the decision maker will compare two components at a time with respect to an upper level “control” criterion (Meade & Presley, 2002). Although there are other competitive methodologies that could be used to resolve the problem under concern, popularity of the AHP comes from its transparency, simplicity and capacity to integrate a large amount of heterogeneous data (Blagojevic, 2016).

The SA PBMR programme was an R&D initiative that required monitoring and appraising for it to accomplish its commercialisation objectives. The problem of R&D initiative evaluation, however, requires practical and efficient decision-making tools to support reasonable investment programmes (Shin, Yoo, & Kwak, 2007). This challenge is also exacerbated by the fact that traditional approaches to strategic investment appraisal such as payback, accounting rate of return on investment, residual income and discounted cash flow are problematic because they provide a narrow view, are unable to account for nonfinancial benefits and focus on short term during strategic decision-making (Alder, 2000). According to Georghiou and Roessner (2000), methods are needed that capture more fully the non-economic benefits from research or at least the benefits not easily translated into monetized form by those who receive them directly (e.g., private firms) or who seek to develop valid metrics (e.g., professional evaluators). In accordance with the country-specific conditions and constraints (i.e., political imperatives, geographic situations, and population density), each country should have its own weighting approach for performing nuclear energy system assessment in a national energy strategy (Gao et al., 2018). According to Lerche et al. (2019) methods of Multi-Criteria Decision Making (MCDM) from Operations Research are helpful regarding the energy transition challenge, as

they are able to assess the sustainability of local energy concepts, since they not only offer stakeholders the opportunity to participate, but also consider multiple conflicting criteria. Unlike simple cost-benefit models that are uni-dimensional, MCDM models allow stakeholders to compare options across several dimensions (Stein, 2013). Kazibudzki and Křupka (2019) emphasized that thus far only a few papers have dealt with the problem concerning the relation between the level of the pairwise judgments (in) consistency and the size of possible estimation errors for established vector of priority ratios. According to Vaidya and Kumar (2006), some key and basic steps involved in the AHP methodology are as follows:

1. State the problem;
2. Broaden the objectives of the problem or consider all actors, objectives and its outcome;
3. Identify the criteria that influence the behaviour;
4. Structure the problem in a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives;
5. Compare each element in the corresponding level and calibrate them on the numerical scale. This requires $n(n - 1)/2$ comparisons, where n is the number of elements with the considerations that diagonal elements are equal or '1' and the other elements will simply be the reciprocals of the earlier comparisons;
6. Perform calculations to find the maximum Eigen value, consistency index or deviation from consistency CI, consistency ratio (CR), and normalized values for each criteria/alternative; and
7. If the maximum Eigen value, CI, and CR are satisfactory, then decisions are taken based on the normalized values; else, the procedure is repeated until these values lie in a desired range.

Other major reasons for the popularity of AHP is that the decision maker does not require advanced knowledge of either mathematics or decision analysis to perform first five steps listed above (Nilashi et al., 2011). Calculations required in step 6 and 7 can be undertaken manually or by using AHP Expert Choice (EC) software. EC software is a multi-objective decision support tool based on the AHP, a mathematical theory first developed at the Wharton School of the University of Pennsylvania by one of Expert Choice's founders Thomas L. Saaty who is also the originator of AHP method (Adamović, 2007). EC is a user-friendly supporting software that has largely contributed to the success of the AHP approach (Alessio & Ashraf, 2009).

Because the AHP is easy to understand and flexible, it has been used as a stand-alone or together with other techniques to develop strategic decision-making frameworks or models in different sectors including the nuclear industry.

2.6.1 AHP used in the Aircraft Industry

Oeltjenbruns, Kolarik, and Schnadt-Kirschner (1995), together with the Deutsche Aerospace Airbus management used the AHP to structure systematically their decision-making problem for the purposes of evaluating all investment alternatives and were able to arrive at the following conclusions and recommendations:

- The feasibility of the AHP as a decision-making tool for the justification of complex investment alternatives in advanced machinery was successfully demonstrated at Deutsche Aerospace Airbus, Varel;
- Technological and strategic criteria were considered to a much greater extent than in previous analyses;
- Input from experienced engineers was largely enhanced;
- group decision making was appreciated by employees and raised motivation for the project;
- The systematic approach (of the AHP) assisted managers to better understand the processes they used in reaching investment decisions;
- The decision support software, AutoMan, served to support and facilitate the AHP application; and
- Both AHP and AutoMan appear to be flexible enough to support equipment justification in a wide variety of manufacturing environments.

2.6.2 AHP used for coal fired plant decisions

Yagmur (2016) used an AHP based study to determine Turkey's localization equipment for a thermal power plant construction and the results indicated that the boiler was had the highest localization ranking followed by heaters and fans. The AHP study by Zaman et al. (2018) investigated the important

factors that are challenging or delaying coal-based power generation in Bangladesh and the experts interviewed concluded that socio-economic and environmental aspects were the main factors whilst technological aspects and sector regulations were less important. The objective of the study by Bangviwat and Sittikruear (2018) was to find out the preferred measures for people directly exposed to the adverse effects of the coal-fired plant pollution and the results indicated that the interviewees credited corporate social responsibility (CSR) programmes and flue gas desulfurization as main factors that contributed to gaining back public acceptability.

2.6.3 AHP used in the Renewables Sector

In their AHP based study meant to facilitate energy resource planning activities, Erol and Kılıkıs (2012) ascertained that solar energy investments have the highest priority and can be realized by local residents and government, while industry and government can make investments for geothermal power plants and de-centralized lignite power plants using clean technology. The evaluation of the ten types of power plants including nuclear by Chatzimouratidis and Pilavachi (2009) with regard to technological, economic and sustainability criteria by the application of the AHP led to the conclusion that renewable energy power plants are the best solutions for the future. Amer and Daim (2011) used the AHP for the first time for the energy sector of Pakistan to explore some renewable energy options for Pakistan electricity generation from multiple perspectives comprising technical, economic, social, environmental and political aspects and concluded Biomass energy and wind energy were the most preferred. Erol and Kılıkıs (2012) developed an AHP method to facilitate energy resource planning at a built environment district in Turkey and concluded that solar energy investments have the highest priority hence the realization by local residents and government, while industry and government can make investments for geothermal power plants and de-centralized lignite power plants using clean technology. Luthra et al. (2015) utilised the AHP for the purposes of identifying and ranking barriers with respect to India's adoption of renewable or sustainable energy technologies and concluded that lack of political commitment, ecological issues and scarcity of natural and renewable resources as the top three barriers.

2.6.4 Utilization of AHP in the Nuclear Sector

According to the IAEA (2019), the AHP is one of the most ideal multi-criteria decision analysis options for undertaking comparative evaluation of nuclear energy systems. The basis of this endorsement is that the AHP is a very useful and objective process to evaluate quantitatively the qualitative issues that are difficult to compare quantitatively (Lee & Koh, 2002). Stein (2013) developed an AHP based model that was to rank electric power plants using wind, solar, geothermal, biomass, hydropower (i.e., renewable sources), nuclear, oil, natural gas and coal in terms of four comprehensive criteria clusters: financial, technical, environmental and socio-economic-political. Through the employment of AHP, Black et al. (2015) established that emerging economies with increasing GDP and energy demand that possess a robust infrastructure, energy production from high greenhouse gas (GHG) sources, and governmental policies favourable to foreign investment are well-suited for future SMR deployment. Shin et al. (2007) used the AHP to conduct a study aimed at addressing the evaluating practice of Korea's national nuclear R&D (NNRD) programme, establish the basis framework for the evaluation, implement the exploratory evaluation research, and suggest a supplementary plan based on results in order to manage future nuclear R&D programmes effectively. The AHP was used by Chatzimouratidis and Pilavachi (2008) to evaluate 10 types of power plants available at present including fossil fuel, nuclear as well as renewable energy-based power plants, with regard to their overall impact on the living standards of local communities. A study by Sabharwall, Kim and Patterson (2012) evaluated two heat exchanger options for next generation nuclear reactors using the AHP and the helical coiled heat exchanger was preferred for its material performance (corrosion), technology readiness, system integration, inspection, maintenance, and operability, while the printed circuit heat exchangers was preferred for its thermal and structural performance. Hossen, Kang and Kim (2015) used combined AHP and Relative Importance Index (RII) methods to assess qualitatively and quantitatively the severity and frequency of occurrence of delay factors of NPP schedule delay risk and found out that the top five most important sub-sub-factors are as follows:

- policy changes political instability and public intervention;

- uncompromising regulatory criteria and licensing documents conflicting with existing regulations;
- robust design document review procedures;
- redesign due to errors in design and design changes; and
- worldwide shortage of qualified and experienced nuclear specific equipment manufacturers.

Agar et al. (2019) employed the AHP pairwise comparisons to obtain from nuclear cost experts rankings of different factors in terms of their relative importance on the commercial success of a near-term deployable SMR. Lee and Hwang (2010) used the AHP to prioritize the following strategically promising nuclear technologies for commercial export from S Korea:

- (1) Maintenance and repair technology;
- (2) Construction technology;
- (3) Manufacturing equipment and components;
- (4) Nuclear fuel design and fabrication technology;
- (5) Quality control and assurance;
- (6) Process management technology;
- (7) Radioactive isotope technology;
- (8) Radiation safety control technology; and
- (9) Design technology of nuclear power plants.

2.6.5 A Hybrid of AHP and SWOT

When using SWOT on its own, the analysis lacks the possibility of comprehensively appraising the strategic decision-making situation since it merely pinpoints the number of factors in strength, weakness, and opportunity or threat groups and does not pinpoint the most significant group (Kurttila et al., 2000). Reinsberger et al. (2015) stated that because the SWOT represents a mere qualitative analysis, the combination with the AHP makes the comparison of the alternatives commensurable. Posch et al. (2015) observed that while SWOT is able to pinpoint specific factors, it does not provide

information on the relative importance of these factors since there is no prioritizing or weighting of the selected factors in terms of their relative importance. Hence, some studies have demonstrated the addressing of the aforementioned inadequacies by combining the SWOT technique with the AHP that has a measuring ability. As noted earlier on, SWOT is an acronym for strengths, weaknesses, opportunities and threats used as a strategic planning tool to evaluate the strengths, weaknesses, opportunities, and threats involved in a project or in a business venture (Arslan & Er, 2008). Eslamipoor and Sepehriar (2014)'s case study examined the firm relocation decision-making factors using a combination of SWOT and AHP.

2.7 Summary

As observed in various publications, various business or industry sectors utilise SWOT, PESTEL, LCA, and AHP in different settings and circumstances for decision-making. Among the aforementioned techniques, only the AHP has both qualitative and quantitative analysis abilities. As it is the case with some studies reviewed, coupling decision-making techniques can result in enhanced modelling. Table 2-3 below lists the individual decision-making technique abilities and limitations. Based on the reviewed literature, an AHP and SWOT combination is more popular than the AHP and PESTEL hybrid.

Table 2-3: Summary and findings on SWOT, PESTEL, AHP, Life Cycle Assessment capabilities and limitations

Tool	Abilities/Advantages during strategy formulation	Limitations/Disadvantages during strategy formulation
Analytical Hierarchy Process	• Conducting an AHP allows researchers to quantify factors based on expert judgment and, therefore, can be used to understand decision problems better and aid policy processes (Zaman et al., 2018). • The consistency ratio (CR) validates the consistency of pairwise comparisons, thus minimizing errors of arbitrary subjective evaluations (Papalexandrou, Pilavachi and Chatzimouratidis, 2008). • Allows the evaluation of multiple, sometimes conflicting, criteria (Stein, 2013). • It integrates individual judgments of industry experts to determine priority scales through pairwise comparison matrices (Büyükoçkan & Karabulut, 2014).	• Not all factors can be included in the AHP, and the results of the AHP can only identify relative but no absolute priorities. In addition, the outcome depends on the participating experts and, therefore, a balanced expert sample that brings in different perspectives must be compiled. • Unlike the PESTEL and SWOT, the AHP is not that much more robust in holistically identifying factors.

Tool	Abilities/Advantages during strategy formulation	Limitations/Disadvantages during strategy formulation
	• A systematic decision-making approach capable of decomposing the problem into several sub-problems in terms of the hierarchical levels, which then represent a set of criteria or attributes relative to each sub-problem (Gao et al., 2018). • Ability to undertake a pairwise comparison of the options; • Enhance input and learning from industry experts; • Rank and prioritise factors; • Assist in arriving at a consensus; • Quantify intangible and tangible factors • Calculate consistency of expert group's arriving at the final ranking of the factors	• Needs to be assisted by other techniques to enhance the structured approach.
SWOT analysis	• Used to identify organization's factors and categorise them as being external and internal • Can narrow down organization and country factors into internal and external	• Not a systematic approach; • Not able to undertake a pairwise comparison of the options; • Represents a mere qualitative analysis (Reinsberger et al., 2015) • Inability to rank external and internal factors; • Inability to enhance stakeholders to have consensus on focus areas • The collection of external or internal factors not as holistically structured as the one provided by PESTEL
PESTEL	• Ability comprehensively identify external factors in the categories namely political, economic, social, technological, environmental and legal factors • Ability to assist in holistically identifying external	• Not able to take into consideration the relations and interactions between factors (Yüksel, 2012) • Not a systematic approach; • Not able to undertake a pairwise comparison of the options; • Does not identify internal factors of the organization; • Inability to rank external factors; • Inability to enhance stakeholders to have consensus on focus areas • Not able to measure consistency • Enables the consideration of sustainability factors
Life Cycle Assessment (LCA)	• Because it is holistic, systemic and rigorous, Life Cycle Assessment is the preferred tool when it comes to access information about potential and real impacts of products life cycle (UNEP, 2009). • Results of an LCA study will let companies know which aspects of their production are efficient, and where they can improve efficiency to reduce environmental impacts (UNEP, 2009).	• Life cycle assessments, until now, have generally been used to analyse the effects that a product or process will have on the environment (UNEP, 2009). • In many cases it has concentrated on the assessment of the financial and technical feasibility of a project only (Lopes & Flavell, 1998)

Tool	Abilities/Advantages during strategy formulation	Limitations/Disadvantages during strategy formulation
• Social and socio-economic life cycle assessment (S-LCA)	• Enable the making choices will have social and socio-economic effects as well, not only on workers but also on entire communities where production takes place (UNEP, 2009). • Social and socio-economic life cycle assessments add extra dimensions of impact analysis, valuable information for those who seek to produce or purchase responsibly (UNEP, 2009).	• Databases for specific social and socio-economic impacts are at a minimum (UNEP, 2009). • They are challenging to conduct because qualitative data is often subjective and therefore must be handled by capable experts (UNEP, 2009).
Value chain and Value chain analysis	• Defines a representation of a firm's value-adding activities, based on its pricing strategy and cost structure (Porter, 1985). • Value chain analysis can be used to formulate competitive strategies, understand the source(s) of competitive advantage, and identify and/or develop the linkages and interrelationships between activities that create value (Ensign, 2001). • The identification of phases of the value chain that need to be focused on from the beginning and up to the end of the programme; • Allocation of appropriate resources for the various phases to be started and completed • The estimation, evaluation and quantification of value to be derived within each value chain phase • Enables the visualization of areas in which an organization or country can be involved in	• Cannot assist in giving a measure of intangible factors • Not able to measure the consistency of the decision-making process

In the next Methodology chapter, the decision-making techniques (AHP, PESTEL, SWOT and LCA) described in this chapter are combined and superimposed on ten nuclear facilities as part of developing the conceptual SA decision-making model and meeting the set specific objectives. The aim is that components of the model will complement each other with their individual attributes. In addition, an instrument derived from the model is used for gathering and archiving strategic factors data. This is undertaken in a standardised structured and retrievable manner to enable further case study qualitative and quantitative analysis.

3 Research Design and Methodology

3.1 Introduction

In this chapter, the overall research study design is presented. This was preceded by development of two conceptual models that were later consolidated into one final conceptual model. As per stated objective in Section 1.2.2, the three hierarchal model conceptions combined the popular decision-making techniques (PESTEL, SWOT, LCA and AHP) respectively presented in Sections 2.3, 2.4, 2.5, 2.6, thereby enhancing chances of their respective qualities to complement each other during the utilization of the models.

The secondary data gathering or nuclear sector strategic factors collection and archiving structure instrument derived from the conceptual model is presented in Section 3.3. The collected data in the form of external and internal strategic factors are documented in a retrievable manner from Section 3.3.1 to Section 3.3.10. Thus, the partial meeting of the other objective that was aimed at demonstrating the model's ability to be used to collect and archive the SA nuclear sector related data in a retrievable manner. The other aspect of the objective i.e., the analysing of internal and external SA nuclear sector factors for strategic decision-making purposes is met in Chapter 4 through the case study.

3.1.1 Research Study Design

The key activities and processes undertaken for this empirical research study are shown in Figure 3-1 below. The figure depicts a hybrid (mixed) research design enabling the collection of secondary data for generating primary data for strategic decision-making purposes. All the indicated twenty-five steps or processes enabled the systematic iterative and integrative model development and utilization in this chapter and the ensuing Chapter 4.

It is important to note that SA sector related literature review for secondary data gathering and analysis (refer to step 5 to step 8 of Figure 3-1 below) is guided by the following criteria:

- Whether the factors contained in the literature is related to the listed nuclear facilities;
- Whether the identified factor can be categorised within the SWOT's strengths, weaknesses, opportunities and threats categories;
- Whether the identified factor can be categorised as per PESTEL political, economic, social, technological, environmental and legal categories;
- Whether the factor is within one of life cycle phases as per life cycle assessment; and
- That the collected data or documented factors have to be ultimately operationalised for decision-making purposes using step 11 to steps 25 of the research design (Figure 3-1). These steps are based on the qualitative and quantitative analysis attributes of the AHP technique.

Convenience and purposive sampling were ascertained to be the most appropriate for this research study. Convenience and purposive are non-random sampling techniques that are easy to set up and are affordable in terms of cost. However, they have the following disadvantages:

- The non-random selection of participants results in the researcher being subjective and biased in choosing the subjects of the study (Etikan, Musa & Alkassim, 2016);
- According to Business Research Methodology (n.d.) purposive sampling is vulnerability to errors in judgment by researcher, has low level of reliability and high levels of bias, and cannot be used to generalize research findings.

The above mentioned sampling shortcomings were minimised by the utilization of firstly the UNICEF and HBR Guidelines which caused the participants to use a common basis for interpreting e.g. the categories of the factors. The utilization of extraction and listing instrument further minimised the biasness by virtue of participants having a similar way verifying the secondary data during the case

study phase. Matrix questionnaires reduced biasness by providing standard guide for conducting AHP pairwise comparison surveys. Lastly, the measuring of participants' comparison judgements consistencies also in the case study phase provided the final biasness reduction effort.

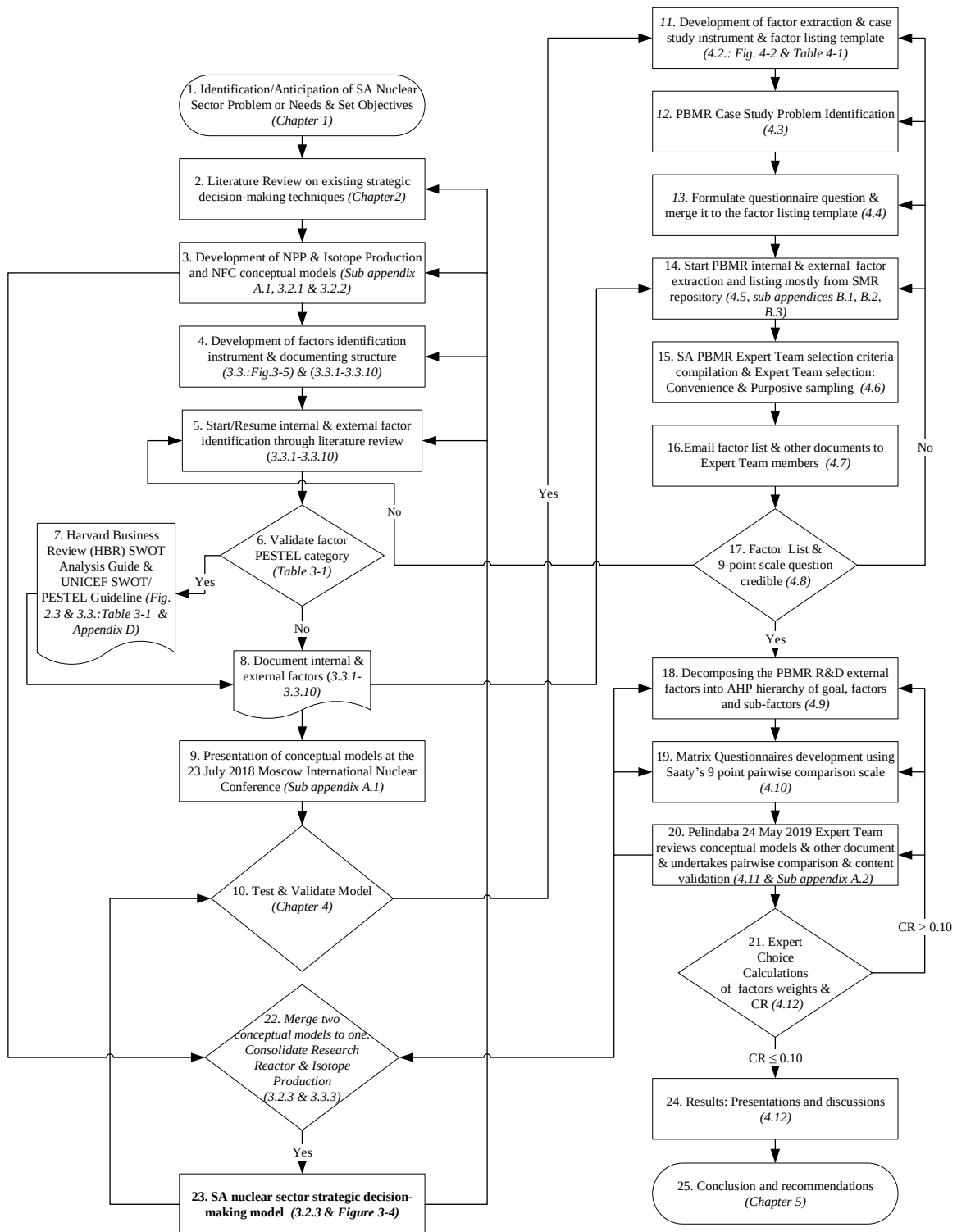


Figure 3-1: Developing & utilization of the SA nuclear sector strategic decision-making model

3.2 Hierarchical Conceptual Models

3.2.1 NPPs and Isotope Production Conceptual Hierarchical Model

Figure 3-2 below shows the conceptual model for identifying and qualitatively and quantitatively analysing local and international nuclear industry factors that have a potential to inform the strategic decision-making process. The basis of analysis is the hierarchical conceptual model structure of the AHP technique hence it shows the links i.e. from the bottom of the nuclear facilities (level 5) to the value chain (level 4) which is linked to the PESTEL analysis (level 3). The lines also show a link between the PESTEL and SWOT. The top level is the goal, which is the identified and analysed nuclear industry factors relevant to making decisions on PWR, research reactor, small modular reactor and radioisotopes production facilities.

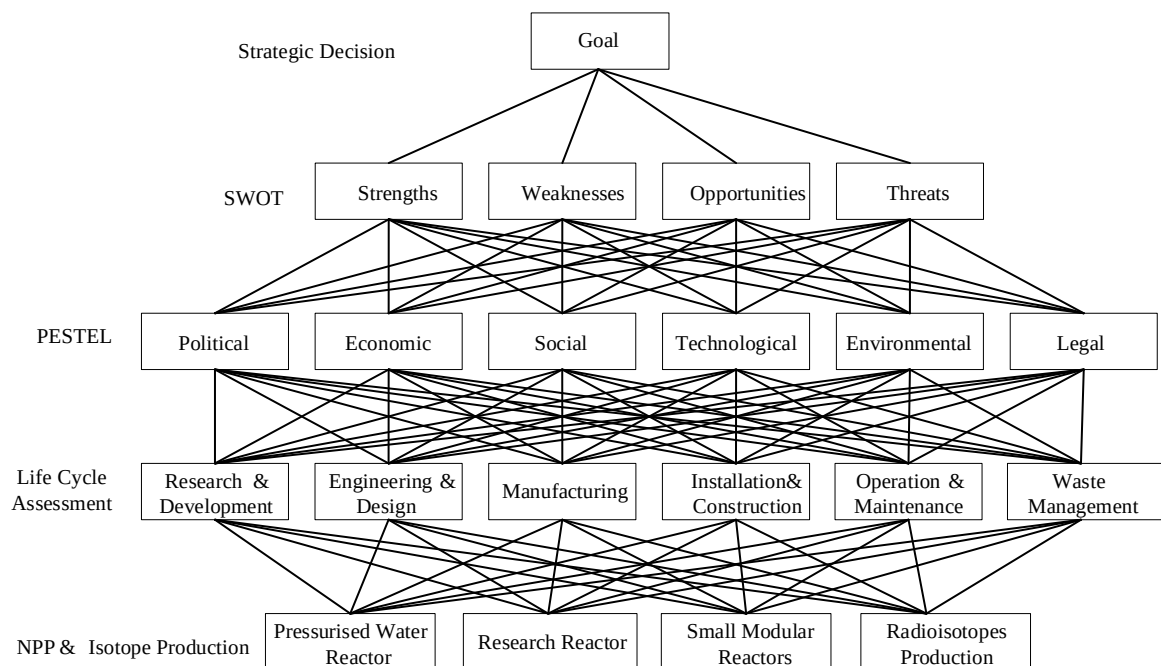


Figure 3-2: NPPs and Isotope Production AHP Factors Identification and Analysis Conceptual Model

3.2.2 Nuclear Fuel Cycle Conceptual Hierarchical Model Development

For the initial identification and qualitatively and quantitatively evaluation of local and international nuclear industries' nuclear fuel cycle (NFC) value chain factors, the Nuclear Fuel Cycle Conceptual Hierarchical Model (Figure 3-3) below was used. This AHP based model is used for identifying and analysing the individual NFC phases' factors from a life cycle, PESTEL and SWOT perspectives.

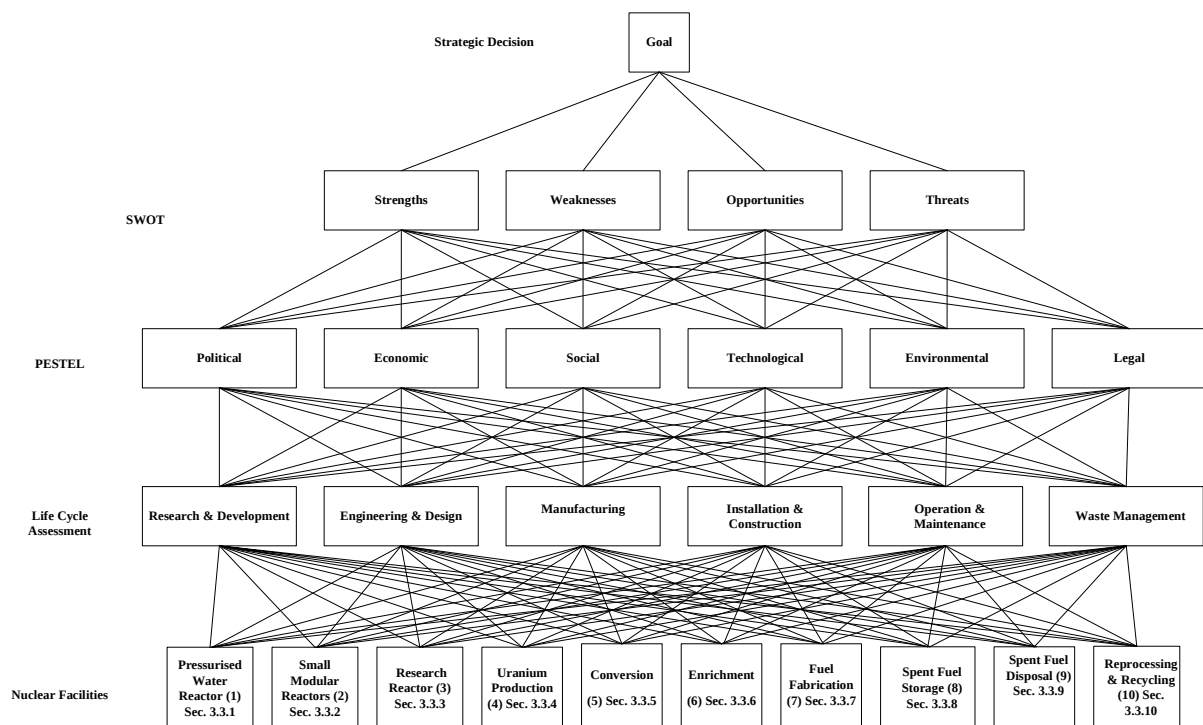


Figure 3-3: Nuclear Fuel Cycle AHP Factors Identification and Analysis Conceptual Model

3.2.3 Consolidated Conceptual Model

At the 23 July 2018 Pelindaba pairwise workshop, the Expert Team (ET) recommended that the conceptual models shown above as Figure 3-2 and Figure 3-3 needed to be merged into one hierarchical structure. In addition, the ET suggested that the isotope production strategic factors needed to be consolidated into the RR category. The reasoning behind the consolidation was that the SAFARI-1

research reactor enabled the SA isotope production. This being the case, Figure 3-4 below shows the consolidated hierarchical conceptual model, which shows all the ten nuclear facilities excluding the isotope production as one of the nuclear facilities or categories. Accordingly, all the isotope production strategic factors appear within RR category. In the main, the PESTEL enables holistic identification of the SA nuclear industry related factors that are ultimately summarised and categorised as per SWOT technique categories namely strengths, weaknesses, threats, and opportunities

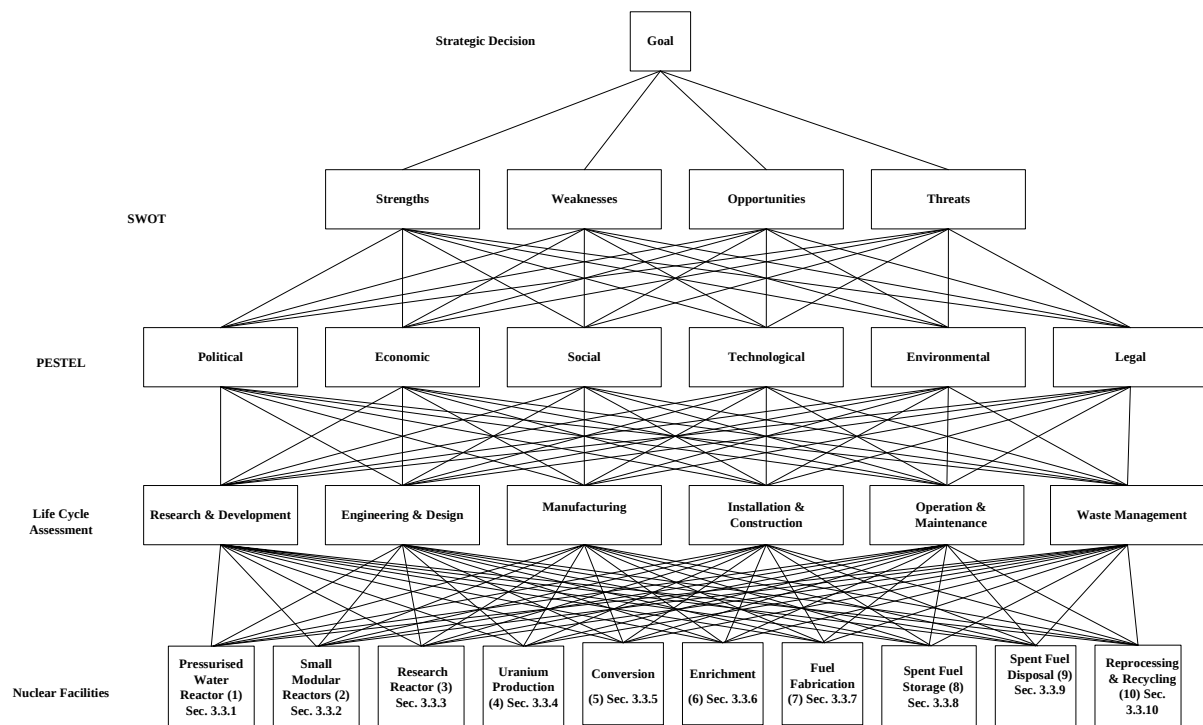


Figure 3-4: SA Nuclear Sector Strategic Decision-Making Conceptual Model

3.3 Instrument for Nuclear Sector Secondary Data Collection and Documenting in the Repository

Figure 3-5 below shows the internal and external factors identification and documenting structure instrument derived from the consolidated conceptual model. It depicts the approach which was followed

in identifying, structuring and documenting strategic factors (secondary data) for the individual 10 nuclear facilities or areas (pressurised water reactor, research reactor, small modular reactor, uranium production, conversion, enrichment, fuel fabrication, reprocessing and recycling, spent fuel storage and spent fuel disposal) shown above in Figure 3-4. The generic nature of the model is demonstrated through the utilization of the below instrument for collecting secondary data for each nuclear installation. The utilisation of the instrument at this stage of the study demonstrates some aspects of model but at the same time prepare for the accomplishment of the other objectives namely:

- Synchronisation which enables the simultaneous utilization of qualitative analysis qualities of the four decision-making techniques
- Reflect on possible needs that will need to be responded to as far as the ten nuclear facilities are concerned so as to have a value adding and forward looking secondary data collecting process;
- The superimposing of the amalgamated techniques on the ten nuclear facilities acts as unravelling guide for or trigger of the possible future needs that will need responses. As an example SA might have need to select one PWR or SMR partner among many possible international nuclear vendors. This triggers the advance gathering of secondary data on the PWR and SMR technologies and their owners so that such data can be operationalised for decision making purposes;
- Documenting of the secondary data in the repository, which enables reviewing of the data and updating, based on immediate or future needs. This responds to the continuous collecting of data aspect of the objective.

For validating and verifying (refer to steps 6 and 7 in Figure 3-1 above or steps 3 and 4 in Figure 3-5 below) the placing or categorization of the strategic factors, the Harvard Business Review (HBR) SWOT Analysis Guideline (Figure 2-3) and UNICEF Guideline (Table 3-1 shown below) and in Appendix D were used. The guides assisted in checking the factor categorization from both SWOT and

PESTEL perspective. In this regard, steps 3 and 4 are vital in situations in which there is ambiguity in terms of categorization of factors during the data gathering process.



Figure 3-5: Internal and External Factors Identification and Documenting Structure Instrument

Table 3-1: UNICEF PESTEL Factor Categorization Guide

A. Political
1. Government policies: National, state/provincial, local, other.
2. Government resource allocations.
3. Stakeholder needs or demands.
4. Lobbying/campaigning by interest groups: local, national, international. Influences/pressures from international actors, e.g. other governments, international organizations, etc.
5. Armed conflicts.
6. Changes in power, influence, connectedness of key relevant actors/groups.
7. Expected direction of future political change: future policy prospects; upcoming elections and possible change in government (local, state, national) and its consequences; other relevant political trends.
B. Economic
1. Economic situation: local, national, regional, global.
2. Economic situation of specific relevant communities or population groups (including employment, taxation, mobility, etc.).
3. Economic situation and prospects of any relevant industries.
4. Infrastructure: local, national, and other.
5. Financial situation of key partners or other relevant entities.
6. Availability of private sector resources relevant for the project/initiative.
7. Expected direction of economic change: prevailing economic trends, trade and market cycles; expected economic interventions by governments and their consequences; other relevant economic trends.
C. Social
1. Demographics and population trends.
2. Health among populations.
3. Education levels.
4. Access to essential services.
5. Public perceptions (of an issue, an initiative, an organization or other actor).
6. Relevant customs, traditional beliefs, attitudes (e.g. towards children, adolescents, gender, etc.)
7. Media views.
8. Role models, celebrities, spokespersons.
9. Knowledge, attitudes and practices of a particular population group (with regard to a relevant issue).
10. Potential for knowledge exchange.
11. Migration (which also has political, economic and legal dimensions).
12. Major relevant events (upcoming or already happening) and cultural trends.
13. History, to the extent that it affects social attitudes and perceptions.
14. Factors in social identity, e.g. religious, socio-ethnic, cultural, etc.
15. Dynamics of how social change happens in the given context.
16. Management style, staff attitudes, organizational culture (within a major relevant organization).
17. Expected direction of social change: broad trends in change of social attitudes (e.g. towards a relevant issue); other relevant social trends.
18. Credibility of information sources or communication channels (e.g. media outlets, well-known individuals, etc.) among a target population. Reach of information sources/communication channels among a target population.
D. Technological
1. Population groups' access to technologies.
2. Patterns of use of existing technologies (which may be changing, e.g. evolving use of mobile phones).
3. New technologies that could impact the context significantly, or that could be used to achieve objectives
4. Technologies and related infrastructure/manufacturing / importing requirements for an initiative to succeed
5. Possible replacement/alternative technologies
6. Potential for innovation
7. Technology transfer, access, licensing issues, other issues related to intellectual property rights.
8. Foreseeable technological trends: economic and social impact of adoption of existing technologies; rate of technological change; other technological trends.
E. Environmental
1. Contextually relevant environmental issues: global (e.g. climate change), regional (e.g. flooding, droughts, etc.) or local (e.g. contamination of water supplies).
2. Relevant environmental regulations or requirements (e.g. for assessing potential climate change impacts of specific activities, conforming to national or international environmental regimes, etc.).
3. Environmental impacts of planned or ongoing activities
4. Climate, seasonality, potential impacts of weather.
5. Trends or expected future developments in the environment.
6. Geographical location

F. Legal
1. Human rights (including but not limited to child rights and gender rights).
2. Existing legislation having an impact on any relevant factors (economic, social, technological, environmental or other factors relevant to the issue), or affecting population groups relevant to the issue, or impacting the work of the organization or its partnerships.
3. Pending or future legislation.
4. International treaties/agreements, either existing or in preparation.
5. Standards, oversight, regulation and regulatory bodies, and expected changes in these.
6. Ethical issues.

Source: https://www.unicef.org/knowledge-exchange/files/SWOT_and_PESTEL_production.p

3.3.1 Pressurised Water Reactor Factors

South Korea credited the success of its NPP localization programme to the internal and external factors shown below in Table 3-2.

Table 3-2: Success factors of the South Korean technological localization

Internal Factors	External Factors
Aggressive development strategies and programmes of the government	The willingness of foreign donors to transfer technology (Market conditions)
The leading role of the utility firm	Absence of international lobby in collaboration with local lobby groups against nuclear programmes (Social conditions)
The development and cooperation of the related organizations	
The development of human resources and their self-dedicated efforts	

Source: *Sung and Hong (1999)*

The South African nuclear industry and its stakeholders need to generate e.g. pressurised water reactor construction information continuously so as have an appreciation of local and international factors that can impede or enhance the successful planning and implementation of such initiatives. It is because of having such secondary data well ahead of time that brings about more effective strategic decision-making resulting in the realisation of set political, economic, social, technological, environmental and legal objectives. This possible renaissance for nuclear power plants is fuelled basically by two arguments: one, its relatively low carbon emissions; and second, its higher security of supply and lower price volatility compared to fossil fuel alternatives (Linares & Conchado, 2013). According to the NEA and IAEA (2014) report, key factors influencing future nuclear energy capacity include:

- projected baseload electricity demand;

- the economic competitiveness of nuclear power plants as well as funding arrangements for such capital-intensive initiatives;
- the cost of fuel for other electricity generating technologies;
- non-proliferation concerns; and
- proposed waste management strategies and public acceptance of nuclear energy, which is a particularly important factor in some countries after the Fukushima Daiichi accident.

Since the dawn of democracy in 1994, SA has been grappling with when and how to fund the procurement and when to construct additional NPPs for generating electricity. Koeberg NPP installed in the 1980s, is still the only nuclear plant in Africa that generates electricity. The apartheid government sponsored the Koeberg NPP construction. Table 3-3 below shows different funding methods or strategies employed in different countries to enable nuclear new builds as of March 2017.

Table 3-3: Funding methods as of March 2017

Country	Units	MW _e	Construction Start	Financing Type/Model
China	22	20,500	2009-2015	Government/Vendor
Russia	7	5520	1983-2010	Government
India	5	2990	2002-2011	Government/Vendor
USA	4	4468	1972-2013	Government/Private sector
UAE	4	5380	2012-2016	Government/Vendor
South Korea	3	4020	2008-2013	Government
Pakistan	3	2343	2011	Government/Vendor
Belarus	2	2218	2013-2014	Government/Vendor
Japan	2	2683	2007-2010	Government/Other
Slovakia	2	880	1985	Government/Corporate Finance
Ukraine	2	2068	1986-1987	In process
Argentina	1	25	2014	Government
Brazil	1	1245	2010	Government/Vendor
Finland	1	1600	2005	Government/Corporate Finance/Project Finance (Mankala Model)
France	1	1600	2007	Corporate Finance

Source: Barkatullah and Ahmad (2017)

Rather than rely on learning curves to predict future costs, decision makers should focus on pursuing and developing policies that aim to drive the price of clean energy technologies down i.e., innovation policy, industrial policy, trade policy, and energy policy (Lovering & Nordhaus, 2016).

According to Thomas (2012), since 1998, the South African government and Eskom have pursued nuclear power with enthusiasm, but with no success. Around 2005 the South African utility Eskom spent time and resources planning for a 20GW PWR programme that was code-named “nuclear one”. I took part in the weekly workshops that were conducted at Eskom’s headquarters in Johannesburg at which domestic South African industry, various government departments, utility personnel and McKinsey consultants deliberated on how and when critical PWR SSCs and related services were to be localised. The strategic decision-making process for or against implementation of NPP installation can be more daunting because of the following factors or occurrences:

- Recent nuclear new builds in the USA and Europe had to be abandoned or discontinued due to e.g. construction cost overruns which rendered them uncompetitive when compared to other electricity generating technologies;
- In South Africa, there have been different strong sentiments among stakeholders about which electricity generating technologies should be implemented when, how, by who and why?
- One of the biggest needs or expectations from the public in a developing country like SA is for the Government to stimulate economic growth and increase the social rate of return through initiatives undertaken by state owned entities. The South African SCM Review Update, 2016 also stated that procurement of goods, services and works over the next three years were to amount a total of R1.5 trillion across all spheres of government;
- High level of misconduct perceptions in SA connected with the implementation of state-owned entities’ initiatives;

- In the case of SA and other countries or democracies, nuclear infrastructure programmes are undertaken by state owned entities that have to motivate for e.g. funding and guarantees from the state;
- Installation of NPPs has to compete with other electricity generating technologies for implementation funding;
- The nuclear industry is highly regulated and infrastructure installations have to go through a significant number of approval gates as compared to non-nuclear energy technologies;
- Those responsible for implementation of NPP construction have to convince stakeholders that nuclear facilities will meet the stringent safety requirements taking into consideration public fears and perceptions due to nuclear incidents namely USSR's Chernobyl, USA's Three Mile Island and 2011 Fukushima accident in Japan;
- Proponents of nuclear programmes have to convince those in favour of other technologies that e.g. the political, economic, social, technological, environmental and legal benefits will surpass benefits from non-nuclear technologies; and
- Policymakers have to convince both the nuclear programme proponents and opponents that the capacity allocated to nuclear is appropriate. Golay (2001) noted that those against nuclear have been able to utilise the decentralised structure particularly the US safety regulatory system, which is not accountable for the economic implications of its decisions and processes to make it effectively impossible to build new NPP, and to make it needlessly expensive to operate the existing ones.

With the aforementioned challenges in mind, the development of a strategic decision-making model is crucial in enabling stakeholders to have consensus in responding to the when, who, what, and how aspects of the SA new nuclear build. The development of nuclear power industry largely relies on policy, while policy-making is dependent on various factors, including economic, political and social factors (Zeng et al., 2016).

3.3.1.1 PWR Political Factors

Linares and Conchado (2013) acknowledged that a nuclear policy should not only consider economic costs but also consider all advantages and disadvantages of nuclear power plants to make a final decision; whether to allow new investments or forbid them, whether to penalize nuclear power plants or support them. The steadily growing public reluctance, especially in the most developed countries, to accept new large industrial facilities has an impact on choices and policies in the electricity sector and affects the implementation of all power plants, irrespective of their type (IAEA, 1997). In countries where the political climate is overwhelmingly against nuclear power and where nuclear power accounts for a large share of electricity generation, the NPP managers are confronted with an interesting societal dilemma: they have to defend the *raison d'être* of their industry while maintaining capability for a steady supply of electricity for society (Kettunen, Reiman & Wahlstrom, 2007). Collective political actors such as political parties, interest groups, or administrative agencies in democratic systems need to collaborate with others in order to get access to information and resources, influence decision-makers, coordinate their activities, set up advocacy coalitions, and thereby achieve their policy preferences (Fischer, 2015). Notably, governments of the world have indicated a desire to reduce emissions of carbon dioxide; the agreement implementing the outcomes of the 2015 Paris Climate Conference of the United Nations Framework Convention on Climate Change is the most salient indication of these policies (Magwood & Paillere, 2018). The SA government needs to be clear in its various policies such as the Nuclear Energy Policy and National Development Plan (NDP) in terms of which SOEs and what roles they should play when it comes to partaking in local, regional and global endeavours. Table 3-5 below shows approaches in the international political economy, in general on energy issues in different countries in the world. For example, Europe is a classic example of liberalised region whereby nuclear entities such as EDF and Areva offer their services across the region. Electricité de France (EDF) is a vertically integrated energy group with a diversified presence in France, the UK, Italy, Belgium, Hungary, Spain, Poland, Switzerland, the Netherlands, the US, Austria, China, Laos, and Vietnam (Electricité de France, 2017). Table 3-4 below shows the different combinations of risks allocation

arrangements and financing arrangements on new nuclear builds in liberalised and regulated markets. The strategic decision-making model can be used by SA government for selecting the best method of financing SA nuclear new builds by taking a leaf at how similar initiatives have been funded in other countries.

Table 3-4: The different combinations of risks allocation arrangements and financing arrangements on nuclear new builds in liberalised and regulated markets

Type of reforms	Decentralised market industries with IPP companies	Decentralised market industries	Liberalised industries with large vertical companies	Liberalised industries with medium-size vertical companies
Reference case	South Texas Project	Finnish plant Olkiluoto III	French EPR Flamanville 3	UK projects US project Eastern Europe projects
Allocation of Construction risks	On Government <i>Standby insurance</i> <i>Governmental loan guarantee on 80%</i>	On Vendor <i>Turnkey contracts</i>	On producer	On producer consortium
Allocation of market risks on consumers	PPA with municipalities / historic suppliers	PPA with large industrial users / historic suppliers	Large base of sticky consumers	Large base of sticky consumers
Structure of financing	Project finance	Hybrid finance	Corporate finance	Corporate finance
Capital structure ratio debt/equity	70/30	75/25	50/50	50/50
WACC In nominal	9.2%*	5%	9.3 %	NA

Source: Finon and Roques (2008)

*Assumption: Normal financing conditions equivalent to those on coal and gas generation projects with 12% of Return on equity and 8% of interest rate on debt in nominal and after tax.

In SA, the financing of PWR construction has been a major challenge unlike the financing of coal and renewable installations. This being the case, one would expect SA entities such as Eskom, NECSA and the SA supply chain e.g. construction industry to collaborate in raising funding and undertaking energy new builds in the SADC region. In SA, it seems there is no concerted effort to utilise the capabilities within the SOEs to realise some of the NDP objectives. In the absence of appreciating and harnessing the SOEs potential, the realisation of the NDP objectives remains a pipe dream. The promotion of regional integration is part of the SA government policy as reflected in its NDP. The NDP states that

SA needs to implement a focused regional integration strategy with emphasis on the following, which also includes energy related initiatives:

- Road, rail and port infrastructure in the region;
- Reducing red tape, corruption and delays at border posts;
- Using financial institutions to partner with businesses wanting to expand on the continent;
- Strengthening regional cooperation in food and energy markets and water management; and
- Identifying and promoting practical opportunities for cooperation based on complementary national endowments.

According to Zeng et al. (2016), in recent years the Chinese State Council has approved NPP construction in succession and implemented a series of nuclear policies to approve nuclear power by undertaking the following:

- (1) After Japan's Fukushima accident, the government of China improved the safety standards of national nuclear power to improve the safety level of nuclear power and develop a safe, efficient nuclear industry;
- (2) Because current nuclear units are distributed in coastal areas, new nuclear units will be constructed in inland areas that are densely populated, such as Jiangxi, Hunan, Guangxi, Sichuan and Henan; and
- (3) Economisation of China's nuclear power industry will realise the domestication and standardisation of nuclear facility production and mass production based on the introduction of foreign advanced technology and independent development. This economisation will also reduce the costs of nuclear power efficiently.

Changes within the energy markets have tested the viability of established NPP industries. Finon and Staropoli (2001) noted the exposure of the French national nuclear system in recent years to a series of external shocks such as the liberalization of the European power markets, a depression in the worldwide nuclear market, competition from new power generation technology such as gas turbines, and the internationalization and concentration of the electromechanical industry. As shown in Table 3-5 below, the state remains apart from energy issues, allowing free markets to play the dominant role when liberalization is the option.

Table 3-5: Major approaches in international political economy, in general and on energy issues

	Primary assumptions, key actors	Energy assumptions, actors, examples
Realism	• The world is prone to conflict. States cannot trust other states or international organizations; • States are the most important actors.	• States should control energy as a means to power; • Russia's use of natural gas pipelines to exert pressure on Ukraine and Belarus is an example of realist energy policies.
Liberalism	• The world tends toward cooperation; • While states are important, there are many other key actors, such as parliaments, lobbying organizations, and multinational corporations	• The state should remain apart from energy issues, allowing free markets to play the dominant role; • Key players include private energy companies, consumers; • Australian policy in which the state does not subsidize energy companies and there are no energy "champions" is an example of energy liberalism.
Neo-Liberalism	• Same as liberalism, but with a focus on institutions, such as the United Nations and NATO	• International organizations can play a key role in energy issues; • OPEC, International Energy Agency, International Monetary Fund, World Bank, and World Trade Organization are key energy actors; • Without OPEC, the oil exporting states would have even less control over global energy prices.
Historical structuralism, critical theories	• Non-material factors, notably ideas (fascism, capitalism, Marxism) and identities (based on gender, historical culture, etc.) often play a key role in world events. IPE scholars should explain how ideas and identities at the local, national and global levels form and change.	• Ideas about the value of energy, which energy forms are best, how gender affects views of energy, and a state's identity on energy issues (as separate from material wealth) are constructivist approaches; • India's position as a developing state that identifies with and leads poor countries against the developed global North is being contested by policy makers.

Source: Hancock and Vivoda (2014)

3.3.1.1.1 PWR R&D Political Considerations

In various countries, the research and development on nuclear power are driven by government policies and legislation. De Jesus (1983) noted that most of the nuclear field scientific research carried out in

South Africa was directly or indirectly sponsored by the Government through its agencies such as Nuclear Development Corporation of South Africa (NUCOR) (former Atomic Energy Board) and Uranium Enrichment Corporation of South Africa (UCOR) that have perhaps played the greatest role. In this regard presently, the SA Nuclear Energy Act stipulates that NECSA's responsibility is to undertake nuclear R&D. Despite the operating of Koeberg Nuclear Power Station (KNPS), SA has not been undertaking any PWR related R&D unlike other countries such as France, USA, Russia, Canada, China and South Korea. Specifically, in France, the Ministry of Industry has always played a central role in co-ordinating (Finon & Staropoli, 2010). In the aforementioned countries, the government policies aimed from the onset at developing indigenous PWR technologies. According to Valentine and Sovacool (2010), nations that have staunchly supported a nuclear power development path include Japan, France and South Korea yet countries that feature fluctuating levels of support and opposition include the United States, Canada and Taiwan. Ideally, the SA ASME entity and its supply chain could have been given an advantage of manufacturing and supplying e.g. KNPS's spent fuel plant casks if there was a deliberate arrangement supported by NECSA's R&D. An American entity known as Holtec, made a strategic decision to focus on providing nuclear waste solutions in the USA and abroad. China, France and South Korea are examples of countries that adapted a PWR value chain localization and technology transfer strategy when they initiated their nuclear programmes. According to Chadda (2009), countries derive the following benefits through NPP localization:

- Saving foreign currency;
- Increase in capacity factor and reduction in gestation period for timely supply of spare components, from localized suppliers;
- Quality management culture to local suppliers. This additionally offers a strong driving force to improve the quality of both nuclear and non-nuclear products and competitiveness;
- This benefit of nuclear power technology transfer is also propagated into other industrial sectors including steel-making, ship-building as well as heavy equipment manufacturing; and

- For the new entrants or also those who are in the process of adopting and scaling up manufacturing capacities as per improved and latest machineries and technology, cannot evolve competitively in isolation until tailored to safety, quality, regulatory international standards and rules

3.3.1.1.2 PWR Engineering Design Political Considerations

In 2017, the ASME entity at NECSA designed an ASME III air receiver for the KNPS as part of its “N” Stamp recertification. In South Korea, Doosan that has ASME III N Stamp certification provides design engineering design services for the supply of nuclear and non–nuclear components e.g. steam generator forgings and machining of ship crankshafts.

3.3.1.1.3 PWR Component Manufacturing Political Considerations

The SA Department of Science and Technology sponsored the initial ASME III certification of the NECSA pressure vessel-manufacturing unit. Strategically positioning through SA government issued mandate for the ASME entity to be the main supplier of manufactured nuclear sector plants components can enhance its viability. The same manufacturing capabilities can also be utilised to supply components to other sectors such as those for the oil and gas sectors. The South Korean entity Doosan was deliberately set to manufacture ASME III pressure vessels such as steam generators and reactor pressure vessels for the South Korean nuclear industry. Diversifying the market supply enables Doosan to have additional revenue streams. Component design and manufacturing technologies for PWR plants as well as turbine generator were set up at Doosan that became a private entity in 2000 and today it is by far the largest producer of desalination plants in the world, particularly well known to Middle Eastern customers like UAE (Kim, 2011).

3.3.1.1.4 PWR Construction Political Considerations

Since 1994, SA has been making efforts to increase its PWR electricity generating capacity based on its Energy Integrated Resource Plans but with no success. According to UNICEF (2015), changes in power is one of the factors that has an impact in government policies. The 2018 change of the political

administration in SA caused a shift from implementing the 9600 MW PWR installation to the implementation of the renewables programme. Otherwise, worldwide the recent construction cost overruns, time overruns and nuclear accidents due to natural disasters have negatively influenced NPP installation initiatives. According to Magwood IV and Paillere (2018), the cost of constructing and operating NPP is under tremendous scrutiny in the shadow of recent financially prompted plant closures and cost overruns in highly visible nuclear new builds. The Fukushima disaster has had perhaps an even stronger negative impact worldwide, leading to Germany, Switzerland, and Italy to announce plans to phase out their nuclear power programmes and causing China to suspend approvals for new reactors (Davies, 2012). Nevertheless, South Korea is a good example of a government taking a strategic decision of building a fully-fledged local PWR SSCs supply chain that has eventually gone international. In 2011, South Korean firms celebrated their first international bidding success on winning a \$20 billion contract to build four nuclear reactors in the United Arab Emirates, outcompeting French, US and Japanese firms (Metzler, 2012).

3.3.1.1.5 PWR Operation and Maintenance Political Considerations

The new challenges in nuclear waste management are to extend the life of existing and new wet and dry storage facilities and guarantee their safe performance for much longer periods of time (Fukuda et al., 2003). Nuclear accidents due to natural adversities such as earthquakes and tsunamis can result in countries policy shifts. The Fukushima disaster triggered three reactor meltdowns, a series of explosions and a radiation leak that forced 150,000 people to flee nearby villages (Słodkowski & Saito, 2013). Table 3-6 below lists policy responses taken by various countries after the Fukushima accident that took place in March 2011. Specifically, Figure 3-6 below shows that when the meltdown at Fukushima-Daiichi Nuclear Power Plant happened on March 11, 2011 it resulted in a series of plant shutdowns and a second Nuclear Phase out Bill in Germany.

Table 3-6: Policy responses to the Fukushima Daiichi accident

Countries	Policy responses
Belgium, Germany, Switzerland	Nuclear phase out - no new build
Japan	Plants under construction suspended, Fukushima 1-4 earmarked for decommissioning, remaining 50 plants successively shut down by 5 May 2012. Two restarts in July 2012. Future use of nuclear power contested. Subsequently, phase out intentions by late 2030s announced
China	The award of new construction licences was suspended but lifted again in October 2012
Belarus, Turkey, UAE	First plant ordered
Chile, Indonesia, Malaysia, Morocco, Thailand, Saudi Arabia	Active preparation with final decision delayed or no final decision
Bangladesh, Vietnam, Egypt, Jordan, Nigeria, Poland	Continue preparing infrastructure
Italy, Kuwait, Senegal, Venezuela	Plans to introduce nuclear power cancelled

Source: Rogner (2013)

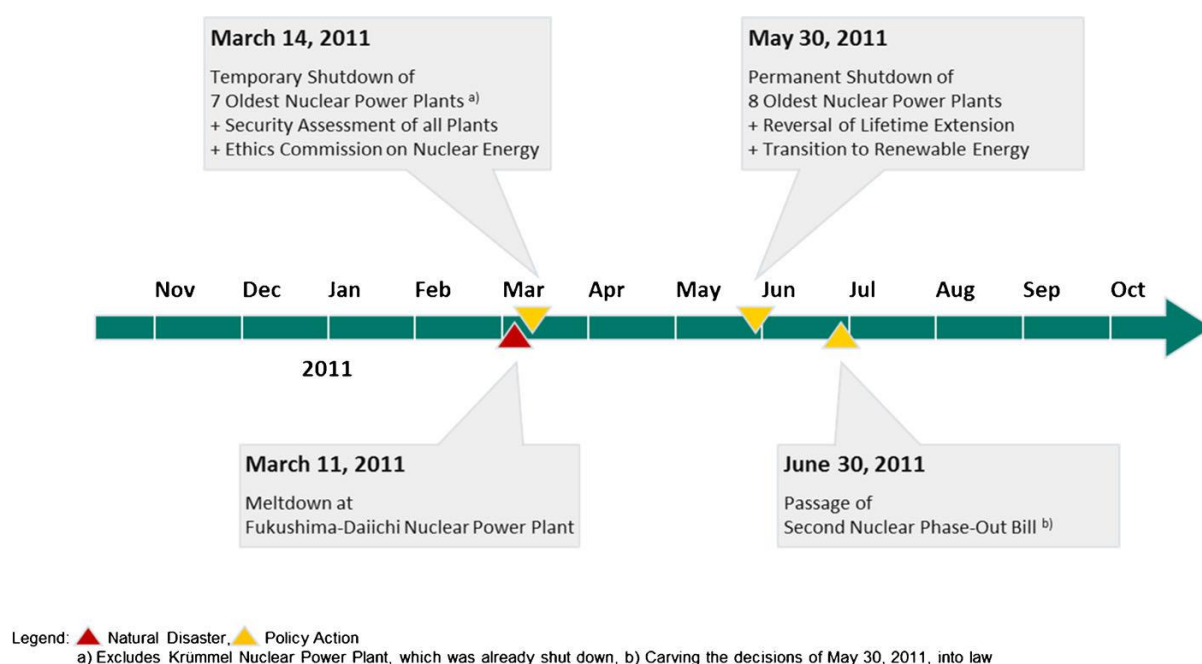


Figure 3-6: Timeline of policy action following Fukushima

Source: Goebel et al. (2015)

The SA government support of the continued operation and life extension of the Koeberg Power Station is well articulated. According to the IRP (2019), Koeberg Power Station reaches end of design life in

2024 and in order to avoid the demise of the nuclear power in the energy mix, South Africa has made a decision regarding its design life extension and the expansion of the nuclear power programme into the future.

3.3.1.1.6 PWR Waste Management and Disposal Political Considerations

A typical 1,000 MWe PWR operating at about 90 percent capacity factor with a burnup level of 50,000 MWth-Day/MT will discharge about 20 MT of SNF per year (Braun & Forest, 2013). Nation states have taken different paths to nuclear waste management and are at various stages of the development of a nuclear waste management strategy (Sanders & Sanders, 2016).

According to the IAEA (2009g), the development of the strategy for managing spent fuel and radioactive waste must incorporate relevant national policies e.g. as follows:

- National policy on the recycling and reuse of materials;
- National policy on the clearance of materials from regulatory control;
- National policy on environmental protection (in some countries, certain disposal options are not allowed, e.g. surface disposal of radioactive waste);
- National policy on the export/import of radioactive waste, e.g. conditions on the import and/or export of radioactive waste; an intention to store/dispose of radioactive waste on national territory; and/or an intention to seek international/regional solutions;
- National policy on the management of spent fuel, e.g. whether spent fuel is considered as a resource (with the application of reprocessing i.e., nationally or internationally), a waste (with the intent to dispose of it as a waste) or whether it is intended to return spent fuel to the supplier;
- National policy on the management of disused sealed radioactive sources, e.g. return of the disused sealed radioactive sources to the supplier; management of the sources on national territory; or international radioactive waste management solutions;
- National policy on the management of naturally occurring radioactive materials (NORM), i.e. whether NORM is regulated as a radioactive material or as a chemically toxic material; and

- National policy on public information and involvement, e.g. the State's position on informing and consulting the public about proposed plans for radioactive waste management.

3.3.1.2 PWR Economic Factors

In the Index of Economic Freedom (2018) list of 180 countries in the world SA is ranked 77th which gives it a mostly free economic freedom score. SA takes the fourth highest position in Africa trailing Mauritius, Botswana and Rwanda who are respectively 21st, 35th and 39th on the world stage. The World Bank (n.d.) states that SA's GDP per capita in 2017 was \$6,151.08 with that of Mauritius, Botswana and Rwanda being at \$10,490.50, \$7,595.61 and \$748.29 respectively. Income per capita is a measure of the amount of money earned per person in a certain area and it can apply to the average per-person income for a city, region or country, and is an indicator of the living conditions and quality of life in different areas (Wikipedia, 2018). A trend commonly experienced by the SA electricity utility is that of payments defaults by municipalities. In its Integrated Report (2018) Eskom reported that total invoiced municipal arrear debt (shown in Figure 3-7) increased significantly, to R13.6 billion (including interest) at year end (March 2017: R9.4 billion) and the top 20 defaulting municipalities constitute 82% of total invoiced municipal arrear debt. The mentioned defaults have detrimental effects on the SA utility's balance sheet, which needs to be healthy for it to maintain plants or for it to be able to finance new generating capacity.

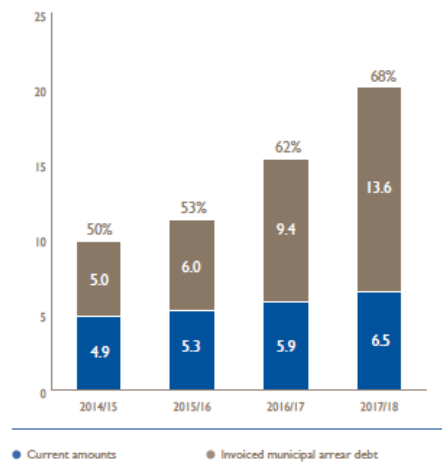


Figure 3-7: Invoiced municipal arrear debt (including interest) and arrear debt percentage at 31 March 2018, R billion

Within the energy market, the financing of PWRs has to compete not only with non-nuclear electricity generating technologies but also with other types of nuclear reactors such as small modular reactors (SMR) and boiling water reactors (BWR). The main reactor types currently competing in the international nuclear power market are the BWR and PWR (pressurized water reactor), and Hitachi and GE believed that they needed to combine their business resources and adopt a common strategy to promote the BWR globally (Masui et al., 2008). Similarly, SA can adopt a strategy in which a nuclear entity can form an alliance with a well-established nuclear vendor to develop PWRs for the African continent market. The abundance of shale gas in the USA has affected the NPP installation. The deployment of additional PWRs or continuing operation of some existing NPP in the USA is being impacted upon by less expensive energy feed stocks such as gas which have drastically reduced the cost of energy. According to Kidd (2013), gas plants are now a formidable rival to nuclear in competitive power markets, where future selling prices of electricity are also uncertain. On the same note, Bill Mohl the president of Energy Wholesale Commodities was quoted by Forbes (2017) stating that record low gas prices due primarily to supply from the Marcellus Shale formation, have driven down power prices by about 45 percent, or by about \$36 per megawatt-hour, over the last ten years, to a record low of \$28 per megawatt-hour. At times, a comparison of PWRs against coal-fired plants is undertaken when

decisions are to be made on which electricity-generating technologies should be prioritised for installation. Since NPP compete mainly with fossil fuels, one can ascertain that nuclear power can become competitive if the economic impediments for nuclear power principally those related to the delays involved in plant licensing are relieved, and if the external costs of fossil fuels, particularly the costs of mitigating greenhouse gases, are included in their electricity generation costs (Rosner, 2008).

According to the NEA (2016), financing new NPPs is so difficult and complex because of:

- unstable electricity prices in a liberalized market;
- electricity market designs that do not provide investment signals for low-carbon technologies;
- insufficient carbon pricing to promote nuclear investments;
- explicit governmental support for renewables;
- uncertain and changing political support;
- poor social and political perception of safety;
- historical nuclear new build budget and schedule overruns; and
- long-term nature of capital investments.

Specifically, for NPP economic characteristics include investment costs, fixed and variable operation and maintenance costs, imported and domestic fuel costs and estimates of levelized costs and shadow prices (IAEA, (2009f). This being the case, the NEA (2016) suggested that the following in order to address key challenges for financing new NPP:

- conducting electricity market reform to level the playing field across all energy sources;
- demonstrating an ability to construct NPP in time and budget;
- removing taxes and penalties explicitly placed on nuclear;
- establishing strong governmental support for nuclear energy;
- harmonizing regulatory requirements internationally;

- employing effective programme management mechanisms;
- communicating clearly and early with all stakeholders;
- demonstrating a strong nuclear safety culture;
- choosing proven technologies for deployment;
- leveraging contracting mechanisms to ensure a long-term revenue stream; and
- employing vendors and operators with positive nuclear experience.

A method to measure economic growth rate involves inquiring whether there has been a real increase (excluding price increases) in GDP (Gross Domestic Product) from one year to the other as GDP represents the market equivalent of all measurable values produced by one economy (Caliskan, 2015). According to WNA (2019), early in 2016 Rosatom said that Russia's GDP gained two roubles for every one rouble invested in building nuclear power plants abroad, as well as enhanced trade. It is normal for governments to fund and guide their NPP entities and then latter on be at arm's length as entities become financially secure. Minin and Vlcek (2017) noted that in future ties between Rosatom and the government will be of lesser importance, allowing for increased financial independence on the part of the company, which is earning an increasing share of its revenues from profitable nuclear new builds abroad at the same time its share of electricity on the domestic free market is gradually rising. According to Brook et al. (2014), important conditions for economic viability of nuclear energy are:

- presence of a 'level playing field', i.e. an open market that is not skewed in favour of some technologies by means of subsidies and/or by a legally imposed priority access for delivery to the electrical grid at a fixed high price that are unavailable to nuclear;
- standardization of the plants, built in large series and supported by a standardized supply chain;
- a long-term governmental energy policy (stable over a time period of several decades) including, among other features, good (unbiased, accurate, evidence-based) public information;

- a stable and streamlined licensing process that is technology-neutral, risk-informed and capable of resolving promptly any safety issues that may arise during construction and operation;
- careful siting considerations to avoid areas most prone to severe natural hazards; and
- introduction of the concept of payment for ‘external costs’ (e.g. air pollution, solid wastes, decommissioning) that is applied to all energy technologies based on common standards.

The French nuclear industry ranks first on the world market of nuclear equipment and services (Finon & Staropoli, 2001). This being the case, the nuclear electricity generation in France has had profound impact in the French economy. According to the INE (1990), the French nuclear energy has had the following impact on the French economy:

- the nuclear industry involves 120 000 jobs;
- has significantly improved the balance of payments by reducing energy imports and making electricity exports possible;
- sector basically includes electricity generation power plant construction and maintenance fuel cycle industry;
- nuclear technologies need a lot of capital investment (mainly from loans, some from foreign countries); and
- added value or the money earned by the operation of the facilities.

3.3.1.2.1 PWR R&D Economic Considerations

The French company EDF reported revenues of (Euro) EUR71, 203 million for the fiscal year ended December 2016 (FY2016), a decrease of 5.1% over FY2015 (MarketLine Company Profile: Electricité de France (2017). New nuclear build is characterised by 3 years for preparation, 5 to 6 years for construction and high front-end cash outflows of €4 to 5bn for a 1500 MW FOAK plant and €3 bn for a standard plant compared to an investment cost of €500 million for a large 600 MW CCGT (Finon &

Roques, 2008). Similarly, Poneman (2017) stated that nuclear power plants are expensive, typically costing more than \$5 billion to build a 1,000-megawatt facility, which produces roughly enough electricity to power a city the size of San Francisco. According to NEA (2009), investing in new NPPs can be challenging because of the following:

- the high capital cost and technical complexity of NPPs, which present relatively high risks during construction (delays and cost overruns) and operation (equipment failures and unplanned outages); and
- The relatively long period required to recoup investments or repay loans for NPP construction, which increases the risk from electricity market uncertainties.

Otherwise, research, development and demonstration (RD&D) will require significant investments with strong support from governments in order to develop new technologies to realize the full potential of nuclear in the fight against climate change (IAEA, 2016). Table 3-7 below shows a summary of Generation III/III+ reactors that are presently ready for commercialization. Finon and Staropoli (2001) noted that the new competitive electrical supply industry (ESI) is not favourable to nuclear investment for two main reasons: the high capital intensity of the equipment, which imposes long pay-out beyond the profitability horizon of private producers, and specific risks perceived by investors (such as regulatory risk, political risk of shut-down and a nuclear phase-out).

Table 3-7: Summary of Generation III/III+ reactors ready for commercial deployment as of Dec. 2017

Vendor	Design/ Technology Name	Reactor Type	Electricity Generation Capacity
Areva	EPR (III+)	PWR	1650
AECL	Enhanced CANDU 6 (III)	HWR	700
	6 (III) ACR-1000 (III+)		1200
CNNC-CGNPC	Hualong One (III)	PWR	1150
GE-Hitachi/Toshiba	ABWR (III)	BWR	1350
GE-Hitachi	ESBWR (III+)	BWR	1520
KHNP	APR-1400 (III)	PWR	1400
MHI-Areva	ATMEA1 (III+)	PWR	1100
MHI-Westinghouse	APWR (III)	PWR	1700
Rosatom	AES-2006 (III+)	PWR	1200
SNPTC	CAP-1400 (III)	PWR	1500

Vendor	Design/ Technology Name	Reactor Type	Electricity Generation Capacity
Westinghouse	AP1000 (III+)	PWR	1200

Source: Nian (2018)

3.3.1.2.2 PWR Engineering Design Economic Considerations

The French and South Korean PWR programmes have benefited from having standardised designs. A standardised design reduces engineering costs, licensing problems, equipment prices, construction time and site costs (Plante, 2000). According to Grubler (2010), the reasons behind the French PWR programme being the most successful scaling up of a complex large technology are the following:

- a unique institutional setting allowing centralized decision-making,
- regulatory stability,
- dedicated efforts for standardized reactor designs (which benefited from knowledge spill overs via the Westinghouse license), and
- a powerful nationalized utility, EDF, whose substantial in-house engineering resources enabled it to act as principal and agent of reactor construction simultaneously.

Along with the maturity of a project, the status of a project can be in the conceptual design phase, basic design phase, or detailed design phase (Cho et al., 2011). Hence, the incorporation of standard features is in the conceptual design up to detailed design phase. Besharatia, Azarma, Kannan, (2006) noted that the following three main factors influence a successful product design selection:

- a) market demand based on customers' preferences;
- b) designer's preferences based on his/her knowledge and experience with design issues and market issues; and
- c) uncertainty in achieving the predicted design attributes levels or performance.

NPP designers ensure that the components, systems and structures of the plant have the appropriate characteristics, specifications and material composition, and are combined and laid out in such a way as to meet the general plant performance specifications (INSAG, 1999).

3.3.1.2.3 PWR Manufacturing Economic Considerations

Traditionally, manufacturing refers to an industrial production process that transforms raw materials into finished products for selling in the market (Esmaeilian, Behdad & Wang, 2016). Cost reductions are realised across the fleet of NPP plants during the fabrication of SSCs because of standardization. Indoctrinating personnel on manufacturing processes and quality standards is more effective when there is repetition of fabricating items of the same design features. The efficiencies result in cost reductions since e.g., manufacturing equipment setup time is reduced. The French nuclear manufacturing supply chain benefited from manufacturing standard SSCs since enhanced learning reduced operational costs. In SA like in other countries such as France, S Korea and China a nuclear new build programme composed of a PWR fleet of the same design can enhance the establishment of a nuclear components manufacturing supply chain. Ability to adhere to ASME codes and standards will be one of the requirements for the entities supplying materials and components. Manufacturer qualification must consider the manufacturer's staff, fabrication facilities, testing equipment and quality assurance (Roos et al., 2014). Benchmarking against competitors is necessary in situations in which competitive advantage is possible by utilising existing resources and capabilities or in situations whereby resources and capabilities that are still to be developed (Dombrowskia et al., 2016). According to Hallgren and Olhager (2006), the basis of manufacturing firms' ability to create strategic alignment between market opportunities and manufacturing capabilities is their competitive position. Conditions in which a manufactured component is used can determine the complexity category of a manufacturing firm or its section i.e. in situations in which an entity manufactures a variety of products under one roof. For instance, a firm or a section within the same firm that manufactures nuclear safety grade components will be more complex e.g. in terms of component cost structure or quality requirements as compared to a firm or section that manufactures NPP balance of plant components. ElMaraghy et al. (2012) noted

that the categories for complexity in manufacturing processes are as follows: (i) complexity of manufacturing complex parts, (ii) complexity in assembly, as well as (iii) combinatorial complexity costs due to product variety. The Civil Nuclear Sharing in Growth (CNSIG) is a four-year programme of high-intensity support for 10 key suppliers, which is responsible for developing the UK manufacturing (IAEA, 2014).

De Wet (2020) reported that the SA Koeberg Power Plant 20-year life extension was part of an upgrade which cost in excess of R5billion and the steam generators (SG) are highly complex, designed in France and fabricated in China. The Chinese fabricator Shanghai Electric is the entity which has the capability to manufacture SGs and reactor pressure vessels (RPVs). Figure 3-8 below shows the first of six SGs having been delivered to SA and being readied to be transported to Koeberg Nuclear Station from the Cape Town harbour.



Figure 3-8: The first of the six Koeberg steam generators in Cape Town

3.3.1.2.4 PWR Construction Economic Considerations

South African entities were encouraged to participate in providing services during the Koeberg Nuclear Power Plant construction in the Western Cape Province. For economic reasons and in the interest of South Africa's foreign exchange budget, foreign input on design and on construction work, especially for civil and structural works, could be reduced (INE, 1990). Table 3-8 provides a list of SA entities and the services they provided during Koeberg installation.

Table 3-8: Local entities that provided services during the PWR installation in South Africa

	South African Company	Services provided during Koeberg Construction
1.	African Cables	Various electrical cables.
2.	Alfa Laval (Alsa)	Turbine lubricating oil purification plants, heat exchangers, inter coolers
3.	Air Products	Bulk and cylinder gases, gas reticulation
4.	Atomic Energy Board of South Africa	Licensing

	South African Company	Services provided during Koeberg Construction
5.	Babcock Africa	Turbine hall and radioactive waste piping.
6.	Barlows Heavy Eng.	LP inner casings.
7.	Brodericks Engineering	HP outer casings, bearing pedestals
8.	Brown Boveri	Switchgear, electrolyzers.
9.	Cape Steel (Consani)	Reinforced stop logs, hangers, embedded steelwork
10.	Cape Quarries Assn.	Crushed stone aggregate and rubble (Ready Mix Materials)
11.	CGEE Alstom (Cegelec)	C&I Systems
12.	Chubb	Security doors.
13.	Circle Pumps (Mellor Pumps)	Various pumps
14.	CIW	Water treatment, condensate polishing plants, potable water lines, deluge systems.
15.	Cold Air Installations	Ventilation systems for external buildings
16.	Cyclops	Engineering Tanks.
17.	Dillinger Engineering	Pipework erection.
18.	Elca Engineering	Governing fluid tanks associated pumps, pipes
19.	Floccotan	Activated carbon for water purification.
20.	Genrec and Wadeville Engineering	Exhaust box sole plates, turbine hall and fuel handling cranes and structures, condenser shell fabrication and erection, general installation and heavy lifting
21.	J C Groenewaldt	Electrical and instrumentation
22.	A G Haeffele Sons	Waterproofing
23.	Harrison White	Electrical and instrumentation
24.	Hawker Siddeley Brackett	Circulating water filtration
25.	I.E.S. (Cementation)	Cooling water system butterfly valves
26.	Industrial Machinery Supplies (IMS)	Emergency diesel generating sets for admin building; quality control and contract engineering support services for consortium members Alstom and Framatome
27.	Insor	Security analysis and concept, planning and engineering
28.	John Thompson Africa	Auxiliary boiler plant
29.	Kaefer Insulation	Turbine and pipework insulation sound hoods
30.	Krugersdorp Engineering	Tanks, Vessels
31.	Lloyds Register	Inspection of turbine casings, electrical ducting
32.	LTA	All reinforced concrete work, structural steelwork
33.	Mannesman Demag	Polar Crane, handling systems
34.	Murray Roberts	Civil works, reinforcing steel, structural steel, nuclear piping, air conditioning, electrical work, plumbing, water proofing crane installation, crushed aggregate
35.	Plascon	Decontaminable paints, water-based epoxies
36.	Pretoria Portland Cement	Cement, especially sulphate resistant cement
37.	R J Southey	Painting, application of water-based epoxies
38.	Schindler	Security access control systems.
39.	Simon Carves	Seawater chlorination system
40.	Southern Pipeline Contractors	Cooling water ducts
41.	Universal Engineering	Brackets, steelwork
42.	Vecor Heavy Engineering	BP stop and governor valves, sole plates

	South African Company	Services provided during Koeberg Construction
43.	Watermeyer Halcrow & Partners	Feasibility studies; design and installation complete sea water cooling system, intake basin, pump station, outfall.

Source: INE (1990)

Capital cost is the most important factor in the economic aspects of a nuclear power plant due to the large upfront cost (Graves et al., 2015). Linares and Conchado (2013) contend that of total costs for nuclear electricity, approximately 70% come from investment cost (20% from O&M costs, and 10% from fuel). Thomas (2010a) noted that the construction cost parts are made up of three elements: the cost of building the plant; the cost of capital to finance build; and the reliability of the plant (the more out put the plant produces, the more thinly the fixed costs can be spread). Construction and commissioning are the phases during which the civil works are carried out, the components and subsystems are mounted and tested and the whole plant is thoroughly tested (Bredimas, (2014).

The success of a construction business depends upon its understanding of how internal and external factors affect the business and how to deal with them (cidb, n.d.). The internal and external factors might be respectively be identified by examining the availability of resources within the company and in its supply chain. Evaluation of the competitiveness will require the examining of its internal capabilities and those of its partners who are involved in its products or services. This being the case, the availability of private sector resources relevant to nuclear new builds is an economic imperative (Upson & Baker, 1996). The companies' competitiveness is also constrained by legislation within a specific country in which it is operating. The common key risks identified by the top-10 SA construction companies within the South African environment include risks to transformation, health, safety and environmental sustainability, followed by growth and expansion, and compliance with laws and regulations (PWC, 2013).

Four-unit NPP construction by Rosatom abroad keeps 24,000 people in work in various segments of the nuclear industry inside Russia, while each rouble of the nuclear loan brings 1.8 roubles into the economy by way of orders for Russian enterprises, including fuel supplies, staff training, decommissioning services, and so on (Minin & Vlcek, 2017). Likewise, the Nuttall and Storey (2014) publication states that the 104 nuclear units in the U.S. generate substantial domestic economic value in electricity sales and revenue of \$40-\$50 billion each year with over 100,000 workers contributing to production. In Europe, France is one country that has benefited from the operation of its PWR fleet. According to Kidd (2009), electricity is France's fourth-largest export and next-door Italy, without any operating nuclear power plants, is Europe's largest net importer of electricity, most of it ultimately coming from France.

Despite the installation of 500 NPPs and a number of other nuclear facilities throughout the 20th century, the on-time construction completion is still an enormous challenge due to a number of uncertainties and risks (Invernizzi, Locatelli & Brookes, 2017). The Nolan and Xiaoqiang (1999) study that reviewed the latest nuclear new builds in the world concluded that out of 35-cost reduction opportunities identified the ones shown in Table 3-9 below are suggested findings aimed at reducing nuclear new build cost and risk within the listed UK programme cost driver categories. For instance, as shown the first finding was to complete plant design prior to starting construction. This was indicated as being within the vendor plant design category.

Table 3-9: Prioritised actions for reducing UK nuclear new build costs and risks

Finding	Cost Driver Category
1) Complete plant design prior to starting construction	Vendor Plant Design
2) Follow contracting best practices	Project Development and Governance
3) Project owner should develop multiple units at a single site	Project Development and Governance
4) Innovate new methods for developing alignment with labour around nuclear projects	Labour
5) Government support should be contingent on systematic application of best practices and cost reduction measures	Political and Regulatory Context

Finding	Cost Driver Category
6) Design a UK programme to maximise and incentivise learning, potentially led by a newly-created entity	Political and Regulatory Context
7) Government must play a role in supporting financing process	Political and Regulatory Context
8) Transform regulatory interaction to focus on cost-effective safety	Political and Regulatory Context

Source: Energy Technology Institute (2018)

3.3.1.2.5 PWR Operation and Maintenance Economic Considerations

EDF's high level of vertical integration gives it the freedom to run operations independently to an extent and it also enables the group to reduce costs by streamlining different processes, as it can exercise more control over its processes. In SA, local e.g. plate material, forgings and dish end suppliers do get opportunities to be involved in the Koeberg NPP SSCs replacements i.e. on their own or in collaboration with NECSA. For instance, a SA private sector construction company Group 5 was involved in the removal and replacement of Koeberg nuclear power plant refuelling water storage tanks (PTR). On this component replacement, NECSA was responsible for supplying the duplex stainless-steel materials by virtue of having the ASME III certification, which gives it a Material Organization (MO) status. The duplex stainless steel from which PTR tank shells were fabricated was manufactured by the Columbus Stainless factory based in SA having been qualified and then latter supervised by the SA ASME III material organization. This therefore is a typical example of how the maintenance support of the local PWR can provide revenue for both the ASME III entity and companies that constitute its supply chain. The lack of sufficient infrastructure installation initiatives in SA is presently affecting most of the big local construction companies, thereby weakening future nuclear energy sector installation resources. In different regions of the world, there have been various strategic efforts aimed at developing supply chains to support the nuclear new builds and for the maintenance of NPP that are in operation. A study by KPMG estimated SA's Koeberg Nuclear Power Station's combined impact through investment and operations over the period 2012-13 to 2015-16 was ZAR53.3 billion of which ZAR30.2 billion was in Western Cape and ZAR23.1 billion in the rest of South Africa (KPMG, 2017). It is therefore important

for nuclear programme planners to highlight the benefits derived from NPPs during their operation and maintenance. Taking a strategic decision that most of the NPP maintenance services provision should be made by domestic entities requires planning accordingly in terms of the right NPP capacity that will stimulate the local supply chain to invest in supporting the local utility's maintenance and operation programme. Based on economic benefits experienced by countries that have significant numbers of installed NPPs, South Africa has been considering its own fleet approach for the its nuclear new build.

3.3.1.2.6 PWR Nuclear Waste and Disposal Economic Considerations

As part of the nuclear fuel cycle back-end, concrete casts accommodate weld-sealed stainless-steel canisters that contain NPP spent fuel for dry environment storage in several countries (Matsumura, 2008). Otherwise, the AREVA group performs all operations in France for the back-end nuclear fuel cycle (MarketLine Company Profile: EDF, 2017). In particular, the French reprocessing capacity and technology is a major export earner (Kidd, 2009). Low wholesale prices have accelerated reactor closure plans and Holtec predicts the U.S. decommissioning market could be valued at around \$14 billion in 2018-2028 (Nuclear Energy Insider, 2018). Considerable decommissioning work is expected in the years to come based on the that 157 nuclear power reactors worldwide have been permanently shut down or are undergoing decommissioning (IAEA, 2016e). Cho et al. (2011) noted that calculating both the net present value (NPV) and levelized unit costs (LUC) is important just as establishing the effect of the following cost factors on competitiveness for each storage type:

- the sensitivity analysis on discount rate,
- metal cask price,
- operation and maintenance (O&M) cost of metal cask, and
- facility size.

3.3.1.3 PWR Social Factors

The Human Development Index was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone (UNDP,

2018). Gao et al. (2018) contend that nuclear power has undesirable side effects from potential hazards such as nuclear accidents, radioactive exposure, ecological pollution, nuclear proliferation, and threats related to terrorism. Besides political trust, certain interests or value preferences regarding green development and climate mitigation also increase nuclear legitimacy among the public (Dai, 2017).

Table 3-10 below shows events classifications on the scale of seven levels: Levels 4–7 are termed “accidents” and Levels 1–3 “incidents” (IAEA, 2013c). Chernobyl and Three Mile Island were respectively level 7 and level 5 on the International Nuclear and Radiological Event Scale (INES). From a social perspective, the Three Mile Island nuclear accident of March 1979 had profound negative impacts. Table 3-11 below shows aftermath after the Three Mile Island accident in the USA. In March 2011, an unprecedented large earthquake and resulting tsunami led to the Fukushima Daiichi plant in Japan losing on-site electrical power for so long that three reactor cores melted, hydrogen explosions wrecked the upper part of the reactor buildings where the spent fuel pools were, and widespread radiation releases resulted (McDonald, 2016).

Table 3-10: Criteria for rating events using the International Nuclear and Radiological Event Scale (INES)

Description and ENES Level	People and the environment	Radiological barriers and controls facilities	Defence in Depth
Major accident Level 7	Major release of radioactive material with widespread health and environmental		
Serious accident Level 6	Significant release of radioactive material likely to require implementation of planned countermeasures		
Accident with wider consequences Level 5	- Limited release of radioactive material likely to require implementation of some planned countermeasures. - Several deaths from radiation.	- Severe damage to the reactor core. - Release of large quantities of radioactive material within an installation with high probability of significant public exposure. This could arise from a major criticality accident or fire.	
Accident with local consequences Level 4	- Major release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls. - At least one death from radiation.	- Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory. - Release of significant quantities of radioactive material within an installation with a high	

Description and ENES Level	People and the environment	Radiological barriers and controls facilities	Defence in Depth
		probability of significant public exposure.	
Serious incident Level 3	- Exposure in excess of ten times the statutory annual limit for workers. - Non-lethal deterministic health effect (e.g. burns) from radiation.	- Exposure rate of more than 1 Sv/hr in an operating area. - Severe contamination in an area not expected by design, with a low probability of significant public exposure.	- Near accident at a nuclear power plant with no safety provisions remaining. - Lost or stolen highly radioactive sealed source. - Misdelivered highly radioactive sealed source without adequate radiation procedures in place to handle it.
Incident Level 2	- Exposure of a member of public in excess of 10mSv - Exposure of a worker in excess of the statutory annual limits.	- Radiation levels in an operating area of more than 50mSv/h. - Significant contamination within the facility into an area not expected by design.	- Significant failures in safety provisions but with actual consequences. - Found highly radioactive sealed orphan source, device or transport package and safety provisions intact. - Inadequate packaging of highly radioactive sealed source.
Anomaly Level 1			- Overexposure of the member of the public in excess of statutory limits. - Minor problems with safety components with significant defence in depth remaining. - Low activity lost or stolen radioactive source device or transport package.
		No safety significance (Below scale/Level 0)	

Source: IAEA (2013c)

Table 3-11: Three Mile Island accident and its aftermath

	Enormous effect on the local economy of the Harrisburg, Pennsylvania region
1	Local estimates of wages lost as a result of the accident ranged from \$5.7 million to \$8.2 million in manufacturing
2	From \$2.8 million to \$3.8 million lost in the non-manufacturing sector
3	An estimated \$6 million to \$8 million were lost in revenues partly due to the decline in tourism
4	Losses in the agricultural sector were about \$1 million
5	As some 34,000 people left the area, 256,000 person-days were lost
6	The accident provoked a rash of further nuclear plant new build cancellations and sixteen reactor orders in other parts of the country were withdrawn
7	Utilities in Ohio and Pennsylvania scrapped their plans for 4 nuclear plants despite an existing investment of \$250 million

Source: Nian (2015)

3.3.1.3.1 PWR R&D Social Considerations

Public perceptions of nuclear energy can make or break NPP construction initiatives. Because of concerns about nuclear accidents and the handling and storage of spent fuel, nuclear power has long been controversial among the public (Ho, 2008). Entities in countries in which the nuclear sector is at an advanced stage have invested and keep on investing in developing solutions to avoid past nuclear accidents with the main objective being to avoid safety risks. The public sentiments are to an extent based on e.g. recent and past nuclear incidents and accidents. Hence, assessment and investigations on past nuclear accidents enable the incorporation of new safety features on the existing and future plants. Nuclear power safety depends on the same factors as in any complex industry, among which intelligent planning, proper design with safety margins and back-up systems, high-quality components and a well-developed safety culture (He et al., 2013).

3.3.1.3.2 PWR Engineering Design Social Considerations

The nuclear industry has attempted on several occasions to engage the public at a more fundamental level through consultative processes with varying degrees of success, although it has never gone so far as to incorporate direct public input into nuclear plant design (Goodfellow, Williams & Azapagic, 2011). The trend of the society benefiting from the nuclear programme is more vivid in countries like France that have been consistent in the designing of PWRs. Kidd (2009) stated that the French programme has been led by a technocratic elite, drawn largely from the Corps des Mines, but backed by successive generations of well-educated and trained experts.

3.3.1.3.3 PWR Manufacturing Social Considerations

Thomas (2012) noted that the fact that nuclear power has not come to dominate electricity generation is seen as being due to a combination of public opposition and dealing with the safety issues raised by accidents such as those at Three Mile Island (1978), Chernobyl (1986) and Fukushima (2011).

The primary reason manufacturing exists is to provide the goods, services, and systems needed by society hence manufacturing employs a large segment of society – and the money secured through this employment helps to support families and individuals (Sutherland et al., 2016). According to the USA Department of Commerce, every \$1 billion of exports by U.S. companies represents 5,000 to 10,000 jobs (NEI, 2012). For manufacturing components for Koeberg construction, local companies were also involved in all delivery to site of all cranes, manufacturing of many non-nuclear vessels and other non-nuclear supplies such as piping and steelwork, stainless steel cladding of the reactor buildings, all power and non-nuclear instrument cabling and cable trays (de Vries, 2016).

3.3.1.3.4 PWR Construction Social Considerations

Employment derived from construction of NPPs is one of the benefits derived from such programmes. Both brown and green field NPP initiatives will require competences ranging from artisans to engineers. For the 20% local content during Koeberg construction the French civil contractor invited SA construction companies such as Murray & Roberts, Grinaker-LTA and others to form Koeberg Civil Contractors (KCC) thereby providing work for up to 4000 local workers at the peak of construction (de Vries, 2016). The SA ASME III entity and its local supply chain will therefore benefit from similar nuclear new builds especially when it comes to mechanical works. The best situation is to prepare and position such an entity to partake in the construction or installation of mechanical SSCs within the NPP balance of plant and nuclear island. Figure 3-9 below shows social settings that also manifest themselves in SA environment when state sponsored infrastructure construction initiatives are up for discussion in the public domain. In SA the opposition political parties, media and civil society are heavily active in the NPP construction discourse. Hence, the halting of the additional PWRs technologies procurement process after the opposition political party challenged the process legitimacy through the courts in 2018.

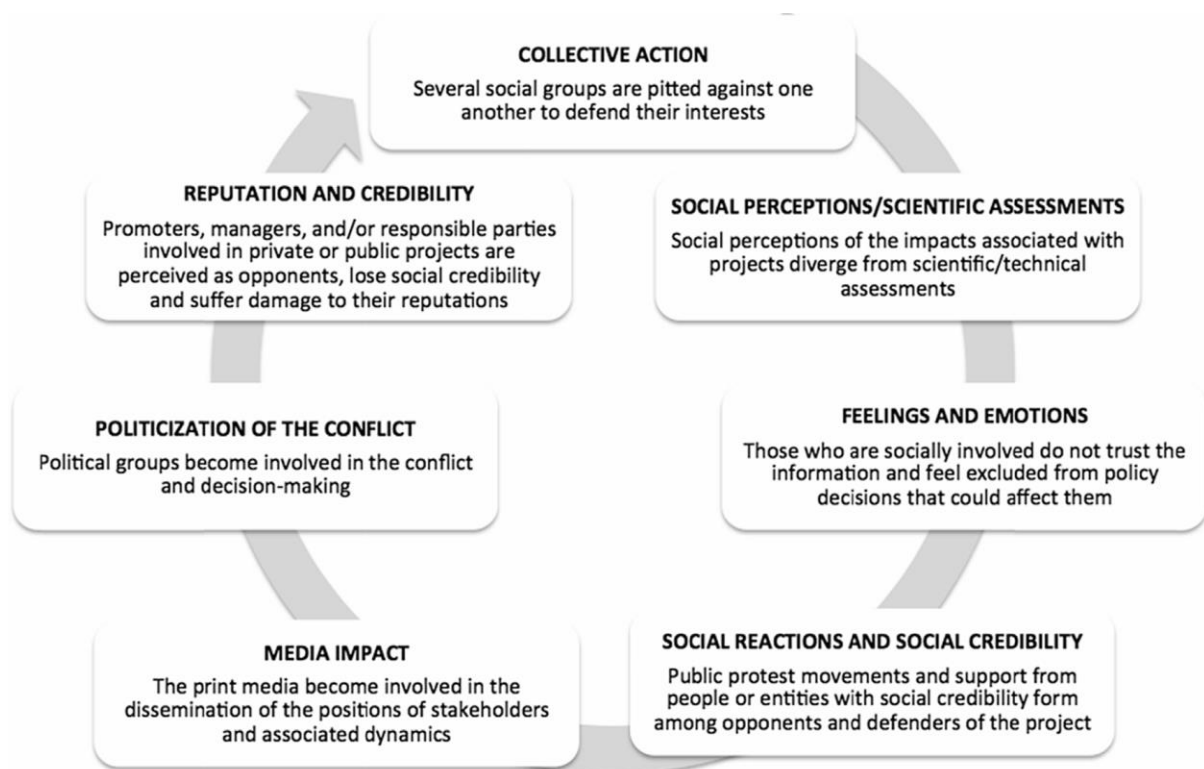


Figure 3-9: Common factors in socio-environmental conflicts (own elaboration)

Source: Gjorgieva, Volkanovski and Sansavini. (2017).

Despite the challenges and setbacks in increasing NPP generating capacity after 1994, it is important to mention that there was technology localization during the SA Koeberg installation in the 80s. For instance, the INE (1990) noted that the transfer of technology to the local manufacturing and construction industries took place mainly in the following fields:

- coastal engineering;
- civil construction procedures;
- de-contaminable paints, water based solvent free epoxies;
- upgrading and testing of steel castings;
- turbine casing manufacture;
- electrical cables,
- water treatment plants; and

- quality assurance

3.3.1.3.5 PWR Operation and Maintenance Social Considerations

Continued high quality operation of nuclear facilities and the progressive implementation of international safety regimes should help in alleviating public concerns (IAEA, 1997). South Africa's Koeberg Nuclear Power station has accorded the country the opportunity of acquiring a wide spectrum of skills in plant operation, radiological and environmental protection and radioactive waste management amongst others (SA National Treasury, 2016). To enable the empowering of individuals for their duties during Koeberg's operational phase, Eskom with the assistance of the Vendors and EdF in France developed detailed training programmes for two pilot groups of 16 recruited from within Eskom, with a sprinkling of ex-nuclear Navy personnel (Oaten, 1990). Ideally, the operation of a nuclear plant requires 400 to 700 direct permanent jobs (NEI, 2012). Table 3-12 below shows a National Energy Institute (NEI) comparison of operational job quantities for different electricity generating technologies.

Table 3-12: Electricity Generating Plants Job Requirements

Technology	Jobs/MWe	Average (MWe)	Size	Direct Jobs	Local	Average Salary (\$/hour)	Workforce Income (\$ Million/year)
Nuclear	0.50	1,000		504		\$31	\$32.49
Coal	0.19	1,000		187		\$28	\$10.99
Hydro>500 MW	0.11	1,375		156		\$33	\$10.79
Hydro Pumped Storage	0.10	890		85		\$38	\$6.70
Hydro>20 MW	0.19	450		86		\$33	\$5.79
Concentrating Solar Power	0.47	100		47		\$27	\$2.62
Gas Combined Cycle	0.05	630		34		\$28	\$2.02
Solar Photovoltaic	1.06	10		11		\$15	\$0.33
Micro Hydro< 20 MW	0.45	10		5		\$35	\$0.33
Wind	0.05	75		4		\$35	\$0.29

Source: Nuclear Energy Institute (2012)

3.3.1.3.6 PWR Waste Management and Disposal Social Considerations

When deciding on a particular waste management system, many factors must be considered including, technical experience, economic, licensability, and public acceptance (Cho et al., 2011). Consideration of the aforementioned factors usually takes place during siting. In the USA, the concentrating locations

at major plants (CLAMP) is a national and region strategy to counter a public not in my back yard (NIMBY) siting reaction (Groult, 2007).

3.3.1.4 PWR Technological Factors

Technology involves application of science especially for industrial or commercial purposes and use of scientific methods and materials in order to achieve a commercial or industrial purpose and making “innovations” to the production machines, production methods and products in order to increase the production volume or efficiency all resulting in competition advantages and profit increases (Cabrera-Palmer & Rothwell, 2008). For resource-poor Japan, developing the most technologically advanced energy infrastructure was akin to developing a new type of resource - a technological resource (Valentine & Sovacool, 2010). In some countries such as Russia, France and South Korea, the choice of technology is the main link to national policy than commercial considerations (WNA, 2013). In the past, technology transfer and joint project developments were the basis of deriving indigenous technologies, as seen in the case of Japan, South Korea, and China, mainly because there were demonstrated Generation II technologies available for direct technology transfer (Nian, 2018).

3.3.1.4.1 PWR R&D Technological Considerations

According to MarketLine Company Profile: EDF (2017), the focus of the French EDF’s research and development initiatives is on developing the following:

- tools and methods to improve operations and optimize the lifespan of facilities without compromising on safety;
- ways of integrating of new technologies and develops technical solutions to expand the life of equipment as well as the transmission capacity of infrastructures;
- cooperation with the sales and marketing teams to develop tools to support customer relations, energy efficiency solutions, and product and service offers; and
- developing tools and simulation models that help to anticipate market trends.

It is envisioned that the archiving of related nuclear sector data in this very section of the study can assist the SA industry sector in meeting the aim of “anticipating market trends” as stated in the fourth bullet point above”. In SA, NECSA’s mandate is to undertake, cause to be undertaken or promote the development of nuclear technology, nuclear-related technology and knowledge, and nuclear research (SA Nuclear Energy Act, 1999). It is in such R&D initiatives that nuclear related products that can become engineering and manufacturing sales opportunities are developed. Throughout the world, the nuclear industry has good examples of entities, which have developed products or technologies through their research and development endeavours. Such initiatives have resulted in downstream manufacturing industrialization for the supply of required e.g. mechanical, control and instrumentation, electrical and civil works components. The ownership of such intellectual property has enabled entities to benefit within all the stages of the value chain. Unlike past situations, newcomers can directly participate in international R&D collaborations without the need to resolve intellectual property related issues arising from a direct technology transfer as seen in CPR-1000 case (Nian, 2018). As an example, the products can be nuclear power plants, canisters for spent fuel, fuel plants, turbines etc. Sealed multi-purpose canisters (MPCs), also called dual-purpose canisters (DPCs), each holding up to 89 fuel assemblies with inert gas, are commonly used for transporting, storing and eventual disposal of used fuel (WNA, 2017).

The development within the supply chain of PWR materials that can withstand radiation and meet safety requirements is important. Figure 3-10 below lists the alloys used throughout the PWR primary and secondary circuits, all of which are in contact with high-temperature water and are subject to significant mechanical stress.

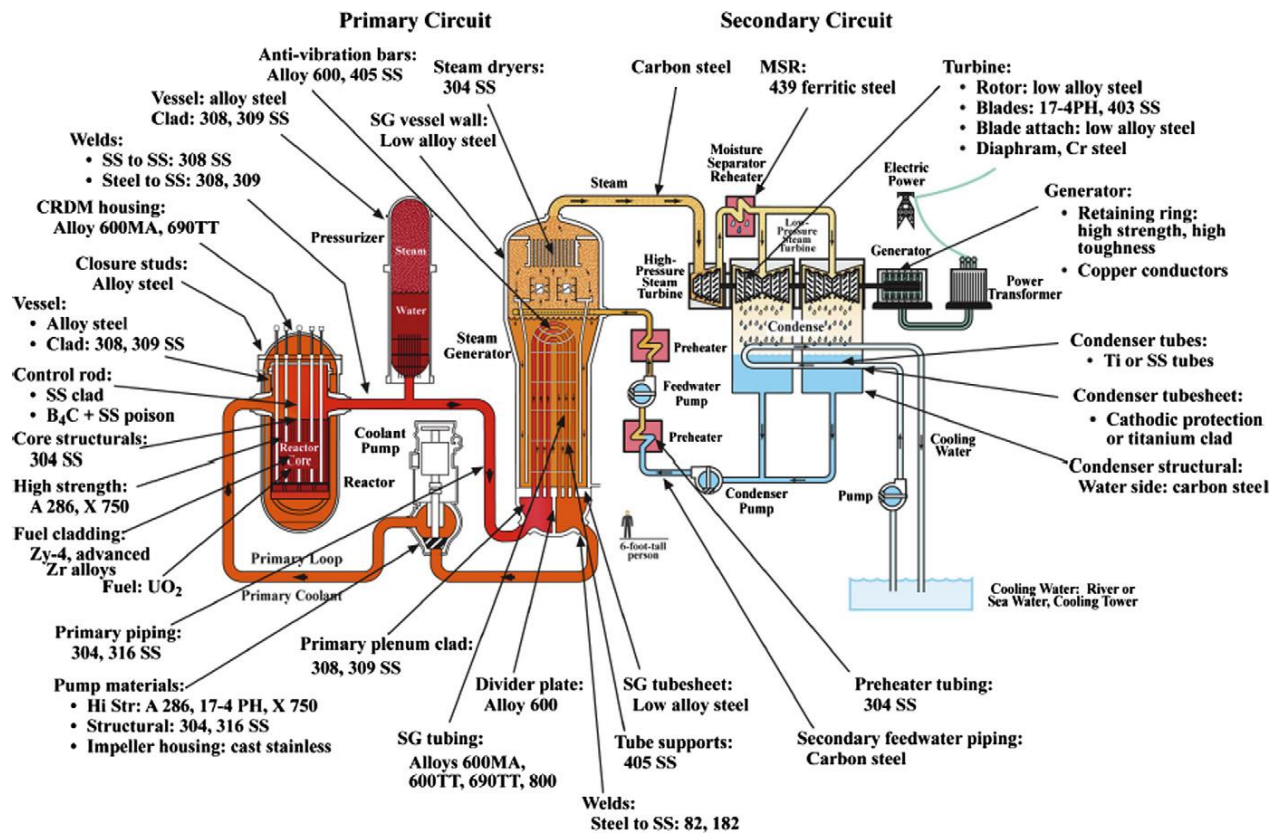


Figure 3-10: Schematic of the primary and secondary circuits of a pressurized water reactor and materials of construction

Source: Zinkle and Was (2013)

3.3.1.4.2 PWR Design Engineering Technological Considerations

According to Thomas (2010b), the EPR design is in crisis as evidenced by the following:

- Construction has gone dramatically wrong at the two sites in Europe where it is being built;
- The prices it is being offered at are so high that all contests where the EPR has been bid have either been abandoned (South Africa and Canada) or the contract has gone to a much lower bid from a competitor (UAE);
- Potential markets such as USA, UK and Italy all look problematic and reactor orders, if placed at all, will be much later than expected; and
- The process of obtaining safety approval in France, UK and USA is incomplete and, even if successful, the features needed to achieve regulatory approval may add significantly to costs.

Technology transfer is a technology factor for consideration when undertaking a PESTEL analysis (UNICEF, 2015). For instance, China and South Korea are good examples of countries that have been recipients of transferred PWR engineering design capabilities from Westinghouse. China is currently benefitting from Generation III technology transfer agreements and it expects that the transfer will allow its nuclear energy sector to become more self-sufficient as it applies the technology domestically and considers exporting its own designs (Zhou et al., 2011). Hence, the National Science and Technology developed the CAP1400 from China's nuclear R&D system and manufacturing capability, as well as AP1000 technology introduction and assimilation that resulted in an advanced large passive PWR with independent intellectual property rights (Zheng et al., 2016). Bearing in mind that NECSA has the responsibility for SA nuclear R&D and managing of nuclear waste from different streams it could have been strategic for them to have developed, designed and licensed spent fuel canisters for Koeberg. If this was the case, then the local ASME III entity could have been involved in the designing and manufacturing of the canisters.

3.3.1.4.3 PWR Manufacturing Technological Considerations

Each multi-purpose canister (MPC) constructed using 13 mm welded stainless steel with a secure lid and internal fuel basket to hold and keep the fuel assemblies separate, is designed for up to 45 kW heat load (WNA, 2017). If NECSA's R&D had developed its own canister technology, it could have enabled its ASME III entity and its supply chain to manufacture the MPCs for local and international spent fuel needs.

3.3.1.4.4 PWR Construction Technological Considerations

According to de Vries (2016), the reference plants for the Koeberg NPS construction were French PWRs as follows:

- Koeberg units were just two units of the French CP1 series of state-of-the-art-plants already under construction in France;
- Bugey for the conventional part of the plant; and

- Gravelines for the seaboard pump house.

As for Koeberg operational and maintenance support, the SA utility Eskom has a list of graded suppliers who are able to provide construction or installations services for the nuclear island, balance of plant and conventional island SSCs. Such installation or construction technologies are required e.g. during the replacement of components such as steam generators and turbines. Some of the technologies are available within Eskom itself such as those found within its subsidiary Rotek which specialises in turbine and generator maintenance i.e., in collaboration with the original technology providers such as Alstom, Siemens and General Electric.

3.3.1.4.5 PWR Operation and Maintenance Technological Considerations

Eskom in collaboration with the French Framatome and EDF developed the initial Koeberg plant operating capabilities. Eskom also takes the lead in making sure that there are always sufficient operational competences and that there is adequate maintenance of Koeberg SSCs in accordance with SA National Nuclear Regulator (NNR) requirements. The National Nuclear Regulator (2017a) noted that during the year under review, the manufacturing of replacement steam generators (RSGs) had progressed at various facilities, with most of the components delivered to Shanghai Electric Nuclear Power Equipment (SENPEC) in China for their final assembly.

3.3.1.4.6 PWR Waste Management and Disposal Technological Considerations

Nuclear power is strategically and quantitatively an important contributor to global electricity generation capacity and produces a small amount of potentially highly hazardous wastes that require careful management (Chapman & Hooper, 2012). Eskom Koeberg procures waste management technologies such as those used for nuclear spent fuel from local and foreign entities. For instance, the US entity Holtec supplied some spent nuclear fuel containers for Koeberg. Local SA entities supply concrete drums for low-level nuclear waste. The low-level waste generated at Koeberg ends up at Vaalputs that is SA's nuclear waste disposal site. Used fuel is currently stored in the spent fuel pools as well as four dry storage casks located in the Cask Storage Building (NNR Annual Report, 2016-2017).

If local spent nuclear fuel (SNF) containers technology was available locally, Eskom could have favourably considered it from a localization point of view. Unfortunately, the required SNF casks for dry storage for Koeberg are from foreign entities that have strategically positioned themselves supply such.

3.3.1.5 PWR Environmental Factors

The international response to climate change began with the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 following the United Nations Conference on Environment and Development (UNCED) or “Earth Summit” in Rio de Janeiro (Weisser, Howells, Rogner, 2008). There is a relatively strong relationship between emissions per capita and income per capita, with wealthier countries having higher emissions per capita due to higher rates of consumption and more energy-intensive lifestyles. Modifying the energy mix in South Africa is extremely challenging, especially since a rapid decrease in coal use would result in lay-offs in the mining sector, intensifying the already severe socio-economic challenges and the electricity shortages further complicate the transition process (United Nations, 2018). While nuclear power has contributed to meeting the world's soaring energy demand, it has also produced significant side effects that include nuclear accidents, radioactive waste, nuclear proliferation, and fear of radiation being used in acts of terror (Choi, Hyo & Ko, 2016). From a climate perspective, nuclear power is a major opportunity for decarbonizing the global energy sector, as the emissions of a nuclear power plant's entire life cycle are similar to those of renewable energies (Pravalie & Bandoc, 2018). According to May (2017), nuclear energy, hydroelectric power, and renewables are all needed to meet the goals of the 2015 Paris Agreement on climate change, and the 10 largest emitters of greenhouse gasses all plan to use nuclear power in some way to deal with the climate crisis. Indicators in the environmental dimension of sustainable development measure the impact of energy systems on the environment such as global climate change, air pollution, water pollution, wastes, land degradation and deforestation (IAEA, 2009f). The impetus for increasing nuclear power share in China is increasingly due to air pollution from coal-fired plants (Zhang, Liu & Wang, 2016). Having already made a sizeable contribution to

climate change mitigation by avoiding nearly 2 billion tonnes of carbon dioxide every year, nuclear power can directly contribute to the United Nations Sustainable Development Goals. Table 3-13 below is a comparison of different technologies undertaken by the World Nuclear Association that shows nuclear is one of lowest in terms of gas emissions:

Table 3-13: Summary of Lifecycle GHG Emission Intensity

Technology	Mean	Low	High
	tonnes CO ₂ e/GWh		
Lignite	1,054	790	1,372
Coal	888	756	1,310
Oil	733	547	935
Natural Gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

Source: World Nuclear Association (2011).

Even though nuclear energy is considered to be beneficial for human society economically and, more recently, climatically, one of its major disadvantages with global-scale implications must be noted is the risk of environmental radioactive pollution or contamination (Pravalie & Bandoc, 2018). Additionally, Magwood and Paillere (2018) stated that new NPP installations face the following challenges:

- expectations for nuclear safety have risen considerably in the aftermath of the Fukushima Daiichi accident in March 2011;
- market prices for electricity in many countries have become highly uncertain with the advent of various well-intentioned but disruptive governmental actions and the accelerating introduction of state-supported wind and solar capacity;
- fossil fuel (coal and gas) prices have also dropped, especially due to the development of non-conventional gas resources in some countries, impacting the profitability of nuclear power plant operation;

- governments around the world have struggled to meet their commitments regarding the disposal of spent nuclear fuel; and
- while civilian nuclear power plants present no significant technical risk of nuclear proliferation, some suspect a few governments might use civilian nuclear activities to cloak covert weapons programmes.

3.3.1.5.1 PWR R&D Environmental Considerations

The design shall take due account of relevant available experience gained in the design, construction and operation of other nuclear power plants, and of the results of relevant research programmes (IAEA, 2016d). R&D of PWR designs take into consideration past nuclear accidents so as to make sure the new designs will be fail proof. The three major accidents in the nuclear industry were TMI, Chernobyl and Fukushima (Andersson et al., 2013). The accident at the Fukushima Daiichi nuclear power plant in Japan followed the Great East Japan Earthquake and Tsunami of 11 March 2011 (IAEA, 2016d). The lessons learnt post-Fukushima demonstrate the need to re-examine the existing nuclear power plant's responses to external events of higher magnitude (e.g. earthquakes, floods and extreme weather conditions) than those previously considered (Nian, 2017).

3.3.1.5.2 PWR Design Engineering Environmental Considerations

The design for safety of a nuclear power plant applies the safety principle that practical measures are there to mitigate the consequences for human life and health and for the environment of nuclear or radiation accidents (IAEA, 2016c). At present, the main suppliers of nuclear grade engineering design service for Koeberg are mostly foreign entities or local subsidiaries of foreign entities. Because containment is the last barrier of defence in depth, the containment design criteria deserve special treatment and enough technical detail to ensure its inviolability in case of various accidents, including severe accidents (Alvarenga & Frutuoso-Melo, 2015). "Defence in depth," means the application of more than a single protective measure for a given radiation or nuclear safety objective, so that the objective is achieved even if one of the protective measures fails.

3.3.1.5.3 PWR Manufacturing Environmental Considerations

With NPPs, there are usual concerns about greenhouse gas (GHG) emitted during the manufacturing of nuclear components. However, if one takes into consideration the 60 years life span of modern NPPs the benefits of due to lack of toxic emissions during the operation phase will surely outweigh the GHG emitted during manufacturing.

3.3.1.5.4 PWR Construction Environmental Considerations

The single most common concern in the Environmental Impact Assessment (EIA) is nuclear safety yet initially omitted from this assessment (Heydenrych, 2016).

3.3.1.5.5 PWR Operation and Maintenance Environmental Considerations

The SA nuclear sector needs to collect data or information pertaining to environmental benefits derived from operating NPPs for electricity generation in order to inform the strategic decision-making processes. Annually, the 435 operating nuclear power plants prevent the emission of more than 2 billion tons of CO₂ (Brook et al., 2014). Chapman and Hooper (2012) contend that of a year's electricity generated from a 1 GW NPP produces about 25 tonnes of spent nuclear fuel (SNF) and a few hundred m³ of other waste, compared to a coal fired plant of the same size producing the following:

- 6.5 million tonnes of CO₂;
- more than 300,000 tonnes of ash with around 400 tonnes of toxic heavy metals; and
- radioactive uranium and thorium and if not scrubbed out over 5000 tonnes of noxious gases.

The operation and maintenance (O&M) are the stage where the GHG emissions from tasks such as operating diesel generators during an outage, employee travel to work, and repair, replacement, refurbishment, or upgrades that take place during each plant's lifetime are captured (Carless, Griffin & Fischbeck, 2016). Pearce (2012) stated that for a global large-scale sustainable nuclear energy system to replace fossil fuel combustion the following is required:

- a radical improvement in greenhouse gas emissions intensity by improved technology and efficiency through the entire life cycle to prevent energy cannibalism during rapid growth;
- the elimination of nuclear insecurity to reduce the risks associated with nuclear power so that the free market can indemnify it without substantial public nuclear energy insurance subsidies;
- the elimination of radioactive waste at the end of life and minimization of environmental impact during mining and operations; and
- the nuclear industry must regain public trust or face obsolescence as many renewable energy technologies quickly improve both technical and economic performance.

Accordingly, gaining public support has become more challenging with misperceived fears in the wake of the accident at the Fukushima Daiichi nuclear power plant (IFNEC-NEA, 2016).

3.3.1.5.6 PWR Waste Management and Disposal Environmental Considerations

The use of nuclear energy also poses an environmental and societal threat due to the difficult management of spent/used nuclear fuel waste (Pravalie & Bandoc, 2018). For instance, a 1 GW_e reactor will produce on average 25–30 tons of spent fuel a year that can result in 2–11 m³ of vitrified high-level waste and 100–400m³ of other waste categories (Decamps & Dujacquier, 1997). Specially designed interim surface or sub-surface storage waste facilities are in use currently in many countries to ensure the safe storage of hazardous radioactive waste pending the availability of a long-term disposal option WNA, (2018a). As for the NPP itself, the design shall be such as to ensure that the generation of radioactive waste and discharges are to the minimum practicable in terms of both activity and volume, by means of appropriate design measures and operational and decommissioning practices (IAEA, 2016c). Presently most of Koeberg's spent fuel is stored in water-filled pools at the site. NECSA operates the Vaalputs National Radioactive Waste Disposal Facility for Low Level Waste (LLW) and Intermediate Level Waste (ILW). Figure 3-11 below shows a flowchart of radioactive waste management.

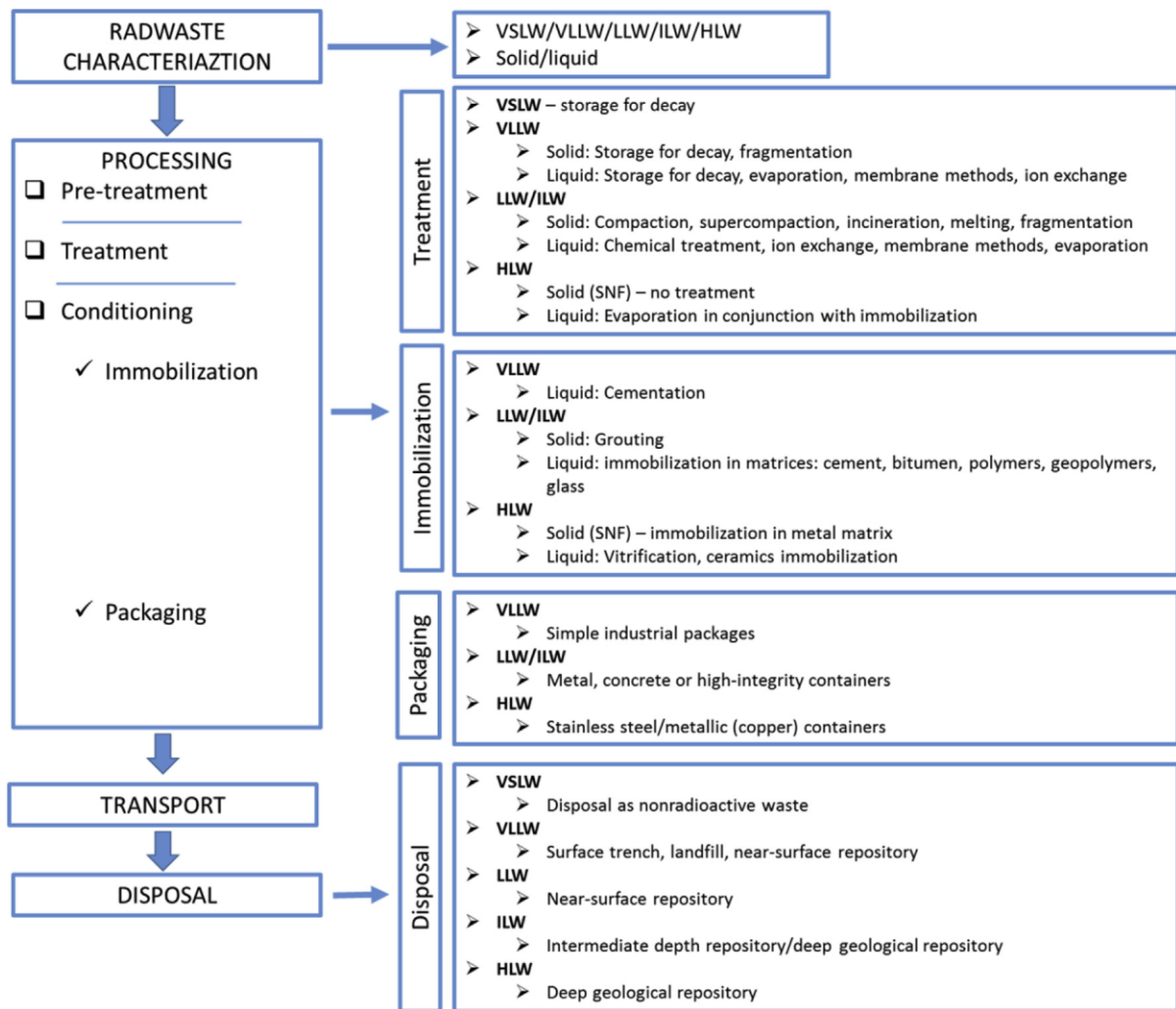


Figure 3-11: Scheme of radioactive waste management

Source: Kotatkova, Zatloukal, Reiterman and Kolar (2017).

Due to the lack of sufficient data regarding completed nuclear decommissioning projects and Programmes (NDPs), the difficulty in gaining appropriate information, and the overall NDPs' uniqueness in terms of complexity and variety, there is a huge gap in the literature concerning benchmarking of NDPs (Invernizzi, Locatelli & Brookes, 2017). Currently, most nuclear waste is stored near nuclear power plants, either in water-filled pools at reactor sites or in canisters at nearby interim storage facilities (Stefanelli, Seidl & Siegrist, 2017). Most of Koeberg's spent fuel is stored in water-filled pools at the site. The accumulating nuclear waste from power plants, medical and research facilities must be stored safely for 10^5 – 10^6 years until the radioactivity has decayed to a level below which any release of radionuclides to the environment no longer poses an unacceptable risk (Martin et

al., 2016). At present, specially designed interim surface or sub-surface storage waste facilities are in use in many countries to ensure the safe storage of hazardous radioactive waste pending the availability of a long-term disposal option.

3.3.1.6 PWR Legal Factors

UNICEF (2015) states that consideration of the following legal factors is necessary when undertaking a PESTEL analysis:

- Existing legislation having an impact on any relevant factors (economic, social, technological, environmental or other factors relevant to the issue), or affecting population groups relevant to the issue, or affecting the work of the organization or its partnerships.
- Standards, oversight, regulation and regulatory bodies, and expected changes in these.

The regulations and requirements that set forth the licensing process for nuclear power plants are from national laws and a national authority prescribes them (WNA, (2015a). The Nuclear Energy Act of 1999 and the National Nuclear Regulator Act of 1999 are examples of SA national laws and the National Nuclear Regulator has the authority to see to it that nuclear installations in SA that include the KNPS, adhere to the laws. Nuclear Regulator (2016) states that by taking full cognizance of its mandate, and depending on the application, the NNR could issue the following types of authorisations for nuclear installations:

- (a) Nuclear Installation Licence (NIL) to site, construct and/or operate or decommission or decontaminate the installation, or
- (b) Nuclear Installation Site Licence (NISL) 1 for new nuclear installations; (c) Authorisations to Design a nuclear installation, or
- (c) Authorisation to Manufacture components.

Otherwise, the basis of choosing equipment manufacturers is by allowing them to demonstrate their capabilities in meeting the special and exacting requirements for nuclear power plants, which are often

specific to the nuclear industry and their adherence to codes and standards containing acceptance criteria for the final work products (INSAG, 1999). In SA, the regulator details the requirements for quality and safety management systems for licensees, applicants of a nuclear licence, as well as designers and suppliers involved in the design, manufacturing, construction, commissioning, operation, modification and potential decommissioning for a nuclear installation (NNR, 2008). Original vendors themselves have tended to increase their numbers of sub suppliers, making tracking and auditing of parts production more difficult (IAEA, 2016f). The SA NNR requires SA ASME III 'N' Stamp certificate holder organization to audit its suppliers. A Certificate Holder may subcontract to another organization the surveying and auditing of subcontractors and Material Organizations, but must retain the responsibility for these activities and for the qualification of these subcontractors and Material Organizations (ASME, 2015). The audit terms of reference may entail the following:

- Management systems to rate their effectiveness in controlling activity;
- The effectiveness of boundary interfaces (e.g. the degree in which information flows between strategical, tactical and operational levels of the organization); and
- Current working and supervisory.

According to IAEA (2009d) the stages of and occasions in a plant's lifetime in which the use of safety analyses is relevant include:

- Design;
- Commissioning;
- Operation and shutdown;
- Modification of design or operation;
- Periodic safety review; and
- Life extension i.e., in countries where licences are issued for a limited duration.

Otherwise, the design, construction, operation, condition monitoring and maintenance of a nuclear waste facility shall provide for the ageing of systems, structures and components important to operational safety in order to ensure that they meet the design-basis requirements with necessary safety margins throughout the service life of the facility (STUK, 2016). Amft, Leisvik and Carroll (2017) noted that in Sweden a licence holder for nuclear activities is responsible for ensuring that:

- all necessary measures are taken in order to maintain safety, considering the nature of the operation and under what circumstances it is conducted; and
- safe management and disposal of nuclear waste and nuclear material produced during operation and the complete safe decommissioning of facilities.

Table 3-14 below shows key USA laws applied in the nuclear energy sector.

Table 3-14: Key USA laws in the nuclear energy sector

Law	Purpose
Atomic Energy Act of 1954	The centrepiece of nuclear legislation in the US is the Atomic Energy Act of 1954, which is a comprehensive Federal statute that regulates possession and use of radioactive material and facilities that produce or use such material. There are also several other statutes that cover more specific aspects of the regulation of radioactive material and facilities, for example, in radiological protection, radiological waste management, non-proliferation, exports and nuclear security.
Price-Anderson Act of 1957	This was inserted into the Atomic Energy Act 1954 as S.170 and has been revised several times, and more recently so by the Energy Policy Act of 2005. The purpose of the act is to provide a Federal compensation fund of \$10 billion should there be a nuclear accident. The Act does limit liability and does not guarantee payment should possible funds be exhausted already.
Energy Reorganisation Act of 1974	The Atomic Energy Commission (AEC) was abolished and the Nuclear Regulatory Commission created, with other functions going to what later became the Department of Energy. Department of Energy Organisation Act of 1977 – This combined several government energy agencies together to form the Department of Energy (DOE). The DOE then became responsible for the development and production of nuclear weapons, the promotion of nuclear energy and other energy related work.
Waste Policy Act 1982	This aimed to provide for the development of repositories for the disposal of high-level radioactive waste and spent nuclear fuel. Its other main aims were to establish a programme of research, development, and demonstration regarding the disposal of high-level radioactive waste and spent nuclear fuel.
The Energy Policy Act of 2005	This encourages the development of low carbon energy and specifically nuclear power, with several forms of incentives introduced. These take the form of loan guarantees, carbon free production tax credits, protection tax credits, and a new form of risk insurance for the first six nuclear reactors. The aim of the legislation is to move the US towards a national goal of energy independence with the aid of nuclear power. It also continued the Price-Anderson Act.

Source: Heffron (2013)

3.3.1.6.1 PWR R&D Legal Considerations

At present SA is not involved in developing its own indigenous PWR. Hence, there are no local laboratories requiring approval by the regulator for testing SSCs as part of NPP development. However, PWR operational experiences all over the world have been the basis for KNPS together with NNR to undertake safety related assessments of the two units.

3.3.1.6.2 PWR Design Engineering Legal Considerations

It is important to view quality as requiring a number of steps namely design, specification, procurement, quality control, testing, inspection, and installation (IEEE, 1985). ASME Section M 1971 (with addenda up to winter 1973) provided the design basis for Koeberg. Systems, structures and components (SSCs) performing long-term safety functions, shall be designed, manufactured and installed so that their quality level, and the assessments, inspections and tests required to verify their quality level, are commensurate with the safety significance of the item in question (STUK, 2016). Engineering design rules are the relevant national or international codes, standards and proven engineering practices applied to the design of SSCs to meet the applicable design requirements (IAEA, 2014d). As an example in SA the SABS's SANS (2012) states that the Pressure Equipment Regulations (PER) in the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993) has to be considered for SSCs to be designed for local pressure vessel designs. NECSA's ASME III entity adheres to ASME VIII and III codes and standards when supplying SSCs for BOP and nuclear island. Kidd (2013) states that it is important that SSCs important to safety of nuclear facilities fabrication, erection, and testing meet the quality standards commensurate with the importance of the safety functions.

3.3.1.6.3 PWR Manufacturing Legal Considerations

The South African AEB (1979) reported that it deployed its Licensing Branch inspectors and an inspection engineer to Koeberg nuclear power station to monitor respectively the quality of components throughout the year and in to ensure day-to-day adherence to the Branch's requirements. The IAEA (2016c) states that a qualification programme for items important to safety shall be implemented to

verify that items important to safety at a nuclear power plant are capable of performing their intended functions when necessary, and in the prevailing environmental conditions, throughout their design life, with due account taken of plant conditions during maintenance and testing. This being the case, manufacturing and construction should comply with detailed specifications for processes and products, and for methods of testing and inspection (INSAG, 1999). As for the SA ASME III entity, its operations comprise the ASME VIII or ASME III engineering design, procuring of materials, fabrication (boiler making, welding and machining), and quality control (inspection and non-destructive examination). The aforementioned capabilities are undertaken also in compliance with ISO 9001, ISO 3834 ASME VIII, and ASME III quality management systems (QMS). The WNA (2013) contends that concerning component manufacturing, its member countries' respondents to its survey noted the following range of activities as being carried out by the regulator, authorized inspection bodies, the vendor or the licensee:

- Review of component specifications;
- Qualification of manufacturing programme;
- Qualification of manufacturer. Approval of quality assurance (QA) programme (licensee and manufacturer); and
- Inspection and oversight during manufacturing.

The ASME 'N' Stamp entity and its supply chain has kept and maintain records of SSCs manufactured and supplied to KNPS. The record keeping is a key practice by ASME III entities and it is an aspect frequently audited by customers or prospective customers and the USA ASME organization respectively for future orders and recertification. The IAEA (2016f) states that some procurement related records include:

- (a) Equipment, material order or contract numbers;
- (b) Design documents;
- (c) Manufacturing drawings;

- (d) Procurement specifications;
- (e) Quality plans (for each process, from raw material production to final product quality inspection and test records);
- (f) Raw material and purchased part quality records;
 - Material quality certificates
 - Chemical composition certificates
 - Material property tests
 - Non-destructive testing (NDT) records
 - FAT records
 - Repair and material substitution records
 - Other inspection records
- (g) Fabrication records;
 - Weld procedures
 - Weld electrodes used
 - Personnel qualification
 - Supplier materials approvals (including furnace number and batch number)
 - Welding material batch
 - NDT inspection results
 - Destructive test records
- (h) Manufacturing process test reports and records;
 - Heat treatment
 - NDT

3.3.1.6.4 PWR Construction Legal Considerations

The actual SA Koeberg Nuclear Power Plant construction code was the French CPFC (January 1974) which later became RCC-M that formed the basis of the requirements for any future component procurement from France (INE, 1990). The SA AEB provided the regulatory licensing services for

Koeberg installations. In addition, PWR new build construction in SA is required to adhere to the 1998 National Environmental Management Act (NEMA) and the Environmental Impact Assessment (EIA) regulations of 2014 requirements. WNN (2017a) reported that the Environmental Impact Assessment (EIA) for the construction of a new SA PWR station of up to 4000 MW, known as Nuclear-1, considered three alternative sites namely Bantamsklip, on the Southern Cape coast, Duynefontein, in the Western Cape and Thyspunt, in the Eastern Cape.

3.3.1.6.5 PWR Operation and Maintenance Legal Considerations

During the design phase of a PWR, the future operation and maintenance requirements are concurrently considered. Hence, items important to safety for a nuclear power plant shall be designed to be calibrated, tested, maintained, repaired or replaced, inspected and monitored as required to ensure their capability of performing their functions and to maintain their integrity in all conditions specified in their design basis (IAEA, 2016c). Unlike during KNPS construction period when AEB was responsible for regulatory requirements, nowadays SA's Eskom has to submit applications to NNR for approval to undertake maintenance or component replacement installation related activities. Oaten (1990) stated that for repair/replacement Koeberg adopted ASME XI 1980). In the aftermath of the Fukushima accident, the European Commission tightened nuclear safety rules and many European countries turned away from nuclear power (Osicka & Cernoch, 2017). Because the Fukushima accident NPP operators and regulators had to undertake some re-evaluations as to whether their plants could withstand similar disasters. Likewise, in SA the nuclear facilities operators and NNR had to undertake some related assessments.

According to the IAEA (2002c), many Member States have no absolute limit on the life of a nuclear power plant, and as long as the nuclear power plant can demonstrate that it is safe to operate, they can continue operating beyond the original design life. The SA utility Eskom has initiated preparations and processes to extend the life of Koeberg to 2044, subject to the necessary regulatory approvals in

response to that by year 2024, 1 800 MW of nuclear power generation will reach end-of-life (IRP, 2019).

3.3.1.6.6 PWR Waste Management and Disposal Legal Considerations

A policy for spent fuel and radioactive waste management should include a set of goals or requirements to ensure the safe and efficient management of spent fuel and radioactive waste in the country (IAEA, 2009g). For the management of nuclear waste in SA, the government enacted the National Radioactive Waste Disposal Institute Act (2008) that provides for the establishment of a National Radioactive Waste Disposal Institute (NRWDI) in order to manage the following:

- radioactive waste disposal on a national basis;
- to provide for its functions and for the manner in which it is to be managed; and
- to regulate its staff matters; and to provide for matters connected therewith.

Table 3-15 below lists some of the legislation to be taken into consideration when undertaking nuclear waste initiatives in SA.

Table 3-15: Relevant legislation for SA nuclear waste

Nuclear Energy Act	Nuclear Energy Act (Act No 46 of 1999)
NNR Act	National Nuclear Regulator Act (Act No.47 of 1999)
NEMA	National Environmental Management Act, 1998 (Act No. 107 of 1998)
MPRDA	Mineral and Petroleum Resources Development Amendment Act 49 of 2008
NRWDI Act	National Radioactive Waste Disposal Institute Act, No 53 2008
Mine Health & Safety Act	Health and Safety Act, 1996 (Act No. 29 of 1996)
Hazardous Substances Act	Hazardous Substances Act 1973 Act 15 of 1973
National Water Act	National Water Act (Act 36 of 1998)
PFMA	Public Finance Management Act No. 1 of 1999 (PFMA)
PAJA	Promotion of Administrative Justice Act (PAJA), (Act No. 3 of 2000)

3.3.2 Small Modular Reactor (SMR) Factors

South Africa (SA) pursued the development of the pebble bed modular reactor (PBMR) from 1998 up to 2010. According to Brey (2001), the SA utility Eskom first identified the PBMR as an option for its electricity generation in 1993 whereby it contracted Integrators of System Technology (IST) to perform a technical and economic study as part of a feasibility study. Söderholm et al. (2014) stated that a module is one or more of the following:

- (1) a complete steam supply system module already loaded with fuel;
- (2) a plant whose large components or modules are standard and factory manufactured (modular manufacturing and construction); and
- (3) an overall plant design comprising multiple small reactor units on a single site, deployed in sequence.

In the SA situation, the consideration of the SMR opportunities is relevant because SA invested a significant amount of time and resources working towards its PBMR or high temperature gas reactor (HTGR). Worldwide, approximately 50 small (<300 MW_e) to medium-sized (<700 MW_e) reactors (SMRs) concepts are being pursued for use in electricity and cogeneration (combined heat and power) markets (Shropshire, 2011). According to the classification that is adopted by the IAEA, small reactors are reactors with an equivalent electric power less than 300 MW, while medium sized reactors are reactors with an equivalent electric power between 300 and 700 MW (IAEA (2013a). Locatelli, Bingham and Mancini (2014) stated that SMRs are also categorised as Generation III+ Light Water Reactor (LWR) and Generation IV reactors. Similarly, the WNA (2015a) noted that SMRs are defined as nuclear reactors generally 300MW_e equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times. Some of the PBMR or HTGR conceptual designs fall under the grouping of SMR by virtue of being less than 300MW_e. The IAEA (2014a) contends that the driving forces in the development of such reactors are:

1. meeting the need for flexible power generation for wider ranges of users and applications;

2. replacing the ageing fossil fuel-fired power plants;
3. enhancing safety performance through inherent and passive safety features;
4. offering better economic affordability;
5. suitability for non-electric applications; options for remote regions without established electricity grid infrastructures; and
6. offering possibilities for synergetic energy systems that combine nuclear and alternate energy sources.

Consequently, Vujic et al. (2012) noted that there is a need for SMRs to overcome the following challenges in order to enhance deployability in the near future:

7. Economics of SMRs needs more analysis in order to show possible advantages over large LWRs;
8. Spent nuclear fuel from small reactors could be located in remote areas, which will make its transport more difficult. Also, spent fuel will be spread across many more sites while currently it is congregated at a limited number of locations;
9. Public acceptance of new concepts; and
10. Obtaining design certification and licensing may take longer than expected.

For non-electric uses, Locatelli et al. (2017) stated that candidate systems for cogeneration with nuclear power are as follows:

- (1) seawater desalination plant;
- (2) gasoline production plant;
- (3) oil sand extraction facility;
- (4) algae-Biofuel production plant;
- (5) district heating;
- (6) Diesel-like fuel production from waste plastic pyrolysis;
- (7) Waste wood palletisation plant; and
- (8) Hydrogen production from water splitting plant.

To avoid making wrong and costly choices, decision makers need to base the way forward on studies that have ranked or quantified the factors that can enhance or impede the success of a given undertaking. Decision makers ought to find ways to rank such factors before making decisions. A SWOT analysis-based study conducted by Knol et al. (2016) about the European HTR R&D programme ARCHER (Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D) arrived at the following findings:

- Large market forms opportunity for low CO₂ emission HTR technology;
- There is a large European knowledge and experience base;
- Energy from an HTR is affordable, reliable (i.e., security of supply and safe) and clean (low carbon) which fits European energy policies;
- HTR heat provision is flexible (large range of pressures and temperatures);
- HTR fits very well in small grids. Many heat intensive industrial complexes are located in such areas;
- Nuclear safety concepts are difficult to explain to the public at large;
- Nuclear risks and liabilities are hindering deployment;
- European energy is divided and different in each member state; and
- A consistent and up-to-date regulatory framework is lacking.

Available studies on the SA PBMR programme do not indicate which identified factors were the most critical in causing the abandonment. This lack of clarity creates the following challenges:

- If the programme is resumed, there is a possibility that past mistakes can be repeated;
- Inability to learn from past mistakes; and
- Lack of consensus among stakeholders on the way forward.

Without indicating which of the attributes were the most important and which ones were less important, Vujic, Anti and Vukmirovi (2012) stated that, overall, the following are advantages of SMRs:

- (1) Power generating systems for areas difficult to access or without infrastructure for transportation of fuel;
- (2) Modular concept that reduces the amount of work on-site, makes it simpler and faster to construct;
- (3) Long-life cycle and reduced need for refuelling (perhaps every 10-15 years);
- (4) Design simplicity;
- (5) Passive safety;
- (6) Expanded potential siting options since more sites are suitable for SMRs;
- (7) Smaller nuclear island and footprint of the whole nuclear power plant;
- (8) Low operation and maintenance costs;
- (9) Lower initial costs and risks; and
- (10) Proliferation resistance.

3.3.2.1 SMR Political Factors

The SA Department of Minerals and Energy Nuclear Energy Policy (DME, 2008) stated that the PBMR Company was developing a fuel manufacturing plant and a demonstration high temperature gas cooled reactor, which is a low power output reactor designed toward meeting Generation IV requirements, applicable to both electricity generation and process heat applications. Since 1999, the SA government and other international energy companies such as Westinghouse and Exelon were the main sponsors of the development of the PBMR technology. According to McKune (2010) in February 2010, Finance Minister Pravin Gordhan announced that the South African government would stop funding the development of a demonstration power plant for the Pebble Bed Modular Reactor (Pty) Ltd (PBMR). Soon after that, all that remained of the PBMR Company was given a care and maintenance status within Eskom. Implications of such decisions are that SA will have to depend on other countries to supply it with SMR rather than depending on its own innovation. Figure 3-12 below shows that by end of 2009 a total amount of R8.8 billion had been spent towards the development of SA PBMR.

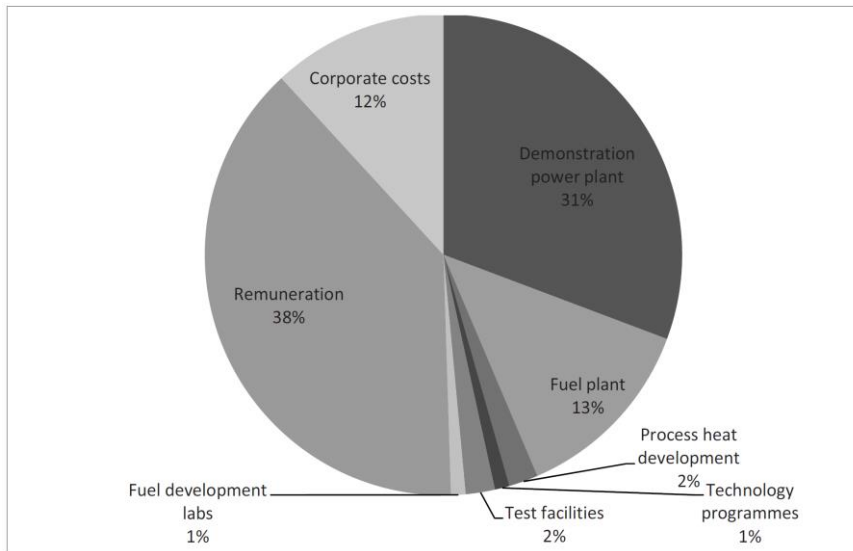


Figure 3-12: Breakdown of the South African PBMR expenditure (R8.8 billion) as of 31 December 2009
Source: Pebble Bed Modular Reactor Company as cited by McKune (2010)

The future of nuclear energy will be limited if it cannot compete effectively with other low-carbon technologies - more so considering the fact that alternative technologies, in particular renewable technologies such as solar or wind, have benefited from generous policies (i.e. feed-in tariffs) that helped their deployment (Magwood & Paillere, 2018).

The South African News Agency (2010) reported that the South African Department of Public Enterprises Minister, Ms Barbara Hogan announced the discontinuing of the Pebble Bed Modular Reactor (PBMR) programme on the 16 September 2010 telling parliament that the following were reasons for such an action:

- The SA government, after careful deliberation, analysis and review, and mindful of the fiscal constraints in these hard-economic times, has had to decide to no longer invest in this programme;
- that the PBMR had not been able to secure an anchor customer or another investment partner and that further investment in the programme could well be in excess of an additional R30 billion;

- The programme has been missing deadlines constantly, with the construction of the first demonstration model delayed further and further into the future;
- the opportunity afforded to PBMR to participate in the US's Next Generation Nuclear Plant (NGNP) programme as part of the Westinghouse consortium was lost in May, 2010 when Westinghouse withdrew from the programme; and
- the severity of the economic downturn at the time, and the strains that it had placed on the fiscus, as well as the nature and scale of government's the then developmental priorities, forced government to reprioritise its spending obligations and therefore, of necessity, to make certain tough decisions - this being one of them.

Following the Minister's address, the PBMR Company outgoing CEO Mr Jaco Kriek said the continuous argument about the choice of configuration always created a divide within the PBMR technical staff and with client office (Holtzhausen, 2011). This lack of consensus among major stakeholders when making critical decisions is one of the reasons behind investigating the developing a novel consensus enhancing tool.

3.3.2.1.1 SMR Research and Development Political Considerations

In April 2000, the SA national electricity utility, Eskom, obtained Cabinet approval to carry out a feasibility study for constructing the prototype of a new design of the pebble bed modular reactor (Auf der Heyde & Thomas, 2002). Hence, SA declared its intention to pursue a Pressurised Water Reactor (PWR) Programme and a nationally developed Pebble Bed Modular Reactor Programme subject to the success of the first demonstration unit (SA DME, 2008). Internationally, the PBMR Company made submissions to and participated in the US Department of Energy (DOE) sponsored Next Generation Nuclear Plant (NGNP) programme. The US DOE selected the Very High Temperature Gas Cooled Reactor System (VHTR) for the Next Generation Nuclear Power (NGNP) Project, a programme to demonstrate emissions-free nuclear-assisted electricity and hydrogen production by 2015 (INEEL, (2003). Kadak (2016) noted that the status currently was the relegation of the high temperature reactors

to completing research programmes on advanced fuels, graphite and materials with no plans to build a demonstration plant as required by the US Congress in 2005 despite initial high hopes and expectations of this US programme.

3.3.2.1.2 SMR Design Engineering Political Considerations

In SA, the PBMR Company had the overall responsibility of the engineering design and integration of the PBMR plant. Contracts for engineering design of specific systems, structures and components were between PBMR and other companies such as IST, ENSA, MHI and Westinghouse. Argentina, Canada, China, France, India, Italy, Japan, the Republic of Korea, Pakistan, the Russian Federation and the United States of America are countries with active programmes on SMR design development and deployment (IAEA, 2013a).

3.3.2.1.3 SMR Manufacturing Political Considerations

Creating additional manufacturing opportunities along the value chain must be one of the priorities when formulating policies and strategies for implementing SMR programmes. Low carbon, economic, job creation, and new international market opportunities are factors that are driving the renewed interest on SMRs (Shropshire, 2011).

3.3.2.1.4 SMR Construction Political Considerations

Governments do have a responsibility to make sure that policies put in place will also take into consideration the availability and involvement of local construction entities such as it happened during the installation Koeberg. Such policies can benefit the local construction companies and assist e.g. in the reduction of unemployment.

3.3.2.1.5 SMR Operation & Maintenance Political Considerations

According to the DME (2008), NECSA also hosts the development laboratories for the PBMR fuel and the PBMR Helium Test Facility (HTF). The utilisation of NECSA facilities makes sense since the complex has regulatory approvals to undertake nuclear research and development.

3.3.2.1.6 SMR Waste Management and Disposal Political Considerations

To a certain extent nuclear waste management is one of the factors posed to benefit from the introduction of future SMRs. Some of the technologies such as the molten salt SMRs aim to reduce fissile materials by reutilising some of the spent fuel materials and plutonium.

3.3.2.2 SMR Economic Factors

Nuclear energy contributes to a relatively smaller share of the total electricity generation because the higher upfront costs of nuclear reactors compared to fossil fuel technologies make the nuclear option less competitive (Iyer et al., 2014). The business case for SMR installation may be much more attractive to investors because of reduced risk in construction, technology, regulatory, safety, operation, and societal (IFNEC-NEA, 2016). Locatelli, Bingham and Mancini (2014) stated that according to the economy of scale, the specific capital cost (currency/KWe) of a nuclear reactor decreases with increasing size, due to the rate reduction of unique set-up costs in investment activities and the more efficient use of raw materials and the exploitation of higher performances characterizing larger equipment. Further, the general expectation is that the first movers will have a considerable advantage in capturing the global SMR market and this would help create domestic jobs in the design and manufacture of these technologies (Ramana, Hopkins & Glaser, 2013). Carelli et al. (2010) noted that small modular reactors are ideal in the following conditions:

- (i) electrical grids with limited capacity, where power variations in excess of 10% of the total grid capacity can endanger grid operation and stability;
- (ii) remote areas requiring smaller, localised power centres, to avoid long and expensive transmission lines;
- (iii) a geography and demography featuring mid-size urban and power needing areas fairly scattered, rather than concentrated in a few “metropolitan areas”;
- (iv) financial capabilities which preclude raising the huge capitals required by LR;

- (v) the need for cogeneration (i.e. desalination, district heating, industrial steam) although in principle cogeneration is independent on the size of the NPP, in practice economic considerations have driven the large reactors to be essentially pure electricity producers.

SMRs are cost competitive with large reactors when the power required is 1-3 GW_e, since there is compensation of economies of scale by the “economy of multiples” (Magwood IV & Paillere, 2018). As power generation sources differ in size, consistency in generation, efficiency and fuel, a levelized cost is advantageous for making meaningful comparisons (Richards, Sabharwall & Memmott, 2017).

3.3.2.2.1 SMR Research & Development Economic Considerations

On SA government’s abandonment of the PBMR programme, de Vries (2016) stated that it is not proper to use economy as a decisive factor on first-of-a-kind (FOAK) installations instead consideration of economic feasibility and optimality need to take place after the first prototypes has been demonstrated to be work. Europe benefits from an excellent manufacturing industry capable of supporting HTR R&D&D, although it would require upgrading existing manufacturing lines and competences (Bredimas, Kugeler & Fütterer, 2014). For its first plant, the PBMR Company had contractual arrangements with overseas entities such as Mitsubishi Heavy Industries, ENSA and Howden to manufacture and supply SSCs. Worldwide, a few SMR designs have reached the commercialisation phase, whereas the rest are at conceptual phase (especially Generation IV designs), substantial R&D efforts are required (Rowinski, White & Zhao, 2015). The development of various SMRs is continuing and, in contrast to many of the organisations pursuing the development of Generation IV systems, SMR technologies are receiving very substantial resources and investment from large industrial companies a factor that improves the prospects for commercialisation in the near future (Magwood IV & Paillere, 2018).

3.3.2.2.2 SMR Design Engineering Economic Considerations

Accordingly, SMRs are designed with competitiveness in mind i.e., against other technology designs such as large NPP and renewables. Söderholm et al. (2014) stated that the basis of SMRs

competitiveness is as follows: (1) Simplification of the design (2) The use of passive safety systems (3) Standardization (4) Mass production (5) Short construction time (6) Ramp-up (serial) construction to enable self-financing

3.3.2.2.3 SMR Manufacturing Economic Considerations

From an economic standpoint, the smaller size of the SMR means a potential loss of economies of scale in generation associated with large reactors, but promises future economies of scale in manufacture and deployment (Iyer et al., 2014). Accordingly, Locatelli, Bingham and Mancini (2014) noted that the term “modular” definition in this context is as follows:

- (1) a single reactor that can be grouped with others to form a large nuclear plant; and
- (2) whose design incorporates mainly pre-fabricated modules assembled on site.

The adverse impacts of the economy of scale are compensated for by offering the economy of mass production of multiple prefabricated modules, a simplified and standardized design, shorter construction time, less operation and maintenance cost, the option of incremental capacity increase, cogeneration and non-electric applications (Hidayatullah, Susyadi & Subki, 2015).

3.3.2.2.4 SMR Construction Economic Considerations

SMRs, due to their inherently modular approach, are easier to build and, because of their smaller size, the FOAK impact on cost escalation has a limited effect (Locatelli, Bingham & Mancini, 2014). Most nuclear plants take 5-7 years to begin operations and providing a return on investment whilst SMRs are expected to be able to be fully installed (12 x 50 MWe modules) within 40 months (IFNEC-NEA, 2016). In addition, the cost of constructing and operating new nuclear plants is under tremendous scrutiny in the shadow of recent financially prompted plant closures and cost overruns in highly visible nuclear new builds (Magwood IV & Paillere, 2018). Locatelli, Bingham and Mancini (2014) also noted that GEN III+ SMRs’ principles are the same physical principles of current large reactors, and it is possible

to achieve a deployment of approximately 2-3 years. Likewise, the WNA (2015a) stated that the enormous potential of SMRs rests on a number of factors:

- Because of their small size and modularity, SMRs could almost be completely built in a controlled factory setting and installed module by module, improving the level of construction quality and efficiency; and
- Their small size and passive safety features make them attractive to countries with smaller grids and less experience of nuclear power.

3.3.2.2.5 SMR Operation and Maintenance Economic Considerations

The most significant component of operation and maintenance (O&M) cost in the SMRs is the direct and indirect cost of personnel; it is therefore essential for the operators of SMRs to improve the efficiency and effectiveness of their organizational structures and staffing in order to maintain the economic viability of their plants (IAEA, 2001a). Likewise, Wood, Upadhyaya and Floyd (2017) also noted that the most significant controllable contributor to day-to-day costs arises from operations and maintenance (O&M) activities, which heavily depend on staffing size and plant availability

SMR reactors have an advantage in that they can be deployed and operated e.g. in situations in which the transmission infrastructure is well established especially in developing countries.

3.3.2.2.6 SMR Waste Management & Disposal Economic Considerations

Pertaining to SMRs, Vujic et al. (2012) noted that other issues, which need addressing, are the cost of reactor decommissioning and spent nuclear fuel management. Whereas Carless, Griffin and Fischbeck (2016) stated that design features such as flexibility, reduced costs of SMRs are some key features that may reduce the life-cycle GHG emissions due to reasons given below:

- Longer refuelling cycles. Typically, Generation II NPPs need refuelling every 12-18 months, whereas the expectation is to refuel SMRs every 24 months as a minimum. There are some SMR

designs that will not need refuelling during their lifetime. Within this design after the fuel is depleted, the core is removed for decommissioning;

- Increased thermal efficiency. Generation II and III+ NPPs typically have a thermal efficiency of 30%-33%. While this is also true for most SMR designs, a thermal efficiency of around 48% is what the General Electric's Energy Multiplier Module (EM²) Gen-IV SMR aims to achieve. This higher efficiency increases the amount of energy you receive per unit of fuel;
- Improved construction efficiency through modularity. Building on site is typical of the Generation II NPPs. Generation III+ plants such as the Westinghouse AP1000 have introduced modularity into the design; resulting in several structural and mechanical components being built in a factory and shipped to site where it is assembled. SMRs are designed to be totally modular in their design;
- Shorter, more efficient supply chain. SMRs are a fraction of the size of Generation II and III+ plants. Typically, Generation II and III+ plant components are large leaving only a few vendors with the resources available to manufacture these components. SMRs will utilize smaller components meaning additional vendors can be included in the supply chain;
- Lower operation and maintenance cost. The simpler design of SMRs will employ fewer materials as well as have a majority if not all of their components manufactured in a factory. The benefits of having a simpler design will allow for fewer pumps, valves, and components. This will increase the quality and therefore reduce the amount of maintenance required during the lifetime of the plant;
- Reduction in construction time and mass production. Typically, 7 years was the time required to construct a Generation II NPPs. Generation III+ plants reduced this time to 5 years. SMRs have the ability to be mass produced reducing overall construction time. It is expected that some SMRs can be fully constructed in 18 months; and
- Simpler decommissioning. Simpler methods of disassembly that will involve disconnection of transportable reusable modules.

3.3.2.3 SMR Social Factors

As a necessity, access to affordable energy that enables efficient economic and social development, prosperity, health, education, and security of a people (Vujic, Anti & Vukmirovi, 2012). SMRs are relatively new entrants in the energy markets and promoting SMRs could improve the positioning and competitiveness of domestic industries in the global value chain and possibly create employment opportunities (Iyer et al., 2014).

3.3.2.3.1 SMR Research and Development Social Considerations

Those who were in the forefront in the development of the SA PBMR technology were usually citing the derived benefits such as local skills development, employment opportunities and future electricity generation. These social issues resonated well with the SA government, which was the main sponsor of the programme. Yamano, Shioda and Sawada (2008) stated that in order to restore both society's sense of security and its trust in nuclear technology, nuclear industry organizations and their personnel need to work with a deeper understanding of public opinion, based on "co-evolution" with society. Figure 3-13 below illustrates the co-evolution concept of technology and society.

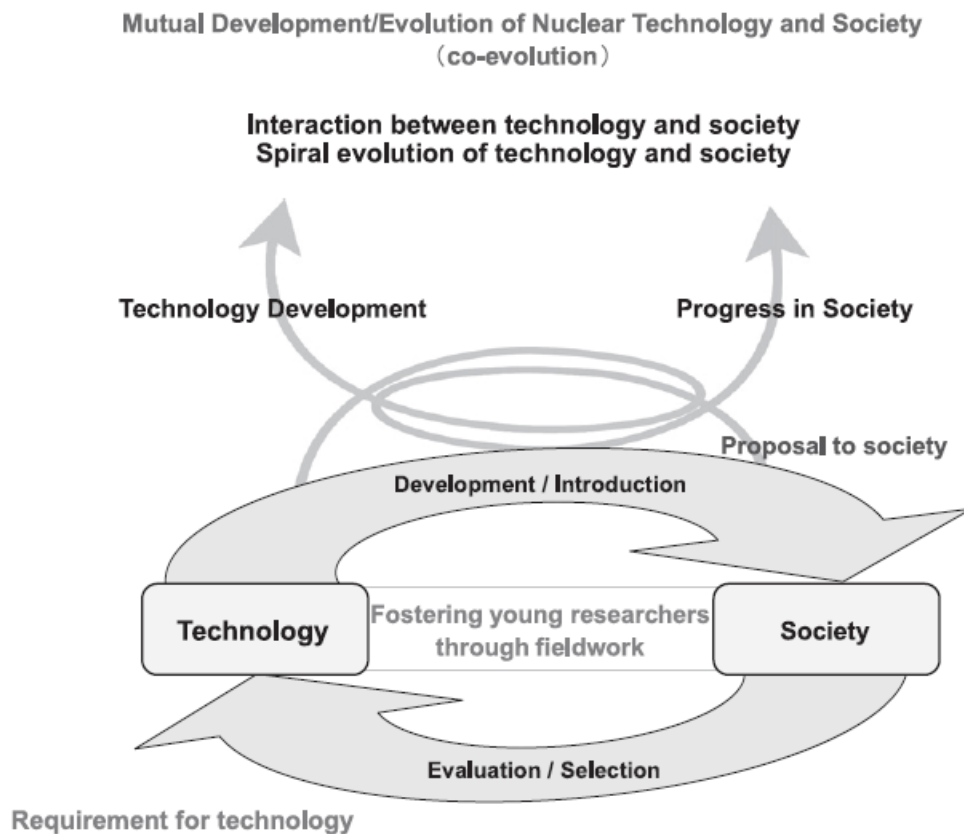


Figure 3-13: The concept of “co-evolution” of technology and society
Source: Yamano, Shioda and Sawada (2008)

3.3.2.3.2 SMR Design Engineering Social Considerations

SMR designs take into consideration the possibility of addressing public concerns such as on safety, environment, construction capital costs and employment. Goodfellow, Williams and Azapagic (2011) stated that given the inertia of perceptions of nuclear power, going beyond awareness raising to engaging the public in the design process of nuclear power plants has a potential to offer a more transparent, participatory approach to improve the governance of energy supply options.

3.3.2.3.3 SMR Manufacturing Social Considerations

The manufacturing of components and the assembling of modules in the factory is bound to create employment for vendor countries and for those countries that will be procuring SMR. This being the case it will also be prudent to allow the public to have a say on the manufacturing of SMR SSCs.

3.3.2.3.4 SMR Construction Social Considerations

Locatelli and Mancini (2011) stated that during the construction phase there are three different impacts on employment: (1) Direct: People employed in the manufacturing of components and modules, on-site construction and operation of NPP. (2) Indirect: Jobs created in the extended nuclear supply chain: suppliers of equipment manufacturers, suppliers of machineries and building materials, agencies for inspection and safety controls. (3) Induced: Jobs created in non-nuclear industries due to the new jobs added in the previous categories.

3.3.2.3.5 SMR Operation and Maintenance Social Considerations

The current US nuclear industry average for O&M staff is roughly one person per every 2 megawatts of generated power (Wood, Upadhyaya & Floyd, 2017). In this regard, the SMR technologies advocates and implementers will need to articulate benefits in the form of number of hired personnel that will operate and maintain the plants. In addition, the public needs assurance at the early stage of the SMR programmes that nothing will harm the people or environment during the operation of the plants.

3.3.2.3.6 SMR Waste Management and Disposal Social Considerations

Nuclear power produces radioactive wastes and there are public concerns about safety (Kupitz, 1995). The impact to the society of high-level waste in the form of nuclear spent fuel is one of the issues of concern to the public. This is an important factor more so if one takes into consideration that a spent fuel storage facility was one the sources of radiation after the Fukushima accident in Japan. For the SMR to be competitive that is against conventional NPP and other electricity generating technologies the issue managing nuclear waste should be one of the priorities.

3.3.2.4 SMR Technological Factors

Although many of the SMR designs use large-sized reactors as their basis, there are several issues with the deployment of SMRs, such as the safety of operation, staffing and security requirements, emergency planning, licensing and certification, and legal and regulatory framework (Nian, 2017).

3.3.2.4.1 SMR Research and Development Technological Considerations

Tremendous progress has been made in the R&D of SMR technologies be it PWR based SMRs and HTR in countries such as China, USA, Russia and South Korea. However, there are technical and institutional challenges to be addressed with further R&D such as, testing and validation of technological innovations in components, systems and engineering (especially testing and fabrication of fuel), fear of first-of-a-kind reactor designs, economy of scale, perceived risk factors for nuclear power plants, and regulatory and licensing issues (Vujic et al., 2012). Hidayatullah, Susyadi and Subki (2015) noted that the following means and mechanisms for enhancing international collaboration could increase the pace of work on SMRs:

- Collaboration of technology holders and users through collaborative programmes and studies on SMRs by sharing experiences in R&D Government commitments and support both at national and international level in the establishment of technical partnerships between the industry, business, R&D organizations and universities;
- Formation and encouragement of international design consortiums like IRIS can foster collaborative efforts for development of SMRs; and
- Formation of international and national research centres, experimental centres and scientific user facilities to increase effectiveness of education and training needed for the development and deployment of SMRs.

High-temperature gas-cooled reactor (HTGR) is one of the advanced nuclear power systems that are part of the Generation-IV reactors (Jianan, Jiong, Kozlowski & Fu, 2018). Generation IV reactor concepts include both thermal and fast spectrum reactors using coolants such as gas (helium, carbon dioxide), liquid metal (sodium, lead-bismuth), molten salt (fluoride salts with dissolved fuel), and supercritical water (Wood, Upadhyaya & Floyd, 2017). The SA PBMR or Advanced High Temperature Reactor as it is being referred to by Eskom of late will be categorised as one of innovative designs as shown in Figure 3-14 below.

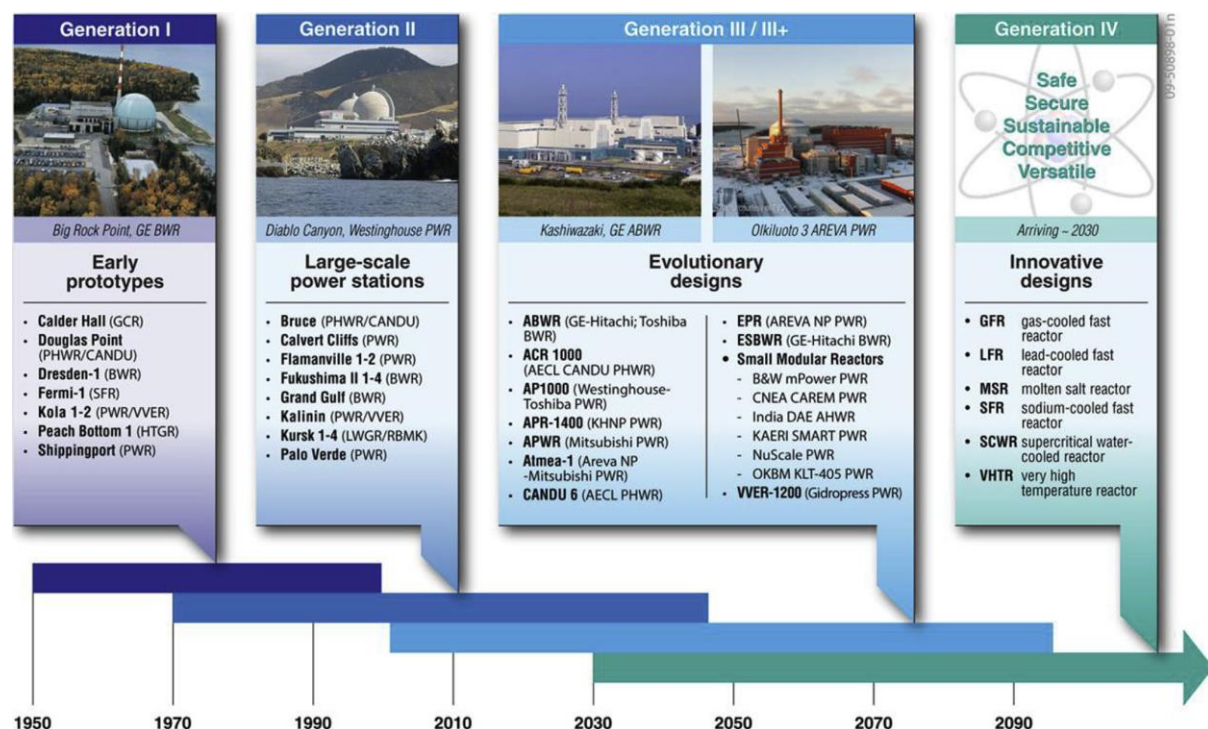


Figure 3-14: Generation of Nuclear Reactor Systems

If the technology demonstration is successful, HTR-PMs may expect commercial deployment by 2030 in China followed by export to the global market (Nian, 2018). Table 3-16 below shows the features of the SA PBMR, Chinese HTR-PM and the USA GT-MHR gas cooled reactors.

Table 3-16: Summary of Gas Cooled Reactors.

Design name	GT-MHR	HTR-PM	PBMR
Origin country	USA	China	South Africa
Electric power MW _e	150	200	164
Efficiency (%)	42	40	41
Thermodynamic cycle	Bryton Cycle	Steam Rankine Cycle	Bryton Cycle
Coolant	Helium	Helium	Helium
Reactor pressure (MPa)	6.39	7	9
Core outlet temperature	750	750	900
Design life (years)	60	40	60
Fuel type	TRISO UO ₂	TRISO UO ₂	TRISO UO ₂
Enrichment (%)	15.5	8.5	9.6
Refuelling period (months)	18	Constant	10

Source: Rowinski, White and Zhao (2015)

3.3.2.4.2 SMR Design Engineering Technological Considerations

SMRs are under development for all principal reactor lines: water-cooled reactors, high temperature gas cooled reactors, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors (IAEA, 2016b). According to IAEA Director General's "International Status and Prospects for Report by the "Nuclear Power 2017" significant advances have also been made in the design and technology development of small and medium sized or modular reactors (SMRs). Liu and Fan (2014) stated that the common design goal of SMR fuel and core is higher burnup and longer lifecycles, which results in the following:

- A higher burnup value which leads to a more fully utilization of uranium resources; and
- A longer refuelling interval will decrease proliferation risks and lower chances of radiation escaping containment.

Carless, Griffin and Fischbeck (2016) noted that while there are many commonalities between Generation II and III+ nuclear plants and SMRs, there are key differences inherent in the design of SMRs such as:

- Longer refuelling cycles;
- Increased thermal efficiency;
- Improved construction efficiency through modularity;

- Shorter, more efficient supply chain;
- Lower operation and maintenance costs;
- Reduction in construction time and mass production; and
- Simpler decommissioning.

Another possible classification subdivides SMRs into two broad groups i.e. those for early deployment based on a proven light water reactor (LWR) technology, and those for longer-term deployment, based on other, more advanced designs Vujic et al. (2012). Classification of SMRs according to generation, neutron spectrum and coolant as below in Figure 3-15.

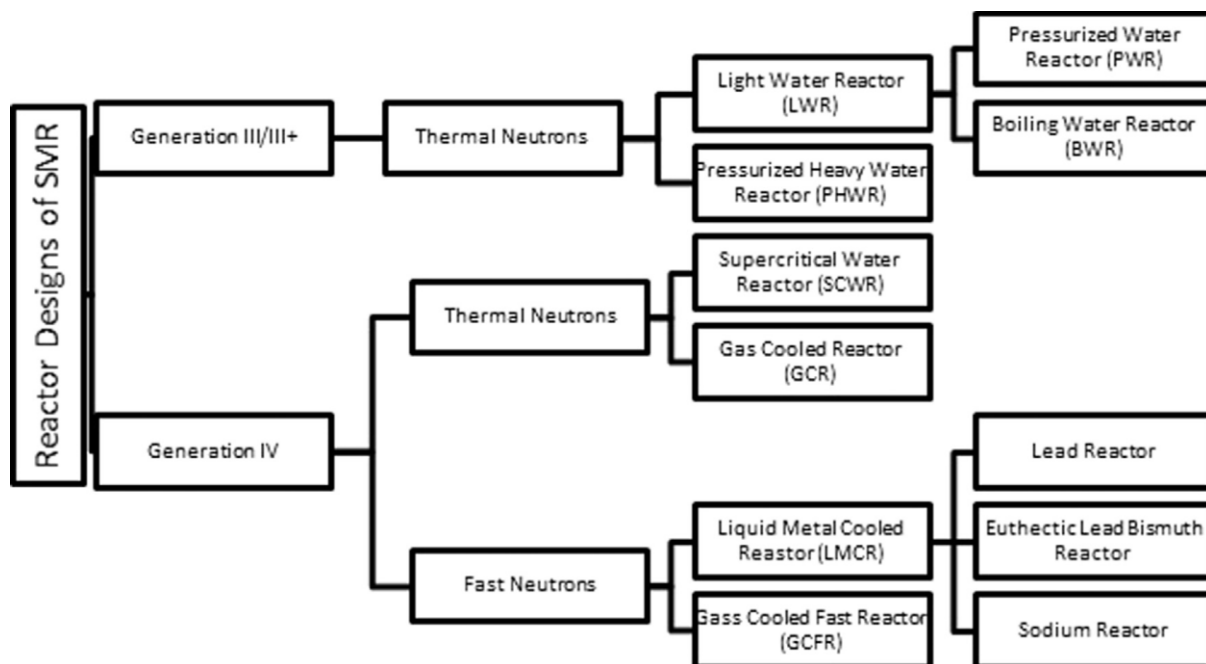


Figure 3-15: Classification of SMR

Source: Rowinski, White and Zhao (2015)

The WNA (2015a) states that SMR design features are as follows:

- Small power and compact architecture and usually (at least for NSSS and associated safety systems) employment of passive concepts. Therefore, there is less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation;
- The compact architecture enables modularity of fabrication (in factory), which can also facilitate implementation of higher quality standards;
- Lower power leading to reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors);
- Potential for sub-grade (underground or underwater) location of the reactor unit providing more protection from natural (e.g. seismic or tsunami according to the location) or man-made (e.g. aircraft impact) hazards;
- The modular design and small size lend itself to having multiple units on the same site;
- Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining, desalination; and
- Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.

3.3.2.4.3 SMR Manufacturing Technological Considerations

According to WNA (2015a), the following are different ways of series fabrication of (identical) reactor modules:

- At a factory location in one country for installation in that country or another country;
- At several factory locations in a country for installation in that country or another country;
- At several factory locations in a different country for installation in that country or another country;
- and
- At several factory locations in different countries for installation in different countries.

3.3.2.4.4 SMR Construction Technological Considerations

The assembling of SMR modules in factories significantly reduces time spent on site during construction. Fabricating modules in the factory reduces a significant amount of site work. This being the case, factory fabrication of components, pre-testing of components prior to installation, and modularization are considerations for reducing on-site construction labour (Kupitz, 1995). In the past, the SA PBMR R&D was ahead of every country in having the first advanced NPP to be constructed. Instead, the Chinese PBMR ultimately took the honours. After the first concrete pour on December 9, 2012 at the Shidao Bay site in Rongcheng, Shandong Province, China and on June 2015 the construction of the reactor building for the world's first high-temperature gas cooled reactor pebble-bed module (HTR-PM) demonstration power plant was completed.

3.3.2.4.5 SMR Operation and Maintenance Technological Considerations

The Peach Bottom Unit No. 1 Atomic Power Station which successfully operated between 1966 (first criticality, Core 1), and 1974 (end-of-life, Core-2) was the first installation of a HTGR in the United States (Scheffel, Baldwin & Tomlin, 1976). Figure 3-16 below shows construction and operation times for HTGR some of which such are no longer in operation.

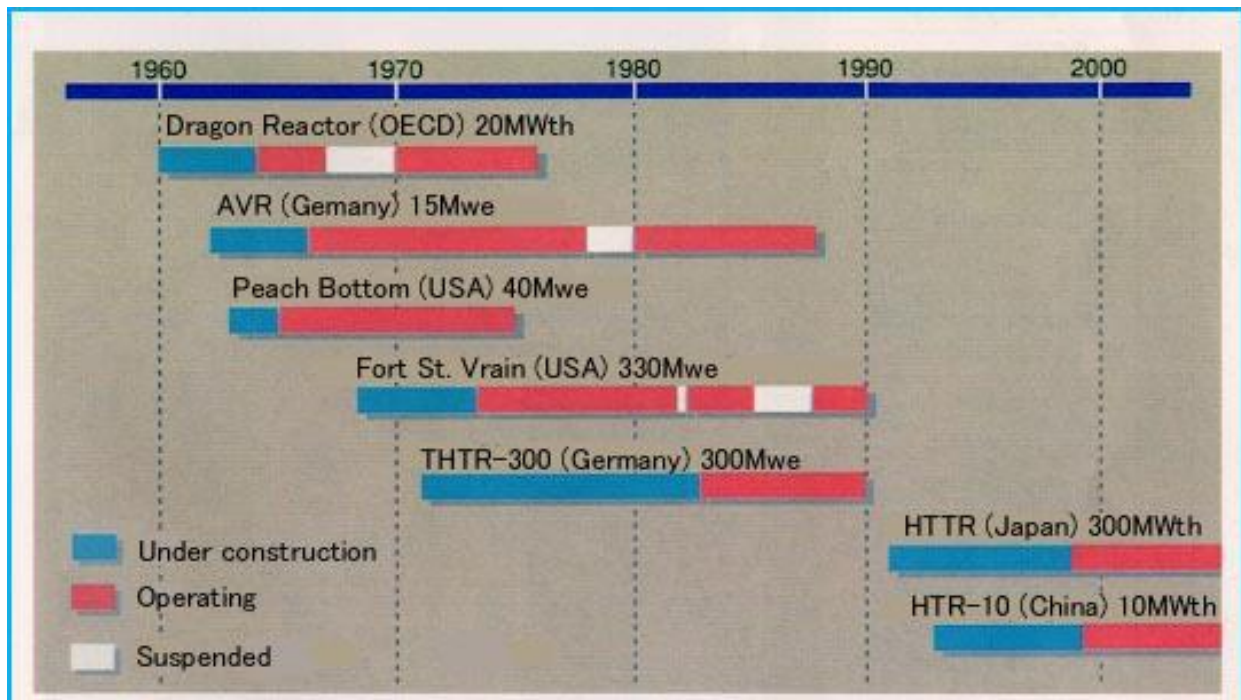


Figure 3-16: Bar Chart of Construction and Operational Timeframes of Seven HTGR Power Plants

Source: <http://www.jaea.go.jp/jaeri/english/ff/ff43/randd01.html> cited by McDowell et al. (2011)

3.3.2.4.6 SMR Waste Management and Disposal Technological Considerations

Several countries are progressively implementing existing technological solutions to radioactive waste management and disposal for Generation II and Generation III plants (Kupitz, 1995). As for HTGR, there are lessons learnt from the decommissioning of the German plant that stopped its operation in 1988 having operated successfully for 21 years. According to Printz, Quade and Wahl (1998) after the AVR shut down its operator applied for safe store decommissioning which was split into the following two phases:

- Phase 1 covered defueling of about 100,000 spherical fuel elements and dismantling of the turbine hall and of other buildings outside the reactor. This phase 1 finish was scheduled for the end of 1997; and
- Phase 2 that included the dismantling inside the reactor building to yield a safe sealing of the remaining radioactive areas.

3.3.2.5 SMR Environmental Factors

The three historical commercial nuclear power plant (NPP) accidents (Three Mile Island, Chernobyl, and Fukushima) have promoted higher safety standards on inherited safety and probabilistic safety objectives, stricter requirements for the prevention and mitigation of severe accidents, and the implementation of the passive safety concept (Zheng et al., 2016). The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation (IAEA, 2014d). Environmentally driven incentives can come through carbon taxes, emissions trading, or subsidies for non-emitting generators of power (WNA, n.d.).

3.3.2.5.1 SMR Research and Development Environmental Considerations

The reduction of CO₂ emissions by nuclear power plants is an acknowledged notion backed by studies that focus on large nuclear plants; however, there is a need for analysis of energy systems using small nuclear plants. Research and Development of SMR incorporates safety aspects with the aim of making sure plant operates safely. According to Vujic, Anti and Vukmirovi (2012), SMRs offer increased safety by:

- eliminating most of accident initiators (for example, large pipes in primary circuit);
- improving decay heat removal and including more efficient passive heat removal from reactor vessel;
- more in-factory fabrications;
- transportability and site selection flexibility;
- smaller plant footprint and use of seismic isolators for increased seismic safety and
- reduced investment risk.

3.3.2.5.2 SMR Design Engineering Environmental Considerations

These SMRs generally incorporate improvements of the safety concepts, including features that will allow operators more time to perform safety actions and provide increased protection against any possible releases of radioactivity to the environment (IAEA, 2001a). In addition, the SMR versatility makes them to be contenders to replace small old coal plants that will become uneconomical in the coming years due to stricter environmental regulations (OECD, 2013).

3.3.2.5.3 SMR Manufacturing Environmental Considerations

Process heat production and provision without emitting GHG is one of the drivers for developing HTGR such as Chinese PBMR and SA PBMR, which was in 2010 put under care and maintenance. According to the IAEA (2016b), other than district heating, the production related areas in which SMR will find use are (1) District heating; (2) Seawater desalination; (3) Pulp and paper manufacture; (4) Methanol production; (5) Heavy oil desulfurization; (6) Petroleum refining; (7) Methane reforming hydrogen production; (8) Thermochemical hydrogen production; (9) Coal gasification and (10) Blast furnace steel making.

3.3.2.5.4 SMR Construction Environmental Considerations

Environmental impact assessments (EIA) are required for the SMRs construction. For instance, the SA demo PBMR plant meant for construction at the Koeberg nuclear power plant site adhered to the South African National Environmental Management Act (NEMA) that stipulates EIA process guidelines.

3.3.2.5.5 SMR Operation and Maintenance Environmental Considerations

Given that safety is a fundamental requirement in nuclear power plant operation, improvements in operability and maintainability will also improve safety (IAEA, 1994a).

3.3.2.5.6 SMR Waste Management & Disposal Environmental Considerations

Despite the fact that large PWRs have been in operation for a long time and some of them are now due for decommissioning or disposal of their spent fuel, there are still challenges on waste management. Waste management is therefore still an important issue for SMRs. Mobbs et al. (2017) stated that even if disposal facilities are available, other factors may need to be considered when deciding how remediation wastes could be managed namely:

- treatment options;
- site location and distance to a waste management facility (proximity principle);
- facilities serving the site and facility (rail, truck, vessel);
- types of waste (not radioactive, mixed chemical and radioactive waste, LLW, ILW);
- volume of waste;
- properties of the waste (physical characteristics, hazardous/non-hazardous characteristics);
- appropriate permits and licenses in place at the disposal facility to accept the waste;
- timing and status of facility approval; and
- local and national policies.

3.3.2.6 SMR Legal Factors

As far as the licensing and regulatory issues are concerned, the most important aspects of the SMRs assessment are reactor safety (including seismic safety), radiation protection, and power plant security (Vujic, Bergmann, Skoda & Miletic, 2012). A major barrier is the licensing process, historically developed for large reactors, preventing the simple deployment of several identical units in different countries (Sainati, Locatelli & Brookes, 2015). The WNA (2015a) noted that the various national systems today follow similar paths in approving nuclear power plant construction and operation and generally includes the following elements: (1) Taking the decision to build and operate a plant; (2) Selecting and approving a site; (3) Certifying a reactor design; and (4) Assessing and approving a

construction licence and an operating licence. Söderholm et al. (2014) contended that the main SMR features to consider in licensing are as follows:

- (1) Standardization of the design;
- (2) Modularity;
- (3) Mass production; and
- (4) Serial construction.

3.3.2.6.1 SMR Research and Development Legal Considerations

Kadak (2016) stated that with its Energy Policy Act of 2005 and Next-Generation Nuclear Plant programme the US has only been able to complete the development of advanced fuels, graphite and materials and unsuccessful on the main objective of constructing and operating a process heat for hydrogen production HTGR by 2021 due to the following reasons but not limited to:

- insufficient government funding requirements for research;
- unrealistically high temperature requirements for the reactor;
- the delay in the need for a “hydrogen” economy;
- competition from light water small modular light water reactors;
- little utility interest in new technologies;
- very low natural gas prices in the US; and
- a challenging licensing process in the US for non-water reactors.

The lack of enacting a HTGR legislation to cater for PBMR R&D in SA has been one the reasons given by some of why the programme never saw the light of the day. Despite absence of such legislation, the SA PBMR Company took part in and contributed to the US’s success of HTGR advanced fuel, graphite and materials initiatives.

The use of reliable components and procedures enables achievement of the first priority of accident prevention in a nuclear installation operated by personnel that are committed to a strong safety culture (NNR, 2015a). The reliability of NPP SSCs can be tested and validated through R&D undertakings. Laboratory tests are undertaken for proving that SMR SSCs meet specifications and ultimately contribute to safety requirements. For instance, when PBMR was developing its modular reactor it built Helium Test Facility at NECSA that was for testing specific component materials in terms of their ability to function when exposed to hot helium. The development of safer technologies and improvement of safety and regulatory measures has benefited from nuclear accidents lessons learnt. As an example, the three historical commercial nuclear power plant (NPP) accidents (Three Mile Island, Chernobyl, and Fukushima) have promoted higher safety standards on inherited safety and probabilistic safety objectives, stricter requirements for the prevention and mitigation of severe accidents, and the implementation of the passive safety concept (Zheng et al., 2016). International nuclear organizations, such as the IAEA, have revised their safety standards and guides in response to the lessons learnt from the Fukushima Daiichi accident and other incidents reported throughout the history of nuclear power (WNA, n.d.). The revisions at IAEA level have therefore been cascaded to regulators in different countries some of which are involved in the development and licensing of SMRs. In retrospect, Nian (2015) noted that Fukushima was a turning point in three ways:

- (1) It caused rampant fear of nuclear power and a strong public rejection worldwide. It has led to countries like Germany and Switzerland completely phasing out nuclear power in their energy mix;
- (2) It was a wake-up call for the nuclear industry to invigorate science and technology innovation to build safer reactor systems; and
- (3) Most importantly, it was an alarm for the regulators to review the development in nuclear governance.

3.3.2.6.2 SMR Design Engineering Legal Consideration

It should be verified that the system is able to perform its function with the reliability that was assumed in the safety analysis i.e., on completion of the identification of the systems and their individual components engineering design requirements is done (IAEA, 2014c). Nuclear power plants coupled with heat utilization units (such as for district heating) and/or water desalination units shall be designed to prevent processes that transport radionuclides from the nuclear plant to the desalination unit or the district heating unit under conditions of operational states and in accident conditions (IAEA, 2016b). In the United States, for example, the Department of Energy has offered up to \$452 million to support engineering, design certification, and licensing of two SMR designs (Ramana, Hopkins & Glaser, 2013).

3.3.2.6.3 SMR Manufacturing Legal Consideration

The NNR Regulatory oversight during the manufacturing process involves inspections and audits on the relevant processes at the license applicant as well as its suppliers of components and services (NNR, (2015a). For instance, NNR conducted some inspection and audit of the Shanghai Electric manufacturing factory in China prior to the manufacturing of the Koeberg replacement steam generators.

3.3.2.6.4 SMR Construction Legal Consideration

In SA, the NNR Act provides for such a mechanism whereby Eskom can apply to the regulator for a Nuclear Installation Licence for siting which when issued enables the regulatory control of the development of licensed site and its vicinity in adherence to the Act (DME, 2008). Thus, the NNR in its Annual Report of 2001 to 2002 noted that it received nuclear installation license application from South African electricity utility, lodged in terms of NNR Act, Act No 47 of 1999 for the prospective siting, construction, operation, decontamination and decommissioning of a demonstration unit 110 MW electricity generating power station making use of PBMR design. On its part, China has gone beyond the construction-licensing phase of its 200MW PBMR programme. After the National Nuclear

Safety Administration (NNSA) of China issued a construction permit and all government approval procedures were complete, the first concrete pouring started for the HTGR pebble-bed module (HTR-PM) demonstration power plant on December 9, 2012, in Rongcheng, Shandong Province (Zhang et al., 2016).

3.3.2.6.5 SMR Operation and Maintenance Legal Considerations

Provision shall be made for ensuring that doses to operating personnel at the nuclear power plant will be maintained below the dose limits and will be kept as low as reasonably achievable, and that the relevant dose constraints will be taken into consideration (IAEA, 2016c).

3.3.2.6.6 SMR Waste Management and Disposal Legal Considerations

There is a need to establish an adequate legal framework that will cover issues of nuclear liability, safety and radiation protection, environmental protection, control of operation, waste management and decommissioning, security and non-proliferation (IAEA, 2014). Hence, in its application for the PBMR installation, the SA electricity utility included

3.3.3 Research Reactor (RR) Factors

An important characteristic of research reactors is that they are interdisciplinary tools used in a variety of fields: scientific research, applied or engineering oriented research and training (IAEA, 1988). The IAEA (n.d.) states that research reactors fulfil diverse needs, including medical and industrial isotope production, elemental analysis, silicon doping, neutron beam-based science and applications, education and training, scientific research, and technology development (this includes support for existing and advanced nuclear power technologies). According to 2016 figures in the IAEA Research Reactor Database, 747 research reactors were built in 67 countries and of those, 243 reactors were in operation in 55 countries (IAEA, 2017d). NECSA's SAFARI-1 has been in operation for over 50 years. NECSA is therefore the operating organization of the RR. 'Operating organization' means the organization which undertakes one or more of the siting, design, construction, commissioning, operation,

modification and decommissioning of a research reactor and is authorized (SAFARI-1 is a Material Testing Reactor (MTR) type tank-in-pool research reactor with a licensed operating power of 20 MW and is located at Pelindaba, Pretoria, South Africa. The commissioning SAFARI-1 was in 1965, and has been in operation ever since (Tillwick, 2010). Though the reactor had used Highly Enriched Uranium (HEU) fuel for most of its time in operation, it currently utilizes Low Enriched Uranium (LEU) fuel since converting in 2009 (Rogner, 2013). Safety and integrity of a research reactor that has been in operation for over 40 years requires frequent and thorough inspection of all the safety-related components of the facility (Moatty & Khattab, 2013). Otherwise, in terms of usage, Nuttall and Storey (2014) stated that in general a research reactor will be utilized predominantly in one or more of the following ways:

- Isotope production - as used in medicine, industry and research;
- Neutron scattering - examining the deep structure of materials;
- Neutron radiography-archaeology, biology, aeronautics, car industry and materials studies;
- Materials and fuel irradiation for nuclear energy - issues of fuel ageing, optimization and testing and material needs for both current and future reactors (fission and fusion);
- Transmutation-materials for the electronics industry (e.g. semiconductor doping);
- Teaching and training-biology, physics and nuclear engineering (including training nuclear operators);
- Neutron Activation Analysis - qualitative and quantitative techniques for trace elements;
- Geochronology e-dating small quantities of minerals; and
- Boron Capture Therapy cancer treatment by loading a tumour with Boron and then irradiating it.

The most common research reactor is the ‘Pool’ type including the more actively cooled ‘tank reactor’ concept (Nuttall & Storey, 2014). Strategic issues (shown in Table 3-17 below) are those issues that will have an impact on, or constrain, the facility’s strategic plan (IAEA, 2001b).

Table 3-17: Strategic Issues that constrain the nuclear facility strategic plan

a.	Operations	These strategies are required to give an indication of the typical operation of the facility in terms of power levels and operational schedules.
b.	Cost recovery	In certain instances, it will be necessary for the facility to generate income to justify its financial expenditure. The cash flow will depend on the method of recovery of funds from the various users of the facility, either commercial or institutional.
c.	Business and competitor analysis	The evaluation of these abilities should enable a determination as to whether or not the facility should attempt to enter into a competitive market with respect to certain commercial products or services.
d.	Maintenance	The status of the facility is normally directly related to its age and the degree of utilization in the past. Maintenance requirements will be identified according to the condition of plant equipment and associated instrumentation.
e.	Licensing and regulatory	These issues are defined by the authorities controlling the facility licence and should receive the necessary attention to ensure that the operation of the facility is not interrupted due to either unsafe or irregular applications.
f.	Quality management	It is advisable that a nuclear facility be operated according to a suitable quality management system. This ensures that the necessary operations are performed in a controlled and acceptable way, at the same time ensuring that customer quality requirements are satisfied.
g.	Health, safety and environment	A facility should be implementing procedures and policies to ensure conventional (industrial) safety conditions for personnel and the public. At the same time the health and environmental requirements should be taken into consideration.
h.	Technical co-operation and information exchange	It is often beneficial for a facility to have technical assistance in operation and utilization experiences. This co-operation and information can be provided from various sources, e.g. IAEA, nuclear societies, other facilities or specialist groups, both internal and external to your own institution.
i.	Life limiting factors	At this point, the strategic plan should carefully evaluate the personnel resources available to perform the various activities. The responsible management should then, by consensus, consider the allocation of the various tasks to personnel according to their abilities and future potential.

Source: International Atomic Energy Agency (2001b)

NECSA is involved in the production and supply of medical isotopes through its subsidiary known as NTP. The provision of isotope production facility's structures, systems and components engineering and manufacturing services needs to be evaluated and considered using the SWOT-PESTEL-AHP hybrid model as part of an effort for possibly increasing the involvement of the ASME III entity and its supply chain. As an example, the ASME III business unit fabricates medical radioisotopes transportation containers, replacement equipment for the plant and nuclear waste containers. Medical

diagnostic imaging techniques using technetium-99m (^{99m}Tc) account for approximately 80% of all nuclear medicine procedures, representing 30-40 million examinations worldwide every year Nuclear (NNR, 2016).

The Nuclear Energy Agency (NEA) Steering Committee for Nuclear Energy established the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR) in April 2009 (NEA, 2010c). According to NEA (2014), the United States and Europe account for approximately two-thirds of global $^{99}\text{Mo}/^{99m}\text{Tc}$ demand (Europe is the largest producer, while the United States is the largest consumer) and should be at the forefront of efforts to implement the HLG-MR policy principles shown below in Table 3-18. While there were no major supply shortages of the medical isotope molybdenum-99 during 2015, operational challenges at processing facilities and older research reactors continue. Politicians the world over are challenged in evaluating and making decisions on which R&D initiatives must be prioritised for funding i.e., how, when and why? Rautman, Reid and Ryder (1993) in their study on the USA isotope production and utilisation found that essentially all USA commercial applications of isotopes, government and university collaborated in the development with both small and large businesses taking the responsibility of commercialization. In South Africa, the government articulates its political stance through its Nuclear Energy Policy. One of the main functions of NECSA is to undertake and promote research and development (R&D) in the field of nuclear energy and radiation sciences and technology and, subject to the Safeguards Agreement, to make these generally available (Nuclear Energy Act, 1999). The Safari-1 research reactor is part of the R&D infrastructure that enables NECSA to be involved in medical isotopes since the reactor enables the irradiation of target plates. The RR creates engineering, manufacturing and maintenance opportunities such as replacement of plant components, plant upgrades, waste management, containers for the transportation of medical isotopes and nuclear waste concrete containers. Market share on the supply of medical isotope is a possible factor of for the number of medical isotope containers procured from local suppliers. Powe, Worsley and Ruth (2010) noted that the largest and most productive reactors have been the Canadian NRU reactor and the

Dutch HFR-Petten reactor with the two reactors accounting for 60%-80% of worldwide production, although the NRU reactor alone was capable of supplying up to 80% of the world's supply of ⁹⁹Mo. The IAEA Research Reactor Database contains information on 650 research reactors that have been built, of which 283 are operational in 58 countries (85 in 40 developing countries), 258 are shut down, and 109 have been decommissioned (Dodd et al., 2002).

Table 3-18: High-level Group on the Security of Supply of Medical Radioisotopes policy principles

Policy Principle	Supply Chain Requirements
Principle 1	All ^{99m} Tc supply chain participants should implement full-cost recovery, including costs related to capital replacement.
Principle 2	Reserve capacity should be sourced and paid for by the supply chain. A common approach should be used to determine the amount of reserve capacity required.
Principle 3	Recognising and encouraging the role of the market, governments should: • establish the proper environment for infrastructure investment; • set the rules and establish the regulatory environment for safe and efficient market operation; • ensure that all market-ready technologies implement full-cost recovery methodology; and • refrain from direct intervention in day-to-day market operations as such intervention may hinder long-term security of supply and governments should target a period of three years to fully implement this principle, allowing time for the market to adjust to the new pricing paradigm while not delaying the move to a secure and reliable supply chain
Principle 4	Given their political commitments to non-proliferation and nuclear security, governments should provide support, as appropriate, to reactors and processors to facilitate the conversion of their facilities to low-enriched uranium or to transition away from the use of highly enriched uranium, wherever technically and economically feasible.
Principle 5	International collaboration should be continued through a policy and information sharing forum, recognising the importance of a globally consistent approach to addressing security of supply of ⁹⁹ Mo/ ^{99m} Tc and the value of international consensus in encouraging domestic action
Principle 6	There is a need for periodic review of the supply chain to verify whether ⁹⁹ Mo/ ^{99m} Tc producers are implementing full-cost recovery and whether essential players are implementing the other approaches agreed to by the HLG-MR, and that the co-ordination of operating schedules or other operational activities have no negative effects on market operations.

Source: Nuclear Energy Agency (2014)

According to the Nuclear Energy Agency (2010b), changes are required to address market, policy and technological failures listed below in Table 3-19.

Table 3-19: Required changes for economic sustainability

Type of Failures	Description of Failures
Market failure	Patients benefit from there being a reliable supply of ^{99m} Tc through having access to timely medical diagnostic imaging. Since the benefits may not be fully accounted for in the pricing structure, a positive externality exists. This positive externality should be addressed at the health care system level through reimbursement rates, not at the research reactor level.
Market failure	Imperfect information related to the full costs of waste management, reactor operations, fuel consumption, etc. not being known or included in the price structure provides a significant deficiency in the pricing mechanism. In many cases, the full costs for ⁹⁹ Mo provision were not transparent to or appreciated by governments who were subsidising the production.
Market failure	The existence of significant market power creates a barrier to developing a proper pricing mechanism for the efficient allocation of resources.

Type of Failures	Description of Failures
Policy failure	The historical commercialisation route of the processing industry set the industry on the path toward unsustainable pricing and reinforced market power, resulting in the perpetuation of an uneconomical pricing structure and potentially inefficient use of ^{99}Mo .
Technology failure	The development of new ^{99}Mo production capacity was stalled for a decade or more given the development of the MAPLES project in Canada, which was expected to have production capacity in excess of 100% of world demand. However, this project was cancelled by the Government of Canada in 2008. If this project had proceeded there theoretically would have been sufficient capacity at the moment to meet global needs. However, the project could have created some other market failures if it had proceeded, including market power and reliability concerns as a result of the possibility of a single point of failure.

Source: Nuclear Energy Agency (2010b)

3.3.3.1 RR Political Factors

At present, the SA Department of Energy (DoE) is the government department that has oversight of NECSA's research reactor related activities. Normally this body (typically a government Department) handles the political and financial policies that will be applicable to the facility and as such, it could be a major role player in the decision or strategy making process (IAEA, 2001b).

The U.S. reduced enrichment research and test reactor (RERTR) programme is a major national programme which is currently under way in the U.S., centred at the Argonne National Laboratory (ANL), to reduce the nuclear weapon proliferation potential of research and test reactor fuels (Barkatullah and Ahmad, 2017). The RERTR programme was initiated by the U.S. Department of Energy in 1978 and during the Programme's existence, over 40 research reactors have been converted from HEU (= or >20% ^{235}U) to LEU (< 20% ^{235}U) fuels, and processes have been developed for producing radioisotopes with LEU targets (ANL (n.d.)).

Governments are involved in the global $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$ supply chain primarily at both ends i.e. at the reactor and end-user levels (NEA, 2005). Nowadays, the impact of science and technology upon politics is so great that there is a constant need for qualified experts to advise and provide authoritative information to politicians, as well as ensure that these issues do not cause additional anxiety among the population (Lavoie, 2010). So, with the current shortage in isotope production, the political push to remove HEU and the risk faced to this production by key research reactors that are getting older, there is an urgent need for the construction of new research reactors (Nuttall & Storey, 2014).

3.3.3.1.1 RR Research and Development Political Considerations

Nuclear new build stakeholders including policy makers are sometimes interested in the social rate of returns especially when implementing state funded initiatives. Hence, the conversion of the South African research reactor SAFARI-1 and the related local fuel manufacture to LEU utilisation was authorised by the Department of Minerals and Energy (DME) in July 2005 (Piani, 2007). Table 3-20 below shows that in a study conducted by Inglesi-Lotz (2017) the nuclear programmes in Canada, Germany, France, Italy, Japan, UK and US have a positive social rate percentage in all considered countries.

Table 3-20: Social rate of return estimates by country (percent).

	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7
	Energy efficiency	Fossil fuels	Renewable energies	Nuclear	Hydrogen and fuel cells	Other power & storage technologies	Other cross cutting technologies
Canada	1.423	-0.635	-2.082	3.64	-25.259	-1.590	-0.777
France	1.122	-0.558	-0.271	4.861	2.216	1.035	1.136
Germany	1.125	-0.294	-7.780	3.571	65.884	-0.726	0.689
Italy	1.183	-0.204	-9.257	3.341	-2.560	-3.971	0.473
Japan	1.236	-0.693	1.48	5.603	10.685	1.775	0.405
UK	0.931	-0.487	1.299	2.611	-0.185	2.666	-0.588
US	1.234	-0.635	0.591	2.897	-3.837	0.723	-0.102

Source: Inglesi-Lotz (2017)

It is important for SA government to put in place policies that encourage and promote state owned entities to undertake R&D continuously for the purposes of maximising the benefits along the value chains. Such policies will be an assurance that there is a deliberate effort to sustain the viability of SOEs and ultimately reduce the dependency on government funding.

3.3.3.1.2 RR Design Engineering Political Considerations

A significant number of Governments are responsible for funding not only the R&D initiatives that use research reactors but also for the development and design engineering of new research reactors. Safety is an area of concern in nuclear power and research in the area includes work on reactor core and containment strategies and technologies; sensors, instrumentation, automation, and control

technologies; radiation shielding; modelling and simulation; improvements in reactor designs; and nuclear detection technologies (Schuelke-Leech, 2014).

Newly developed technologies have to go through a design-engineering phase. It is crucial that the government as a sponsor of such developments be aware of the importance of such design-engineering resources. The ASME entity and its supply chain can provide design-engineering services in support of the R&D efforts as part of assisting the government to meet its goals of localization or enabling local manufacturing.

3.3.3.1.3 RR Manufacturing Political Considerations

Just as the other funds required for R&D and design engineering, that some governments do sponsor the manufacturing of the research reactor SSCs as well. In some situations, some of the Government institutions or laboratories e.g. are able to recover some of their costs through commercial undertakings such as selling research reactors and related services. Hence, South Africa also has an Oak Ridge type research reactor, called SAFARI, operated by the South African Atomic Energy Corporation (AEC) at their Pelindaba site near Pretoria (Bredell & Stott, 1998).

Laboratory scale, prototypes or demonstrations for developed isotope production technologies through R&D requires the manufacturing of components. The SA ASME entity is able to manufacture such components. It is important to note that in the SA Department of Trade and Industry's Industrial Policy Action Plan (IPAP2) the medical isotope manufacturing is not included in the pharmaceuticals sector profile section. The exclusion of NECSA's isotope production capability in IPAP2 is therefore a gap that will require engagement between the NECSA management and SA government departments.

3.3.3.1.4 RR Construction Political Considerations

The WNA (2018) notes that Government support may (and does) exist for research reactor programmes in countries politically opposed to nuclear power e.g. the FRM-II research reactor at the Technical University in Munich was subsequently commissioned in 2005 and Open Pool Australian Light Water (OPAL) Reactor started operations in 2007.

The NECSA's ASME III entity can get involved in the installation of SSCs for the R&D medical isotope related prototypes or demo plants. Presently the entity has been involved in the installation of some replacement SSCs for the existing NTP plants.

3.3.3.1.5 RR Operation and Maintenance Political Considerations

It is clear from Figure 3-17 below that the political climate, the priority of the South African strategic programmes and the impact of boycotts related to the supply of nuclear fuel to South Africa significantly affected SAFARI-1 utilisation for the period 1977 to 1993.

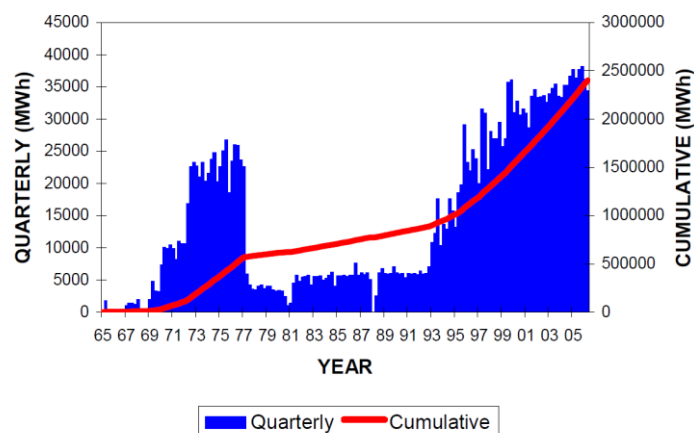


Figure 3-17: SAFARI-1 Power History (MWh/quarter and Cumulative)
Source: Jamie and Kocher (2007)

Replacements of assets such as a RR at NECSA will require government submissions, motivation and approvals i.e. in accordance with specific government policies. For instance, the replacement of the SAFARI-1 will require approvals from the DoE and National Treasury. In this case, NECSA will have taken into consideration relevant alternatives e.g. life extension. For state owned entities, the life extensions or replacements of assets that will be worth multi-millions or billions will often require political approvals in accordance with legislation or regulations meant foster accountability. In SA, the Public Finance Management Act of 1999 (Act No.1 of 1999) enables the political oversight on SOEs.

The SA ASME III entity is able to supply operation and maintenance related installation services to radioisotope production plants. Government policies that promote such collaborations might be required so that the ASME III can maintain its nuclear SSCs maintenance support capabilities.

3.3.3.1.6 RR Waste Management and Disposal Political Considerations

According to Yanev (2013), governments will always have a major role in nuclear energy for two main reasons: first, the life cycle of a nuclear power programme including waste management could be longer than that of most organizations and second, nuclear power incorporates international commitments by governments in such areas as safety, safeguards, and regulation. In this regard, the (IAEA, 2017a) contends that a State needs to consider many factors when developing a back end strategy for its research reactor SNF and currently the choices are limited to three strategies namely:

- (a) Direct disposal (or once through fuel cycle);
- (b) Storage and postponed decision (or wait and see option); and
- (c) Reprocessing and recycling (or closed fuel cycle).

As for possible localization nuclear waste management technologies, political backing can be required for the initial capacitating of the ASME III entity to develop waste management capabilities e.g. containers for transporting nuclear waste and waste storage containers.

3.3.3.2 RR Economic Factors

According to Dodd et al. (2002), the climate for research reactors is changing for several reasons:

- The original mission for some facilities has been accomplished or is no longer needed;
- Some old applications are now obsolescent;
- Fiscal realities have forced some governments to cut back support for research reactors;
- The stagnation of nuclear power in many industrialized countries decreased the demand for nuclear education and training; and
- Simulators have taken over part of nuclear power plant operator training unlike whereas in the past research reactors were utilised.

Tillwick (2011) stated that the following are the South African SAFARI-1 research reactor issues worth noting about past developments:

- (1) 90% is funded by NTP commercial sales;
- (2) NTP also funds LEU fuel element final disposal, and D&D of SAFARI-1 from April 2010;
- (3) 10% funded by NECSA for historical liabilities;
- (4) Reactor needed until early 2020s for commercial production;
- (5) With operation of Dedicated Isotope Production Reactor (DIPR) in early 2020s SAFARI-1 will function as back up and focus on R&D;
- (6) HEU to LEU conversion of fuel was completed; and
- (7) ^{99}Mo target plate were licensed by the local regulator.

3.3.3.2.1 RR Research and Development Economic Considerations

According to IAEA (2011d) the South African Fundamental Atomic Reactor Installation (SAFARI-1)'s research and development activities are as follows:

- Neutron diffraction for magnetic phase analysis, residual strain, chemical phase analysis, crystallography, magnetic phase analysis, nuclear materials research (potential users are industry and academia);
- Small angle neutron scattering for materials research;
- Utilization of beam ports for beam tube experiments, basic and
- applied research in physics and nuclear engineering.

NECSA through its subsidiary NTP is involved in medical isotope production. NM can work towards increasing the supply of medical isotope containers, waste containers and replacing plant equipment. During strategic planning, global medical isotope production changes are factors that are worth considering, not only by NTP but also by the NECSA ASME III certified entity. NTP supplies ^{99}Mo to 50 countries around the world, as well as meeting all of South Africa's own requirements and is one of the world's top three producers, being responsible for between 25% and 33% of global production (Engineering News, 2017). For instance, if NTP increases its global supply it will have a positive impact on NM's value propositions. Many countries have shown interest in ^{99}Mo production due to recent shortages, looming retirement of aging reactors, and a predicted 1-2% growth in ^{99}Mo demand. One of the largest producers of ^{99}Mo globally is Canadian Nuclear Laboratories' Chalk River Laboratories in Ontario, Canada whereby highly-enriched uranium targets are irradiated to produce ^{99}Mo , which is then extracted on-site using chemical dissolution (Johnson et al, 2017).

Typical decisions to invest in new products, processes, or facilities in a new region are determined by a range of factors, such as costs of inputs into production, sophistication of markets, and access to natural and human resources as well as finance and banking as fundamental firm inputs. According to The Untold Story (1997), the state impacts of nuclear technologies reflect many factors: the location of specific plants and activity, the facilities that fabricate commodities using the technology, the final user of the commodities and services, the final waste disposal site and related factors.

The IAEA (2008b) states that the use of aqueous homogeneous reactors (AHRs) or solution reactors presents an attractive alternative to the conventional target irradiation method of producing ^{99}Mo and the principal advantages of aqueous fuel systems include:

- Flexibility with respect to reactor parameter variation, fuel selection, and geometry;
- Inherent nuclear safety characteristics;
- Efficient neutron utilization for isotope production;
- Elimination of targets, less uranium waste generated per curie of ^{99}Mo produced, and overall simpler waste management;
- Ability to process other isotopes such as ^{133}Xe , ^{89}Sr , ^{90}Y , ^{131}I more efficiently using off gas extraction; and
- Less capital cost and potential lower operating costs.

3.3.3.2.2 RR Design Engineering Economic Considerations

The NECSA management is responsible for making sure that there is an availability of resources to undertake design-engineering activities for the SAFARI-1. In the main, NECSA's Engineering Services is capable to undertake SAFARI-1's SSCs design engineering. The economic viability of NECSA's medical isotope production is dependent on the SAFARI-1 operational performance.

The world market for medical diagnostics and therapy is reportedly approximately \$12 billion and their predictions that it can increase to \$68 billion in 2030 (Zhuikov, 2014). The demand for medical isotopes

across the world has been under great pressure for some time as the demand continues to increase, but shortages of suitable research reactors are impeding the supply (Nuttall & Storey, 2014). In the USA, the present isotope supply and-use system is made up of the commercial sector, government sector, university community, and medical R&D community (Rivarda et al., 2005). Technetium-99m (^{99m}Tc ; $T_{1/2} = 6 \text{ h}$), the daughter product of Molybdenum-99 (^{99}Mo ; $T_{1/2} = 66 \text{ h}$), is the most widely needed radionuclide in the world, used for well over 30 million medical diagnostic procedures annually and comprising over 80% of all diagnostic nuclear medicine procedures (Mushtaq et al., 2012). Lavoie (2010) contends that it is also difficult to project the demand for ^{99}Mo as it relates to healthcare policies and practices, demographics, potential markets in developing countries, and technological alternatives. Categories of radioactive sources within the NECSA environment are shown in Table 3-21 below.

Table 3-21: Categories of Radioactive Sources Manufactured at NECSA's NTP

Product Category	Example
Sources used in public access facilities (radiopharmaceuticals)	^{99m}Tc , ^{131}I
Sources used in public areas (well logging or pipeline radiography, radiochemical products)	^{192}Ir , ^{137}Cs , ^{60}Co , ^{99}Mo , ^{32}P , ^{131}I

Source: Zondo (2003)

It is important that competent and qualified personnel conduct designs of electrical, mechanical, C&I and civil SSCs for the medical radioisotope production plant. The importance of this is not only for the safety of the nuclear facility but also for enhancing the security of supply of the produced products. The operational reliability of the isotope production plant ultimately has a huge impact on the business viability of NTP and that of the ASME section that supplies engineering design services.

3.3.3.2.3 RR Manufacturing Economic Considerations

Research reactor SSCs important to safety and those that are not can be manufactured by the ASME III entity respectively e.g. in accordance to ASME III and ASME VIII standards and as per approval by the regulator. Advance planning on this is important so that the ASME III entity can resource accordingly to fabricate the required SSCs as part of the ageing management plan.

Medical isotope supply chain irradiators have indicated some operational costs increases through the Nuclear Energy Agency's high-level group on the security of supply of medical radioisotopes (HLG-MR) which has been monitoring the full cost recovery (FCR) which is expected to be implemented by the group members. The increase in their cost base has been associated with essential maintenance, safety related activities and low-enriched uranium (LEU) conversion (NEA, 2017).

The conversion of medical isotope production processes from HEU to LEU targets continue, with the Australian Nuclear Science and Technology Organisation (ANSTO) and NTP Radioisotopes, South Africa, as the major suppliers of LEU-based ^{99}Mo (IAEA, 2016d). Molybdenum-99 has a half-life of 2.75 days which is sufficiently short to ensure effective $^{99\text{m}}\text{Tc}$ generation, but also places severe time pressure on the supply chain from reactor to clinical use (Nuttall & Storey, 2014). Figure 3-18 below shows the production cycle of ^{99}Mo illustrating growth during irradiation followed by losses due to chemical processing and radioactive decay (IAEA, 2013c). Again, with reference to Figure 3-18 below, it is important to note that a six-day curie is the measurement of the remaining radioactivity of ^{99}Mo six days after it leaves the processing facility (i.e. at the end of processing-EOP) and in International System (SI) Units, 1Ci is equal to 37 Giga Becquerel (IAEA, 2013c). As a rough estimate, the use of LEU would at best decrease production by a factor of two, so twice as many research reactors of the same output would be required to produce the same quantity of medical isotopes (Nuttall and Storey, 2014).

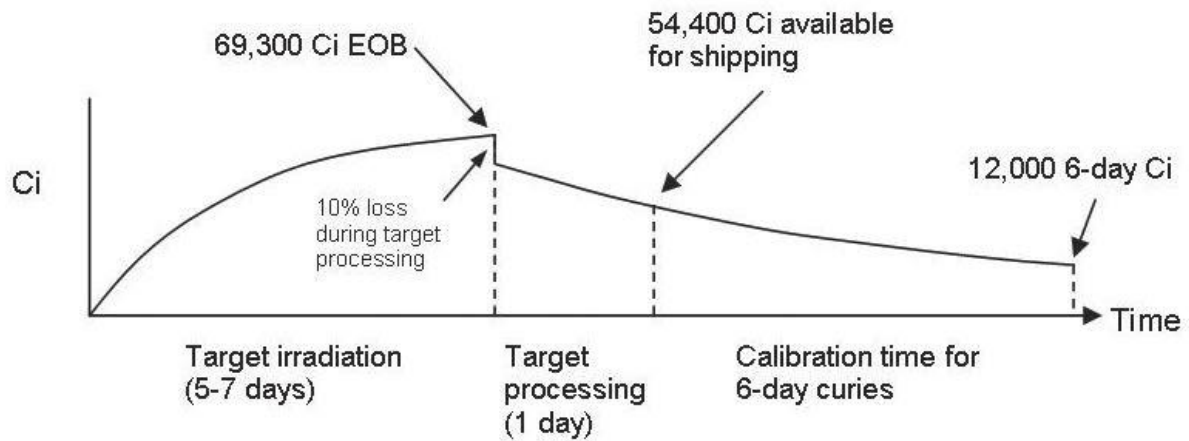


Figure 3-18: ^{99}Mo production and decay timeline (typical).

Source: International Atomic Energy Agency (2013c)

3.3.3.2.4 RR Construction Economic Considerations

According to the IAEA (2011) through the past 45 years, the SA research reactor has undergone some modernization several times and the successful commercial use of the reactor allows constant development and improvement of facilities and infrastructure increasing utilization opportunities.

Future medical isotope production and supply will be dependent on governments and companies having appropriate techniques to decide on when and which RR to procure and construct and why? Such was the Canadian government and ACEL in 2007 and 2008 when it was originally anticipated that an extension of the life of the NRU reactor would support the production of radioisotopes until the MAPLE reactors (MAPLE 1 and MAPLE 2) came online (Lavoie, 2010). According to the NEA (2016) market conditions report, the global demand estimate has been maintained at a level of around 9000 six-day Ci ^{99}Mo per week EOP.

3.3.3.2.5 RR Operation and Maintenance Economic Considerations

For major SSCs that are essential to safe plant operation, the operating organization should consider preparing contingency plans or exceptional maintenance plans to deal with their potential degradation or failure caused by potential ageing mechanisms and effects (IAEA, 2008e). The operation of RRs is expensive due to age-induced maintenance costs and the governments' subsidising of the storage of generated large amount of long-lived nuclear waste (Galea, Ross & Wells, 2014). The SA ASME III entity can be involved in RR maintenance planning implementation rather than depending on foreign entities. The SA SAFARI-1 management embarked on an ageing management programme to upgrade various reactor structures, systems and components in addition to other improvement (IAEA, 2011d). This will enable an extension of its life up to 20 years to 2030. For strategic reasons the life of RR's SSCs is extended at times. Figure 3-19 below shows economic, technical, social, environmental benefits for life extension of safety critical equipment for a given plant (Shafiee & Animah, 2017).

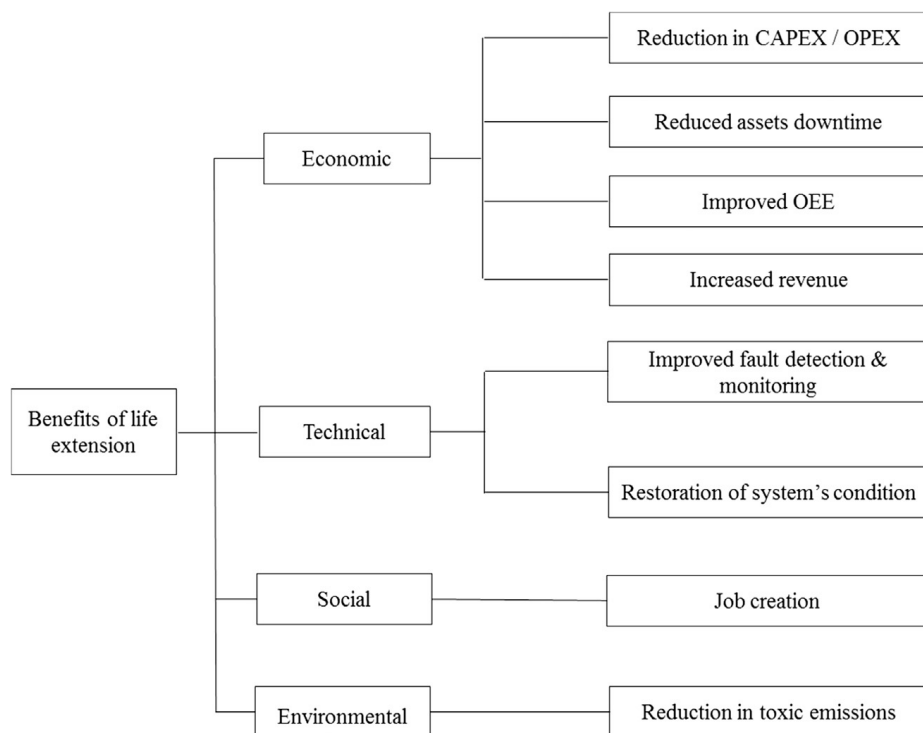


Figure 3-19: Benefits associated with life extension of safety critical systems

Source: Shafiee and Animah (2017)

Ageing management, sustainability of fuel supply, options related to spent fuel management, and enhancement of research reactor utilization are the major challenges for the research reactor community. Tillwick (2011) stated that the SAFARI-1 Reactor maintenance scheduled down time per annum was as follows:

- Ten 5-day shutdowns with 21 to 35 days operating cycle;
- One 12-day shutdown; and
- Total scheduled shutdown time is ~62 days with 303 operation days at full power.

ASME NQA 1 Subpart 2.18 provides amplified requirements for maintenance of nuclear facility components and systems (ASME NQA-1a, 2009). Safety of nuclear research reactors (RR) is one of the most important conditions for their acceptance hence in-service inspection (ISI) has a significant role in avoidances of failure in reactor components just the same as in assurance of their integrity (Moatty & Khattab, 2013). Maintenance costs include the cost of replacing equipment and the temporary staff hired during the maintenance break world (Bredimas, 2014). NECSA's ASME III capabilities provide an opportunity for reducing the outsourcing of maintenance services for e.g. its research reactor, medical isotope and fluorine plants. The deterioration and failure of systems might incur high costs, due to production losses and delays, unplanned intervention on the system and safety hazards (Bertolini & Bevilacqua, 2006). Likewise, Mosher (2007) stated that unplanned production downtime, missed contract deadlines, costly machinery replacements, as well as safety problems, environmental concerns, and regulatory violations are all potential consequences of a maintenance programme that fails to predict and monitor equipment problems. Condition-based maintenance (CBM) is a maintenance programme that recommends maintenance decisions based on the information collected through condition monitoring and it consists of three main steps: data acquisition, data processing and maintenance decision-making (Jardine & Banjevic, 2006). In 2008–2009, the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL) tested the potential of predictive or condition-based maintenance techniques to reduce maintenance costs, minimize the risk of

catastrophic failures, and maximize system availability by attaching wireless-based sensors to selected rotating equipment at HFIR (Hashemian, 2011).

The conversion of medical isotope production processes from HEU to LEU targets continues, with the Australian Nuclear Science and Technology Organisation (ANSTO) and NTP Radioisotopes, South Africa, as the major suppliers of LEU-based molybdenum-99 (IAEA, 2016d). Manufacturers are looking for opportunities to provide the maintenance service within the in-service phase of the product life cycle to generate additional revenue and profit (Roy et al., 2016). The maintenance of the SAFARI-1 Reactor at NECSA provides revenue-generating opportunities for NM provided it has positioned itself accordingly.

3.3.3.2.6 RR Waste Management and Disposal Economic Considerations

One of NECSA's mandates is to transport source material, special nuclear material, nuclear fuel, irradiated nuclear fuel, radioactive material and radioactive waste or cause it to be undertaken (Nuclear Energy Act, 1999). The NECSA's ASME III certified entity is in a position to give support in e.g., developing, engineering and design of nuclear waste facilities, waste storage and transportation containers. Timing of such a development is crucial so that customers will be in a position to get the necessary support when they need it.

From the conversion of target material from HEU to LEU, radioactive wastes increase by decreased production yield because of the increase in the number of targets used to have the same productivity (Lee, Beyer & Lee, 2016). Three potential effects on radioactive waste generation exist if LEU rather than HEU is used for the production of ^{99}Mo : (1) Increased amounts of irradiated-uranium by-product that must be solidified, stored, and transported to a reprocessing plant. (2) Increased radioactive waste generation (spent chemicals and equipment, wipes, lab ware, etc.) due to processing more uranium for

the same ^{99}Mo yield- (3) Increased amounts of ^{239}Pu and other transuranic elements, causing waste to be designated as TRU (i.e., not as low-level) waste, thus increasing the cost and difficulties of disposal (IAEA, 1989).

Entities involved in radioisotope production are developing economically competitive ways of addressing nuclear waste from medical isotope manufacturing. For instance, Figure 3-20 below is a description by Cheung et al. (2012) of the ANSTO developed hot-isostatic pressing (HIP) which is employed to consolidate the processed waste and achieve substantial waste volume reductions compared to a cementation option.

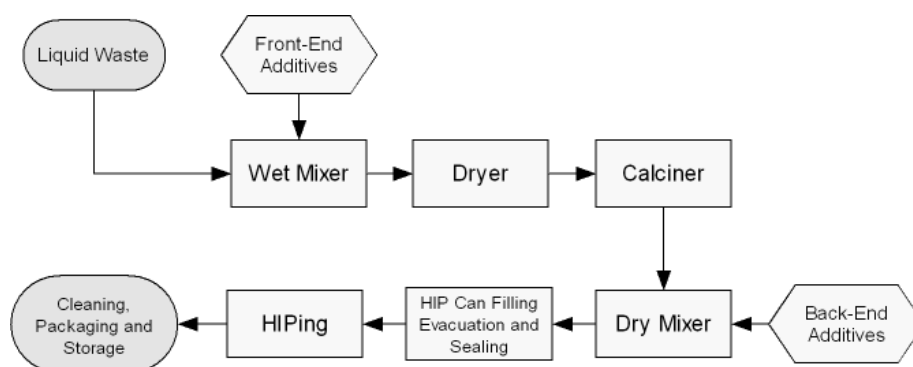


Figure 3-20: Plant treatment stages for converting liquid ^{99}Mo process alkaline ILLW & legacy acidic waste to stable, solid, waste forms
 Source: Cheung et al. (2012)

3.3.3.3 RR Social Factors

For over 50 years, research reactors have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training (Dodd et al., 2002).

In support of member countries, the IAEA has come up with guidelines pertaining to the utilisation of medical isotopes. The need for support remains, with more than 90% of patients in low-income countries lacking access to radiotherapy (Abdel-Wahab et al., 2017). Recently, some governments have started to question their social contract with the medical community and with the reactor operators.

3.3.3.3.1 RR Research and Development Social Considerations

Countries that developed RR have the benefit of using them for their country and populace needs such in health, industrial and agricultural sectors. Some countries have developed RR related capabilities through both self-development and technology transfer. In response to increased worries over the potential use of HEU from research reactors in the manufacturing of nuclear weapons, the U.S Department of Energy (DOE) initiated the Reduced Enrichment for Research and Test Reactors (RERTR) in 1978 to develop the technology necessary for converting research reactors to use low enriched uranium (LEU) fuel (Roglans-Ribas & Landers, 2011). For instance, in order to establish, validate and qualify the South African local manufacture of LEU fuel, NECSA has entered into a co-operation and technology transfer agreement with AREVA CERCA, the French manufacturer of Research Reactor fuel elements (Jamie & Kocher, 2010). By so doing they create employment for their citizens since there will be requirements for different skills ranging from e.g. scientists to engineers who will be involved in developing of electrical, mechanical, civil and control and instrumentation SSCs. The WNA (n.d.) states that Argentina's National Atomic Energy Commission (Comisión Nacional de Energía Atómica, CNEA) was set up in 1950 and resulted in a spate of activity centred on nuclear R&D, including construction of several research reactors. If SA could embark on developing a research reactor through NECSA, it can strengthen its research and development position by virtue of owning the intellectual property. Argentina is now one of the countries, which is a position to market its RRs to other countries and by so doing generate revenue and create employment of its citizens within its nuclear sector. Miller and Abbate (2003) stated that the Australian Nuclear Science and Technology Organisation (ANSTO) was acquiring a new high-performance Research Reactor known as the RRR and Argentina's INVAP was responsible for the design and the construction at the Lucas Heights

Research Laboratories (Sydney). Subsequently, in May 2013 INVAP was awarded contracts to build the RA-10 research reactor in Argentina and the Brazil Multipurpose Reactor (RMB) there, with Australia's OPAL reactor being the reference design for both (WNN, 2018).

Medical research is of strategic social and economic importance and it has an impact on the long-term performances of national health systems, including quality of life and life expectancy, and health care efficiency and costs (NEA, 2005). One of the main drivers in the advances of nuclear medicine is the improvement of improving the well-being of people the people. The area of nuclear medicine also provides employment to citizens of countries that have invested in R&D in radioisotopes. Studies of the US economy in 1992 showed that the economic benefit in terms of jobs and revenues arising from the use of nuclear science and technology in medicine, manufacturing applications, research, food irradiation, waste management, transport, and the like was approximately four to five times as large as: the economic benefit arising from the nuclear generation power (Graham, 1998).

3.3.3.3.2 RR Design Engineering Social Considerations

Nuclear power requires a high level of knowledge in virtually every field of engineering and science (Yanev, 2013). As stated earlier on, the entities that embark on developing and designing their own RR create additional social benefits for the countries they belong to seeing that as they sell the RR more citizens get involved in related design and construction.

Civil, mechanical, electrical and control and instrumentation skills are required for designing isotope production facilities. Various plant SSCs have to meet quality and safety requirements as stipulated by e.g. the nuclear regulator.

3.3.3.3 RR Manufacturing Social Considerations

The RR technology owner is in a position to make a call on who is going to undertake the manufacturing of the SSCs. Making a call on the SSCs suppliers is possible by the fact that some of the equipment manufacturers will have been involved in the development phase. Such suppliers may have negotiated contractual arrangements that they will be the only ones to supply such special SSCs since they will have invested their resources.

The USA has had positive social impacts due to its involvement in nuclear isotope production. A 1994 study by Management Information Service, Inc., showed the following beneficial economic and employment impacts of radioisotopes and radioactive materials in 1991: \$257 billion in total industry sales; 3.7 million jobs; \$11 billion in total industry profits; and \$45 billion in federal, state, and local government tax revenues. For example, each day, 41,000 nuclear medical procedures are performed in the United States using ^{99m}Tc , a radioisotope obtained from the decay of molybdenum-99 (Nagurney & Nagurney, 2012). In addition, radio therapy medical interventions become affordable in countries that own and continuously come up with the related technologies (Collins & Ottinger, 2003). However according to the NEA (2010b), there are indications that the traditional social contract that supported ^{99}Mo production has started to change and this change in the social contract has come about due to governments questioning whether it is still in the public interest, based on a number of reasons:

- Increased awareness by governments of the amount that they were subsidising ^{99}Mo production and the related waste management (with all its responsibilities);
- The growing proportion of reactor use for ^{99}Mo production brings with it questions of the government's role in a commercial activity, not only from a philosophical perspective but also a regulatory one;
- The taxpayer-funded subsidisation was mostly supporting the health care system of other countries, since much of the product was exported; and

- The taxpayer may not benefit from the subsidisation when the irradiated targets or bulk ^{99}Mo are exported and the generators are then imported back into the country.

3.3.3.3.4 RR Construction Social Considerations

Original equipment manufacturers (OEMs) usually want to have a say on the installation of their equipment seeing that it is in their interest that the installation does not result in the malfunctioning of the equipment or safety incident or accident.

Potential and current processors and irradiators have to formulate strategies for refurbishing or replacing of existing ^{99}Mo production facilities. As mentioned earlier on, the appetite for governments to subsidise ^{99}Mo production is waning. This changing social contract is also relevant when looking at the possible development of new multipurpose research reactors that are being discussed to replace ageing reactors, as well as efforts to encourage the development of other production options (NEA, 2017).

3.3.3.3.5 RR Operation and Maintenance Social Considerations

Likewise, manufacturers and providers of RR SSCS invest in additional resources for operational support. The interest and support given by the original equipment manufacturers is more crucial for SSCs important to safety.

Employment opportunities are available for the operation or maintenance of the target irradiation and processing facilities. Plant operators are required for the production of medical isotopes. From time to time mechanical, control and instrumentation, electrical and civil works components have to be replaced by competent personnel based on e.g. the maintenance plans.

3.3.3.3.6 RR Waste Management & Disposal Social Considerations

Social benefits are also realised in the waste management and disposal phase of the developed RR seeing that this aspect is also part of the R&D initiatives. As an example, the company will have developed and localised human resources and infrastructure for RR fuel front-end and back-end. There are always public concerns about the management of residual waste emanating from the radioisotope production or used source materials.

3.3.3.4 RR Technological Factors

Table 3-22 below lists five different types and subtypes of RR technologies. NECSA's SAFARI reactor is a water-cooled reactor and is a tank type. As shown in the next the SAFARI is tank-in-pool reactor, which is water-cooled and an MTR. According to Tillwick (2011) for lifetime extension, SAFARI-1 is actively implementing an ageing management programme to extend its life to 2030. Table 3-23 below indicates some of the SAFARI-1 reactor specifications. This compared with Australia which is already installing its advanced research reactor (RRR) which has some of its features listed in Table 3-24 below. The SAFARI-1 and the Australian RRR have thermal power of 20MW each. The two research reactors support the two countries' medical isotope production businesses. This being the case, it is important for SA stakeholders to be aware of how other countries are positioning their SOEs who are potential partners or competitors.

Table 3-22: Research Reactor Categories

Category	General reactor characteristics	
	Type	Subtype
I	Critical facilities	Solid fuel system
		Liquid fuel system
		Gaseous fuel system
II	Water cooled reactor with closed primary coolant system	Tank type reactors
		Pressurised water reactors
		Water-cooled graphite reactors
III	Pool-type reactors	-
IV	Liquid-metal-cooled reactors	-
V	Transient reactors	Fast-burst-type reactors
		Pulse type
VI	Air-cooled graphite reactors	-

Source: Argonne National Laboratory (n.d.)

Table 3-23: SAFARI 1 Research Reactor Specifications

Location	Building P-1800 Pelindaba West
Technology Type	Tank-in-pool similar in type to the Oak Ridge Reactor.
Coolant	Light-water-moderated and cooled, beryllium and water reflected. Designed and built as a general research tool and belongs to MTR class.
Thermal power	20 MW
Use	Chiefly used for medical and industrial isotopes, activation analyses, material modification (such as neutron transmutation doping of silicon for semi-conductor industry) and numerous support services such as neutron radiography, and neutron diffraction which are of both industrial and academic interest

Source: Tillwick, (2011)

Table 3-24: Characteristics of ANSTO Research Reactor being constructed by INVAP of Argentina

Topic	Data
Reactor type	Open pool
Core thermal power	20 MW
Average core power density	280 kW/L
Core fuel load – BOC (beginning of reactor cycle)	6.25 kg U-235
Average cycle length	29 full power days
Fuel type	19.7% enriched U ₃ Si ₂ -Al dispersion
Fuel assembly residence times	190 full power days
Number of plates per fuel assembly	21

Source: Miller and Abbate (2003)

McGinnes (2007) stated that radionuclides used in nuclear medicine can be categorised into two forms:

- Open sources which have relatively low activity and consist of radioactively labelled chemical compounds used for imaging of internal organs, studying of bodily functions and localised irradiation of cancer cells; and
- Sealed sources (Fig. 2.10) that generally have high activity and are used for irradiation of tumours. Sealed sources are used in two applications: the first is “brachytherapy”, where the source is placed directly in, or very near, the tumour; the second is “teletherapy”, where very highly active sources of ⁶⁰Co or ¹³⁷Cs are used externally.

As it is well known, the production of radionuclides is carried out using nuclear reactors as well as accelerators/cyclotrons (Qaim, 2017). NECSA successfully demonstrated their capability to produce ⁹⁹Mo from LEU targets in 2010 (IAEA, 2013c). According to Dash, Knapp and Pillai (2013) the choice of an effective separation process to provide ^{99m}Tc from ⁹⁹Mo is based on a number of considerations.

- The physical or chemical techniques used should have high throughput capabilities;

- The separation process should be rapid to reduce the decay losses of ^{99m}Tc as well to minimize the ^{99g}Tc content in the separated product;
- The yield of ^{99m}Tc should be high;
- Reproducible radio nuclides, radiochemical and chemical purity of ^{99m}Tc should be within the pharmacopeia acceptable range;
- Radioactive concentration (RAC) of the separated ^{99m}Tc should be adequate to permit radiolabelling using current generation of kits;
- Human intervention should be minimal; and
- Technetium-99 m should be obtained in a ready to use form preferably in 0.9% NaCl and compatible with the existing freeze-dried kits.

According to IAEA (2013c) almost all the ^{99m}Tc used for this purpose is obtained from the radioactive decay of molybdenum-99 (^{99}Mo), which is produced by processing irradiated uranium targets in Belgium (IRE), Canada (AECL/Nordion), the Netherlands (Covidien) and South Africa (NTP). NECSA's ability to master this technology has enabled its subsidiary to be one of the major suppliers of the ^{99}Mo with the ASME entity fabricating the containers used to transport the product all over the world.

3.3.3.4.1 RR Research and Development Technological Considerations

The International Energy Agency (IEA) monitors energy RD&D spending in OECD member countries such as USA, Japan and South Korea. Figure 3-21 below shows that investment in nuclear energy RD&D was dominant in 1974 with 74% of total public energy RD&D budget, witnessed year-on-year reductions as they fell to 19% in 2017 (IEA, 2018).

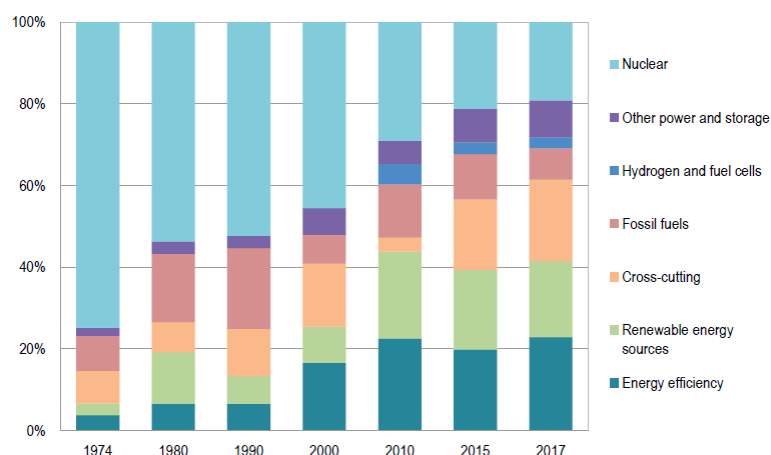


Figure 3-21: Evolution of IEA member countries total public energy RD&D by technology
Source: IEA (2018).

Due to ageing of some RR, countries have been considering alternative technologies for production of medical isotopes. According to Galea, Ross and Wells (2014) the Canadian government created the Non-reactor based medical Isotope Supply Programme (NISP) to promote research into alternative methods for producing medical isotopes.

Where an unproven design or feature is introduced or where there is a departure from an established engineering practice, a process shall be established under the management system to ensure that safety is demonstrated by means of appropriate supporting research programmes, performance tests with specific acceptance criteria or the examination of operating experience from other relevant applications (IAEA, 2016e). The ASME III entity can be involved in the demonstration of safety initiatives e.g. in the design, manufacturing and drop testing of developed metallic or concrete nuclear waste containers.

The need for phasing out highly enriched uranium (HEU) together with the uncertainty in the continued use of a few ageing reactors for the production of ^{99}Mo is prompting the development of alternative sources of $^{99\text{m}}\text{Tc}$ (Dash, Knapp & Pillai, 2013). Targets being used by CNEA, ANSTO and NECSA to

produce ^{99}Mo contain uranium-aluminium dispersed in an aluminium matrix (commonly referred to as UA12 or UALx targets) (IAEA, 2013c). As the dramatic increment of intermediate level liquid waste is also expected from the conversion, an effective strategy to reduce the waste generation from the fission ^{99}Mo production is required (Lee, Beyer & Lee, 2016).

Other alternative medical isotope production technologies are also being considered. It is expected that also in the near future the radionuclide production technology will strongly depend on research reactors as well as small and medium-sized cyclotrons, often accelerating multiple particles, to energies up to about 30 MeV (Qaim, 2017). Table 3-25 below shows short term, medium term & long-term molybdenum-99/technetium-99m technologies, which were forecast as of 2010.

Table 3-25: Short Term, Medium Term & Long-Term Molybdenum-99/Technetium-99m

Time Period	Type of Technology	Activities
Short Term (2010-2017)	- Uranium fission in research reactors (HEU2 and LEU targets); - Solution reactor technology; - Neutron activation of ^{98}Mo in a nuclear reactor; - Direct ^{99}mTc production with cyclotrons	(7 years is an estimate of the order of magnitude for a time needed to build a new research reactor from tendering)
Medium Term (2017-2025)	- Photo fission route using an electron accelerator; - Photonuclear reaction $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$ using an electron accelerator.	For these methods, preliminary feasibility tests have been performed, and for some of them the construction of experimental facilities is planned.
Long Term (Beyond 2025)	- Neutron fission using spallation neutron sources; - Technology using $^{100}\text{Mo}(n,2n)^{99}\text{Mo}$ reaction.	For those technologies, only some very general technical information is available, and no economic assessment is currently possible.

Source: Nuclear Energy Agency (2010c)

3.3.3.4.2 RR Design Engineering Technological Considerations

Research reactors are categorized as low flux, medium flux and high flux according to the following levels of thermal neutron flux: (1) Low flux reactor <1.1012 neutrons/cm²/s (2) Medium flux >1.1012 and <1.1014 neutrons/cm²/s and (3) High flux >1.1014 neutrons/cm²/s (Nuttall and Storey 2014). A Materials Test Reactor (MTR) is a high flux research reactor that irradiates materials, components and

fuel that will eventually be inside a power reactor and exposed to neutron flux during normal operation (Nuttall & Storey, 2014). A common RR design (67 units) is the pool-type reactor, where the core is a cluster of fuel elements sitting in a large pool of water (WNA, 2018b).

3.3.3.4.3 RR Manufacturing Technological Considerations

As an example, from a manufacturing perspective factors that can be taken into consideration are (1) manufacturing of required RR nuclear fuel; (2) manufacturing of replacement components as part of maintaining the plant or for a new RR and (3) using the RR for manufacturing target plates as required for the medical isotope plant. According to Hypes, Geist and Santi (2012), material test reactor fuel is often manufactured in the form of thin plates of uranium (often highly enriched) clad in a layer of aluminium. Obviously, the RR life cycle phases will require some manufacturing technological interventions. For instance, cask or canisters used in fabricating technologies will be required to enable the transporting and storage of nuclear spent fuel.

Figure 3-22 below is an illustration by Lee, Beyer and Lee (2016) showing steps for determining a suitable fission ^{99}Mo process strategy.

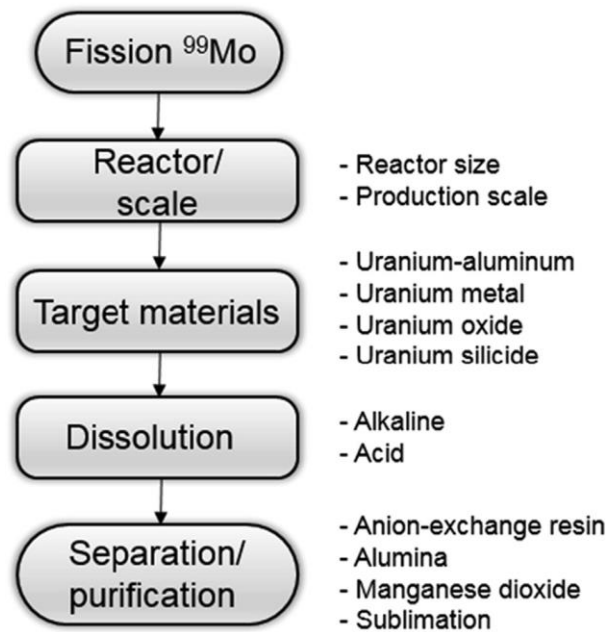


Figure 3-22: Fission ⁹⁹Mo production schemes for selecting production strategy
Source: Lee, Beyer and Lee (2016)

The use of HEU with its higher neutron flux in the production of ⁹⁹Mo speeds up the rate at which the isotope can be produced and this is important in the consequential creation of ^{99m}Tc- that has a half-life of six hours (Nuttall & Storey, 2014). Figure 3-23 below shows technological capabilities steps for fabricating target plates.

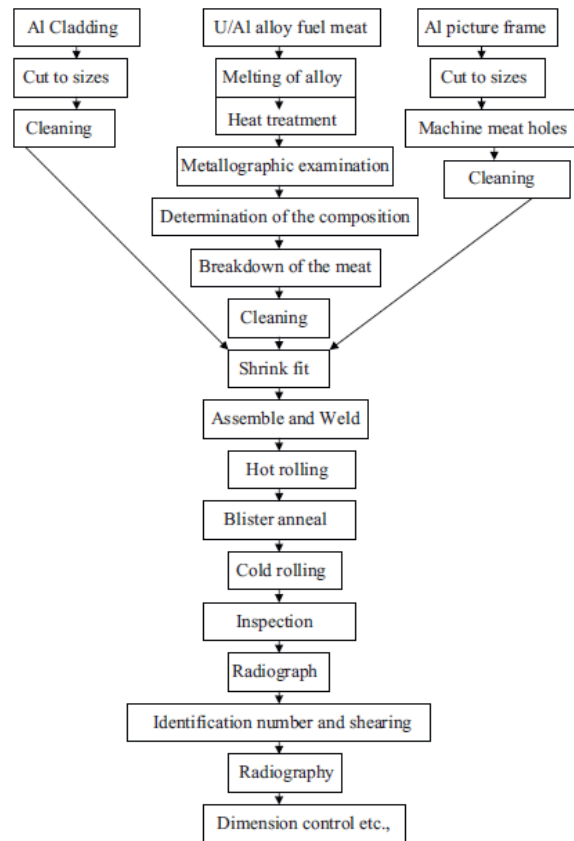


Figure 3-23: Schematic of molybdenum-99 target plate fabrication
 Source: Mushtaq (2011)

According to Stumpf and Ball (2000), to facilitate a smooth switch-over from HEU to LEU Mo-99 targets, equipment modifications, fabrication alterations and/or chemical process changes should be kept to an absolute minimum. Table 3-26 compares the ^{235}U content of HEU and LEU target plates with a mean volume of 4 cm^3 . HEU U-Al targets with $1.4\text{ g}\cdot\text{U}/\text{cm}^3$ have a ^{235}U density 2.5 times higher than that of LEU UAl₂ dispersion targets.

Table 3-26: Comparison of Uranium Densities and ^{235}U Content in a HEU Target, a Conventional LEU Target and a High-Density LEU Target with a Meat Volume of 4 cm^3 .

Target	Enrichment	Uranium Density	Uranium Content	U-235 Content
HEU target	93%	$1.4\text{ g}\cdot\text{U}/\text{cm}^3$	5.6g	5.2g
LEU target	<20%	$2.6\text{ g}\cdot\text{U}/\text{cm}^3$	10.4g	2.1g
High Density LEU target	<20%	$6.5\text{ g}\cdot\text{U}/\text{cm}^3$	26.0g	5.2g

Source: Ryu et al. (2013)

3.3.3.4.4 RR Construction Technological Considerations

The choosing and construction of any type of a RR are dependent on the operator and stakeholder needs. In the case of NECSA, one of its main needs of operating a RR is to support its subsidiary's medical isotope production. The medical isotope production requires the irradiated target plates.

3.3.3.4.5 RR Operation and Maintenance Technological Considerations

It is important that the RR operating organization sees to it that it has the adequate resources (e.g. competences and funds) to maintain the acquired RR. The availability or transfer of operation and maintenance (O&M) technical knowledge from the RR supplier to the operating organization will be dependent on the negotiated arrangements. There is a need for the organization acquiring a RR to have from the onset a downstream strategy on how its SSCs operation & maintenance technological capabilities remain adequate throughout the life of the RR so as operate in accordance to regulatory requirements. Throughout the life of the RR, changes to the maintenance strategy can occur to counter prevailing circumstances at a given time. Table 3-27 below lists strengths and weaknesses of life extension strategies. For instance, in SA a strategic decision taken was to replace the usage of highly enriched uranium (HEU) with low enriched uranium (LEU) for the SAFARI-1 RR. This led to a joint NECSA and Argonne National Laboratory (ANL) technical feasibility study during 1994 and 2001 (Ball, 2009). The IAEA (2008c) states that there is a need to develop a decommissioning plan during the RR operational stage and the operating experience and the latest developments in decommissioning techniques will necessitate the plan's amendment.

Table 3-27: Strengths and weaknesses of life extension strategies

Strategy	Level of improvement	Material addition	Labour cost	Added value	Complexity
Replacement/Repowering	Moderate	High	Moderate	High	Moderate
Reconditioning	High	Low	High	High	High
Condition monitoring	Moderate	Low	Moderate	High	Moderate
Remanufacturing	High	Low	High	High	High
Retrofitting	High	Moderate	Moderate	Moderate	Moderate
Use-up	Low	Low	Low	Low	Low
Refurbishment	High	Moderate	High	High	High
Reclaiming	Low	Low	Low	Moderate	Low
Retro filling	Low	Low	Low	Moderate	Low
Repair	Moderate	Moderate	Low	Moderate	Moderate

Source: Shafiee and Animah (2017).

Research reactors play a crucial part in the irradiation of target plates required by the medical isotope producers such as NTP at NECSA. As the reactors age, there is the requirement for longer downtime periods between production cycles to repair or replace ageing parts or to undertake additional inspections to determine the effects of ageing on the reactor (NEA, 2011). The efficient operation and maintenance of the facilities in which the target plate manufacturing and medical isotope production happen are equally important since it enables minimising of downtime periods. Due to the unforeseen maintenance issues at the National Research Universal (NRU) reactor at Chalk River and coincidental shutdowns of other international reactors, a global shortage of medical isotopes (in particular technetium-99m, ^{99m}Tc) occurred in 2009 (Galea, Ross & Wells, 2014).

3.3.3.4.6 RR Waste Management and Disposal Technological Considerations

A waste management strategy will consider handling of nuclear waste due to the utilisation of the RR. Such waste management strategies meet the world best practices stipulated by the IAEA and the relevant nuclear regulators. The conversion for RR reactors to use LEU instead of the HEU has been to be proven to be technological feasible but has also resulted in additional nuclear waste challenges. Galea, Ross and Wells (2014) stated that while reactors are operated with LEU as per design, this creates less of the desired isotope and more of the undesirable waste.

Consideration of measures to facilitate decommissioning should be during the design stage of the research reactor (IAEA, 2008c). According to Jova Sed and Reisenweaver (2005), the need to review and update the decommissioning plan of a research reactor that is in operation is due to the following:

- decommissioning technological developments;
- incidents that may have occurred including abnormal events;
- amendments in regulations and government policy; and
- cost estimates and financial provisions.

On December 2003, the IAEA Waste Technology Section contracted the South African Nuclear Energy Corporation (NECSA) to develop a basic design for a mobile spent high activity radioactive sources (SHARS) conditioning unit (Liebenberg & Al-Mughrabi, n.d.). Similarly, significant progress was made to link the South African Nuclear Energy Corporation mobile hot cell to the design for borehole disposal; with the intent of minimizing the handling of sources and eliminating unnecessary transport (IAEA, 2016d). From a strategic point of view, it is important for those entities or organizations to be aware of progress being made by other countries on nuclear waste disposal facilities and technology development. Such information as shown in Table 3-28 below can be used to identify possible technology partners or countries from which nuclear waste solutions can be sort.

Table 3-28: Worldwide status of disposal facilities for different waste streams

Category Nuclear Waste Solutions and Status	Country
Trench disposal for VLLW	e.g. in France, Spain, Sweden and the USA
LLW in arid areas	e.g. in Argentina, India, South Africa and the USA
Near surface engineered facilities for LLW	e.g. in China, the Czech Republic, France, India, Japan, Poland, Slovakia, Spain and the United Kingdom
Engineered facilities for low and intermediate level waste (LILW) sited in geological formations at a range of depths	(e.g. in Finland, Germany, Hungary, Sweden and the USA
Disposal facilities for LILW are at different licensing stages	Belgium (Dessel), Bulgaria (Radiana), Canada (Kincardine), Germany (Konrad), Lithuania (Stabatiškės), Romania (Saligny) and Slovenia (Vrbina, Krško)
Posiva received a construction licence for the spent nuclear fuel geological disposal facility in Olkiluoto	Finland

Source: International Atomic Energy Agency (2016d)

3.3.3.5 RR Environmental Factors

The IAEA (2013d) lists the following as key topics for consideration for environmental impact:

- (1) Water usage, impact on aquatic life, birds, plants and animals;
- (2) Visual impact expectations versus projections;
- (3) Impacts on wetland and natural terrain;
- (4) Radiological releases to the environment (normal operation and accident);
- (5) Effect on local industry and economy; and
- (6) Archaeological impact assessment (owner/operator responsibility).

As stated above, radiological risks are one of the key considerations for the EIA. Accordingly, the [281] states that the radiological hazard of RR will depend predominantly on the following aspects:

- (a) Power level of the research reactor and its radionuclide inventory;
- (b) Type of reactor;
- (c) Transient characteristics of the reactor; and
- (d) Irradiation facilities and experimental facilities in and around the reactor core, in particular, beam tubes and any pneumatic ‘rabbit’ systems used to transfer irradiation samples to and from the core.

Similarly, Gjorgieva, Volkanovski and Sansavini (2017) noted that the safety of nuclear power plants (NPPs) depends on the actions taken to prevent nuclear accidents or to limit their consequences.

At NECSA, most disused sources are stored in covered trenches at a site in Pelindaba called the Thabana repository (Streeper, Whitworth & Tompkins, 2009). Table 3-29 below shows the status of repositories in different nations. For instance, the same Table shows that the EU, Russia, China, Brazil, India and Japan were still undertaking research for their repositories.

3.3.3.5.1 RR Research and Development Environmental Considerations

In the case of SSCs, for which there are no appropriate established codes or standards, an approach derived from existing codes or standards for similar equipment having similar environmental and operational requirements may be applied, or, in the absence of such codes and standards, the results of experience, tests, analysis or a combination of these may be applied (IAEA, 2016e).

Worldwide countries involved in nuclear are researching on repositories for disposal of source materials and nuclear spent fuels. In certain situations, the countries are embarking on regional collaborations. For instance, the first row of Table 3-29 below shows EU countries are involved in a multinational regional repository research programme.

Table 3-29: Nation-states planning or researching the possibility of development of a national repository

Nation State	Repository	Status
European Union	SAPIERR II Project (multinational regional repository)	Under research
Latvia	Deep geologic site (consolidation at the Bal done Site)	Planned
Lithuania	Near-surface repository (Stabatiske)	Planned
Russia	Sosnovy Bor (underground repository)	Under research
China	Gobi Desert Beishan Granite Site (underground research laboratory)	Under research
Belarus	Ecores (expansion of current site)	1963 to present
Brazil	Borehole/deep geologic disposal	Under research
United Kingdom	Underground repository	Planned
France	Deep geologic repository	Planned
Germany	Former iron ore mine	Planned
India	Deep geologic repository (crystalline rock)	Under research
Japan	Deep geologic repository	Under research

Source: Streeper, Whitworth and Tompkins (2009)

3.3.3.5.2 RR Design Engineering Environmental Considerations

Noting that there are many different research reactor designs and power levels resulting in a wide range of hazard potential, the State should adopt a graded approach to application of the guidance in this Code

commensurate with the hazard potential, while maintaining a strong nuclear safety culture (IAEA, 2006). For instance, ANSTO produces ^{99}Mo at its Lucas Heights facility as a precursor to the widely used radiopharmaceutical $^{99\text{m}}\text{Tc}$ (Cheung et al., 2012). The design of ANSTO Radioisotope Production facilities is acceptably safe for the period of intended operation and ARPANSA regulatory system provides an effective framework to ensure that the ANSTO Radioisotope Production facilities are operated in a safe manner (Sarkar, 2009).

3.3.3.5.3 RR Manufacturing Environmental Considerations

Fabrication of containers used for transportation or storage of nuclear waste generated through the operation of a RR should be done in accordance to IAEA and NNR requirements i.e. with the consideration of protecting the environment. Just like the design, the fabrication of such containers and research reactor SSCs important to safety have to adhere to graded approach commensurate with the level of radioactivity. As an example, the manufacturing of pressure vessels that are subjected to radioactivity during the RR operation require adherence to ASME III codes and standards yet those for the balance of plant can be manufactured in accordance to ASME VIII with the former being more stringent.

Sarkar (2009) contends that the following are the typical operational limits and conditions (OLCs) considered for the operation of the Mo-99 production facility:

- (a) Minimum plant configuration for safe operation;
- (b) Air pressures in the hot cells, the cell face area and the rear cell area;
- (c) Amount of fissile material to ensure criticality safety; and
- (d) Maximum amount of radioactive material present at any one time in hot cells.

3.3.3.5.4 RR Construction Environmental Considerations

Like any another nuclear facility, an environmental impact assessment is a requirement before the commencement of RR construction. An environmental impact assessment covers not only biophysical impacts, but also assesses prospectively social, economic and other relevant impacts of a proposed activity or facility prior to major decisions being taken (SAIIA, 2012). During the construction of facilities that produce radioactive pharmaceuticals, it is important to take into consideration e.g. how the radioactive products and waste materials will be handled within the facilities themselves in such way that they do not become an environmental hazard or safety risk.

3.3.3.5.5 RR Operation and Maintenance Environmental Considerations

Periodical maintenance of SSCs that are important for safety is required in order to avoid incidents and accidents that can have a negative impact on the environment. Hence, IAEA stipulates that the assessment of the “impact of radiological releases to the environment (normal operation and accident)” is one of key considerations during the environmental impact assessment.

The radiological waste generated within the radioisotope related facilities e.g. those meant for irradiation and processing must be classified so that its impact to the environment is well understood. Technologies used for storage and disposal of such waste will have to be considered with the main objective being safety and protecting the environment.

3.3.3.5.6 RR Waste Management and Disposal Environmental Considerations

According to the IAEA (2011a), gaseous, liquid and solid radioactive wastes are generated in various types and amounts from the operation of research reactors and the nature and the amount of such waste depend on factors including the following:

(a) Type of reactor; (b) Specific design features; (c) Operating procedures and practices; (d) Irradiation of various targets, including those for radioisotope production, neutron activation analysis, etc.; (e)

Maintenance; (f) Modifications to the facility and life extension activities; (g) Refuelling and operational occurrences; (h) Operational history of the facility and (i) Integrity of the fuel.

The used fuel from the SAFARI-1 RR is initially stored in the reactor pool for at least two years to enable the cooling of the used fuel before storage at an authorised dry storage facility at the Pelindaba site. In accordance with the requirements of the SA National Environmental Management Act (NEMA), an environmental assessment is required prior to the construction of a spent fuel management or radioactive waste management facility (NNR, 2011).

Every year, about 15,000 litres of Intermediate level wastes (ILWs) is expected for the production 10,000 6-day Ci/wk fission ⁹⁹Mo from LEU targets, to cover global needs and after cementation, the total volume will become 375,000 litres, corresponding to 1,875 drums (200 litres) (Lee, Beyer & Lee, 2016). Figure 3-24 below shows the radioisotope production steps with waste emanating from the radiochemical separations processing.

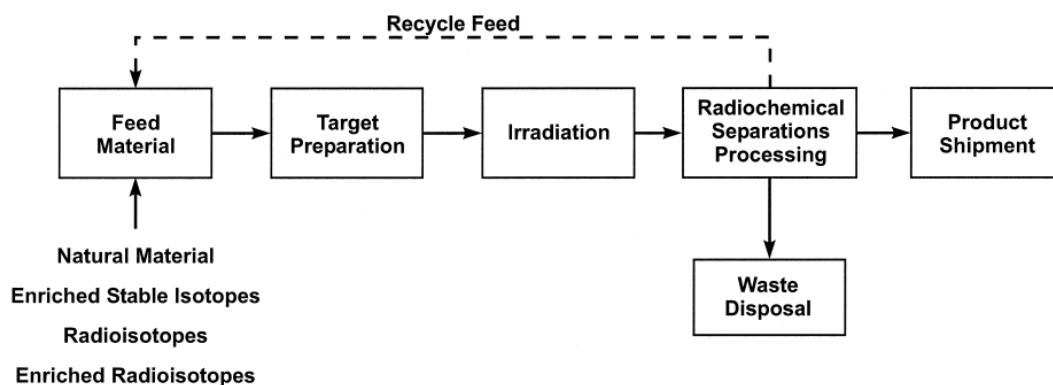


Figure 3-24: Generic steps for radioisotope production
 Source: Collins and Ottinger (2003)

3.3.3.6 RR Legal Factors

The regulatory body is responsible for the establishment of regulations that results in a system of authorization for the regulatory control of nuclear activities and for the enforcement of the regulations (IAEA, 2016e). In SA's case that regulatory body is NNR is responsible for most of RR legal requirements e.g. such as making sure that SSCs that are safety classified are developed, designed, manufactured, installed, operated and maintained in accordance to approved and agreed upon codes and standards. Tillwick (2011) states that SSCs depending on safety classification are subject to the following controls prior to installation:

- Design and procurement control;
- Manufacturing control in SAFARI-1 workshop and in NECSA's ASME VIII and ASME III nuclear manufacturing facility and
- Approval and qualification of supplier, and QC release.

The USA and Russia have been in the forefront in implementing mechanisms for increasing security of the usage of HEU research reactor spent fuel. Messick and Taylor (2009) stated that the U.S. Department of Energy established the Global Threat Reduction Initiative's U.S.-origin fuel removal programme, also known as the Foreign Research Reactor Spent Nuclear Fuel Acceptance Programme, in 1996, and its mission to repatriate U.S.-origin spent nuclear fuel and other weapon-grade nuclear material now extends to 2019. According to the IAEA (2008d), there are five Global Threat Reduction Initiative (GTRI) issues for South Africa namely:

- return to the U.S. of the U.S. origin HEU contained in spent fuel;
- shipment to the U.S. of Republic of South Africa (RSA)- origin HEU contained in spent fuel;
- conversion of the Safari research reactor to LEU;
- commitment by the Nuclear Energy Corporation of South Africa (NECSA) to use LEU targets when the technology can be deployed by a significant industrial producer; and
- disposition of a large quantity of fresh HEU of RSA origin.

A regulatory body is an authority or system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby regulating nuclear, radiation, radioactive waste and transport safety (IAEA, 2006). Likewise, Elabd, Elhefnawy and Badawy (2017) stated that the nuclear and radiological regulatory body (RB) in a State is the official authority in that State to control nuclear materials (NMs) and other radioactive materials (RMs) and all nuclear facilities in that State. Regulatory authorization precedes the implementation each phase of the RR installation. In this regard, the IAEA (2016e) notes that the authorization process may vary among States, but the major stages of the authorization process for nuclear research reactors shall include the following:

- (a) Site evaluation;
- (b) Design;
- (c) Construction;
- (d) Commissioning;
- (e) Operation, including utilization and modification;
- (f) Decommissioning; and
- (g) Release from regulatory control.

The effective and efficient performance of each IAEA member country is of utmost importance. Hence, the OECD (2004) noted that as defined in the previous NEA report a regulatory body is effective when it:

- (a) ensures that an acceptable level of safety is being maintained by the regulated operating organisations;
- (b) develops and maintains an adequate level of competence;
- (c) takes appropriate actions to prevent degradation of safety and to promote safety improvements;
- (d) performs its regulatory functions in a timely and cost-effective manner as well as in a manner that ensures the confidence of the operating organisations, the general public, and the government; and

(e) strives for continuous improvements in its performance.

South African nuclear organizations such as NECSA and NNR are involved in radionuclides sources safety and regulatory compliance endeavours not only locally but internationally especially in the region. Zondo (2003) contended that SA supports a number of initiatives that would go a long way towards improving the security of radioactive sources globally namely:

(a) Fast tracking the development of activities that make the return of a source to the supplier more feasible;

(b) Increased focus on regional and international co-operation on source conditioning and disposal;

(c) Continued support for borehole disposal issues such as technical knowhow, economic aspects, site selection, safety and feedback from the current Technical Co-operation project in Africa; and

(d) Discussions on mechanisms of international direct assistance; (e) Strengthening of regulatory infrastructure in all countries and especially in developing countries.

In SA, nuclear undertakings meant for radioisotope production have to meet the requirements of National-Nuclear-Regulator-Act-No-47-of-1999. For instance, subsection 1 of section 20 of NNR Act (1999) states that no person may site, construct, operate, decontaminate or decommission a nuclear installation, except under the authority of a nuclear installation licence. The NNR takes leaf of relevant IAEA requirements just like other nuclear regulators in the world. For instance, Sarkar (2009) stated that in Australia the main legislation and regulatory framework governing the safety of nuclear installation is the Australian Radiation and Protection and Nuclear Safety Agency Act (ARPANSA) 1998 (the Act) and the Australian Radiation Protection and Nuclear Safety Regulations 1999 (the Regulations).

3.3.3.6.1 RR Research and Development Legal Considerations

Research and development initiatives undertaken whilst developing RR can be utilised by the developer as proof that that various SSCs will meet e.g. IAEA or regulator stipulated safety requirements. Maree

and Mohlala (2017) noted that the National Nuclear Regulator (NNR) and the Department of Health, Directorate Radiation Control (RADCON) regulate radioisotopes in the RSA. The research and development in the area of radionuclides in SA happens at NECSA and the iThemba Labs, which according to its brochure is involved in the following:

- (1) Is the only producer in South Africa of accelerator-based radionuclides, radiopharmaceuticals for nuclear medicine and mainstream radiopharmaceuticals for positron emission tomography (PET) studies;
- (2) house the only PEPT-facility in the Southern hemisphere;
- (3) have the world's only high-resolution magnetic spectrometer (K600) to measure proton energies in the 66 – 200 MeV range. A 0°-mode was recently added to expand capabilities;
- (4) is the only facility to offer both protons and neutrons for particle therapy;
- (5) are the world's only producer of current Good Manufacture Practice (cGMP) $^{68}\text{Ge}/^{68}\text{Ga}$ generators and ^{22}Na -positron sources for annihilation studies, and
- (6) supply 25% of the world's demand for ^{82}Sr .

Most of the countries including SA that are leading in the exporting of medical isotopes have invested immensely in developing radioisotope production know how and technologies. In most cases, they started with pilot plants which led to fully blown facilities. From a legal perspective such know how is legally recognised as intellectual property which can be patented. At the same time, the utilisation of pilot plants enables downstream authorization applications from nuclear regulators such as NNR in SA's case.

3.3.3.6.2 RR Design Engineering Legal Considerations

The engineering design rules that items important to safety at a nuclear power plant shall be specified and shall comply with the relevant national or international codes and standards and with proven engineering practices, with due account taken of their relevance to nuclear power technology (IAEA, 2016c). Figure 3-25 below shows the classification process of a nuclear power plant SSCs for safety

and design purposes. Having regard to section 5 (b) and 20 (1) of the Act, the NNR recognises that, in the exercise of its regulatory control over nuclear installations, there may be circumstances where the NNR may be required to issue an Authorisation to Design a nuclear installation (NNR, 2016).

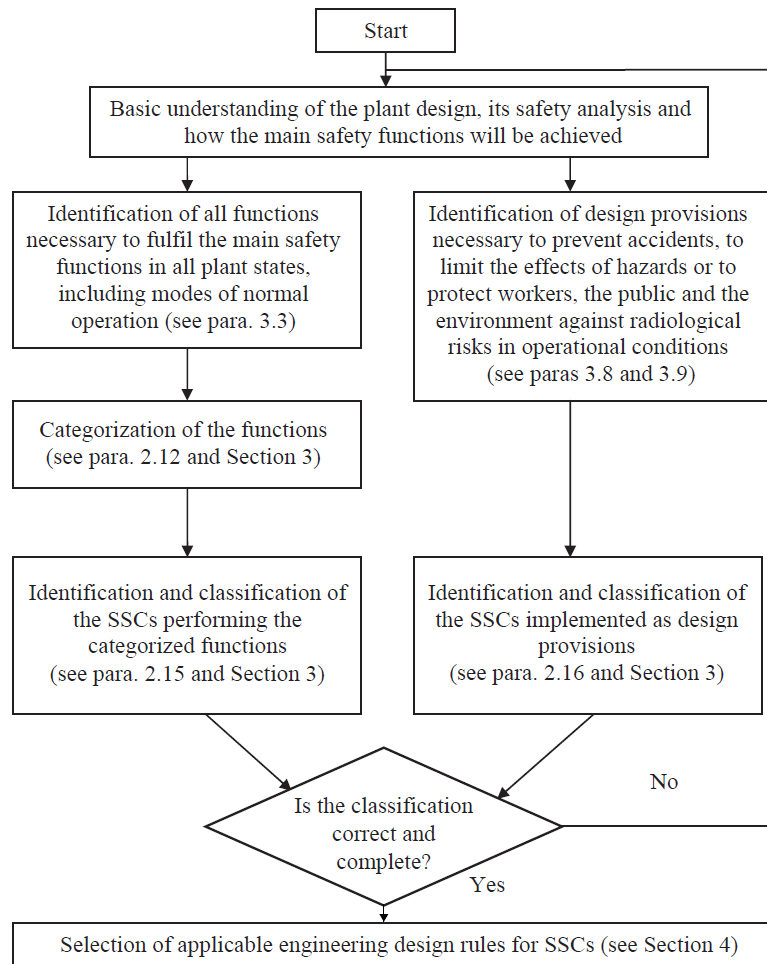


Figure 3-25: Flowchart indicating the classification process with referenced paragraphs of SSG-30
 Source: IAEA (2014d)

3.3.3.6.3 RR Manufacturing Legal Considerations

The regulatory body is responsible for making sure that there is adherence to relevant codes and standards and specifications during the manufacture of safety related SSCs meant for RR construction, maintenance or modifications. In the SA situation, the NNR provides oversight and monitors the aforementioned requirements through the operator's submitted manufacturing quality control plans (QCP). Such NNR approved QCP will be indicating manufacturing hold points which mandates the

witnessing of manufacturing related activities by relevant stakeholders such as the authorised nuclear inspector, NNR and quality inspectors from the manufacturing entity. The National Nuclear Regulator (2015a) states that for component qualification the following are the requirements:

- (1) an audit, and/or inspection plan or quality control plan should be developed, as part of the applicant's oversight programme, and submitted to the Regulator for input and acceptance; and
- (2) These plans should define the hold and witness points during the manufacturing and construction processes for components classified as important to nuclear safety.

First and foremost, the SA NNR is responsible for giving authorisation or licensing of all NTP facilities and activities related to radioisotopes or radiopharmaceutical production including those for waste management. In addition, locally NTP has to adhere to the SA Medicines Control Council (MCC). The MCC's *Guide to good manufacturing practice for medicines in South Africa* states that the manufacture of radiopharmaceuticals in South Africa must comply with the following:

- the requirements of Act 15 of 1973 (Hazardous Substances Act), regulation R247 of 26 February 1993; and
- any directives issued by the Directorate Radiation Control of the South African Department of Health, e.g. those specifying the basic standards for health protection of the general public and workers against the dangers of ionising radiation.

Likewise, NTP has to meet regulatory requirements of its clients in countries outside SA.

3.3.3.6.4 RR Construction Legal Considerations

The IAEA (2006) points out that the state or its nuclear regulator must make sure that there is adherence to applicable codes, standards, specifications and criteria during construction. It is important to note e.g., the applicable codes and standards for construction of SA's RR mechanical works for balance of plant and nuclear islands that can be used can be respectively ASME VIII and ASME III.

For a nuclear installation licence (NIL) to site or construct a nuclear installation, it is important that the NNR be provided with sufficient information in the form of a safety case covering the full technical safety basis, to enable the NNR to perform a detail assessment to the extent possible and therefore determine whether the proposed design will meet the requirements and that all safety issues identified during the safety case review will be mitigated at the appropriate stage of the licensing process (NNR, 2016).

3.3.3.6.5 RR Operation and Maintenance Legal Considerations

In SA, the nuclear regulator NNR authorises the operation RR and the maintenance of SSCs that are important to safety. In this respect, NNR endeavours to make sure that RR operator adheres to relevant requirements during the replacement of SSCs.

NNR issued NECSA licenses giving the authorisation of operation of radioisotope production related facilities such as the SAFARI-1 for RR irradiation, NTP isotope production facility; target plate fabrication facility and isotope production related laboratories. Likewise, in Australia nuclear installations that operate under ARPANSA facility licence include research reactors, radioisotopes production facilities, radioactive waste management and spent fuel management facilities.

3.3.3.6.6 RR Waste Management and Disposal Legal Considerations

According to the IAEA (2017a), two programmes created under the Global Threat Reduction Initiative (GTRI) are as follows:

- The Russian Research Reactor Fuel Return (RRRFR) Programme, for fuel originating in the Russian Federation; and
- The US Foreign Research Reactor Spent Nuclear Fuel (FRR SNF) Acceptance Programme, for fuel originating in the United States of America. Formerly, this named as the Reduced Enrichment for Research and Test Reactors Programme (RERTR).

The USA government through its DOE has taken it upon itself to reduce security threats caused by radioactive materials especially nuclear waste from research reactors. This being the case, the USA DOE GTRI (2014) noted the following:

- GTRI's mission is to reduce and protect vulnerable nuclear and radiological materials at civilian sites around the world that could be used by terrorists to make an improvised nuclear device or radiological dispersal device;
- As part of DOE's overall highly enriched uranium (HEU) minimization strategy, removal efforts began in 1994 and focused on the removal of U.S.-origin HEU and low enriched uranium (LEU) to encourage countries to convert their research reactors from HEU to LEU;
- The removal programme has expanded and accelerated over the last 20 years to address additional forms of nuclear material that could be used to make a nuclear weapon;
- GTRI has removed or eliminated over 5,000 kilograms of HEU since 1994 – enough material for approximately 200 nuclear weapons; and
- Despite programmatic successes, challenges persist because of the remainder of several metric tons of HEU and plutonium.

According to Bredell (1990), the US got back limited quantities of the SAFARI-1 spent fuel derived from its initial supply of research reactor fuel as per contractual arrangements. Pertaining to the NECSA commercial and research programme, Ball (2009) stated that the following support or capabilities are available for the SAFARI-1 research reactor:

- an extensive infrastructure;
- competencies ranging from theoretical reactor physics to radiochemistry and radio-analytical groups;
- a fuel and target fabrication plant;
- hot cell facilities for the production of medical and industrial isotopes;
- a pipe storage facility for the interim dry storage of spent fuel; and
- a disposal site for low and intermediate radioactive waste.

Beghin (1997) noted that radioactive waste is produced through five major activities namely:

- (1) the mining and processing of uranium and thorium ore;
- (2) activities related to the nuclear fuel cycle such as the conversion and enrichment of uranium, the manufacturing of nuclear fuel and the reprocessing of irradiated fuel;
- (3) the activities of nuclear power plants;
- (4) the decontamination and decommissioning of nuclear plants; and
- (5) the non-energy-generating applications of nuclear energy in medicine, research, industry and agriculture.

3.3.4 Uranium Production

Figure 3-26 below shows the connection between uranium production components and other nuclear fuel cycle areas. Until 1948, the development of South Africa's uranium production remained in the hands of the Prime Minister, few very highly placed government officials, CSIR, Geological Survey, and the Government Metallurgical Laboratory (GML, now Mintek) and, through the establishment of the Uranium Research Committee, a handful of top-echelon representatives of the gold extraction industry (Ford, 1993). The first commercial uranium production in South Africa started in 1953 to meet the demand for British/US nuclear weapons with the production firstly peaking in 1959 and declining due to reduced demand only to peak up in 1980 to over 6000 tonnes because of the 1970s world oil crisis (Ainslie, 1997). Natural uranium (U) occurs as a mixture of three radioactive isotopes: ^{238}U , ^{235}U , and ^{234}U thus only ^{235}U is fissionable and makes up about 0.7% of natural U, while ^{238}U is overwhelmingly the most abundant at greater than 99% of the total mass of U (Campbell, Gallegos & Landa, 2015). Table 3-30 below shows that the IAEA denotes the uranium production facilities as: Uranium mines for uranium ore extraction, uranium ore processing facilities for producing yellowcake or in-situ leach facilities and those for uranium recovery from phosphate. Ulrich et al. (2014) stated that the SWOT analysis serves as a systemic framework and it allows us to examine the internal and external factors that determine future U recovery from phosphate rock. In-situ mining is also used for gold and

copper extraction. Figure 3-27 below by Haque and Norgate (2014) shows system boundaries during copper, gold and yellowcake are production. SA has been producing uranium from its gold and diamond mining. In 2015, Tasman RSA, a joint venture involving Tasman Pacific Minerals Limited and Lukisa JV Company (Pty) Ltd., submitted applications for mining rights to commence exploitation of uranium in the Great Karoo of South Africa (Issah & Umejesi, n.d.).

Table 3-30: Components of a Uranium Production Facility

Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
	Uranium Mine	Uranium mines from which uranium ore is extracted
Uranium Production	Uranium Ore Processing	Facilities in which uranium ore is processed to produce yellowcake Uranium Production (includes in-situ-leach facilities)
	Uranium Recovery from Phosphate	Facilities in which uranium is retrieved as by product of phosphate.
	Conversion to UO ₂	Facilities that convert ³⁰⁸ U to UO ₂ to produce PHWR fuel.
	Conversion to UO ₃	Facilities that convert ³⁰⁸ U to UO ₃ , used later for conversion to UO ₂ or UF ₆ .

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

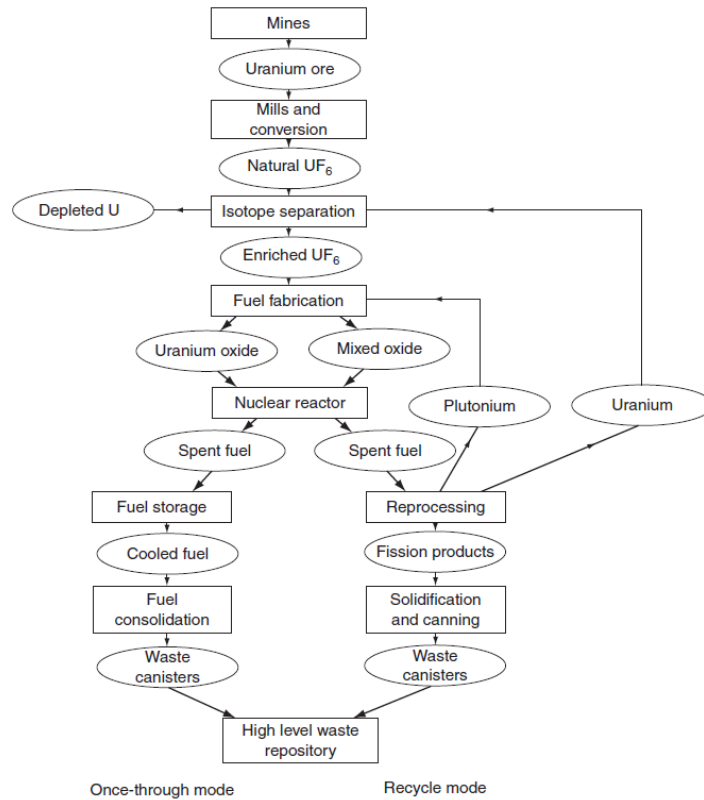


Figure 3-26: Nuclear fuel cycles. The once-through shown on the left is used in the United States; the recycle shown on the right is used in other countries.

Source: Murray (2009)

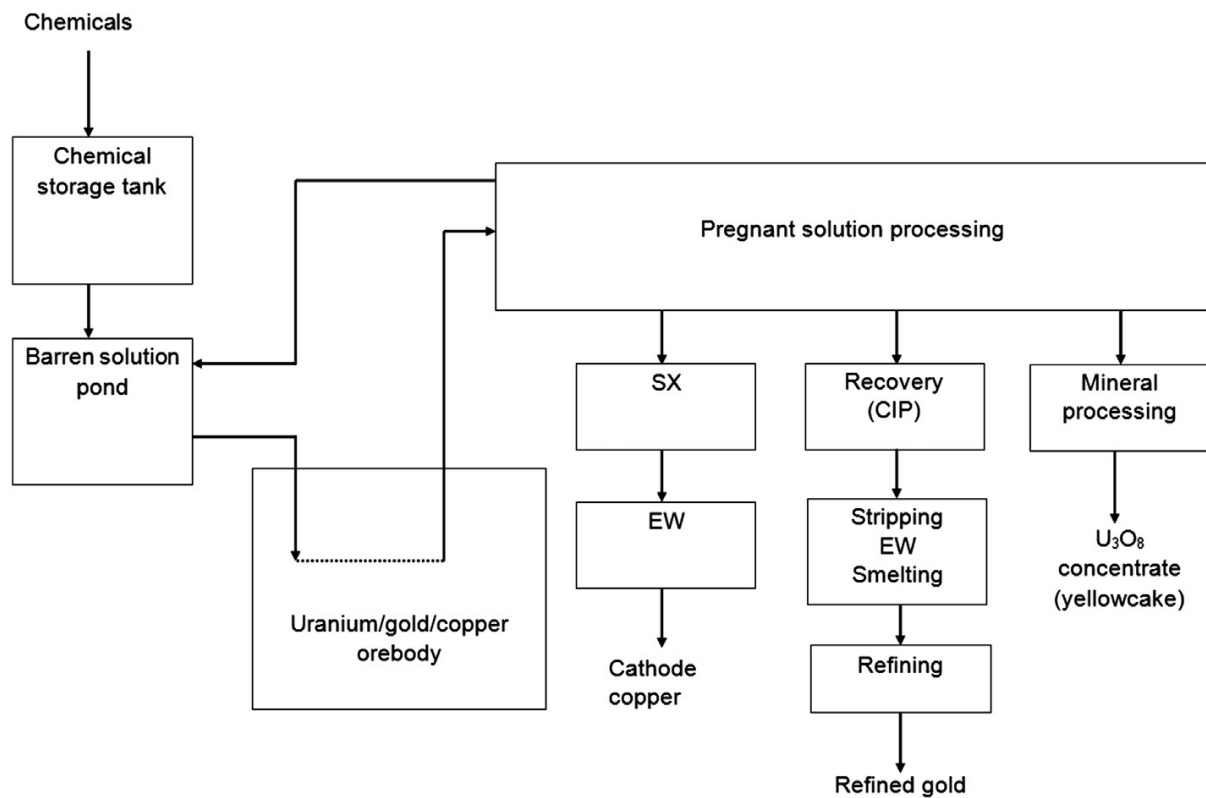


Figure 3-27: System boundaries for the ISL LCA study

3.3.4.1 Uranium Production Political Factors

Unlike many other commodities, many countries consider uranium a strategic commodity and consequently have not always been subject to free market influences (IAEA, 2010). The policies that accompany uranium in various countries are dependent upon a range of domestic, regional and international regulations (Vestergaard, 2015). As many governments have become well aware of past colonial inequalities in sharing the wealth from extracted minerals, they are revising their mining legislation accordingly (Winde et al., 2017). However, since 2011 there have been increasing geopolitical tensions in the region, resulting in foreign companies like Paladin and URU Metals ceasing exploration activities in Niger. In SA, there have been talks on government policy uncertainty (GPU) due to lack of a way forward on what the mining charter should stipulate. The Department of Mineral Resources (DMR) Draft Mining Charter (2018) states that the Mining Charter seeks to achieve the following objectives:

- a) Recognise the internationally accepted right of the state to exercise sovereignty over all its mineral resources;
- b) Deracialise the ownership of the mining industry by redressing the imbalances of the past injustices;
- c) Substantially and meaningfully expand opportunities for Black Persons to enter the mining and minerals industry and to benefit from the exploitation of the nation's mineral resources;
- d) Utilise and expand the existing skills base for the empowerment of the black persons;
- e) Advance employment and diversify the workforce to achieve the competitiveness of the industry and productivity;
- f) Enhance the economic and social welfare of mine communities and major labour sending areas in order to achieve social cohesion;
- g) Promote sustainable development and growth of the mining industry;
- h) Catalyse growth and development of local mining inputs sector by leveraging the procurement spend of the mining industry; and
- i) Promote beneficiation of South Africa's mineral commodities.

The existence of policy and strategies to deal with environmental remediation at the national level is crucial for a successful implementation of a remediation project (Franklin & Fernandes, 2013). The process of remediation of subsurface contamination commonly involves several steps that involves making decisions e.g. on whether to opt for remediation or not, as outlined in Figure 3-28 (Shackelford, 2013).

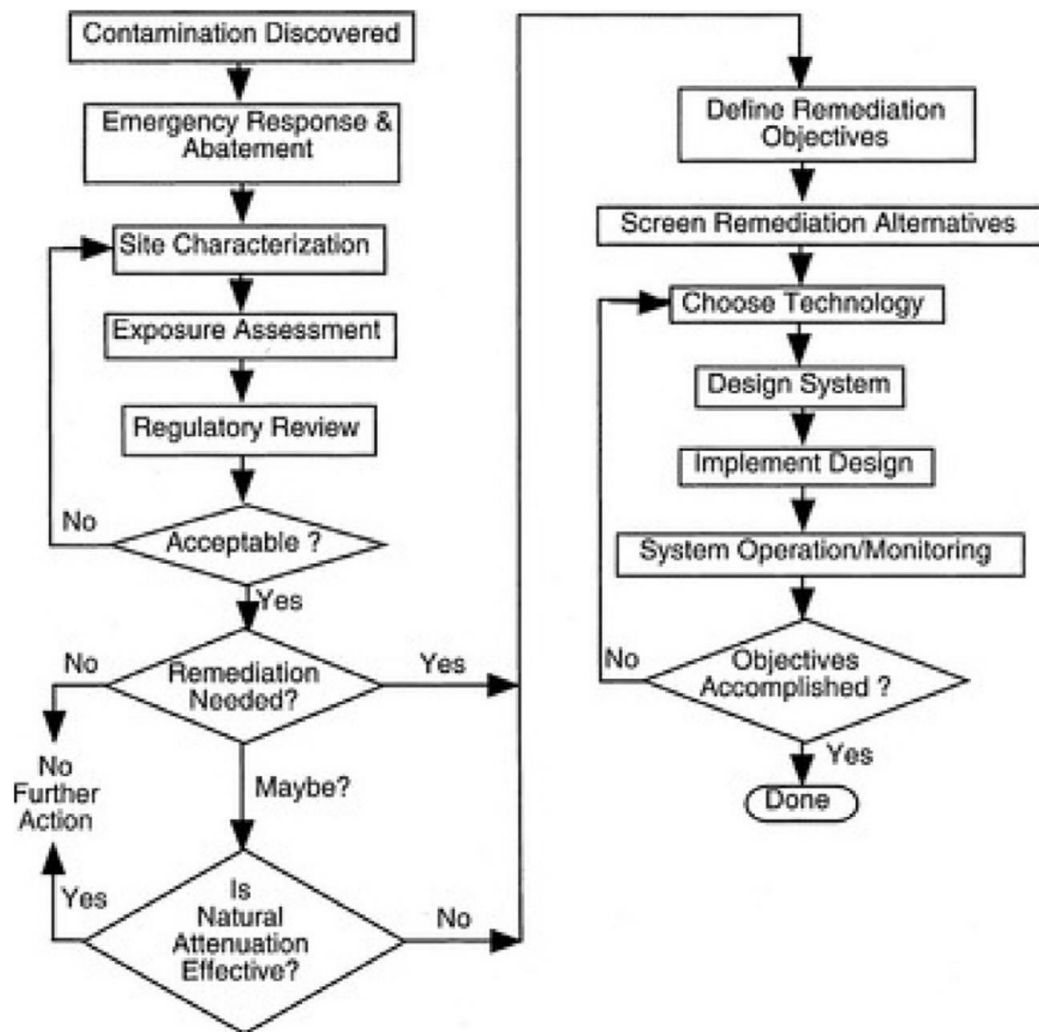


Figure 3-28: Flow chart of remediation process in US
 Source: Shackelford and Jefferis (2000)

3.3.4.1.1 Uranium Production R&D Political Considerations

Local content requirement policies typically call for a foreign investor to source a portion of its procurements from local suppliers in the domestic economy (Macatangay, 2016). The DMR Draft Mining Charter (2018) states that the rights holders must spend a minimum of 70% of its total research and development budget on South African based research organization.

3.3.4.1.2 Uranium Production Design & Engineering Political Considerations

The Radioactive Waste Management Policy and Strategy of South Africa (2005) states that SA as a member state of the IAEA, and in accordance with National and International objectives, it is Government's policy to deal with radioactive waste in a manner that protects human health and the environment, now and in the future in accordance with the following principles:

1. Protection of Human Health: Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health;
 2. Protection of the Environment: Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment;
 3. Protection Beyond National Borders: Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be considered;
 4. Protection of Future Generations: Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today;
 5. Burden on Future Generations: Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations;
 6. National Legal Framework: Radioactive waste shall be managed within an appropriate national legal framework, including clear allocation of responsibilities and provision for independent regulatory functions;
 7. Control of Radioactive Waste Generation: Generation of radioactive waste shall be kept to the minimum practicable;
 8. Radioactive Waste Generation and Management Interdependencies: Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account;
- and

9. Safety of Facilities: The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

3.3.4.1.3 Uranium Production Manufacturing Political Considerations

According to Ford (1993), until 1948 the development of South Africa's uranium production remained in the hands of the Prime Minister and a few very highly placed government officials, together with the heads of the CSIR, the Geological Survey, and the Government Metallurgical Laboratory (GML, now Mintek). In the latter years, new government laws have reorganised the roles of nuclear institutions. For instance, the SA Nuclear Energy Act (1999) states that one of the ancillary powers and functions of Corporation (NECSA) is to manufacture or otherwise produce or acquire, or dispose of, uranium hexafluoride (UF₆). The Department of Mineral Resources of South Africa's Mineral Beneficiation Strategy (2011) states that interventions for the successful implementation of nuclear power generation include:

- a) Quantification of uranium and/or thorium reserves and resources in the country;
- b) Ascertain the economic feasibility of re-establishing uranium enrichment;
- c) Plan for comprehensive waste treatment and mine rehabilitation; and
- d) Finalisation of the uranium policy with all relevant stakeholders.

3.3.4.1.4 Uranium Production Construction Political Considerations

If the resources are made available for the mandated entities to implement the strategy, it can lead to construction of uranium production or beneficiation facilities e.g. those for extraction or producing yellow-cake (U₃O₈). South Africa is currently exporting uranium in its oxide form (U₃O₈), the first stage of beneficiation and imports the enriched uranium from the northern hemisphere for power generation purpose (DMR, 2011). According to the SA Department of Trade and Industry's Industrial Policy Action Plan (2014/15 - 2016/17), R686 million in mining and minerals beneficiation was approved for

the time period of between April 2013 and December 2013. It is not clear if there any funds allocated to the uranium beneficiation facilities.

3.3.4.1.5 Uranium Production Operation and Maintenance Political Considerations

Since one of NECSA's mandate by the Nuclear Energy Act is involvement in the uranium beneficiation activities, it can therefore put systems in place to be able to operate and maintain related facilities. Likewise, private entities which intend to get involved in the operating and maintenance of such uranium production facilities can apply for authorization from various regulatory bodies including the NNR.

3.3.4.1.6 Uranium Production Waste Management and Disposal Political Considerations

Uranium production facilities will have various radioactive waste streams. Countries involved in the uranium production have put in place policies that are in line with world best practices of managing radioactive waste emanating from uranium production activities. Price et al. (2013) stated that the mission of the Fuel Cycle Technologies (FCT) Programme in the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) is to:

- (1) develop sustainable fuel cycle technologies and options; and
- (2) develop used fuel management strategies and technologies that support the federal government's responsibility to manage and dispose of the nation's commercial used nuclear fuel (UNF) and high-level waste. The IAEA (2002) stipulates that States planning to engage in mining and milling activities are required to develop:
 - (a) A national policy for managing the associated waste;
 - (b) A strategy for implementing this policy, including the provision of necessary.

This being the case, in SA the DMR came up with the Radioactive Waste Management Policy and Strategy. Radioactive waste generated by facilities range from low volumes, such as spent radioactive

sources, to large and diffuse volumes, such as tailings from the mining and milling of ores that contain uranium and thorium, and their radioactive decay products (DMR, 2005).

3.3.4.2 Uranium Production Economic Factors

Naturally occurring uranium is composed of about 99.3% ^{238}U , 0.7% ^{235}U and traces of ^{234}U (IAEA: NFCIS, 2009). Most natural uranium is sold via long-term contracts between mining companies and utilities (Rooney, Nuttall & Kazantzis, 2015). Continuing fluctuations of the uranium spot price, which has remained below the production price of most production centres, has not provided the incentive for expansion of the world uranium production IAEA (2001, December). Total exploration and development expenditures in South Africa decreased dramatically from USD 32.8 million in 2012 to USD 1.9 million and USD 1.7 million in 2013 and 2014, respectively, and projected expenditures for 2015 are only modestly higher at USD 5.2 million (Uranium, 2016). Given the unpredictability of factors and risks affecting profits in the mining industry e.g. fluctuating commodity prices and exchange rates, geological uncertainty, natural disasters such as flooding and seismic events, as well as impacts of changing political preferences and public opinion, the ability to respond faster than competitors to price hikes often is vital for survival (Winde et al., 2017). The complex characteristics of the mining industry-in particular the long-term impact of its massive capital expenditure decisions, the intricate interactions between different stakeholders in government (industry, local communities, and regulatory agencies) and the relentless uncertainty associated with global commodity markets - require the development of specific metrics and valuation methods to support robust decision making (Pimentel, Gonz & Barbosa, 2016). Hence, the development of the strategic decision-making model that can enhance the robust decision-making by virtue of having a holistic approach of identifying factors that can be considered to inform the way forward. Figure 3-29 below is a Nuclear Energy Association (NEA) and IAEA classification scheme for uranium resources.

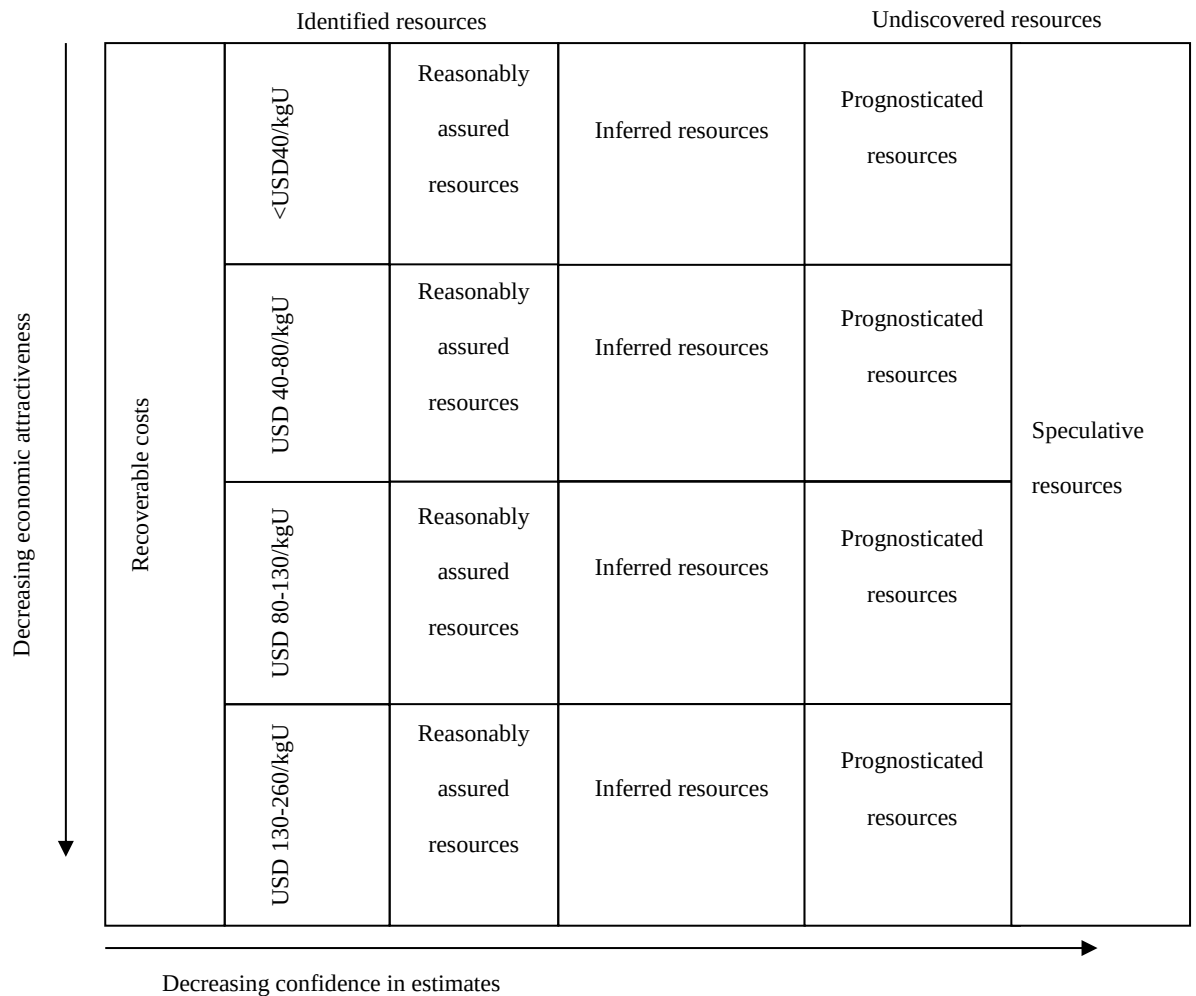


Figure 3-29: NEA-IAEA classification scheme for uranium resources

3.3.4.2.1 Uranium Production R&D Economic Considerations

Uranium production methods have evolved over time through R&D with the aim being to come up with the most efficient and effective ways of uranium production i.e. from a cost perspective. Consequently, South Africa needs to build a strong research capacity on nuclear energy before increasing issuing of uranium mining rights (Matshusa & Makgae, 2017). The development of a cost-effective method to remove uranium from contaminated soils could accelerate the clean-up process and reduce remediation costs (Zhu & Chen, 2009).

3.3.4.2.2 Uranium Production Design and Engineering Economic Considerations

Cost quantifications of various mining site installations (mechanical, electrical, civils and control and instrumentation) enable the economic evaluation of uranium production. Taking into consideration the chosen method of extracting the uranium, the mining initiative has to go through some design-engineering phase, which will enable determination of the scope of work. Chamaret, O'Connor and Récoché (2007) argued that it is obvious that each mining site will present distinct features that invalidate the idea of a 'one-fits-all' indicator set and such features include:

- *Geographical location*: the issues of a mining site located in a desert area (e.g. access to water) will differ from those of a mine in a forest area (deforestation); a mine close to a city will generate different impacts than one in an unpopulated area; issues of a mine in Africa will obviously differ from those of a European or Australian mine due to cultural differences;
- *Infrastructure*: a mining town will generate major perturbations in the traditional ways of living and building; a fly-in fly-out system generates more diffuse impacts, but less local economic benefits;
- *Exploitation type*: an open-pit mine involves questions linked to landscape preservation and an underground mine will raise issues related to future security of the site in terms of subsidence;
- *Extracted substance*: for example, uranium mining implies specific health issues linked to radiological impact; the mining of other metals such as copper, lead, zinc or gold, raises environmental issues related to acid leaching; and
- *Mine cycle phase*: the building phase will not have the same impact (massive population movements) as production (raise of the standard of living, etc.), or post-mine (unemployment, staff conversion).

3.3.4.2.3 Uranium Production Manufacturing Economic Considerations

When the uranium production facilities are to be constructed, there is always a need to establish the cost of required manufactured or assembled mechanical, electrical, civils and control & instrumentation materials and SSCs. Such requirements will be part of the preliminary and final feasibility studies that will establish the viability of the mining venture.

South African private sector companies currently mine and export uranium ore without appreciable levels of beneficiation (Matshusa & Makgae, 2017). The way in which mining ventures contribute to economic development in the region where they take place is important for the mining industry's relations to the local community (Söderholm & Svahn 2015). Some considerable local mineral beneficiation or downstream manufacturing can enhance such relations.

3.3.4.2.4 Uranium Production Construction Economic Considerations

When embarking on uranium production, cost estimation of initial construction activities is part of a process of arriving at overall capital expenditure or costs of possible uranium related activities. According Winde et al. (2017), U-related activities fall into the following five categories: (i) Activities to increase the output from already operating mines ii) Re-activating production at former U-producing mines (iii) Opening of new U-mines (iv) Reprocessing of uraniferous mining waste material (v) Prospecting/exploration vi) International collaboration initiatives in various fields of the nuclear supply chain.

3.3.4.2.5 Uranium Production Operation and Maintenance Economic Considerations

The operations and maintenance costs include salary, sustaining capital, maintenance, and general overhead costs (Graves et al., 2015). Seredkin et al. (2016) stated that the economic advantages of ISR include:

- Smaller costs on the development of mine, processing plant and infrastructure in comparison with conventional open pit and underground mines;
- The ability to start production at low capital cost with following increase a production. This stage allows produce a concentrate and use profitable cash flow to development of mine instead using a borrowed funding; and

- Flexibility of production capacity: reducing capacity during lower prices and increasing capacity during higher prices.

3.3.4.2.6 Uranium Production Waste Management and Disposal Economic Considerations

Polluter pays principle in which the financial burden for the management of radioactive waste shall be borne by the generator of that waste is one the principles stated by the DMR's Radioactive Waste Management Policy and Strategy (2005). This being the case there is an expectation that entities involved in uranium production shall bear the cost of e.g. site remediation. A lack of financial provision for rehabilitation within the South African nuclear energy space is a worrying factor that needs to be addressed as soon as possible (Matshusa & Makgae, 2017).

3.3.4.3 Uranium Production Social Factors

The way in which mining ventures contribute to economic development in the region where they take place is important for the mining industry's relations to the local community (Söderholm & Svahn, 2015). Issah and Umejese (n.d.) stated that the dominant narratives of the South African government on the proposed uranium mining in the Karoo are as follows:

- (i) generation of employment opportunities for the employed youth of the region;
- (ii) an increase in government revenues through taxes from the mining company;
- (iii) the prospect of micro- and macro-economic multipliers; and
- (iv) the construction of nuclear plants to boost the energy supply in the country.

It is clear from the Australian and Canadian cases that sustainability is closely related to participation of neighbouring communities in decisions affecting them, and that a trilateral dialogue between the three main stakeholders namely the community, the company and the government is essential (IAEA, 2009).

3.3.4.3.1 Uranium Production R&D Social Considerations

Modern mineral exploration requires a complex, multidisciplinary approach to be successful and geology, geophysics, geochemistry, and drilling are examples of the disciplines required to effectively explore and develop a mineral deposit (Best, 2015).

3.3.4.3.2 Uranium Production Design and Engineering Social Considerations

The beneficiation of uranium can lead to the generation or utilisation of design engineering skills across the NFC and NPP value chain. Such skills sets will be required e.g. for conceptual design, basic design and detailed design of the required uranium production facilities or processes.

3.3.4.3.3 Uranium Production Manufacturing Social Considerations

Statistics SA (STATS SA) monitors and reports on employment in various sectors of the economy. According to STATS SA (2015) the biggest losses in jobs were recorded in ‘mining of gold and uranium ore’ (a loss of 39 715 jobs), followed by ‘mining of platinum group metal ore’ (a loss of 7 812 jobs) and ‘other stone quarrying, including stone crushing and clay and sandpits’ (a loss of 4512 jobs). Table 3-31 below shows 2012, 2013 and 2014 employment numbers for uranium production in different countries including for SA.

Table 3-31: Employment directly related to uranium production

Country	2012		2013		2014	
	Production employment (person-years)	Production (tU)	Production employment (person-years)	Production (tU)	Production employment (person-years)	Production (tU)
Australia ^(a)	3720	7009	3750	6432	3870	4976
Brazil	340	326	340	192	340	55
Canada ^(b)	1361	8998	1406	9332	1829	9136
China	6860	1450	6950	1500	6960	1550
Czech Republic	1147	228	1137	215	1105	154
Iran	150	24	145	8	135	11
Kazakhstan	5809	21240	6874	22513	6915	22781
Namibia*	2628	4653	1583	4264	1853	3246
Niger*	N/A	4822	N/A	4528	N/A	4057
Russia	5810	2862	7180	3135	6126	2991
South Africa	182	467	175	531	406	566
Ukraine	1450	1012	1590	926	1610	954
United States	856	1595	808	1792	540	1881

Country	2012		2013		2014	
	Production employment (person-years)	Production (tU)	Production employment (person-years)	Production (tU)	Production employment (person-years)	Production (tU)
*NEA/IAEA estimate; N/A = Data not available; (a) Olympic Dam does not differentiate between copper, uranium, silver and gold production; Employment has been estimated for uranium related activities; (b) Employment at mine site only.						

Source: Resources, Production and Demand NEA: OECD 2016

3.3.4.3.4 Uranium Production Construction Social Considerations

Establishing a new mining operation has a significant environmental and social impact on the construction site and surrounding communities (Pimentel, Gonz & Barbosa, 2016). During the construction of uranium production facilities, the technical engineering skills required will be for undertaking erection or installation of electrical, civil works, mechanical and control and instrumentation SSCs. The quantities and diversity of labour will also vary based on mine type e.g., whether it is open cast or underground. The mining operations in remote locations typically have to construct new infrastructure or upgrade existing infrastructure to support the demands of mining and processing operations e.g. airstrips; roads; water supplies; sanitation systems; and electricity supplies (IAEA, 2009).

3.3.4.3.5 Uranium Production Operation and Maintenance Social Considerations

Mining is an industry generally known for being very intensive in capital investments and having a relatively low level of direct employment (Fleming & Measham, 2014). This being the case, it becomes important that the socio-economic evaluation of a uranium production opportunity should take into consideration indirect benefits. Some of the indirect benefits or employment can be semi-skilled or skilled workers within entities contracted to provide operation and maintenance of the uranium-mining establishment.

3.3.4.3.6 Uranium Production Waste Management and Disposal Social Considerations

It is important to have a waste management and disposal plan for uranium mining development programme right from the initiation phase. Social impact assessment is currently the most widely

applied tool used to address the impact and mitigation of social issues associated with mine development (IAEA, 2009).

3.3.4.4 Uranium Production Technological Factors

In SA, the Vaal River tailings storage facility reclamation programme was initiated in 2011 to recover uranium oxide and gold from existing tailings storage facilities by utilising new technology developed by AngloGold (NEA and IAEA, 2014). Advancements in reactor and fuel cycle technology are not only aimed at addressing economic, safety, security, non-proliferation and waste concerns, but also at increasing the efficiency of uranium resource use (NEA and IAEA, 2016). Otherwise, Figure 3-30 below depicts the fuel cycle processes, along with the technology options considered for each and the flow of uranium between them (INL, 2010).

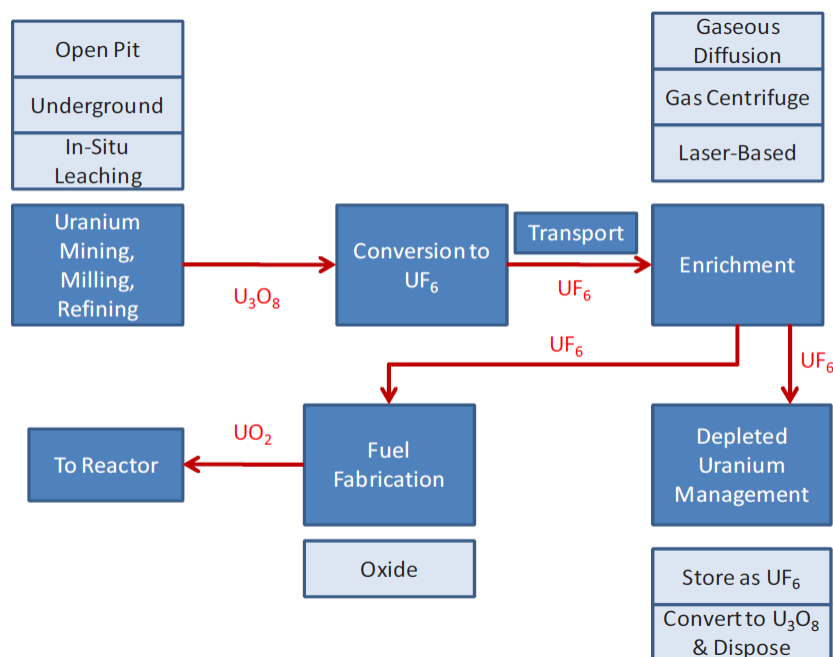


Figure 3-30: Uranium mass flows and front-end technologies
 Source: Idaho National Laboratories (2010)

Table 3-32 below shows that 51% of uranium production is undertaken using the in-situ leaching (ISL) or in situ recovery (ISR) technology followed by underground mining at 14% and the least being heap

leaching which is at less than 1%. The two most critical geological/methodological parameters that must be met for a deposit to be suitable for ISR are (1) that mineralisation must be located in permeable environment (natural or artificial); and, (2) the lixiviant should be suitable for selective leaching of a specific component from mineralised bodies of deposit (Seredkin et al., 2016).

Table 3-32: Uranium world production method contribution as of 1 January 2015

Uranium production method	Percentage world production
In situ leaching (ISL, sometimes referred to as in situ recovery, or ISR)	51%
Underground mining	27%
Open-pit mining	14%
Co-product and by-product recovery from copper and gold operations	7%
Heap leaching	<1%
Other methods	<1%

Source: NEA and IAEA, (2016)

3.3.4.4.1 Uranium Production R&D Technological Considerations

Some uranium extraction and processing mining initiatives start with pilot plants before becoming to a larger scale. According to the IAEA (2002), the detailed design can entail where appropriate fieldwork and laboratory or pilot plant studies and by radiological and environmental impact assessments. In situ recovery (ISR) uranium mining technology was developed independently in both the USSR and in the USA in the late 1950s to early 1960s. Figure 3-33 below shows the in-situ recovery mine. Filippou and King (2011) noted that when coupled with the economic recession of 2008–2009, the large mining houses have now essentially abandoned strategic and long term internal technology development but sooner or later, mines and smelters will face some new challenges never seen before, most commonly due to lower grade ore deposits found in infrastructure challenged locations; the pressures to reduce greenhouse gas emissions and to save costly energy will grow as years go by and other environmental issues, including product stewardship, may force the industry to seek alternative mining and processing technologies.

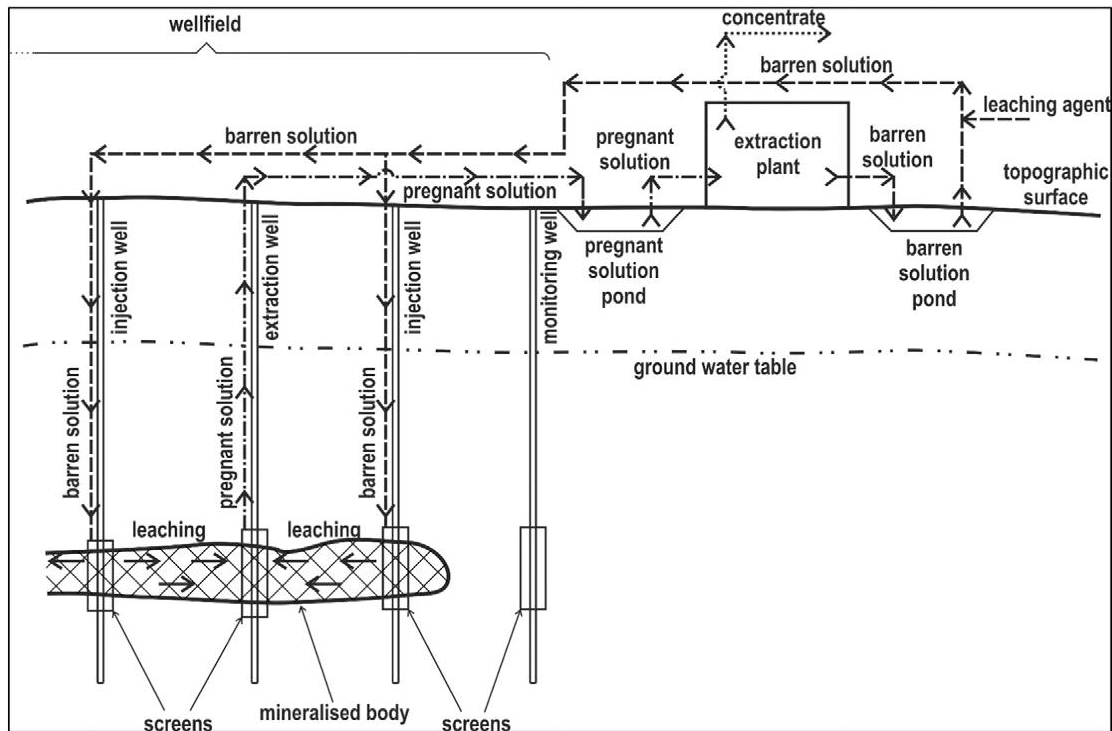


Figure 3-31: Conceptual in situ recovery mine
Seredkin, Zabolotsky and Jeffress (2016)

MINTEK, South Africa's national minerals technology organisation, is ideally placed to assist aspiring producers to fast-track new initiatives into production, both in southern Africa and further afield in the following areas:

- Ore evaluation and characterisation;
- Options around ore upgrading via ore sorting, including radiometric sorting;
- Feed preparation, including comminution and flotation;
- Acid and alkaline atmospheric or pressure leaching;
- Solvent extraction (mixer-settlers or Bateman Pulsed Column);
- Ion exchange (fixed bed columns, NIMCIX fluidized bed, or resin-in-pulp); and,
- $U^{3}O^{8}$ precipitation and refining.

3.3.4.4.2 Uranium Production Design and Engineering Technological Considerations

According to the IAEA (2002), the detailed design should be supported, where appropriate, by fieldwork and laboratory or pilot plant studies and by radiological and environmental impact assessments. Mining, milling and refining processes go through the relevant design phases e.g. a green-field or brownfield can require siting, conceptual design, basic design and detailed design. In addition, the designed technology processes will have taken into consideration methods for uranium production extracting, milling and refining.

3.3.4.4.3 Uranium Production Manufacturing Technological Considerations

Conventional mines have a mill where the ore is crushed, ground and then leached with sulfuric acid to dissolve the uranium oxides (WNA, 2016). Bringing a uranium operation into production involves a sequence of interrelated steps and these are outlined in the simplified diagram of Figure 3-32 below (IAEA, 1991).

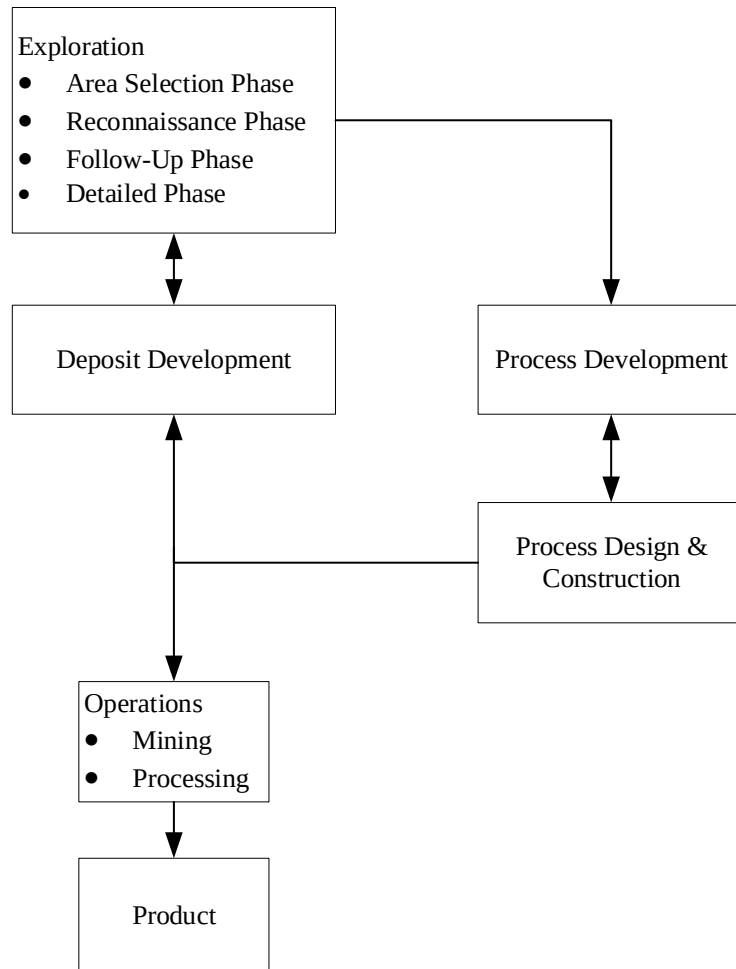


Figure 3-32: Steps of bringing a uranium operation into production

3.3.4.4.4 Uranium Production Construction Technological Considerations

According to White and Bruton (2011), technology is the knowledge, products, processes, tools, and systems used in the creation of goods or in the provision of services. With this definition in mind, it can be said that achieving the final objective of efficiently and effectively producing the uranium product as shown in (Figure 3-32) above is partly dependent on knowledge, products, processes, tools, and systems at the disposal of the uranium mine construction entities.

3.3.4.4.5 Uranium Production Operation & Maintenance Technological Considerations

Table 3-33 below shows “the largest-producing uranium mines” categorised by mine name, country, main owner, extraction method, production capacity and percentage contribution to world production. The owners and operators of the extraction mines are diverse. It is multinationals with public/private cross-ownership in which a number of interests, including economic, commercial and strategic, can overlap or collide. The operation and maintenance (O&M) knowledge and capabilities acquired by respective entities are dependent on the indicated type of mines or extraction technologies namely underground, ISL and open pit.

Table 3-33: The largest-producing uranium mines in 2016

Mine	Country	Main owner	Type	Production (tU)	% of world
McArthur River	Canada	Cameco (69.8%)	underground	6945	11
Cigar Lake	Canada	Cameco (50%)	underground	6666	11
Tortkuduk and Myunkum	Kazakhstan	Katco JV/Areva	ISL	4002	6
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3233	5
Inkai	Kazakhstan	Inkai JV/Cameco	ISL	2291	4
SOMAIR	Niger	Areva (63.6%)	open pit	2164	4
Budenovskoye 2	Kazakhstan	Karatau JV/Kazatomprom-Uranium One	ISL	2081	3
South Inkai	Kazakhstan	Betpak Dala JV/Uranium One	ISL	2056	3
Central Mynkuduk	Kazakhstan	Ken Dala JSC/ Kazatomprom	ISL	2010	3
Ranger	Australia	Rio Tinto (68%)	open pit	1994	3
Langer Heinrich	Namibia	Paladin	open pit	1893	3
Priargunsky	Russia	ARMZ	underground	1873	3
Kharasan 2	Kazakhstan	Baiken-U	ISL	1838	3
Budenovskoye 1, 3 & 4	Kazakhstan	Akbastau JV/Kazatomprom-Uranium One	ISL	1743	3
Rossing	Namibia	Rio Tinto (68.6%)	open pit	1569	2.5
Top 15 total				42,367	68%

Source: WNA (2016)

Note: In some rows, there is more than a single mine, but they are operated and reported on jointly.

3.3.4.4.6 Uranium Production Waste Management and Disposal Technological Considerations

Just like the O&M knowledge, the required waste management technological capabilities are also available to address radioactive waste from the respective extraction methods shown above in Table

3-33. Various uranium production facilities or sites remediation methods developed over the years are available for uranium mining houses to use. For instance, Table 3-34 below summarizes some of the uranium production facilities remediation strategies.

Table 3-34: Main approaches to remediation of waste contaminated areas

Removal of source	• Bulk removal • Surface scraping • Turf cutting
Containment	• Capping • Subsurface barriers
Immobilization	• Cement-based solidification (in situ and ex situ) • Chemical immobilization (in situ and ex situ)
Separation	• Soil washing • Flotation • Chemical/solvent extraction

Source: Fernandes, Franklin and Gomiero (2008).

3.3.4.5 Uranium Production Environmental Factors

Zhu and Chen (2009) noted that from the beginning of the 20th century, radioactive materials have accumulated on the earth's surface as a result of (1) the mining and processing of uranium (U) and thorium (Th) for the use and testing of nuclear weapons and for normal operations, (2) accidents in the civil nuclear power industry and, most recently, (3) the use of depleted uranium in conventional military weapons. To a certain extent, mining in general also contributes to GHG. Uranium mining consumes diesel fuel and electricity (Choi, Hyo & Ko, 2016). This being the case, there are CO₂ emissions during the mining of uranium regardless of whichever method is used. Lower ore grades require more material ore to be mined and processed to get the desired amount of uranium resulting in higher GHG emissions (Carless, Griffin & Fischbeck, 2016). Uranium mining and processing in South Africa has a declining public acceptance owing to negative environmental and health impacts (Matshusa & Makgae, 2017). In retrospect, Figure 3-33 below illustrates that an increase in the use of nuclear power not only benefits the public by reducing the CO₂ footprint of electricity in general, it also reduces the emissions from the front end of the nuclear fuel cycle.

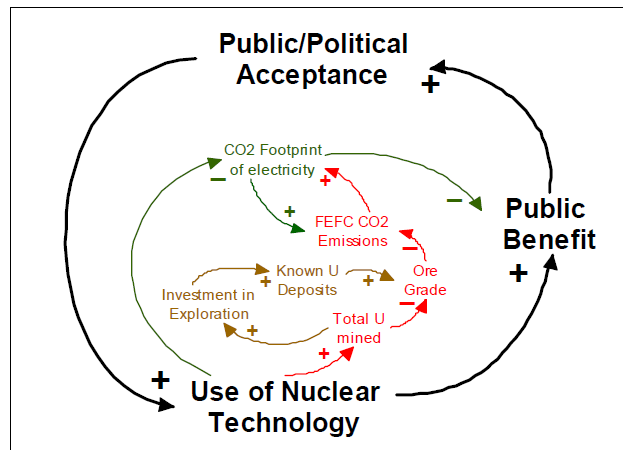


Figure 3-33: Carbon Footprint of Nuclear Power

IAEA (2009) states that the key to sustainable environmental management is to develop a plan that considers the complete life cycle of a uranium operation, which includes:

- exploration;
- feasibility studies;
- construction;
- operation;
 - mining (waste rock management, ore stockpile management and mine water management)
 - processing (tailings management and process water management)
- Decommissioning;
- Remediation; and
- Closure.

In order to enhance the meeting of sustainable development objectives, some SA mining entities are members of international organizations that advocate sustainability. As part of its individual member's pledges on sustainable development, the ICMM SD Framework – Final Principles (2003) states that in striving to achieve this, they will:

1. Implement and maintain ethical business practices and sound systems of corporate governance; 2. Integrate sustainable development considerations within the corporate decision-making process; 3. Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities; 4. Implement risk management strategies based on valid data and sound science; 5. Seek continual improvement of our health and safety performance; 6. Seek continual improvement of our environmental performance; 7. Contribute to conservation of biodiversity and integrated approaches to land use planning; 8. Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products; 9. Contribute to the social, economic and institutional development of the communities in which we operate; and 10. Implement effective and transparent engagement, communication and independently verified reporting arrangements with our stakeholders. ICMC SD Framework Final Principles (2003) states that “As members of International Council on Mining & Metals (ICMM) or as companies that have otherwise agreed to take on the same performance obligations as ICMM members, we seek continual improvement in our performance and contribution to sustainable development so as to enhance shareholder value”.

3.3.4.5.1 Uranium Production R&D Environmental Considerations

Research and development and innovation in the mining sector enables the adaptation of sustainable mining methods. According to Pool (n.d.) technological improvement in the uranium industry is necessary in order to meet increasingly stringent and, in many cases, arbitrary and unrealistic environmental and safety requirements. For instance, in situ recovery (ISR) which was introduced in the USA in 1959 allows the extraction of mineralisation with minimal disturbance to existing natural conditions (Seredkin et al., 2016).

3.3.4.5.2 Uranium Production Design and Engineering Environmental Considerations

In their review that aimed to identify how currently available tools and methodologies contribute to a comprehensive approach for Design for Sustainability (DfS) from a mineral processing perspective,

McLellan et al. (2009) stated that it was apparent that, in order to develop more sustainable processes, key elements of a DfS methodology should include:

- an integrated, consistent, project and operation-wide framework for sustainability thinking;
- initial definition of the problem in sustainability terms, and with an eye to local context;
- generation of alternatives which incorporate sustainability goals;
- assessment of alternatives to compare SD impacts on at least a triple bottom line basis, most likely with some kind of Multi-Criteria Assessment;
- involvement of stakeholders in prioritisation of sustainability goals and for feedback on alternatives;
- and,
- life cycle thinking and a focus on system interactions (at the operation itself, and across the product chain and local environment).

This being the case, it can be said that aims of this development of a strategic decision-making model are in line with the above key elements since it also advocates the possible incorporation of e.g. multi-criteria and life cycle approaches.

3.3.4.5.3 Uranium Production Manufacturing Environmental Considerations

The life cycle stages, system boundaries, output emissions inventoried (CO₂, CH₄, SO_x, and NO_x & TPM) and the reference flow for the nuclear scenario are shown in Figure 3-34 below (Siddiqui and Dincer, 2017).

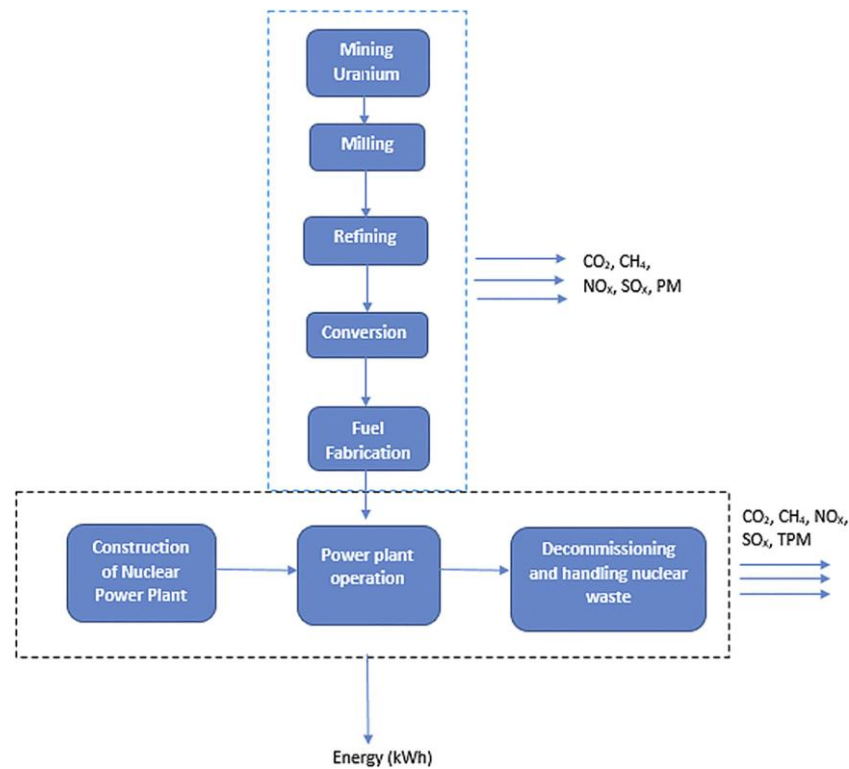


Figure 3-34: System boundary and life cycle stages for nuclear power scenario
 Source: Siddiqui and Dincer (2017).

3.3.4.5.4 Uranium Production Construction Environmental Considerations

New mines or processing plants receive permission for production only when an environmental impact assessment (EIA) and environmental management plan (EMP) are available (Matshusa & Makgae, 2017). One of the crucial factors to be considered for uranium production and all the NFC facilities is the ability of their individual Systems, Structures and Components (SSCs) to for withstand e.g. environmental natural disasters. For instance, the defence-in-depth graded approach in which there are different levels of safety provisions will still apply to NFC facilities just as in the with NPP. Table 3-35 below shows factors listed by Lizot et al. (2015) for consideration when the French Nuclear Safety Authority (ASN) undertook a Complementary Safety Assessments (CSAs) for French NFC facilities. The assessment came about because of the Fukushima-Daiichi accident redress requirements. Such assessments and interventions happen within the aforementioned fifth stage of the NFC cycle that has modifications as one of its components. Although the utilization and modification of nuclear fuel cycle

facilities are activities that are normally included under operation, in some cases they are considered separate stages in the authorization process, since their safety implications give rise to a large amount of review and assessment activities that are repeated a number of times over the lifetime of the facility (IAEA, 2017).

Table 3-35: Main dreaded situations and “Key” Systems, Structures and Components (SSCs) identified by AREVA in the CSAs reports “hardened safety core” resulting from the analysis

Facility	Dreaded situations	“Key” SSCs	“Hardened safety core”
La Hague plants Risks due to thermal release of radioactive materials	Spent fuel storage pools: loss of cooling, leading to an evaporation of water, an increase of the dose rate above the pools and a risk of Fuel assembly dewatering	SSCs related to the cooling of fuel assembly storage pools	• Water basin walls • Facility and storage buildings • Pool stainless steel liners and neoprene supports • Spent fuel storage pools: recirculation of pool water and water injection points. • Support structure of equipment potentially missile • Motor pump sets, emergency pipes and distribution valve chests • Water level and temperature measurement systems • Backup diesel generators and diesel oil reserve
MELOX plant Risks due to containment loss of radioactive material	Process buildings: simultaneous loss of the first and second barriers of static and dynamic containment in the facilities implementing PuO ₂ powder, with maintenance of the third static barrier constituted of the extern envelope of the process buildings Aggravating factor: Fire in premises implementing plutonium dioxide powder and loss of the last filtration level.	• Third static barrier of the process buildings (walls, foundations, doors, filters, valves and ventilation equipment at the limits of the buildings) • Safeguard electric networks	• Process buildings • Third static containment barrier • High depression air extraction network • Seismic detection and cut-off system • Seismic valves on liquid fluids and argon/hydrogen networks • Backup diesel generators and diesel oil supply. • Fire detection and fighting means enabling to face several fires in the process premises; • Measures enabling to limit the propagation of a fire outside the limits of the second containment barrier.
Tricastin and FBFC plants Nature of risks incurred Risks due to containment loss of toxic and	• Loss of all containment barriers of UF₆ storages	• Building • Autoclaves and their potential Aggressors • UF₆ cylinders	• Buildings, autoclaves and UF₆ containers • Flexible pipes and isolation valves • Seismic detection and cut-off system • Gas washing column • Equipment in the vicinity of autoclaves and of the washing column

Table 3-35: Main dreaded situations and “Key” Systems, Structures and Components (SSCs) identified by AREVA in the CSAs reports “hardened safety core” resulting from the analysis

Facility	Dreaded situations	“Key” SSCs	“Hardened safety core”
radioactive material	• Loss of all containment barriers of concentrated HF storages	• Building and retention area • HF storage tanks and their potential aggressors	• Autonomous and mobile device aiming at extracting and treating UF₆ and gas from the storage building • Retentions under HF tanks • Liquid detection in the retention pit • HF detection outside the building • HF recovery tanks and mobile pumps • Equipment in the vicinity of HF detectors • Autonomous and mobile device aiming at recovering the HF solution in suitable retention tanks

Source: Lizot et al. (2015)

3.3.4.5.5 Uranium Production Operation and Maintenance Environmental Considerations

Waste management strategies in mining will depend to a large extent on the characteristics of the operational process, the type of ore and prevailing socio-environmental conditions, amongst other issues (Fernandes, Franklina & Gomiero, 2008).

3.3.4.5.6 Uranium Production Waste Management and Disposal Environmental Considerations

Radwaste is indeed produced throughout the ‘nuclear cycle’, from the initial refining of uranium ore to the final decommissioning of nuclear power plants (Decamps & Dujacquier, 1997). Franklin and Fernandes (2013) contend that one of the first barriers to remediation works is the lack of financial resources as environmental issues used to be taken in the past as marginal costs and were not included in the overall budget of the company.

3.3.4.6 Uranium Production Legal Factors

Company practices differ from one to another; African governments’ capacities to monitor uranium mining vary; countries in which uranium mining takes place are at contrasting stages of development; ecosystems and biodiversity around uranium mines are never the same (SAIIA, 2012). Kessides (2014) noted that a nuclear regulatory agency typically has the following statutory functions: (i) developing regulations and guidance for NPP applicants and licensees; (ii) licensing or certifying applicants to use

nuclear materials or operate nuclear facilities, or decommissioning that permits license termination; (iii) overseeing licensee operations and facilities to ensure compliance with safety requirements; (iii) evaluating operational experience and event reports at licensed facilities or involving licensed activities; and (v) conducting research, holding hearings to address the concerns of parties affected by agency decisions, and obtaining independent reviews to support its regulatory decisions. In SA, any person wishing to site, construct, operate, decontaminate or decommission a nuclear installation may apply in the prescribed format to the chief executive officer for a nuclear installation licence and must furnish such information as the board requires (NNR Act (1999)). Matshusa and Makgae (2017) noted that growing environmental awareness in South Africa during the 1990s resulted in new laws such as:

- the Mineral and Petroleum Resources Development Act (MPRDA) of 2002; 2015 National Environmental Management Act (NEMA) of 1998 regulations on financial provision for prospecting, exploration, and mining or production operations;
- and nuclear energy policy of 2008, being introduced for new mining initiatives.

The SA government has given some minerals some special status. The Engineering News (2007) reported that the SA Minister of Public Enterprises, Mr Alec Erwin having said, “Government has identified uranium as a strategic mineral in securing nuclear energy supply in South Africa”.

SA adheres to the IAEA requirements for its nuclear undertakings. The operating organization shall demonstrate the safety of its facility through a set of documents known as the licensing documentation (or safety case) (IAEA SSR-4, 2017). Compliance with IAEA and local legislation requirements are enforced by the NNR, which oversees safety and regulation of nuclear installations and certain mines, and issues operating licences (DoE, 2008). The NNR regulates the following areas and facilities: the complete nuclear fuel cycle; uranium exploration; uranium mining and milling; uranium enrichment; fuel fabrication; Koeberg nuclear power plant; waste management (Vaalputs); the Safari-1 research reactor; decommissioning of nuclear vessels; and mines and scrap metal dealers. Taking full cognizance

of its mandate, and depending on the application, the NNR could issue the following types of authorisations for nuclear installations: (a) Nuclear Installation Licence (NIL) to site, construct and/or operate or decommission or decontaminate the installation, or (b) Nuclear Installation Site Licence (NISL) for new nuclear installations (c) Authorisation to Design a nuclear installation, or (d) Authorisation to Manufacture components (NNR PP-0009, n.d.).

The Pelindaba Treaty which was signed in 1996 and came into effect in 2009 prohibits the research, development, manufacture, stockpiling, acquisition, testing, possession, control or stationing of nuclear explosive devices in the territory of parties to the Treaty and the dumping of radioactive wastes in the African zone by Treaty parties (African Nuclear-Weapon-Free Zone Treaty, n.d.). Today, thirty-nine states on the African continent have ratified the Pelindaba Treaty, banning nuclear proliferation in Africa and requiring signatories to prevent proliferation (Postar, 2017).

3.3.4.6.1 Uranium Production R&D Legal Considerations

Licensing requirements for a pilot plant operation may vary considerably for different countries and for different locations within a given country (IAEA, 1990).

3.3.4.6.2 Uranium Production Design and Engineering Legal Considerations

The design shall be such that the following main safety functions are met for all facility states of the nuclear fuel cycle facility: (a) Confinement and cooling of radioactive material and associated harmful materials; (b) Protection against radiation exposure; and (c) Maintaining sub-criticality of fissile material (IAEA SSR-4, 2017). For the SA uranium mining sector, the NNR: RG-0018 (n.d.) requires that good mining practice should be followed to a practicable extent and consistently with the requirements for radiological protection, so that the design of the waste management facilities:

a) Maximises the use of natural materials for containment;

- b) Maximises the placement of waste material below ground level, or in some cases under water;
- c) Minimises the impact on the surrounding environment during operations and after closure;
- d) Minimises the need to retrieve or relocate the waste at closure; and
- e) Minimises the need for surveillance and maintenance during operations and for institutional controls after closure.

3.3.4.6.3 Uranium Production Manufacturing Legal Considerations

Tailings storage facilities (TSFs) and other gold and uranium processing facilities in South Africa have to register with the National Nuclear Regulator (NNR) if the radioactivity exceeds 0.5 Bq/g (Sutton & Weiersbye, 2007).

3.3.4.6.4 Uranium Production Construction Legal Considerations

Construction in the context of the NNR Act and RD-0034 includes the carrying out of civil works as well as the assembling of components and parts on site (NNR PP-0009, n.d.)

3.3.4.6.5 Uranium Production Operation and Maintenance Legal Considerations

The following is stipulated by NNR PP-0009 (n.d.) with respect to the nuclear installation licence (NIL) for the operation of a nuclear installation the following needs to be undertaken: (a) Safety assessment documentation (i.e. a safety case) must accompany and support the application for a variation to the NIL; (b) The safety case for a NIL to operate must consider the results of the commissioning testing and should address all outstanding issues; and (c) Subject to the NNR review, the conditions of the NIL will be amended to allow for the operation of the nuclear installation and a variation of the NIL will be issued to the applicant.

3.3.4.6.6 Uranium Production Waste Management and Disposal Legal Considerations

NNR regulations require that radioactive waste management programmes be established, implemented and maintained for the safe storage of radioactive waste with key control measures implemented for the duration of the storage of the waste (NNR-RG-0018, n.d.).

3.3.5 Conversion

The industrial synthesis of UF_6 is the hydro-fluorination of uranium mining concentrates through a process called conversion (Morel et al., 2018). The uranium conversion stage is where the U_3O_8 is stripped of all remaining impurities and converted to UF_6 (Carless, Griffin & Fischbeck, 2016). Ault, Krahn and Croff (2017) contend that uranium conversion achieves two major objectives: moving the uranium into a fluoride chemical form to facilitate subsequent enrichment and purifying the uranium to nuclear-grade impurity levels. The holistic perspective of conversion is given below by the IAEA in Table 3-36 in which it is indicated that there are facilities for:

- conversion of U_3O_8 to UF_4 which is later converted UF_6 for enrichment or to U metal for Magnox fuel;
- conversion of U_3O_8 or UF_4 is converted to UF_6 to be used in enrichment process;
- UF_4 is converted to U metal for Magnox fuel;
- and depleted UF_6 is converted to U_3O_8 for further storage or processing.

The flowchart illustration of various processes which make up the conversion are shown Figure 3-35 below.

Table 3-36: Conversion Stage

Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
Conversion	Conversion to UF_4	Facilities in which is converted to UF_4 which is later converted to UF_6 for enrichment or to U metal for Magnox fuel.
	Conversion to UF_6	Facilities in which U_3O_8 or UF_4 is converted to UF_6 to be used in enrichment process.
	Conversion to U Metal	Facilities in which UF_4 is converted to U metal for Magnox fuel.
	Re-Conversion to U_3O_8 (Dep U)	Facilities in which depleted UF_6 is converted to U_3O_8 for further storage or processing.

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

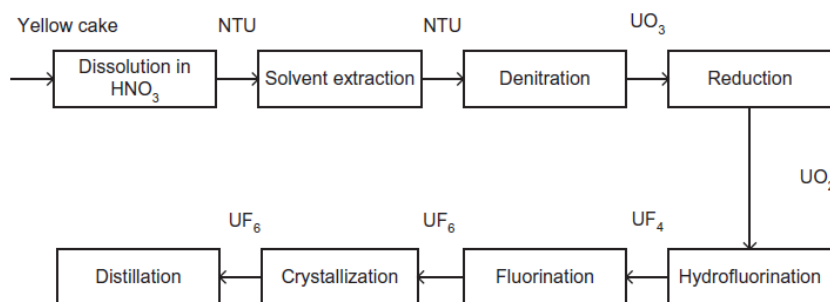


Figure 3-35: Flowchart of UF_6 conversion

Source: Santos et al. (2016)

3.3.5.1 Conversion Political Factors

South Africa has technical expertise on nuclear technology at NECSA, including expertise on uranium conversion and enrichment remaining from South Africa's previous nuclear weapons programme (DoE, 2008).

3.3.5.1.1 Conversion R&D Political Considerations

Government, through NECSA, shall undertake and lead the development of uranium conversion capabilities as part of the beneficiation of uranium (DoE, 2008). In this regard, NECSA can collaborate with other local or international entities in the development of conversion technologies.

3.3.5.1.2 Conversion Design and Engineering Political Considerations

Conceptual design, basic design and detailed design are engineering design phases relevant to the putting up of a conversion plant.

3.3.5.1.3 Conversion Manufacturing Political Considerations

The operating conditions of the conversion plant are considered in order to establish specifications for the required SSCs. During design engineering, materials used to manufacture plant equipment exposed to e.g. the conversion plant toxic nuclear fuel materials, process temperatures and pressures are specified. This being the case, it is important that policies and strategies formulated by strategic decision makers take note of the value created e.g. skills required not only for manufacturing but also for the all

the stages of the value chain. Usually policy and strategy documents highlight only the manufacturing aspect without recognising other value adding stages.

3.3.5.1.4 Conversion Construction Political Considerations

Deciding on having the conversion plant construction capabilities within the plant owner organization (OO) is a strategic decision made by the organization's management. The alternative to having in-house skills can be complemented outsourcing some of the works to some external companies who have chemical plant mechanical, C&I, electrical and civil works installation or construction capabilities. Other countries collaborate with partner countries who already have the latest conversion capabilities by virtue of the country policies promoting such partnerships.

3.3.5.1.5 Conversion Operation and Maintenance Political Considerations

It is important that the government through its policies recognize or promote the operation and maintenance value created by the local entity operating and maintaining the conversion plant. At the same time, the owner organization has to report on the importance of having such competences taking into consideration all the factors that are of interest to the government such as skills development, employment, safety and environment. From a strategic point of view e.g. there should be national clarity on when, how, why, who, what value should be created locally through various stages of uranium beneficiation.

3.3.5.1.6 Conversion Waste Management and Disposal Political Considerations

For countries that have conversion capabilities, it is responsibility of the government to see to it that their related waste management policies are available for implementation. In SA, the adherence to the conversion plant waste management plans is monitored by the NNR.

3.3.5.2 Conversion Economic Factors

There are many facilities operating to convert uranium ore concentrate (yellow-cake) to uranium hexafluoride UF₆ (IAEA, 1994a). According to Schneider et al. (2013), the major suppliers of conversion capability are BNFL (United Kingdom), Cameco (Canada), AREVA subsidiary Comurhex (France), Conver Dyn (US), and Minatom (Russia). Table 3-37 below lists uranium hexafluoride conversion facilities in different countries as of 2015, whereas the uranium de-conversion plants USA, UK, France and Russia are shown below in Table 3-38.

Table 3-37: World Primary Conversion Capacity

Company	Nameplate capacity (tonnes U/yr as UF ₆)	Approximate capacity utilisation 2015	Capacity utilisation 2015, tU/yr
Cameco, Port Hope, ON, Canada	12,500	70%	8750
Springfields Fuels, UK	(closed August 2014)	0%	0
TVEL at Siberian Chemical Combine, Seversk, Russia	12,500	100% assumed	12,500
Comurhex (Areva), Malvesi (UF ₄) & Tricastin (UF ₆), France	15,000	70%	10,500
Converdyn, Metropolis, USA	15,000 – now 7000 from 2017	70%	10,500
CNNC, Lanzhou, China	5000	Unknown	4000
IPEN, Brazil	100	70%	70
World Total	52,100		46,320

Source: World Nuclear Association (2017)

Table 3-38: Uranium Deconversion Plants

Operator	Location	Capacity tU/yr
Areva	Tricastin, France	20,000
	Richland, Washington, USA	small
Urenco ChemPlants	Capenhurst, UK	15,000
Mid America Conversion Services	Portsmouth, Ohio, USA	13,500
	Paducah, Kentucky, USA	18,000
INIS Fluorine Products	Hobbs, New Mexico, USA	6,500 (construction on hold)
Tenex	Zelenogorsk, Russian Federation	10,000

Source: World Nuclear Association (2017)

3.3.5.2.1 Conversion R&D Economic Considerations

Bredell (1990) stated that the improvement of the UF_4 quality as well as modifying the UF_4 distributor at the inlet to the reactor eliminated the clogging of the SA UF_6 reactor problems.

3.3.5.2.2 Conversion Design and Engineering Economic Considerations

Fuel materials and designs are developed, and fabrication technologies are implemented to provide nuclear energy with benefits that outweigh the associated costs and risks, to achieve reliable and economical power generation, improved safety and reduced environmental impact (IAEA, 2013e).

3.3.5.2.3 Conversion Manufacturing Economic Considerations

According to Bredell (1990), facilities provided for the production of hydrogen fluoride (HF) and fluorine (F_2) formed part of the SA conversion plant complex. In the first stage, the uranium is converted into uranium tetrafluoride (UF_4), green salt and in the second stage, the UF_4 is converted into uranium hexafluoride (UF_6) through fluorination. The production of uranium hexafluoride UF_6 for the enrichment plants is carried out in conversion plants and overall, the cost of this process is approximately 4% of the fuel cycle cost (Simnad, 2003). The cost of conversion has been stable for years at \$8/kg of uranium (Rothwell, 2004). Figure 3-36 below shows the wet route of the conversion process starting from dissolution to fluorination.

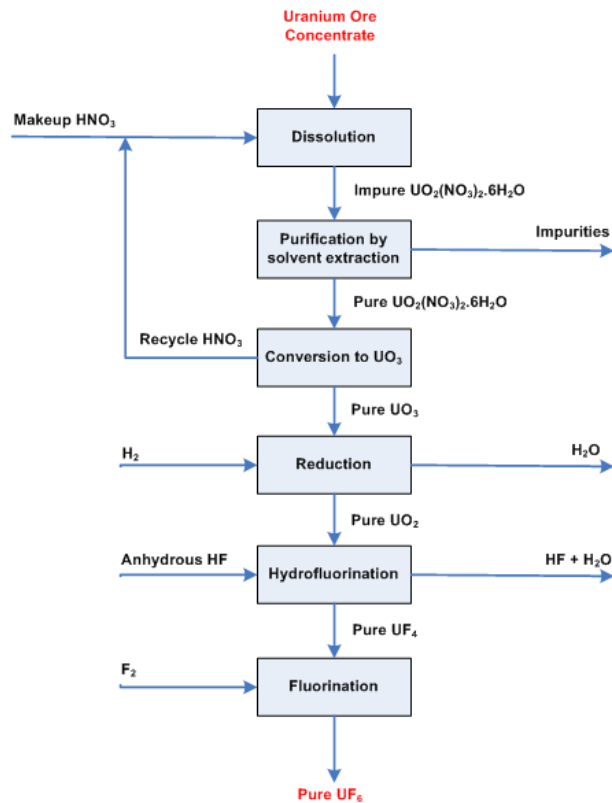


Figure 3-36: Stages in conventional (wet route) UF₆ refining-conversion processes

Source: IAEA (2009e)

3.3.5.2.4 Conversion Construction Economic Considerations

To achieve its uranium enrichment objective then Atomic Energy Corporation of SA installed a conversion plant. In the early 1980s, a uranium conversion plant with a nominal capacity of 1200 t U/a was built by the Atomic Energy Corporation (AEC) at Valindaba near Pretoria to supply uranium hexafluoride (UF₆) to its uranium enrichment facility (Bredell, 1990; Heinonen, 2011b). Figure 3-37 shows that the installed conversion plant capacity should be able to process 162 t of U₃O₈ in order to produce 203t of UF₆. In addition, the illustration shows material quantities for various NFC phases.

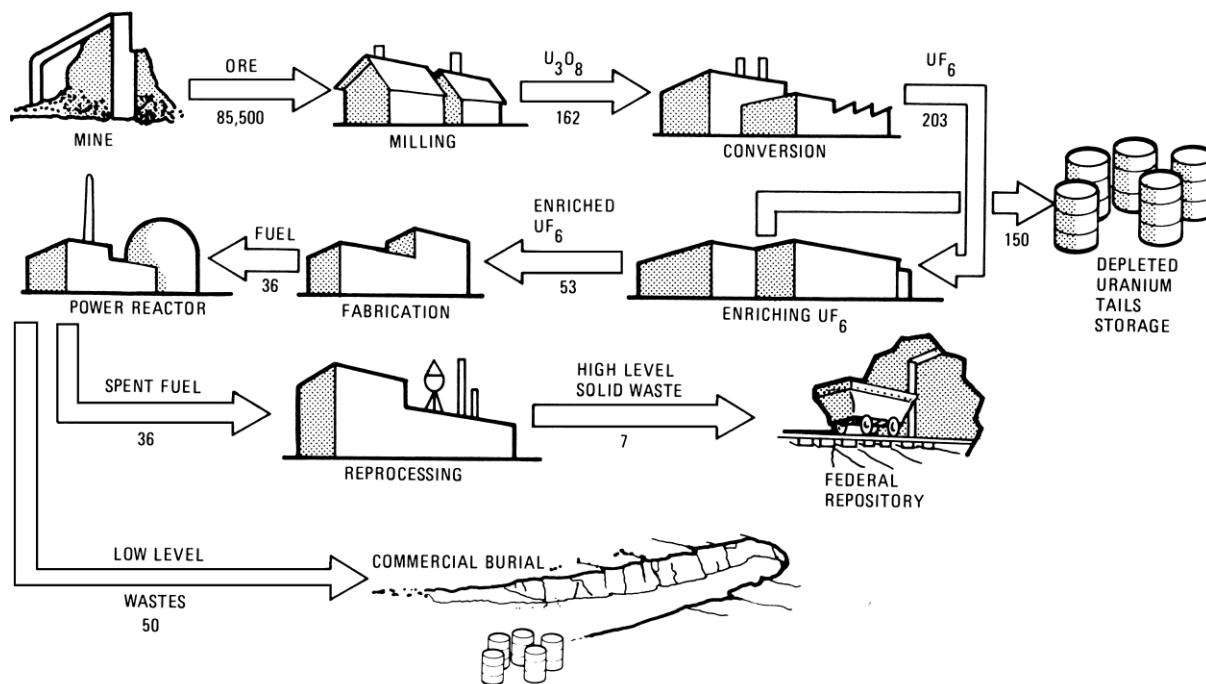


Figure 3-37: Annual quantities (tons) of fuel materials required for operation of 1000-MW(e) light water reactor

Source: Simnad (2003)

3.3.5.2.5 Conversion Operation and Maintenance Economic Considerations

According to Auf der Heyde (1993) the AEC's own figures revealed that the average production costs at the conversion, enrichment (Z), and fabrication (Beva) plants during the period 1988-92 were between ten and twenty times the spot market price during the same period, and this excludes the capital costs of the various plants.

3.3.5.2.6 Conversion Waste Management and Disposal Economic Considerations

The ammonium diuranate (ADU) conversion process that was operated at the NECSA in the past generated a significant amount of waste containing high concentrations of uranium, which can be re-used if the uranium can be recovered in a useful form (Potgieter et al., 2017).

3.3.5.3 Conversion Social Factors

Experts note five significant problems that attract public concern, which in turn constrain the large-scale development of nuclear technology: safety, the threat of unauthorized nuclear material and technology proliferation, radioactive waste management, commercial efficiency, and limited natural nuclear fuel resources (Andrianov, 2015). Having uranium conversion capabilities enables a country to enhance its security of providing nuclear fuel for its purposes or for export. Carlsen (2010) contended that if we're going to consider anything that has to do with nuclear technology, we have to be satisfied as to safety, security, non-proliferation, Economic, extension, availability of fuel and probably five other factors. Figure 3-38 shows the suggested global picture for considering nuclear technology benefits.

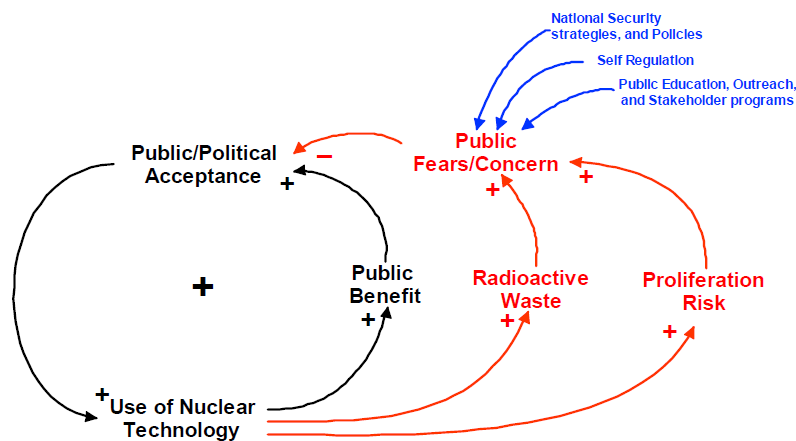


Figure 3-38: Nuclear Reality
Source: Carlsen (2010)

3.3.5.3.1 Conversion R&D Social Considerations

The training of South African scientists for the SA nuclear sector was conducted in countries like the United States, Britain, West Germany, France and Sweden, and there was considerable nuclear cooperation with Israel and Taiwan (Fig, n.d.). Marquard (2006) stated that the AEB found premises outside Pretoria for its nuclear energy research and was transformed from a Board which regulated the

nuclear industry into a large research and development organisation, and finally an industrial operation employing around 6000 people at its peak in the 1980s.

3.3.5.3.2 Conversion Design and Engineering Social Considerations

Expertise in both the chemistry and the engineering aspects of fluorine is essential for the design and running of several of the unit processes in the nuclear fuel cycle (Crouse, 2015). This knowledge enabled NECSA (AEC then) to venture into other areas in which fluorine is used e.g. fluorinating of plastic vehicle fuel tanks.

3.3.5.3.3 Conversion Manufacturing Social Considerations

Through technology transfer and self-development, NECSA developed human capital highly knowledgeable in the production of uranium hexafluoride for SAFARI-1 and Koeberg Nuclear Power Plant nuclear fuel purposes. These capabilities and competencies positioned NECSA to supply UF_6 locally and abroad.

3.3.5.3.4 Conversion Construction Social Considerations

The construction of the SA uranium conversion plant at Pelindaba enabled the production of uranium hexafluoride (UF_6) which is the main feedstock for the enrichment process. In order to undertake the beneficiation, a concentration of uranium-235 up to the required 3.5 per cent, the oxide is mixed with fluorine and heated to form uranium hexafluoride, which is a gas commonly known as 'hex' (Conversion & Enrichment, 2006).

3.3.5.3.5 Conversion Operation and Maintenance Social Considerations

The ammonium diuranate (ADU) conversion process that was operated at the Nuclear Energy Corporation of South Africa (NECSA) in the past generated a significant amount of waste containing high concentrations of uranium, which can be re-used if the uranium can be recovered in a useful form (Potgieter et al., 2017).

3.3.5.3.6 Conversion Waste Management and Disposal Social Considerations

The investigation on recovering and reuse of NECSA's conversion process waste, it was found that the waste material was soluble in HNO_3 , H_2SO_4 , and HCl as well as water, with a maximum uranium extraction of 98% achieved in 3 molar HNO_3 in 1 hour at a temperature of 80°C without the addition of an oxidizing agent (Potgieter, 2017).

3.3.5.4 Conversion Technological Factors

To increase the percentage of fissile uranium (natural uranium contains 0.7% of uranium-235, a radioactive isotope, and 99.3% uranium-238), uranium oxide is converted to uranium hexafluoride, UF_6 (a gas above 56.1°C).

3.3.5.5 Conversion R&D Technological Factors

In the 1960s, South Africa started small-scale uranium conversion experiments (Heinonen, 2011b). Hence, an installation of a new laboratory Static Reactor and a mass measurement for simulating the behaviour of a moving-bed reactor (MBR) was commenced leading to the usage of ammonium diuranate, from four different mines to produce, reduce and hydro-fluorinate a bulk of samples of uranium trioxide (AEB Report, 1979). Although a number of conversion processes have been developed worldwide, only three are used on an industrial scale today and two of these are wet processes: ammonium diuranate (ADU) and ammonium uranyl carbonate (AUC) and the third is a dry process (Abe & Asakura, 2012). A large research investment has since been made worldwide, mainly to increase the discharge burnup and optimize the nuclear fuel cycle and programmes and were initiated to:

- Improve the uranium dioxide (UO_2) fuel density stability, leading to preferred powder manufacturing processes: The Integrated Dry Route developed by BNFL, and the wet routes, ammonium diuranate (ADU) and ammonium uranyl carbonate (AUC);
- Limit the risk of rod failure by pellet-clad mechanical and chemical interaction, by improving the plant operation management.

- Limit the risk of failure by migrating fragments in the primary circuit, adding a filter at the assembly bottom end;
- Justify the load follow operating conditions imposed when nearly 80% of the electricity production is nuclear (France and Belgium);
- Limit the fuel rod bow and the PWR fuel assembly deformation, to facilitate assembly reloading and avoid gap pitching between fuel rods; modification of the spacer grids and mixing grids to increase the assembly rigidity;
- Reducing BWR assembly bow by optimizing the materials used for the channel box, as well as fine-tuning the manufacturing processes;
- Increase the batch discharge burnup up to 60 or 70MWd kgM⁻¹ which requires a detailed understanding of material properties and microstructure evolution with irradiation, in particular, the behaviour of the gaseous and volatile fission product species in UO₂; and
- More generally, improve the material knowledge and modelling, and our insights into the mechanical assembly and rod structure behaviour under irradiation.

3.3.5.5.1 Conversion Design and Engineering Technological Considerations

Figure 3-39 below is an illustration of the South African AEC moving bed reactor (MBR). The AEC utilized MBR for the conversion of uranyl/oxide uranium trioxide (UO₃) to Uranium Tetrafluoride (UF₄) whereby in the first section of the reactor UO₃ is reduced to UO₂ by means of Ammonia (NH₃) and in the second the UO₂ is hydro-fluorinated to UF₄ by means of HF. (Ponelis, Slabber & Zimmer, 1986). Table 3-39 lists the NECSA conversion plant areas for different processes.

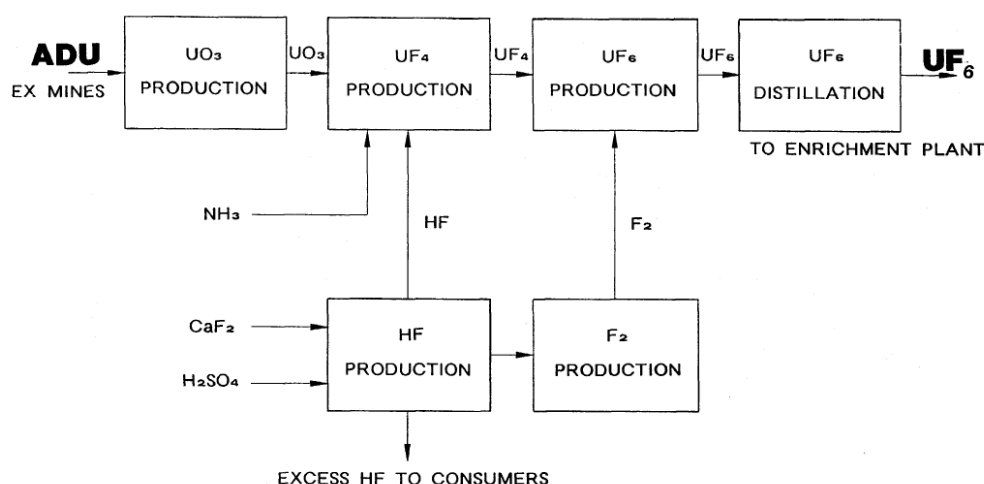


Figure 3-39: Conversion Process

Source: Bredell (1990)

Table 3-39: NECSA uranium conversion plant areas

Area	Process	Floor
54	ADU handling	2
56	UO ₃ production	2
58	UF ₄ production	6
62	Fluorine production	2
64	UF ₆ production and distillation	7
66	UF ₆ Crystallisation, storage, sampling and dispatch	4
70	Uranium handling scrubber and vacuum area	5
76	Control room, workshop and marshalling room	2
Fan store	Storage area for conversion plant waste	1

Source: NNR licence document

3.3.5.5.2 Conversion Manufacturing Technological Considerations

The IAEA (2009) states that conversion of uranium to other forms enables its use by further steps in the fuel cycle such as:

- uranium hexafluoride (UF₆) in case of enriched uranium fuel;
- natural uranium oxide (UO₂) in case of PHWRs; and
- metal uranium in case of fuel based on metallic uranium alloy.

The enrichment process requires the uranium to be in a gaseous form; and the uranium oxide concentrate is therefore first converted to uranium hexafluoride, which is a gas at relatively low temperatures (WNA, 2017). Figure 3-40 below displays the major chemical and energetic inputs to the wet and dry

processes (Rothwell, 2004). In the dry process, uranium oxide concentrates are first calcined (heated strongly) to drive off some impurities, then agglomerated and crushed (WNA, 2017). Whereas in the in the "dry-process" the concentrate is first calcined to U_3O_8 and/or reduced to UO_2 in its impure state (IAEA, 1994a). A dry process has preferable advantages: the process is simple and the equipment is compact; the criticality limitation is less required; and liquid waste treatment is not necessary.

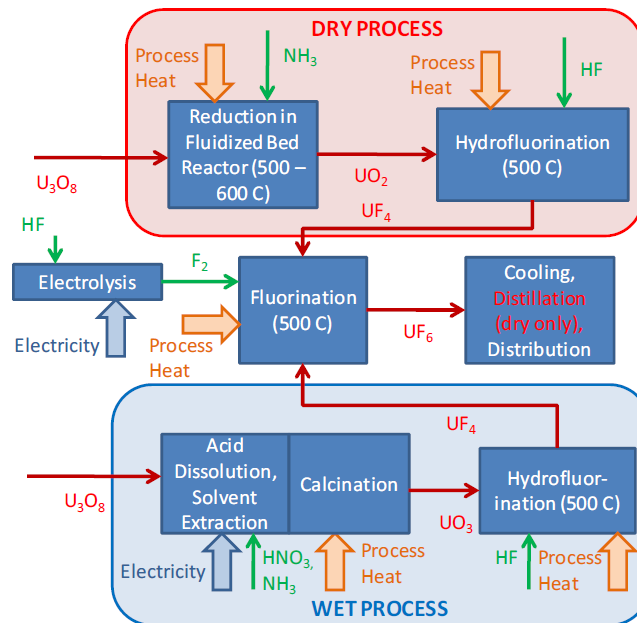


Figure 3-40: Schematic representation of dry and wet processes for UF_6 production
Source: INL (2010)

Figure 3-41 below shows the only facility in the world that has accomplished for more than 20 years the depleted UF_6 de-conversion AREVA's W plant located in France (Morel & Duperret, 2009).

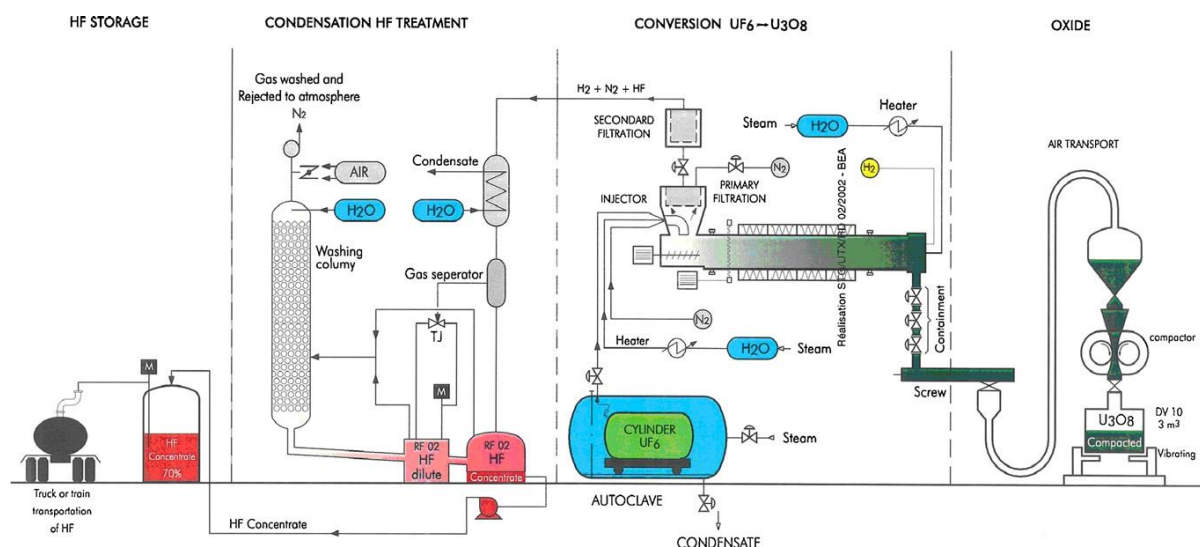


Figure 3-41: UF₆ French deconversion process

Source: Morel and Duperret (2009)

3.3.5.5.3 Conversion Construction Technological Considerations

Figure 3-41 above shows different SSCs that enable the deconversion process i.e. from UF₆ to U₃O₈. The installation of SSCs for such a plant will be in accordance with the safety and commercial requirements.

3.3.5.5.4 Conversion Operation and Maintenance Technological Considerations

There is a possibility of deterioration of equipment during operation of uranium conversion plant due to the corrosive properties of chemicals used as feedstock. During April 1978, the maintenance personnel removed and inspected valves of the South African AEB conversion plant and concluded that the valves performed satisfactorily since there were no signs of corrosion (AEB Report, 1979). The inspection capabilities for AEB were crucial since the Uranium Conversion Plant situated in Pelindaba converted uranium into either ammonium diuranate (ADU) or uranium tri-oxide (UO₃) form, into pure UF₆, which was supplied to enrichment facilities as feed material for the enrichment process (NNR Fourth Report, 2017). The operation and maintenance knowledge or capabilities take into consideration the effect of uranium compounds on the equipment materials and hazardous and toxic nature of substances such as HF. Such operation and maintenance considerations will apply for both conversion

and de-conversion stages. During these stages, the uranium compounds will interact with different metal linings of the fluorination ovens, the piping in the industrial site, and the walls of the containers (Morel et al., 2018).

3.3.5.5 Conversion Waste Management and Disposal Technological Considerations

Figure 3-42 below is an illustration showing the location of the conversion process in the whole front-end of the fuel cycle and indicating that it is one of the sources nuclear waste.

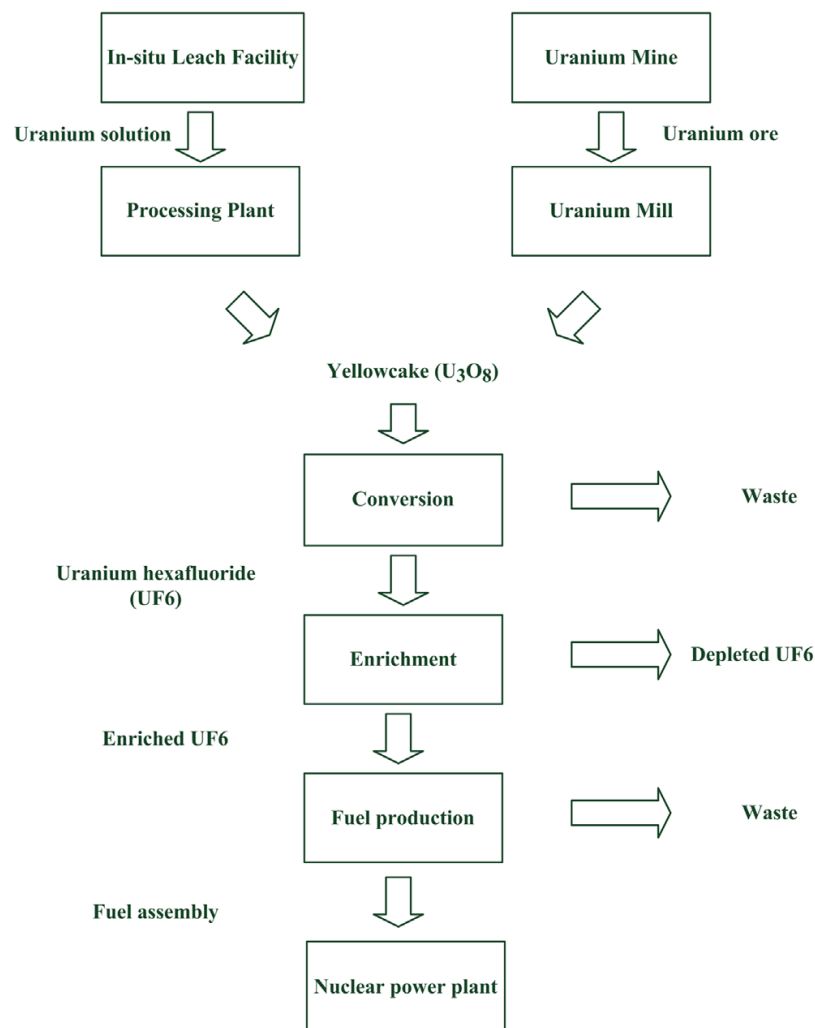


Figure 3-42: Front-end of the 'once-through' uranium fuel cycle
 Source: Warren and De Simone (2014)

3.3.5.6 Conversion Environmental Factors

The NRC (2017) states that nuclear criticality is not a hazard at these facilities because the nuclear material consists of natural uranium throughout the process. During conversion, thermal energy mainly comes from combustion of natural gas (Choi, Hyo & Ko, 2016). The thermal energy source would differ from country to country with some countries using e.g. coal for combustion. Emissions from such combustion methods will have to be taken into consideration when calculating the CO₂ emissions due to the conversion processes. The IAEA (2010a) contends that the following issues are pertinent to conversion facilities:

- The main hazard is the potential release of chemicals, especially HF and UF₆. Controls to address this hazard will adequately protect also against internal radiation exposure;
- A criticality hazard exists only if the conversion facility processes uranium with a ²³⁵U concentration greater than 1%; and
- External exposure is a concern for the handling of residues containing thorium and its daughter products produced in fluorination reactors. External exposure is also a concern in the handling of recently emptied cylinders, especially those used as containers for reprocessed uranium, where there is a build-up of ²³²U.

Facilities that are involved in the production, handling, transportation, and storage of UF₆ should be sited, designed, constructed, modified, operated, maintained, and decommissioned according to a policy of providing for the safety and health of the employees, the safety and health of the public, and for the protection of the environment (IAEA, 1994a). Similarly, IAEA (2010a) states that the safety of conversion facilities and uranium enrichment facilities is made possible by means of their proper siting, design, construction, commissioning, operation including management, and decommissioning.

3.3.5.6.1 Conversion R&D Environmental Considerations

Owing to mounting geopolitical, environmental and economic concerns, investment in research and development (R&D) in the energy sector has become increasingly crucial for sustainability, security

and environmental protection (Corderi & Lin, 2011). Figure 3-43 below is an illustration of how sustainability is becoming the international reference approach to reconciling the different fields of analysis, i.e. the technical performance, economic viability, environmental preservation and societal acceptance (Poinssot, Bourg & Boullis, 2016). It is therefore important that owners of conversion plants are innovative when it comes to making sure that the installation of the plants takes into consideration sustainability. The IAEA (2010a) states that for conversion facilities:

- The main hazard is the potential release of chemicals, especially HF and UF₆. Controls to address this hazard will adequately protect also against internal radiation exposure;
- A criticality hazard exists only if the conversion facility processes uranium with a ²³⁵U concentration greater than 1%;
- External exposure is a concern for the handling of residues containing thorium and its daughter products produced in fluorination reactors; and
- External exposure is also a concern in the handling of recently emptied cylinders, especially those used as containers for reprocessed uranium, where there is a build-up of ²³²U.

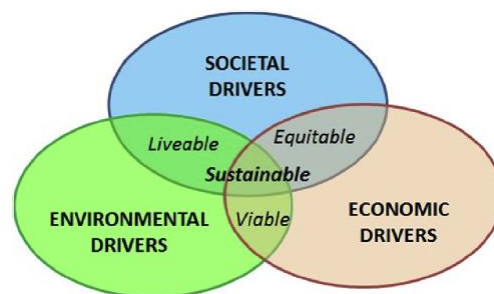


Figure 3-43: The three main pillars of the sustainability, i.e. the ability to preserve the environmental, to promote the economic development and to develop balanced and peaceful relationships.
Source: Poinssot, Bourg and Boullis (2016)

3.3.5.6.2 Conversion Design and Engineering Environmental Considerations

Design of the equipment is another important safety factor hence it is very important that the construction materials for processing equipment be compatible with the process and temperature and pressure conditions must be considered (IAEA, 1994).

3.3.5.6.3 Conversion Manufacturing Environmental Considerations

The major barrier to entry into the fluorochemical industry is the ability to manufacture and, in general, to handle fluorine and its precursor, hydrogen fluoride since both are extraordinarily difficult and dangerous substances with which to work (Crouse, 2015).

3.3.5.6.4 Conversion Construction Environmental Considerations

According to IAEA (2010a), for conversion facilities and enrichment facilities, the criteria used for the construction of the building and the fabrication of the process equipment and components used for facility erection, should be the same as or more stringent than those used for the non-nuclear chemical industry, and should be specified as part of the design (e.g. seismic design).

3.3.5.6.5 Conversion Operation and Maintenance Environmental Considerations

The IAEA (2010a) states that a significant potential hazard associated with these facilities is a loss of the means of confinement resulting in a release of uranium hexafluoride (UF_6) and hazardous chemicals such as hydrofluoric acid (HF) and fluorine (F_2).

3.3.5.6.6 Conversion Waste Management and Disposal Environmental Considerations

Because of the different processes used in the in the dry and wet plants, waste characteristics, quantities, and treatment practices differ at each type of facility (Perkins, 1982).

3.3.5.7 Conversion Legal Factors

The need for legislation concerning activities associated with uranium led to the promulgation of the South African Atomic Energy Act, 1948 and, with it, the creation of the Atomic Energy Board (AEB),

with responsibility for all nuclear matters (de Jesus, 1983). In September 1991, South Africa concluded a Comprehensive Safeguards Agreement (CSA) with the IAEA and submitted its initial declaration on facilities and nuclear material inventories (Heinonen, 2011b).

3.3.5.7.1 Conversion R&D Legal Considerations

The siting, environmental and security management of a conversion plant is subject to the regulations that are in effect for any chemical processing plant involving fluorine-based chemicals (Hore-Lacy, 2013).

3.3.5.7.2 Conversion Design and Engineering Legal Considerations

Provisional facility design information must be submitted by the State to the IAEA when a decision is taken to construct, or to authorize construction, of a nuclear facility (IAEA, 2017b).

3.3.5.7.3 Conversion Manufacturing Legal Considerations

The IAEA (2010a) states that the fabrication of the process equipment and components used in the facility and for their installation, should be the same as or more stringent than those used for the non-nuclear chemical industry, and should be specified as part of the design (e.g. seismic design).

3.3.5.7.4 Conversion Construction Legal Considerations

The extent of regulatory involvement in construction should be commensurate with the hazards posed by the facility over its lifetime (IAEA, 2010a). Figure 3-44 below shows protection barriers that should be considered during construction of a uranium conversion plant.

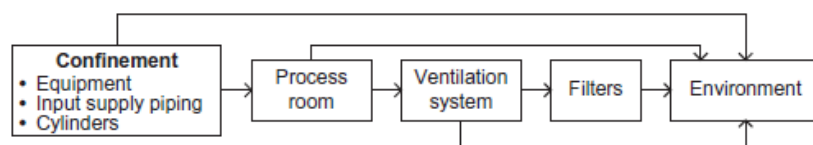


Figure 3-44: Protection barriers

Source: Santos et al. (2016)

3.3.5.7.5 Conversion Operation and Maintenance Legal Considerations

The IAEA (2010a) guidelines state that maintenance should follow good practice with particular consideration given to:

- Work control, e.g. handover and handing back of documents, means of communication and visits to job sites, changes to the planned scope of work, suspension of work and ensuring safe access;
- Equipment isolation, e.g. disconnection of electrical cabling and heat and pressure piping and venting and purging of equipment;
- Testing and monitoring, e.g. checks before commencing work, monitoring during maintenance and checks for recommissioning;
- Safety precautions for work, e.g. specification of safety precautions, ensuring the availability of personal protective equipment and ensuring its use and emergency procedures; and
- Reinstallation of equipment, e.g. reassembly, reconnection of pipes and cables, testing, cleaning the job site and monitoring after recommissioning.

3.3.5.7.6 Conversion Waste Management and Disposal Legal Considerations

Conversion facilities and enrichment facilities should be designed to minimize the generation of waste both in operation and in decommissioning (IAEA, 2010a).

3.3.6 Enrichment

The semi-commercial South African Z-plant which utilised a helicon aerodynamic process for uranium enrichment produced 3.25 % enriched LEU for the Koeberg power station (Global Security, 2011). The enrichment stage is where the uranium in UF_6 from the conversion stage becomes enriched to 3-5% (Carless, Griffin & Fischbeck, 2016). Because thorium contains no naturally occurring fissile material in the way that uranium does, it requires a fissile input from external sources to “jump-start” a thorium

fuel cycle implementation (Ault, Krahn & Croff, 2017). Figure 3-45 shows where the uranium enrichment phase and other related NFC phases occur.

According to the SAIIA (2013), South Africa does not itself enrich uranium for its power generation, instead these services are provided by international corporations such as Areva (France), Westinghouse Electric Company (Japan/US), Tenex (Russia) and Urenco (Germany, The Netherlands and UK).

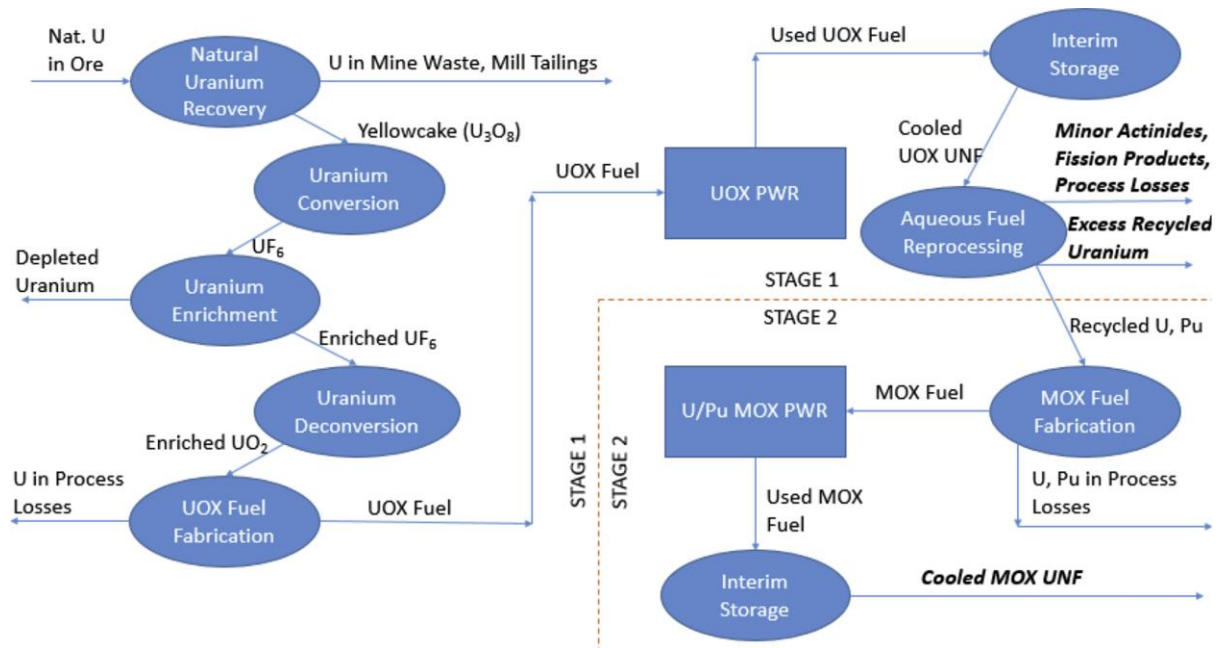


Figure 3-45: Schematic of material flows in the MUPu fuel cycle

Source: Ault, Krahn, Croff (2017)

3.3.6.1 Enrichment Political Factors

To address concerns relating to security of supply, a guarantee of supply of enrichment services should be established through a joint commitment by existing uranium enrichment companies (“enrichers”) in an IAEA-supported mechanism established by multilateral agreements (WNA, n.d.). Figure 3-46 below depicts a “Multi-Layered and Multi-Lateral Guarantee of Supply” suggested by the WNA.

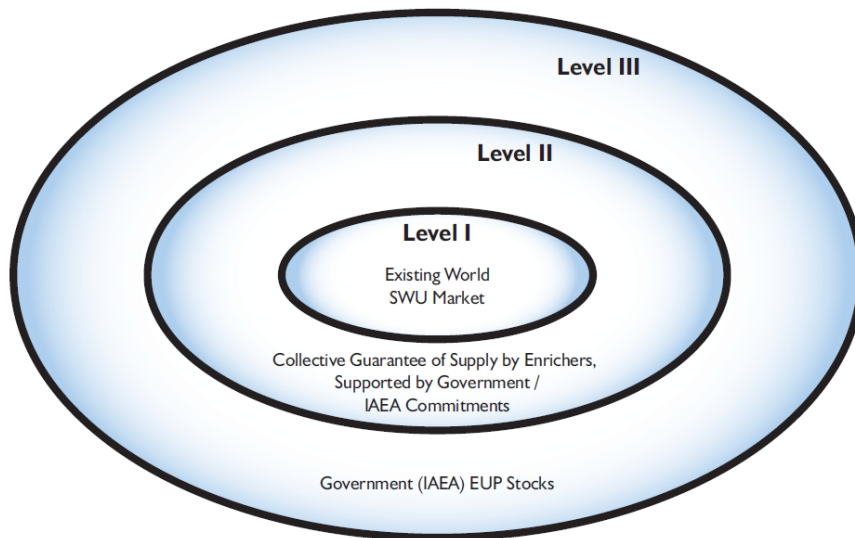


Figure 3-46: Multi-Layered and Multi-Lateral Guarantee of Supply
 Source: WNA (n.d.)

3.3.6.1.1 Enrichment R&D Political Considerations

In 1961, SA's Atomic Energy Board (AEB), established by Parliament in 1948, began general nuclear research and development work at Pelindaba Nuclear Research Centre near Pretoria (Stumpf, 1995). Cassuto (1970) stated that in a statement to the Cape Town Parliament on the 20 July, the South African Prime Minister announced that the Atomic Energy Board had succeeded in developing a new process for uranium enrichment as well as the extensive associated technology, and described this achievement as “unequalled in the history of our country”. On uranium enrichment challenges, Pavlov (2017) contended that self-development of enrichment technology is obviously not realistic:

- firstly, from an economic point of view, as a very complex and expensive technological problem; and
- secondly, due to the fact that despite the absence of formal prohibitions the attempt to start this activity would inevitably cause stiff opposition from the international community as being contrary to the objectives of non-proliferation of sensitive nuclear technologies.

Table 3-40 below lists examples of various governments' research and development initiatives meant to find uses for depleted uranium that is a by-product of the enrichment operations (OECD-NEA and IAEA, 2001)

Table 3-40: Government Sponsored Enrichment Tailings (Depleted Uranium) R&D focus areas per country

Country	Research & Development Programme
US Department of Energy	Areas of interest to the United States that are being considered for research and development are potential uses of depleted uranium as a shielding material, a component of a high-level waste repository, catalyst, semiconductor material, and as a phosphor
Japan Nuclear Cycle Development Institute	In addition to evaluating depleted uranium's use as fuel for the fast breeder reactor, the Institute is actively investigating uses for depleted uranium as a: • Shielding material for spent nuclear fuels storage and shipping casks; • Hydrogen storage alloy that could be used for energy storage when used in conjunction with a fuel cell; • Magnetic material as a substitute for rare-earth magnetic materials; and • Reduction-oxidation flow cell material that would store electrical energy.
Russian Federation	• Conduct scientific research and development related to the continued long-term storage of DUF_6 and is investigating the conversion of the UF_6 to other forms using a plasma process; and • Research is to create a fluorine cycle within the nuclear industry so as to eliminate the need to introduce virgin fluorine, as well as producing a variety of fluorine compounds for a variety of industrial uses, e.g. freon substitutes (khladone) or hydrogen fluoride.
Republic of Korea	• Research objectives include the development of radiation shielding containers (for a variety of specialised uses e.g. transportation containers for medical isotopes), development of nuclear fuel fabrication technology using DU and fundamental research of liquid metal cooled nuclear reactor fuel; • Investigating the optimal storage form and configuration for its depleted uranium stocks; and • The Korea Atomic Energy Research Institute (KAERI) is interested in alternative uses of depleted uranium and is seeking an adequate long-term storage technology.

3.3.6.1.2 Enrichment Design and Engineering Political Considerations

After achieving encouraging laboratory results with an indigenous uranium enrichment process, in 1969 the government approved the construction of a pilot plant to prove the validity of the design in an industrial scale (Stumpf, 1995).

3.3.6.1.3 Enrichment Manufacturing Political Considerations

In 1970, the SA government created a separate state corporation, the Uranium Enrichment Corporation (UCOR) to build the enrichment programme (Albright, 1994).

3.3.6.1.4 Enrichment Construction Political Considerations

On July 20, 1970, Prime Minister John Vorster informed Parliament of the government's intention to build the pilot enrichment plant (the Y-Plant) and stressed that the technology would be for peaceful applications (Stumpf, 1996).

3.3.6.1.5 Enrichment Operation and Maintenance Political Considerations

The South African Y plant at the Pelindaba nuclear centre located near Pretoria that produced highly enriched uranium (HEU) for nuclear weapons experienced operational problems that led to the production of less than expected amounts of weapon-grade uranium and a considerable amount of HEU enriched less than 90 percent (Albright, 2015).

3.3.6.1.6 Enrichment Waste Management and Disposal Political Considerations

Worldwide various governments and entities have different approaches of managing their depleted uranium (DU) which results from enrichment. Table 3-41 below presents various DU management plans.

Table 3-41: Current Stocks of depleted uranium and future plans (as of end of 1999)

Holder	Current storage	Stocks in tU	Management Plans
USA			
USDOE and USEC	UF ₆ in 48-inch containers on rafts at 3 sites in open air. Containers being repainted and rerafted.	~480 000 ^a	Construct 2 deconversion plants to operate by 2005, (technology selection by 2000). Identify uses by 2009.
Russian Federation	UF ₆ in 2.5 m ³ steel vertical containers, some 48-inch containers in open air yards.	~450 000 ^b	Continue storage as UF ₆ as future resource. Investigating deconversion technologies.
	Metal and oxides.	~10 000 ^b	
France			
COGEMA and Eurodif	U ₃ O ₈ in painted steel 3 m ³ containers, 3 high in warehouses on 2 sites.	~140 000	Continue deconversion and storage as U ₃ O ₈ as future resource. Some quantities recycled as MOX fuel.
	UF ₆ in 48-inch containers on rafts in open air.	~50 000	Continue deconversion and storage as U ₃ O ₈ as future resource.

Holder	Current storage	Stocks in tU	Management Plans
UK			
BNFL	UF ₆ in 48-inch and 0236 containers on rafts in open air at 2 sites. 0236 containers being cleaned, recoated and are being moved indoors.	~30 000	Continue storage as future resource. Investigating deconversion technology to produce metal.
Urenco			
Germany, Netherlands, and UK	UF ₆ in 48-inch containers on rafts at 3 sites in open air.	~16 000	Continue storage as UF ₆ as future resource. Re-enrich if economic. Storage as U ₃ O ₈ planned in indefinite future.
Japan			
	UF ₆ in 30-inch and 48-inch containers, in buildings.	~10 000 ^c	Construct deconversion plant to produce uranium oxides to operate in near future (technology selection by 2001). Identify uses and store as future resource.
China			
	UF ₆ in 48-inch and 1m ³ steel vertical containers in controlled condition building.	~2 000 ^d	Continue storage as UF ₆ as future resource.
Republic of Korea			
	UF ₆ in 48-inch containers in open air yard.	~200	Continue storage as UF ₆ as future resource. Investigate uses.
Estimated Total 1 188 200			

Notes:

a) As of mid-2000.

b) Estimate based on the 1996 Uranium Institute Report.

Source: OECD: NEA and IAEA (2001)

c) As of February 2001.

d) As of end of 2000.

In SA, decommissioning and associated waste management of NECSA's two former enrichment plants (the Y and Z plants), as well as the former conversion plant (U plant) and associated facilities, are undertaken by NECSA itself and the financing is carried by the state through the annual state allocation of operational funds (NNR, 2017b).

3.3.6.2 Enrichment Economic Factors

The main purpose of an enrichment facility is to increase the ²³⁵U in comparison to ²³⁸U content (IAEA, 2009e). Figure 3-47 below shows that major entities in the uranium enrichment market with the front-end and enrichment industries 2010 cost worth being respectively \$22 billion and \$8 billion.

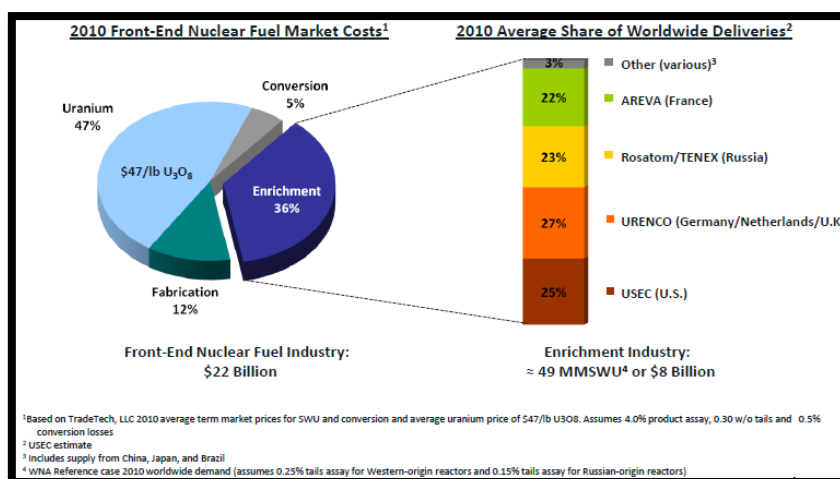


Figure 3-47: 2010 Front-End Nuclear Fuel Market Costs¹ and 2010 Average Share of Worldwide Deliveries²

Source: World Nuclear University (2012)

There are two methods of enriching uranium, gaseous diffusion and gas centrifuge with the former being 40 times more energy intensive than the latter (Carless, Griffin & Fischbeck, 2016). Gaseous diffusion plants (GDPs) provide about 40% of current world enrichment capacity, but are being phased out as newer gas centrifuge enrichment plants (GCEPs) are constructed (Laughter, 2007). Groult et al. (2007) state that in the near future, this technology will be used instead of gaseous diffusion since the latter consumes too much energy (required power of 2500 MW_e). Such a facility is very expensive, of the order of a billion dollars, because of the size and number of components such as separators, pumps, valves, and controls, but the process is basically simple. It might be that the R&D costs for developing of an individual country's uranium enrichment capabilities are usually sponsored by the government thereby not necessitating amortisation. Nevertheless, the economics of enrichment and ultimately that of the nuclear fuel will be influenced by the design engineering, manufacturing, construction, operation and maintenance and waste management and disposal expenses. Consequently, this applies to the enrichment facilities procured electrical, mechanical, C&I and civil SSCs. Table 3-42 below indicates the status of gaseous diffusion plants located in Argentina, China, France and the USA. Similarly, Table 3-43 lists centrifuge plants in countries such as Brazil, France, China and others.

Table 3-42: Gaseous Diffusion Plants

Country	Owner/Controller	Plant Name/Location	Nominal Capacity [1000 SWU/year]
Argentina	CNEA	Pilcaniyeu	20
China	CNNC	Lanzhou (closed?)	(900)
France	EURODIF	Tricastin (closed since June 7, 2012)	(10,800)
United States	Centrus Energy Corp.	Paducah, Kentucky (closed since May 31, 2013)	(11,300)
		Portsmouth, Ohio (closed since May 11, 2001)	(7,400)
Total			20

Source: <http://wise-uranium.org/efac.html#WASTETREAT>

Table 3-43: Centrifuge Plants

Country	Owner/Controller	Plant Name/Location	Nominal Capacity [1000 SWU/year]
Brazil	INB	Resende	?
China	CNNC		1,000
France	EURODIF	Lanzhou	500
France	Société d'Enrichissement du Tricastin (SET)	Georges Besse II, Tricastin	7,500
Germany	Urenco Deutschland GmbH	Gronau	4,100
Korea, DPR		Yongbyon	8
		Tongchang	?
Netherlands	Urenco Nederland BV	Almelo	5,400
Pakistan	Pakistan Atomic Energy Commission (PAEC)	Kahuta	5
Russia	Rosatom	Urals Electrochemical Integrated Enterprise (UEIE), Novouralsk (formerly Sverdlovsk-44, near Ekaterinburg)	10,000
		Siberian Chemical Combine (SKhK) Seversk (formerly Tomsk-7)	3,000
		Electrochemical Plant (ECP), Zelenogorsk (formerly Krasnoyarsk-45)	8,700
		Angarsk Electrolytic Chemical Combine (AEKhK), Angarsk	2,600
United Kingdom	Urenco UK Ltd.	Capenhurst	4,900
USA	Urenco USA	Lea County, NM	4,600
Total			53,567.5

Source: <http://wise-uranium.org/efac.html#WASTETREAT>

3.3.6.2.1 Enrichment R&D Economic Considerations

The further development of the gaseous centrifuge and laser enrichment technologies was to a certain extent driven by having cost competitive separation technologies considering high capital and energy costs associated with the gaseous diffusion method. According to Hore-Lacy (2012), two kinds of laser enrichment processes have been the focus of interest for some time; the first, which involves atoms of uranium, has absorbed billions of research dollars without commercial prospect and the second, using molecules of UF_6 , promises significant economic advantages, including lower energy inputs, lower capital costs and lower tails assays. Improving the cost competitiveness can also entail embarking on some optimization developments within the given gaseous centrifuge plant. Hence, Upson and Baker (1996) contended that the future challenge for R&D will almost certainly be to concentrate on manufacturing and plant performance improvements based on the sixth-generation centrifuge and thus further reduce capital and operating costs.

3.3.6.2.2 Enrichment Design and Engineering Economic Considerations

The most important parameters in centrifuge technology are peripheral rotor speed and rotor length whereby the peripheral speed is limited by the strength of the rotor material (Borisevich & Wood, 2002).

3.3.6.2.3 Enrichment Manufacturing Economic Considerations

Among the NECSA NFC processes, the most inefficient and expensive of these processes was the enrichment plant, which required operating expenditure in the order of R343m/year with an income of only R67 million (Auf der Heyde, 1993). Subsequently, the following factors led to the closure of the entire South African nuclear fuel programme including uranium enrichment:

- Unfavourable economies of scale resulting from the underutilization of the nuclear fuel production capacity; secondly;
- ESKOM's nuclear fuel procurement diversification programme led to increased overseas nuclear fuel supplies and thirdly; and
- The energy inefficiency of the Z plant rendering it internationally uncompetitive.

As is known, uranium enrichment is carried out on industrial scale by means of multistage separation facilities, i.e., separation cascades in which gas centrifuges (GCs) are connected in series and parallel (Sulaberidze et al., 2018). In addition, gas centrifuges require materials which have a high strength to density ratio and such materials are aluminium alloys, titanium alloys, alloy steels or fibre composites (Borisevich & Wood, 2002). Figure 3-48 below shows different components that make up a gas centrifuge. In addition, the illustration shows the feed inlet and product outlet. Simnad (2003) states that the separative work costs are made up of power cost (49%), capital cost (35%), and operating, research, and development cost (16%).

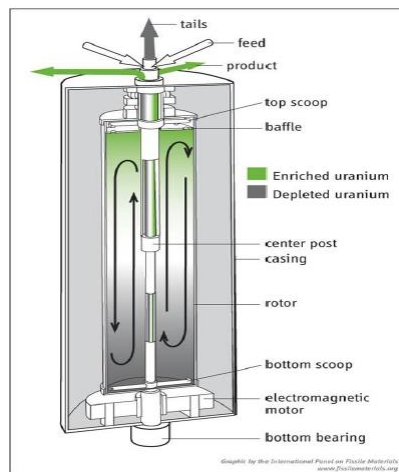


Figure 3-48: Gas Centrifuge
World Nuclear University (2010)

3.3.6.2.4 Enrichment Construction Economic Considerations

Over the years the enriching countries have been moving away from constructing gaseous diffusion plants e.g. because of high capital costs. Such a facility is very expensive, of the order of a billion dollars, because of the size and number of components such as separators, pumps, valves, and controls, but the process is basically simple (Murray & Holbert, 2015). Table 3-44 shows the worldwide enrichment trends whereby in 2017 centrifuge was the dominant method of enrichment. Whereas, Table 3-45 shows the SA NFC capital expenditure.

Table 3-44: Enrichment trend

Supply source:	2007	2017
Diffusion	25%	0
Centrifuge	65%	93%
Laser	0	3%
HEU ex weapons	10%	4%

Source: Manojlović and Trkov (2010)

Table 3-45: Capital expenditure on South African Nuclear Fuel Plants in Rm

Plant	CAPEX	Year ^a	1992 Rand ^b
Conversion	55.200	1985	122.030
Z-Plant	785.000	1987	1383.438
BEVA	267.500	1985	591.357
Y-Plant	210.000	1977	877.222

Source: Auf der Heyde (1993)

^aYear refers to the last year of construction, and is assumed to be the year in which the indicated CAPEX figures appeared on the books of the AEC.

^bInflation rate assumed to be 10% for 1977-92, and 12% for the 1985-92 period.

3.3.6.2.5 Enrichment Operation and Maintenance Economic Considerations

At present, gas centrifugation is the most efficient, economic and reliable technology for production of enriched uranium (Borisevich & Wood, 2002). The reliability of modern centrifuges allows them to operate nonstop for more than 30 years with a failure rate of only a few tenths of 1% per year (Borisevich & Wood, 2013). As shown below in Table 3-46 energy requirements for operating diffusion plants are significantly high as compared to other enrichment methods.

Table 3-46: Energy cost comparison

Method	kWh/SWU
Diffusion	2000-3000
Centrifuge	100-300
Laser	100

Source: Manojlović and Trkov (2010)

3.3.6.2.6 Enrichment Waste Management and Disposal Economic Considerations

South Africa operated two enrichment plants, closed by March 1995, based on the jet nozzle and helicon processes respectively which resulted in 2200t of depleted uranium most of which was sold on the international market (NEA, 2001).

3.3.6.3 Enrichment Social Factors

Kessides (2010) stated that a comprehensive analysis of the life-cycle costs and benefits of nuclear power must address a variety of complex issues related to the following:

- components of nuclear power costs;
- assessment of important negative and positive externalities associated with the nuclear fuel cycle;
- large uncertainties characterizing construction costs and most of the key system parameters; and
- lack of actual construction cost and operating data.

3.3.6.3.1 Enrichment R&D Social Considerations

In the 1950s and 1960s, South Africa's civilian nuclear programme received extensive assistance from abroad, which enabled the sending of staff members to Europe and the United States for training in various nuclear fields (Albright, 1994).

3.3.6.3.2 Enrichment Design and Engineering Social Considerations

For the possibility of building a plutonium production reactor and. associated reprocessing facility the estimated requirements were facilities investment costs ranging from \$250 to \$500 million, 5 to 75 engineers and 50 to 200 skilled technicians over 5 to 7 years (United Nations, 1980). According to

participants and Western government experts, the Y-Plant's success depended principally on the skill and initiative of its scientists and technicians (Albright, 1994).

3.3.6.3.3 Enrichment Manufacturing Social Considerations

The South African aerodynamic enrichment process separated uranium isotopes through centrifugal effects created by the rapid spinning motion of a mixture of uranium hexafluoride gas and hydrogen carrier gas in a small stationary tube (Albright & Stricker, 2016). Accordingly, the creation of competences for the production of hydrogen fluoride (HF) was crucial for SA to be involved in uranium enrichment. Nuclear conversion started at the Atomic Energy Corporation (AEC) (now NECSA) in the 1960s. Yellowcake is first converted to uranium tetrafluoride (UF_4), using HF, after which the compound is treated with fluorine to yield UF_6 which is then reduced to UO_2 for use in fuel elements in pellet form (Crouse, 2015).

3.3.6.3.4 Enrichment Construction Social Considerations

The SA apartheid government was determined to construct enrichment facilities for its weapons programme and for civilian purposes. By the end of 1967, the SA enrichment programme had succeeded in enriching uranium on a laboratory scale and after an external review of the process, the government decided in early 1969 to build a pilot plant (Albright, 1994).

3.3.6.3.5 Enrichment Operation & Maintenance Social Considerations

The operation of the enrichment plant at NECSA then AEB enabled the operation and maintenance of Safari-1 and Koeberg Nuclear Power Plant. The Nuclear Fuel Production (NFP) division of the AEC was responsible for operating and maintaining the conversion, enrichment (Z-) and fuel fabrication (BEVA) plants, as well as the Vaalputs installation, and earth and environmental technologies (Auf der Heyde, 1993). According to Cochran (1994) approximately some 6,100 SWUs were used to produce HEU fuel for the Safari-I reactor-about 80 kilograms of 45 percent-enriched fuel; another 7,400 SWUs were used to produce 2.5 tonnes of 3.25 percent-enriched fuel for the Koeberg reactors.

3.3.6.3.6 Enrichment Waste Management and Disposal Social Considerations

The basis of centrifugation or diffusion processes is mass differentiation between ^{235}U and ^{238}U whereby during the centrifugation, UF_6 molecules go into very high-speed rotating cylinders operating at low pressure and enabling the recovery of depleted $^{235}\text{UF}_6$ at the bottom of the cylinder and enriched UF_6 at the top (Morel & Duperret, 2009). The Washington Post (2015) reported that South Africa handled its uranium enrichment programme liabilities as follows:

- Technicians extracted the highly enriched uranium from the apartheid regime's nuclear weapons in 1990, then melted the fuel down and cast it into ingots; and
- Over the years, some of the cache has been used to make medical isotopes, but roughly 485 pounds remains, and South Africa is keeping a tight grip on it.

3.3.6.4 Enrichment Technological Factors

The South African or UCOR process was of an aerodynamic type and by virtue of careful experimental and advanced theoretical work was possible to develop a separating element, which in effect was a high performance stationary walled centrifuge that used UF_6 in hydrogen as a process fluid (Roüx & Grant, 1975). The brute fact remains that the same fuel-cycle technologies, uranium enrichment and reprocessing that are essential to power a nuclear reactor can, with adjustments, produce material to fuel the core of a nuclear explosive (Heinonen, 2011a). As articulated and shown in Figure 3-49 below by Ault, Krahn and Croff (2017), the consequences of relying on enriched uranium are as follows:

- the front-end facilities associated with enriched uranium (U mining, conversion, enrichment, and de-conversion) will also be required for this thorium-based fuel cycle (albeit to a lesser extent than for the MUPu fuel cycle); and
- the used uranium fuel from Stage 1 is not used in Stage 2, meaning that the MThU fuel cycle will produce two separate streams of used fuel as opposed to MUPu fuel cycle's single spent nuclear fuel (SNF) stream.

Table 3-47: Enrichment Technologies

Based upon the small differences in weight between U^{235} and U^{238}	Based upon differences in atomic or molecular properties
Gaseous Diffusion	Atomic Vapour Laser Isotope Separation (AVLIS)
Gas Centrifuge	Molecular Laser Isotope Separation (MLIS)
	Molecular Laser Isotope Separation (MLIS)
	Aerodynamic Separation Process

Source: World Nuclear University Summer Institute (2012)

3.3.6.4.2 Enrichment Design and Engineering Technological Considerations

Stumpf (1995) contended that the enrichment pilot plant design, only superficially similar to the so-called German Berker process, was much closer to the ordinary centrifuge process except that the centrifuge wall was stationary and a vortex mechanism rapidly spun the uranium hexafluoride (UF_6) and hydrogen gas inside a stationary tube.

3.3.6.4.3 Enrichment Manufacturing Technological Considerations

Centrifuge enrichment technology is far less energy-intensive than diffusion, and the principal reason for this is the far larger per-unit separation efficiency: a ^{235}U atom might pass through as few as ca. 20 units in a centrifuge cascade before emerging as product, as opposed to 1000 diffusion units (Schneider et al., 2014).

3.3.6.4.4 Enrichment Construction Technological Considerations

The size of the plant to be constructed is a strategic decision, which is informed by the market demands for enriched uranium. The owner of the plant has to have knowledge of the enrichment capacity of the plant to be constructed.

3.3.6.4.5 Enrichment Operation and Maintenance Technological Considerations

Bredel (1990) stated that the SA AEC semi-commercial uranium enrichment plant, with a nominal capacity of 300 tons separative work per annum (t SW/a) was in operation at Valindaba near Pretoria. Otherwise, the two most prevalent enrichment techniques are gaseous diffusion, which uses older

technology and requires a lot of energy, and gas centrifuge separation, which uses more advanced technology and is more energy efficient (Laughter, 2007).

3.3.6.4.6 Enrichment Waste Management and Disposal Technological Considerations

The main by-product of enrichment is depleted uranium (DU), principally the ^{238}U isotope, which is stored as UF_6 or ^{308}U (WNA, 2017).

3.3.6.5 Enrichment Environmental Factors

CO_2 emissions from uranium enrichment vary by more than two orders of magnitude because centrifuge technology consumes much less energy than gaseous diffusion technology (Choi, Hyo & Ko, 2016).

3.3.6.5.1 Enrichment R&D Environmental Considerations

Research and development initiatives within the enrichment phase are for enhancing non-proliferation by improving safeguards. The safeguard improvements are ideally incorporated during the design, manufacturing, installation, operation and maintenance and decommissioning of enrichment plant SSCs.

3.3.6.5.2 Enrichment Design and Engineering Environmental Considerations

According to IAEA (2010a), the following particular consideration should be given to the following hazards in the specification of design basis accidents for enrichment facilities:

- (a) The rupture of an overfilled cylinder during heating (input area);
- (b) The rupture of a cylinder containing liquid UF_6 or the rupture of piping containing liquid UF_6 (depending on the facility design for product take-off);
- (c) A large fire, especially for diffusion facilities;
- (d) Natural phenomena such as earthquakes, flooding or tornadoes (see footnote 1);
- (e) An aircraft crash; and
- (f) A nuclear criticality accident.

3.3.6.5.3 Enrichment Manufacturing Environmental Considerations

Assuming that coal-fired power stations provide two-thirds of the electricity, then electricity use in the gaseous diffusion enrichment process will result in another 0.01 to 0.1 deaths per GWy since the hazard from coal-fired plants is much higher than for nuclear (UNEP, 1976). The South African helicon aerodynamic 300 000 SWU/annum enrichment facility known as the Z-plant that was constructed in the later 1970s and early 1980s, and commissioned in 1984 for its 1988 full production was doomed since it was too energy intensive to be viable under any circumstances (Jackson, 1993; Global Security, 2011).

3.3.6.5.4 Enrichment Construction Environmental Considerations

The construction material used in the South African Pilot highly enriched uranium (HEU) enrichment Y-plant was mostly aluminium, selected to combat corrosion, UF₆ degradation and hydrogen ignition (Bredell, 2004).

3.3.6.5.5 Enrichment Operation and Maintenance Environmental Considerations

The IAEA (2010a) states that the following issues must be important for consideration when operating an enrichment plant:

- The main hazard is a potential release of UF₆;
- A criticality hazard exists since the concentration of ²³⁵U present in enrichment facilities is greater than 1%;
- External exposure is a concern in the handling of recently emptied cylinders, especially those used as containers for reprocessed uranium, with build-up of ²³²U.

3.3.6.5.6 Enrichment Waste Management and Disposal Environmental Considerations

Depleted uranium can be safely stored as UF₆ in coated steel containers in outdoor yards i.e. if there is a container management programme to ensure that there is no degradation of the integrity of the containers (OECD-NEA and IAEA, 2001). In addition, stockpiling of depleted uranium residue from enrichment plants makes it possible to consider future recovery of remaining fissile material (IAEA, 1996). The IAEA safeguards inspection at Pelindaba found that the nuclear waste storage facility held tens of thousands of drums containing substantial amounts of high and low enriched uranium waste from the former enrichment plants and other decommissioned facilities (Heinonen, 2011b).

3.3.6.6 Enrichment Legal Factors

According to Smith (2015), because stakeholders differ in their agendas, information needs, access to information, and technological skills, the NRC facilitates public participation in a number of different ways namely:

- by giving the public access to its documents and bases for decision-making;
- by fostering public participation in public meetings; and by providing ways for stakeholders;
- and other members of the public to directly participate in agency decision-making.

3.3.6.6.1 Enrichment R&D Legal Considerations

In order to rationalize the nuclear power programme in South Africa and to render the pertinent activities more efficient and effective, in June 1982 the Nuclear Energy Act, 1982, was passed, through which the public corporation "Atomic Energy Corporation of South Africa Ltd." (AEC) was created, with the statutory research organization "Atomic Energy Board" becoming the "Nuclear Development Corporation of South Africa (Pty) Ltd.", a subsidiary company of the AEC (Jesus, 1983). In recent years, efforts have again intensified to limit the spread of nuclear enrichment by proposing various multinational approaches to reduce proliferation concerns (Heinonen, 2011a).

3.3.6.6.2 Enrichment Design and Engineering Legal Considerations

Regulatory and legislative enforcement is important in assuring that the design engineering of enrichment facilities' SSCs occurs within necessary safeguards and safety requirements.

3.3.6.6.3 Enrichment Manufacturing Legal Considerations

The manufacturing or assembling of enrichment facilities' SSCs that are important to safety will require monitoring by the relevant nuclear regulators. Table 3-48 below shows examples of enrichment facilities SSCs that are important to safety as stipulated by the IAEA (2010a).

Table 3-48: SSCs important to safety, events & operational limits and conditions for enrichment facilities

Process area	Structures, systems and components important to safety
Receipt and storage of feed cylinders	Weighing scales; Cylinder and valve; Isotope measuring device
Feed purification	Pressure measuring device for cold cylinders; Temperature measuring device of UF ₆ ; Pressure measuring device of UF ₆ ; UF ₆ leak detectors; Shielding (if reprocessed uranium); Feed connector and piping; UF ₆ cylinder; Autoclave isolation valve system
Cascade	Vessels, valves and pipes when UF ₆ pressure is above atmospheric pressure; — Leak detectors when UF ₆ pressure in the facility is above atmospheric pressure; — Pressure and temperature measuring devices to control mass flows and to detect leakages or generation of reaction products; — Enrichment measuring device; — Pressure measuring device for product flow; — Isolation; — Process motor trip device; — Neutron poison concentrations in cooler water; — Compressor Heat exchanger tubes in contact with UF ₆ ; — Temperature and pressure measuring devices In-line analysers to monitor for hydrocarbons or Freon® and for detecting ingress of oil or Freon®
Product take-off	Low pressure and temperature measuring devices; High pressure measuring device; Cylinder and valve; Weighing scales; UF ₆ level detector in intermediate product take off tank to confirm correct transfer into cylinders; Pipes, vessels and valve containing UF ₆ ; UF ₆ release detection system;
Off-gas treatment	Cold traps and/or chemical traps; Temperature measuring device for cold traps; Measuring device for effluents discharged into atmosphere.
Tailings take-off	High pressure measuring device; Cylinder and valve; Weighing scales;

Process area	Structures, systems and components important to safety
	UF ₆ level detector in intermediate product take off tank to confirm adequate transfer into cylinders; Pipes, vessels and valve containing UF ₆ ; UF ₆ release detection system.

Source: IAEA (2010a)

3.3.6.6.4 Enrichment Construction Legal Considerations

As construction winds down, the NRC reviews the most safety-significant features and these include chemical safety, fire protection, radiation control, emergency preparedness, training and criticality safety (USANRC, n.d.).

3.3.6.6.5 Enrichment Operation and Maintenance Legal Considerations

The USANRC (n.d.) states that under the Atomic Energy Act in the USA, the NRC licenses and inspects uranium enrichment plants and before issuing a license to construct and operate a plant, the NRC prepares an Environmental Impact Statement (EIS) and a Safety Evaluation Report (SER).

3.3.6.6.6 Enrichment Waste Management and Disposal Legal Considerations

In November 1991, a team of senior IAEA safeguards officials specially appointed by the Agency's Director General carried out the first inspections under the comprehensive safeguards agreement stated that it was reasonable to conclude that the uranium-235 balance of the HEU, LEU, and depleted uranium produced by the pilot enrichment plant was consistent with the uranium feed (IAEA, 1995).

3.3.7 (Fresh) Uranium Fuel Fabrication

The final stage in the nuclear fuel cycle is fuel fabrication where the enriched UF₆ is converted to uranium dioxide (UO₂) in a powder form (Carless, Griffin & Fischbeck, 2016).

3.3.7.1 (Fresh) Uranium Fuel Fabrication Political Factors

The SA Nuclear Energy Policy (2008) states that the Government, through NECSA shall design a strategy to develop nuclear fuel fabrication capabilities and the Government will in the intervening period actively seek to obtain access to established fuel fabrication programmes to ensure security of supply. This being the case, it is important for the SA government to be aware of not only the PWR

NPP plant latest developments but also those pertaining to the NFC. Such information can be used to make strategic decisions specially to do with collaborations meant to drive localization or industrialization. In Korea, the nuclear fuel technologies have been developed by the stepwise strategic approach; whereby Korea Nuclear Fuel (KNF) was established in 1982 to localize nuclear fuel technology, based on various technologies transferred from the former Siemens/KWU, the former Combustion Engineering, and Westinghouse Electric Company (Kim & Suh, 2008).

3.3.7.1.1 (Fresh) Uranium Fuel Fabrication R&D Political Considerations

Over the years, the AEC and its predecessors the Atomic Energy Board and NUCOR were to a greater or lesser extent involved in research and development of fuel fabrication (Venter & Aspeling, 1990). In 1978, the USA Carter Administration utilised the Nuclear Non-Proliferation Act to restrict the export of enriched uranium for SA's Koeberg as well as Safari-1 (van Wyk, 2010). This being the case, the SA government started looking at how it could develop or acquire reactor fuel manufacturing capabilities. During October 1977, the Government of the Republic of South Africa gave instructions for the AEC to prepare for a possible initiative encompassing the erection of a fuel fabrication plant to satisfy ESKOM's requirements for pressurised water re actor (PWR) fuel for the two KOEBERG units near Cape Town.

3.3.7.1.2 (Fresh) Uranium Fuel Fabrication Design and Engineering Political Considerations

The normal practice is that the nuclear vendor interested in transferring nuclear designs to another country always consults its government to seek permission to transfer nuclear designs to another country. Consequently, the French government facilitated the transfer of Koeberg nuclear fuel designs to SA's Atomic Energy Board.

3.3.7.1.3 (Fresh) Uranium Fuel Fabrication Manufacturing Political Considerations

The SA government and the French government facilitated the transfer of some fuel fabrication manufacturing technologies. There is a need to take note of lessons from the past, such as the transfer

in the 1980s of Koeberg fuel manufacturing technology from France to NECSA's former BEVA programme (Stumpf, 2015).

3.3.7.1.4 (Fresh) Uranium Fuel Fabrication Construction Political Considerations

Owing to the difficulties experienced by ESKOM in obtaining nuclear fuel services from abroad, the emphasis within the South African nuclear power industry shifted toward self-sufficiency (Bredell, 2004). During October 1977, the Government of the Republic of South Africa gave instructions for the AEC to prepare for a possible programme encompassing the erection of a fuel fabrication plant to satisfy ESKOM's requirements for pressurised water reactor (PWR) fuel for the two Koeberg units near Cape Town (Venter & Aspeling, 1990). Likewise, because of the threat of sanctions it was decided to erect a fuel fabrication plant for the manufacture of Materials Testing Reactor (MTR) fuel exclusively for use in the AEC's research reactor, SAFARI, as a means to ensure that SAFARI could be kept operational (Venter & Aspeling, 1990). The construction of the nuclear fuel manufacturing plant (code-named BEVA), the installation of a zirconium tubing workshop and high temperature and pressure fuel test facilities, among others, were part of the French nuclear energy technology transfer package (Murphy, 2011). According to the Global Security (2011) the zirconium tubing plant that produced cladding for fuel assemblies used at Koeberg reactors was closed in 1993 and the equipment was sold to the People's Republic of China for R20 million despite having cost R200 million to construct.

3.3.7.1.5 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Political Considerations

The South African NEP (2008) states that the government, through NECSA shall design a strategy to develop nuclear fuel fabrication capabilities. Consequently, NECSA was in the past given the responsibility to operate and maintain of PWR, PBMR and SAFARI fuel fabrication facilities.

3.3.7.1.6 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Political Considerations

The cost of the locally produced fuel assemblies was higher than purchasing on global markets and this led AEC to close down the uneconomic Z-plant March 1995, followed by the closure of the BEVA-facility in 1997 (DBSA, 2006). Subsequently, AEC together with the SA government made the decision to dismantle and decommission the BEVA nuclear fuel fabrication infrastructure. The PBMR nuclear fuel development laboratories were later accommodated in the same BEVA facilities.

3.3.7.2 (Fresh) Uranium Fuel Fabrication Economic Factors

The South African AEC supply of nuclear fuel to Eskom was more expensive than sourcing from the overseas companies. This and the fact that after 1994 there were no economic sanctions against SA led to the closure of the PWR fuel facilities at AEC. The nuclear fuel cost consists of the following components: the cost of conversion (4%), fabrication (8%), waste fund (15%), enrichment (31%), and (42%) for uranium (Vuji, Anti & Vukmirovi, 2012).

3.3.7.3 (Fresh) Uranium Fuel Fabrication R&D Economic Considerations

Although the cost of nuclear fuel fabrication only amounts to around 10% of the fuel costs, the key to cost savings and efficiency enhancements in the entire nuclear fuel cycle lies in advancement of nuclear fuel technology (Kim & Suh, 2008). In order to improve the economic aspects of MOX pellet fabrication and to extend the fabrication process to MOX pellets containing MAs, various R&D programmes have been started especially in France, Germany, Japan, and Russia (Abe & Asakura, 2012).

As for fuel for RR and target plates for medical isotope production, there are security concerns especially when highly enriched uranium is used. Hence, some entities involved in medical isotope production have embarked on switching from HEU based fuels to LEU fuels. Figure 3-50 below shows

major USA suppliers of molybdenum 99's progress in converting from the utilisation of HEU to LEU fuels/target plates.

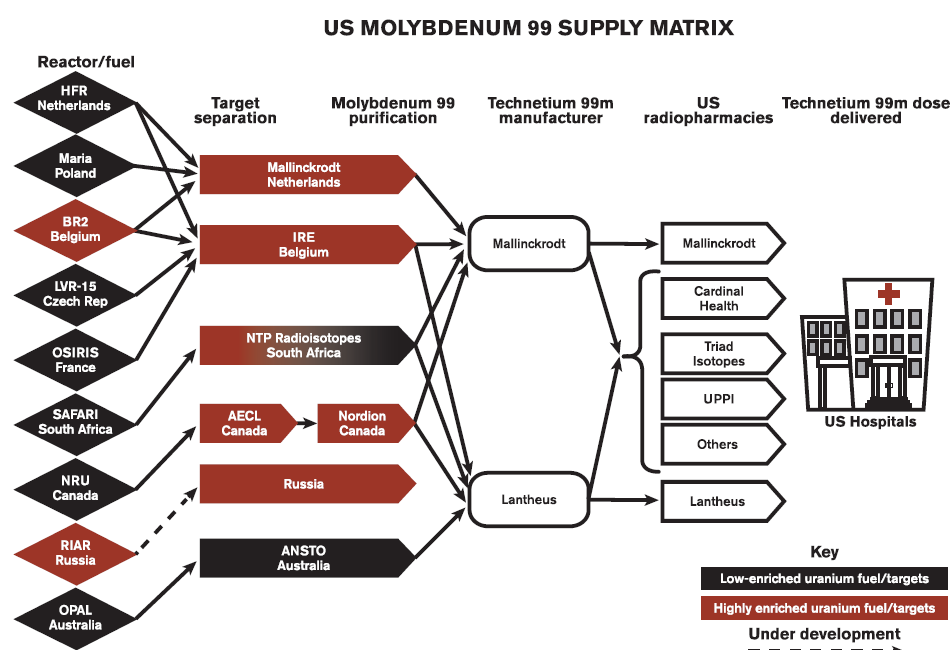


Figure 3-50: Status on converting from HEU fuel/targets to LEU fuel/targets

Source: Adapted from Sher (2014) Original source: US Department of Energy, National Nuclear Security Administration

3.3.7.3.1 (Fresh) Uranium Fuel Fabrication Design and Engineering Economic Considerations

The AEC of South Africa designed its BEVA infrastructure for PWR nuclear fuel manufacturing thereby making sure that processes shown in Table 3-49 were efficiently and effectively undertaken.

Table 3-49: (Fresh) Uranium Fuel Fabrication NFC Stage and Facilities

Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
(Fresh) Uranium Fuel Fabrication	Re-conversion to UO ₂ powder	Facilities, which convert enriched UF ₆ , enriched UF ₆ to UO ₂ powder.
	Fuel fabrication (U Pellet-Pin)	Facilities, which produce fuel pellets and/or pins using UO ₂ powder.
	Fuel Fabrication (U assembly)	Facilities, which produce fuel assemblies using pellets/pins (Sometimes fuel fabrication facilities include all three steps: powder pellet/pin and assembly in one integrated facility).
	Fuel Fabrication (Research Reactor)	Facilities in which to undertake research reactor fuel production.
	Fuel fabrication (Pebble)	Facilities in which to undertake fuel pebbles production for pebble bed reactors.

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

3.3.7.3.2 (Fresh) Uranium Fuel Fabrication Manufacturing Economic Considerations

Although the transfer was technically successful (the BEVA fuel elements in Koeberg performed on par with those in France,) the transfer of technology incurred high costs over a period of about four years (Stumpf, 2015). Nuclear fuel costs have many components—uranium mining and milling, conversion to UF₆, enrichment, reconversion, fuel fabrication, shipping costs, interest costs on fuel in inventory, and spent fuel management and disposition (Harding, 2007). Table 3-50 below shows various light water reactor fuel fabricators in different countries.

Table 3-50: Light Water Reactor Fuel Fabrication Facilities

Country	Owner/Controller	Plant Name/Location	Capacity ^{a)} [MTU/year]
Argentina	Dioxitek S.A	Córdoba ^b	
Belgium	FBFC (100% Areva)	Dessel (closed)	(750)
Brazil	FEC (INB)	Resende	100
China	CNNC	Yibin	400
France	FBFC (100% Areva)	Romans-sur-Isère	1,400
	SICN (100% Areva)	Veurey-Voroise (closed)	(150)
Germany	Advanced Nuclear Fuels (66% Areva, 34% Siemens)	Lingen	650
India		Hyderabad	25
Japan	Global Nuclear Fuel LLC. Ltd.	Kurihama, Yokosuka City	750
	Mitsubishi Nuclear Fuel Co. Ltd. (30% Areva - planned)	Tokai-Mura	440
	Nuclear Fuel Industries Ltd	Kumatori	284
		Tokai-Mura	200
Kazakhstan	Ulba Metallurgical Co. (90% Kazatomprom)	Ust-Kamenogorsk	2,800
South Korea	KEPCO Nuclear Fuel Co. Ltd. (KNFC)	Taejon	550
Pakistan	Pakistan Atomic Energy Commission (PAEC)	Kundian	20
Russia	JSC TVEL	ELEMASH, Elektrostal	1,020
		NCCP Novosibirsk	1,000
Spain	ENUSA	Juzbado	400
Sweden	Westinghouse	Västerås	600
United Kingdom	Springfields Fuels Ltd (Westinghouse)	Springfields, Lancashire	330
USA	Areva NP, Inc.	Richland, Washington	700
	Westinghouse	Hematite, Missouri (closed)	(450)
		Columbia, S. Carolina	1,150
	Global Nuclear Fuel-Americas, L.L.C.	Wilmington, N. Carolina	1,200
Total			14,019

Source: <http://wise-uranium.org/efac.html>

Zirconium is important as a cladding material for PWR nuclear fuel. South Africa supplies approximately 45 percent of all zircon sand globally and despite the large local zircon sand resources and established zircon sand mines, more than 95 percent of the beneficiation capacity for zircon sand is

situated in China (Lubbe, Munsami & Fourie, 2012). According to Stumpf (2015), the incremental improvement in the three somewhat similar production routes for nuclear-grade zirconium certainly falls within the capabilities of South African scientists and engineers, and can benefit both the country and the world's nuclear industry in the long-term.

3.3.7.3.3 (Fresh) Uranium Fuel Fabrication Construction Economic Considerations

SA realised the need to put in place PWR and research reactor fuel manufacturing infrastructure at its Pelindaba site. Venter and Aspeling (1990) indicated that for Koeberg fuel supply, the design capacity of the South African BEVA fuel fabrication plant was 100 tU/a, but it was possible to increase it to 200 tU/a by means of limited capital expenditure and the introduction of a three-shift system. For the research reactor, Jamie and Kocha (2010) stated that a mid-1970s decision to establish MTR uranium-aluminium alloy (UALx) HEU fuel elements and control rods manufacturing capabilities led to South African construction and commissioning of the Fuel Element Production Facility (Elprod). A list of Elprod SA regulator authorised capabilities is in section 3.3.7.7.3.

3.3.7.3.4 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Economic Considerations

The requirement in SA for a metallurgical Hot Cell Complex for the post irradiation examination (PIE) of structural reactor materials became apparent more so because of the importance of proving the PWR fuel performance of a very "new" local fuel design against that of the vendor.

3.3.7.3.5 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Economic Considerations

Avoidance of off specification products during the PWR fuel fabrication is the main method of waste minimization thereby avoiding recovering such products for recycling or reusing at earlier stages of the process (IAEA, 2000b). The IAEA (1976b) states that waste minimization interventions shown in Table

3-51 below are sometimes undertaken. Likewise, Figure 3-51 below illustrates that the kernel scrap listed on the top left corner recovered for the retrieving of U_3O_8 .

Table 3-51: Recovering of off-specification products at UO₂ granulation and pelletizing plants

UO ₂ Granulation and pelleting process	Deviation from specification and recovery action
After granule classification	Recoverable oversize returned to granule preparation or to powder plant
After sintering	Under density rejects taken back for sintering and over-density ones taken back to the powder plant
Screen inspection	Clean sintered scrap taken back to powder room
Final inspection of pellets	Rejects taken back to powder room

Source: IAEA (1976)

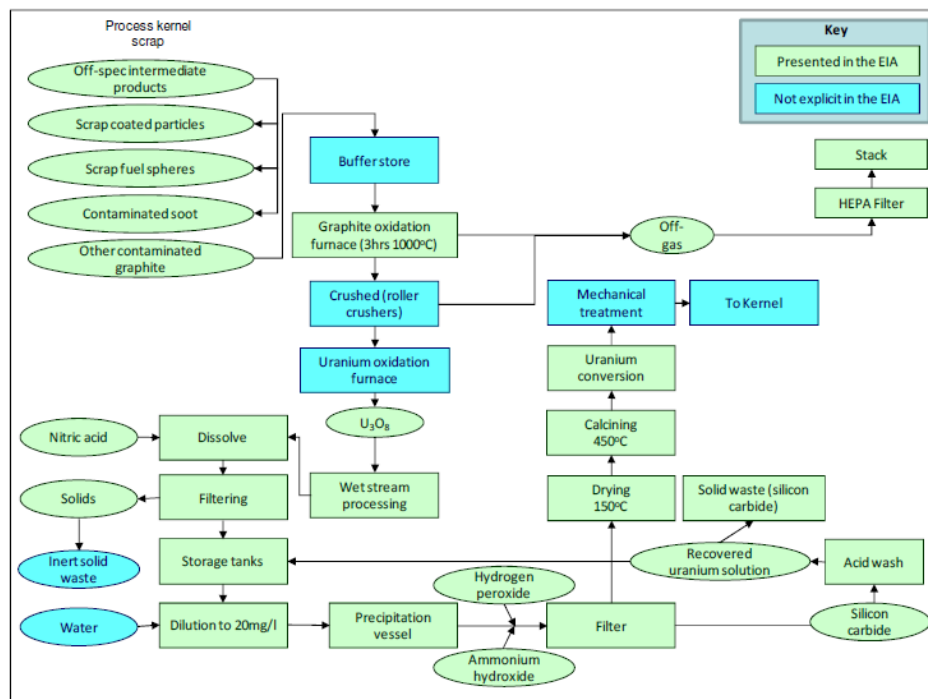


Figure 3-51: Management of PBMF kernel scrap

Source: O'Beirne (2009)

3.3.7.4 (Fresh) Uranium Fuel Fabrication Social Factors

Possible economic sanctions by Western countries were the main driver of SA's decision to develop self-sufficiency nuclear fuel capabilities for the SAFARI-1 research reactor and for its Koeberg PWR units. According to Bredell (2004), the impetus for self-sufficiency resulted largely from the US embargo on enrichment supplies to South Africa introduced in 1976.

3.3.7.4.1 (Fresh) Uranium Fuel Fabrication R&D Social Considerations

Several scientists were sent to receive highly specialized training at universities, research institutions and industrial organizations in the USA, Britain, France, West Germany and other countries and on their return, they initiated Pelindaba's programme (Jesus, 1983). The fuel development team, usually composed of materials scientists, is supported by experts in neutronics, thermal hydraulics, core design, cladding and duct development, nuclear safety, chemistry, remote examination technology, experiment vehicle design, analytical chemistry, microscopy, and more (Walters, 2004).

3.3.7.4.2 (Fresh) Uranium Fuel Fabrication Design and Engineering Social Considerations

To enable the localization of uranium fuel fabrication SA developed engineers that enabled local manufacturing of fuel elements. This was the case for transfer of Koeberg, RR, and PBMR fuel technologies, which SA obtained respectively from France, USA and Germany.

3.3.7.4.3 (Fresh) Uranium Fuel Fabrication Manufacturing Social Considerations

On the horizon in the 80s was a possible embargo on nuclear fuels shipments from the USA to South Africa. The manufacturing of nuclear fuel for Koeberg Nuclear Power Station was meant to enable SA to be able to be self-reliant in the fuelling of its only two electricity generating PWR units.

3.3.7.4.4 (Fresh) Uranium Fuel Fabrication Construction Social Considerations

Because of the threat of sanctions, AEC of South Africa erected a fuel fabrication plant for the manufacture of Materials Testing Reactor (MTR) fuel as a means to ensure the continuous operation of SAFARI-1 research reactor (Venter & Aspeling, 1990). Facilities which were constructed at Pelindaba were for PWR nuclear fuel components machining, assemble and testing. In addition, there was construction of facilities for fabricating target plates for the commercialization of the isotope production. Some of the personnel who were involved in the past nuclear fuel fabrication are still working for the present day NECSA.

3.3.7.4.5 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Social Considerations

The nuclear fuel production facilities required special manufacturing conditions such as clean areas and measuring capabilities to handle tight tolerances. Personnel were trained and skilled to maintain the requirements of e.g. zirconium tube manufacturing facilities.

3.3.7.4.6 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Social Considerations

The management of waste emanating from nuclear fuel fabrication at Pelindaba is an issue of concern not only to the employees who are responsible for the storage and disposal but also to the surrounding communities.

3.3.7.5 (Fresh) Uranium Fuel Fabrication Technological Factors

A Technology Readiness Assessment (TRA) is a formal, systematic, metrics-based process and accompanying report that assesses the maturity of technologies called Critical Technology Elements (CTEs) to be used in systems (DOE, Technology Readiness Guide, 2015). Progress in developing advanced fresh uranium fuel for PWR, SMR or HTR can be monitored using the technology readiness and criteria shown in Figure 3-52 below. A technology element is “critical” if the system being acquired depends on this technology element to meet operational requirements (within acceptable cost and schedule limits) and if the technology element or its application is either new or novel or in an area that poses major technological risk during detailed design or demonstration (DoD Technology Readiness Assessment Deskbook, 2009). The technology readiness levels (TRLs) for nuclear fuels and materials shown in Figure 3-52 below are divided into three major functional categories or phases; TRL 1–3: Proof-of-Concept, TRL 4–6: Proof-of-Principle, and TRL 7–9: Proof-of-Performance (Carmack et al., 2017)

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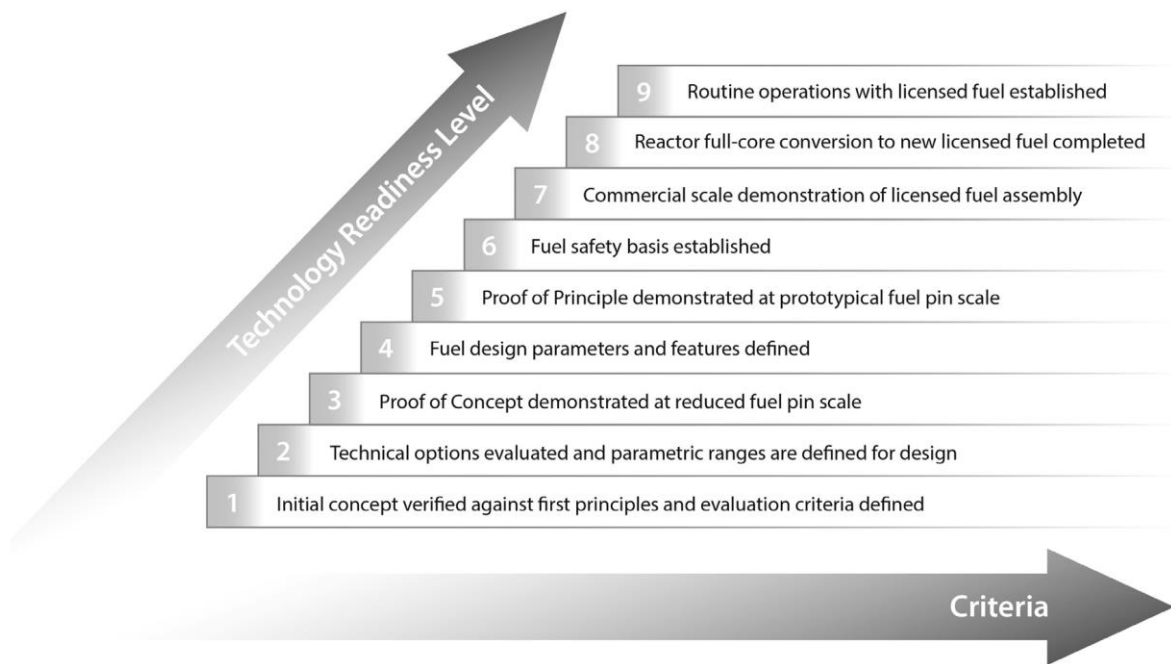


Figure 3-52: High-level TRL completion criteria for nuclear fuels and materials
Source: Carmack et al. (2017)

3.3.7.5.1 (Fresh) Uranium Fuel Fabrication R&D Technological Considerations

Because deployment of new nuclear fuel forms requires a lengthy and expensive research, development, and demonstration programme, applying the assessment process to advanced fuel development is useful as a management, communication, and tracking tool (Carmack et al., 2017). The process of moving from a nuclear fuel concept, dictated by a reactor design, to a fully qualified and licensed fuel system takes 10 years or more hence the schedule for conducting such a programme is controlled by the time it takes to complete the fabrication, irradiation, and examination of a novel fuel type. Over the years, SA has had an opportunity of undertaking development of PWR, RR and HTGR fuels. As for the HTGR, South Africa has been involved in the development of the PBMR fuel at laboratory scale. The Fuel Development Facility Complex (FDL) was set up to investigate and to establish the technology for the manufacturing of the PBMR type of fuel (NNR, 2015d).

3.3.7.5.2 (Fresh) Uranium Fuel Fabrication Design and Engineering Technological Considerations

The fuel elements must accommodate power cycles and meet the design objectives, such as adequate heat transfer, nuclear reactivity, retention of fission products, inherent safety under accident conditions, and retention of structural and mechanical integrity (Simnad, 2003). This being the case undertaking the nuclear fuel engineering design requires the understanding of e.g. PWR, RR and HTGR core SSCs designs. As for the PWR fuel fabrication in South Africa, virtually no information was available on product specifications and design parameters hence AEC engineers were given the task to develop in-house specifications from available ASTM specifications, generic information on PWR reactor plant and fuel, and information available in the literature (INE, 1990). In the latter years, SA got involved in HTGR fuel. Figure 3-53 below shows the design of the SA PBMR fuel elements. Olander (2009) states that the LWR reactor core comprises fuel assemblies in an arrangement that satisfies the following requirements:

- (i) to provide a rigid structure for holding the fuel elements;
- (ii) to deliver the desired thermal power to the coolant;
- (iii) to provide a critical assembly with a minimum of neutron leakage;
- (iv) to provide adequate coolant flow to remove fission heat and sufficient coolant volume for thermalization of fission neutrons by hydrogen; and
- (v) to accommodate control rods that maintain criticality as the fuel is consumed.

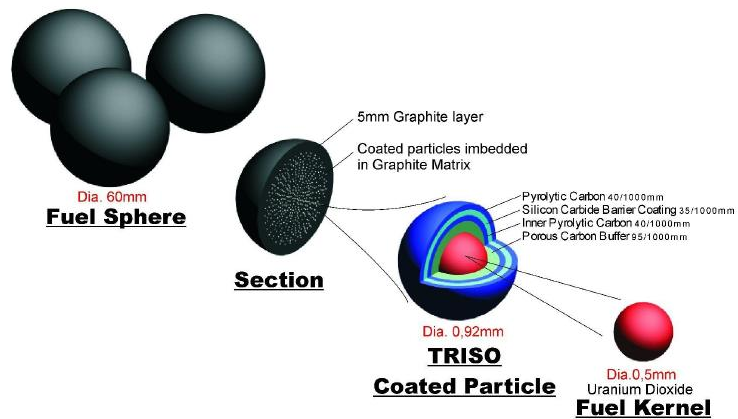


Figure 3-53: Fuel element design for PBMR
Source: IAEA (2011b)

3.3.7.5.3 (Fresh) Uranium Fuel Fabrication Manufacturing Technological Considerations

NECSA then known as Atomic Energy Board was able to develop PWR fuel element manufacturing capabilities because of technology transfer arrangements with French entities. Figure 3-54 shows the generic light water reactor fuel elements.

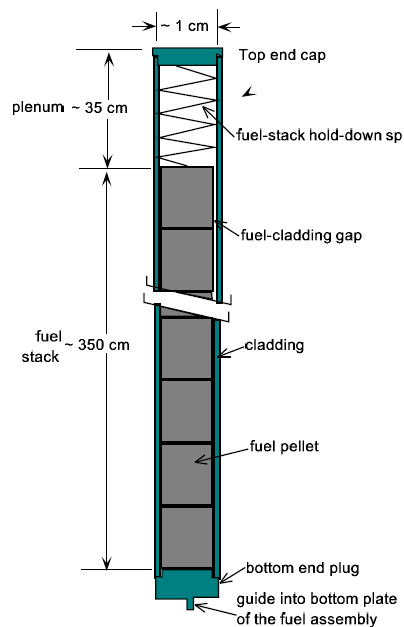


Figure 3-54: Generic LWR fuel element
Source: Olander (2009)

Fuel pellets are made up of uranium dioxide (UO_2). Hence, at the fuel fabrication plant, the enriched UF_6 is converted to uranium dioxide (Chenoweth & Pool, 2003). The UO_2 pellet fabrication process (Figure 3-55 below) consists of mixing the UO_2 powder with additives such as binder, lubricant and pore former materials, granulating to form free-flowing particles, compaction in an automatic press, heating to remove the additives, sintering in a controlled atmosphere, and grinding to a final diameter (Abe & Asakura, 2012). As part of its Koeberg Nuclear Power Plant fuel provision NECSA had a zirconium tube factory at Pelindaba. At AEC, a small team responsible for the Zircaloy tube plant developed various techniques for predicting the resultant texture of Zircaloy-4 cladding tubes for various reduction schedules and tooling designs (INE, 1990).

As for the SA SAFARI-1 research reactor, the AEC's Physical Metallurgy Department possessed a high level of expertise concerning melting and casting technology, and the conventional uranium-aluminium alloy manufacturing route was chosen (INE, 1990).

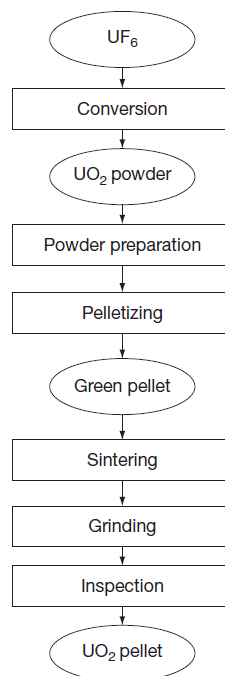


Figure 3-55: Flow sheet for UO_2 pellet production
Source: Abe and Asakura (2012)

3.3.7.5.4 (Fresh) Uranium Fuel Fabrication Construction Technological Considerations

The availability of fuel fabrication infrastructure is important to undertake the various fuel fabrication processes for fuel for NPP at hand. When manufacturing of various fuel elements is completed, the final stage is assembling the elements. Figure 3-56 below shows various fuel assembly activities. Table 3-52 and Table 3-53 below respectively show the PBMR fuel infrastructure and PWR fuel fabrication infrastructure at the South African Pelindaba nuclear site. In the 1990s, SA sold off the PWR fabrication equipment to China, which enabled some of the buildings to be used for the PBMR fuel development (Fig, 2010).

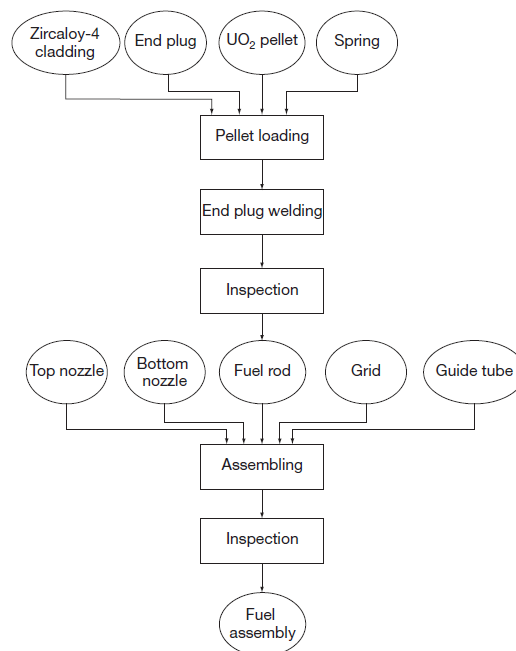


Figure 3-56: PWR fuel assembly steps

Source: Abe and Asakura (2012)

Table 3-52: PBMR Fuel Development Infrastructure at NECSA

	Laboratory/Section	Building Name	Brief Use Description
	Kernel Laboratory	B-D2	Used for development, manufacturing and testing of uranium dioxide for the PBMR type of fuel Optimising kernel production process parameters and to supply kernels to the other FDL Complex laboratories for developmental work
	Storeroom	B-D2-0004	Depleted/natural uranium storage

	Laboratory/Section	Building Name	Brief Use Description
	Coater Laboratory	B-D1	Investigating and developing coating process for kernels
	Graphite Processes Laboratory	B-C3/C5	Used to test and characterise the fuel sphere manufacturing process
	PBMR Quality Control Laboratory	B-D1	Provides analytical service to the FDL and analyses the specified physical and chemical properties of materials.
	Advanced Coater Facility	B-D1	To develop production technology and to optimise the production parameters.
	Uranium Storage Vault	B-D1	The vault is licenced for the storage of enriched uranium i.e. up to 10% ²³⁵ U.

Source: NNR (2015d)

Table 3-53: South African BEVA PWR fuel fabrication infrastructure

Building	Fuel Fabrication Section
D2	Uranium Recovery
D1	Conversion UF ₄ -UO ₂
C3/C5	Pelletizing
E1	Laboratories
K1 & K2	Tooling and press workshops
H4	Services
C1	Zirconium production
C2	Zircalloy tube plant
E4	Stores
E3	Maintenance workshop
H1	Zirconium scrap and effluent treatment
G1	Administration

Source: Venter and Aspeling (1990)

3.3.7.5.5 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Technological Considerations

According to IAEA (1996b), the uranium fuel fabrication operations involve the following stages:

- preparation of UO₂ powder of desired size distribution by comminution, compaction and granulation;
- manufacture of UO₂ pellets;
- sintering of the pellets in hydrogen gas;
- grinding of the sintered pellets to the required size;
- washing, drying and loading the fuel pellets into tubes of Zircaloy or stainless steel and sealing the ends with welded caps; and
- locating fuel rods in fixed parallel arrays forming the reactor fuel assemblies.

As for SA PWR fuel capabilities, Ford (1993) contended that the AEC's fuel-fabrication plant was unique in that it covered the following processes:

- UO₂ production by the reduction of UF₆;
- UO₂ pellet production by the pressing and sintering of UO₂ powders, and subsequent centreless grinding;
- Zircaloy tube and bar production by the tube rocking of hollow-bar stock to final finishing, and non-destructive testing; and
- component manufacturing, including the production of Inconel grid straps, grid assembly, and nozzle fabrication;
- assembly of fuel rods, guide thimbles, the fuel assemblies themselves, and the associated testing and inspection.

Skrzypek and Skrzypek (2014) stated that structural codes are responsible for predicting the nuclear fuel behaviour during reactor operation in various scenarios and particular applications of the codes are as follows:

- Calculations of the fuel rods behaviour during irradiation;
 - (a) during constant irradiation;
 - (b) in transient states; and
 - (c) evaluation of the source terms for accident analyses,
- R&D applications;
- fuel rod design;
- design of new products and fuel cycles and
- supporting fuel loading into the reactor core.
-

3.3.7.5.6 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Technological Considerations

According to the Radioactive Waste Management Policy and Strategy for the Republic of South Africa (2005), the main radioactive waste management options are as follows:

- Regulated disposal;
- Authorized disposal or discharge;
- Authorized re-use or recycling;
- Regulated reprocessing (used nuclear fuel);
- Regulated storage; and
- Clearance.

On making a choice of one SF management technology over others, Twala et al. (2008) stated that the ultimate choice is arrived at by considering each SF technology characteristics that can be viewed as positive or advantageous (e.g. as benefits) and others as negative or disadvantageous (e.g. as costs). This is true especially when individual countries choose among possible technologies such as reprocessing, storage and deep geological disposal of SF. In other countries, such as France and Japan, the SF approach is chemical reprocessing for reclaiming fissile nuclides with the remaining wastes vitrified for geologic disposal (Ewing, 2008).

3.3.7.6 (Fresh) Uranium Fuel Fabrication Environmental Factors

During nuclear fuel fabrication, CO₂ emissions are also associated with direct energy consumption (Choi, Hyo & Ko, 2016). The fuel fabrication operations at SA's Pelindaba site for the Koeberg NPS, SAFARI and PBMR depended on Eskom's mostly coal fired stations that emit CO₂.

3.3.7.6.1 (Fresh) Uranium Fuel Fabrication R&D Environmental Considerations

The density of population near the fuel fabrication facility and the direction of the prevailing wind at the site is a factor for consideration in the site evaluation process to minimize any possible health consequences for people in the event of a release of hazardous chemicals (IAEA, 2010).

3.3.7.6.2 (Fresh) Uranium Fuel Fabrication Design and Engineering Environmental Considerations

Alternative materials such as ferritic or martensitic stainless steels, oxide dispersion strengthened (ODS) alloys, nickel based super alloys and refractory metals and materials (SiC and ZrC) are being developed as candidate fuel cladding materials in order to eliminate zirconium fuel clad that produces hydrogen by oxidation (Vijaya et al., 2013).

3.3.7.6.3 (Fresh) Uranium Fuel Fabrication Manufacturing Environmental Considerations

Uranium fuel-fabrication facilities unlike MOX fuel fabrication facilities have low specific radioactivity of uranium and the gamma dose rate in the working environment meaning that neither special gamma shielding for the facilities, nor strict containment is necessary, in contrast to the plutonium facility (IAEA, 2002).

3.3.7.6.4 (Fresh) Uranium Fuel Fabrication Construction Environmental Considerations

As part of the application to inter alia the SA Department of Environmental Affairs and Tourism (DEAT) for the construction of the PBMR fuel plant an Environmental Impact Assessment (EIA) was completed during 2001 and 2002 and the PFP was subsequently authorised by the Minister of DEAT in January 2007 (O'Beirne, 2009).

3.3.7.6.5 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Environmental Considerations

For a typical standalone fuel fabrication plant, with an equivalent capacity based on 400 t UO₂/y, the electricity consumption is about 2.5 x 10⁴ kWh/tU and the fuel and hydrogen consumption about 3.4 x 10⁷ kJ/tU (IAEA, 2002).

3.3.7.6.6 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Environmental Considerations

Uncertainties in energy demand growth and supply capabilities in the long term are calling for the maintenance of a nuclear infrastructure and continued research and development in the field of advanced reactors, fuel cycle technology and radioactive waste management in order to ensure that nuclear power could contribute significantly to environmentally benign and sustainable development worldwide (IAEA, 1997).

3.3.7.7 (Fresh) Uranium Fuel Fabrication Legal Factors

The regulatory requirements demand that the fuel system survives possible off-normal events without impact to the public (Walters, 2004). In South Africa, the BEVA nuclear fuel fabricating facility differed from other similar facilities in the world in that when it obtained its South African Bureau of Standards ISO 9001 on the 31 August 1995, it already had the ASME NQA-1 system and SABS 0259 accreditation for laboratory standards in place (Venter, 1996).

3.3.7.7.1 (Fresh) Uranium Fuel Fabrication R&D Legal Considerations

Venter and Aspelting (1990) stated that, as part of the quality management programme for the manufacturing of the Koeberg NPS nuclear fuel at NECSA's BEVA facilities the following was undertaken:

- (a) Manufacturing Test Programme, whereby the limits of the operating ranges of the individual processes or facilities were investigated;

- (b) Evaluation Programme, whereby the various facilities and steps within a process line were coupled and the resultant products were fully evaluated to check compliance with specifications;
- (c) Formal qualification of processes, personnel and products, whereby compliance of processes with specific requirements, compliance of operators and inspectors with defined training and ability criteria, and compliance of products inclusive of final fuel assemblies with extended specifications had to be proven;
- (d) Four BEVA manufactured demonstration fuel assemblies successfully completed one reactor cycle at Koeberg NPS after delivery on 14 September 1988;
- (e) At the AEC's Hot Cell in 1990, exhaustive post-irradiation examination of the four-test fuel pins extracted from removable pin fuel assemblies were done;
- (f) Preliminary results showed that there was no difference in performance between the BEVA manufactured demonstration assemblies and the fuel assemblies sourced from abroad and
- (g) The measuring as well as post-irradiation examination of fuel pins was repeated after the second and third irradiation cycles.

3.3.7.7.2 (Fresh) Uranium Fuel Fabrication Design and Engineering Legal Considerations

Fuel elements and assemblies for the nuclear power plant shall be designed to maintain their structural integrity, and to withstand satisfactorily the anticipated radiation levels and other conditions in the reactor core, in combination with all the processes of deterioration that could occur in operational states (IAEA: Safety of NPP Design, 2016). According to IAEA (2010b), particular consideration should be given to the following hazards in the specification of design basis accidents at uranium fuel fabrication facilities:

- (a) A nuclear criticality accident;
- (b) A release of uranium (e.g. in the explosion of a reaction vessel during the conversion process);
- (c) A release of UF_6 due to the rupture of a hot cylinder;
- (d) A release of HF due to the rupture of a storage tank;

- (e) A large fire;
- (f) Natural phenomena such as earthquakes, flooding, or tornadoes; and
- (g) Aircraft crashes.

Koster, Matzner and Nichols (2003) stated that to achieve public safety by virtually guarantying that the maximum PBMR TRISO-coated particles fuel temperatures remain below about 1600° C it was crucial to adhere to the following three well-known principles:

1. Control the heat production in the fuel by limiting decay heat levels and excessive reactivity excursions;
2. Ensure sufficient heat removal capability (including the options of doing this by passive means, so that the fuel will not exceed the specified limit) and
3. Limit the possibilities of chemical degradation of the fuel due to large-scale air or water ingress (in this case, when temperatures exceed 1200 °C the SiC coating are destroyed resulting in corrosion).

3.3.7.7.3 (Fresh) Uranium Fuel Fabrication Manufacturing Legal Considerations

For the SA BEVA fuel fabrication plant, the first priority was to establish a comprehensive Quality Management Programme Plan, which required conforming to the basic requirements of ASME/ANSI NA-1, and the development of system procedures was undertaken (Venter and Aspeling, 1990). According to NNR (2015c), NECSA's ELPROD is authorised by the SA regulator for the following activities:

- i. The receiving of HEU Aluminium alloy billets for fuel plate and target plate manufacturing; ✓
- ii. The manufacture and storage of core strips, core blanks, cores, compacts, fuel plate strips, fuel plates, target plates, fuel elements, and control rods;
- iii. The handling, processing and storage of scrape alloy resulting from the above activities and transfer thereof to Building-2700;

- iv. The handling, processing and storage of radioactive waste and the transfer thereof to other authorized facilities;
- v. The performing of quality control activities on the above products;
- vi. Chemical cleaning of fuel elements and target plates and the components that constitute fuel elements and target plates;
- vii. The manufacturing of components for fuel elements, control rods, and target plates;
- viii. Storage of:
 - a. Fuel elements, control rods, target plates and components thereof in the fuel element vault;
 - b. U-AI alloy billets and other items in the alloy vault;
 - c. Waste drums containing compressible waste in the wire cage outside the manufacturing area;
 - d. Spare rollers for fuel plate rolling; aluminium, stainless steel and cadmium sheets used in the manufacturing of fuel assemblies; and control rods and target plates, in the Component and Equipment Store;
- ix. The transfer of fuel elements, control rods and target plates to the SAFARI-1 Research Reactor
- x. The transfer of samples to Pelindaba Analytical Laboratories (PAL) or other authorized Laboratories for testing; and
- xi. The handling, processing, and storage of radioactive waste and the transfer thereof to other authorised facilities.

3.3.7.7.4 (Fresh) Uranium Fuel Fabrication Construction Legal Considerations

The criteria used for the construction of fuel fabrication facilities and the fabrication of the process equipment and components used in the facility and for their installation should be the same as or more stringent than those used for the non-nuclear chemical industry, and should be specified as part of the design e.g. seismic design (IAEA, 2010b).

3.3.7.7.5 (Fresh) Uranium Fuel Fabrication Operation and Maintenance Legal Considerations

The IAEA (2010b) states that safety analysis for fuel fabrication facilities should be in two major steps namely:

- The assessment of occupational exposure and public exposure for operational states of the facility and comparison with authorized limits for operational states; and
- Determination of the radiological and associated chemical consequences of design basis accidents (or the equivalent) for the public, and verification that they are within the acceptable limits specified for accident conditions.

3.3.7.7.6 (Fresh) Uranium Fuel Fabrication Waste Management and Disposal Legal Considerations

The decommissioning of fuel fabrication facilities is less difficult than that of some other fuel cycle facilities because of the low specific activity of the LEU processed in the operational lifetime of such facilities (IAEA, 2010a). Hence, it was easy to decommission the South African PWR fuel manufacturing facilities at the BEVA site in order to make way for the PBMR fuel operations.

3.3.8 Spent Fuel Storage

The IAEA (1994) states that the back end of the nuclear fuel cycle includes all activities involving the spent fuel produced in the reactor cores and these operations can be conducted in three different ways, which define the fuel cycle namely:

- 2) A closed cycle, with the reprocessing of the spent fuel, and the recovery and recycling of the remaining uranium and plutonium produced;
- 3) An open cycle, with the final disposal of the spent fuel occurring without any fuel recovery after preparation of the fuel for its final disposal;
- 4) Storage of the spent fuel so that it can be retrieved at a later time (perhaps tens of years), an option which defers choice of option (1) or option (2).

One would have expected NECSA or any SA entity to have embarked on developing spent nuclear fuel (SNF) technologies in anticipation of providing a solution for Koeberg running out of space for storing SNF. Spent fuel from the SA Koeberg reactors is at present stored on site. Worldwide, spent fuel from nuclear reactors in storage amounted to around 266 000 t HM and is accumulating at a rate of around 7000 t HM/year. For the South Korean spent fuel storage Cho et al. (2011) noted that several factors needed to be taken into consideration when determining an estimated cost, including generated spent nuclear fuel characteristics, storage scenarios, the size of the interim facility, cost items, and the escalation factor. The option of creating new wet-storage facilities at or away from reactors would likely be prohibitively expensive to build and operate. Deciding which of the two approaches to use should be based on a number of criteria, including which option provides better safety and security, the effects and implications of spent-fuel transportation, which approach is politically and managerially feasible, which option is more cost-effective, and whether specific considerations at a particular storage site could overly delay an option (MacFarlane, 2001).

3.3.8.1 Spent Fuel Storage Political Factors

Figure 3-57 below shows is an illustration of SNF management strategies comprising Spent Fuel Pool Island (SFPI) and Independent Spent Fuel Storage Installation (ISFSI) which have been proven to be successful in the U. S. nuclear industry (Seo, Sohn & Jo, 2018).

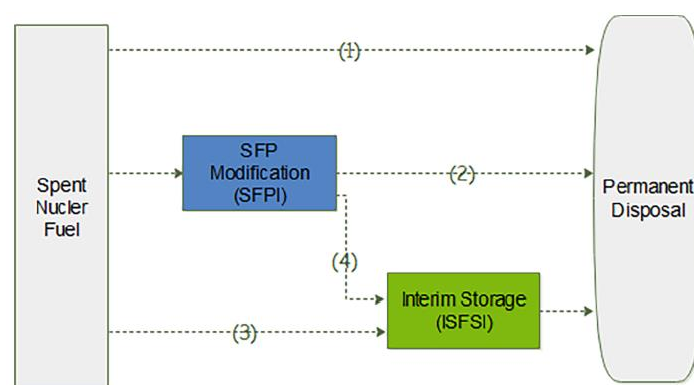


Figure 3-57: SNF management strategies after NPP permanent shutdown
 Source: Seo, Sohn and Jo (2018)

According to Haas and Hamilton (2007), fuel cycle back-end strategies can be categorised into two distinct approaches namely:

11. the first strategy involves storage of spent fuel at reactor sites, with further conditioning and final deep geological storage to follow (typical examples are Sweden and Finland); and
12. the second strategy, on the other hand, involves the reprocessing of spent fuel and conditioning of the resulting high-level waste (HLW) for geological disposal.

Table 3-54 below is an overview of the 32 different countries' spent fuel policies. As stated by Hogselius (2009), SA's current policy is to have an interim storage whilst awaiting further decisions. Table 3-55 below shows an NNR overview matrix for management of used fuel and radioactive waste in SA. Eskom has adopted a strategy to procure more casks as well as to establish an onsite Transient Interim Storage Facility (NNR Annual Report, 2016-2017). The Radioactive Waste Management Policy and Strategy for the RSA (2005) states that waste management in SA shall be managed in accordance with the following policy principles namely:

1. Polluter pays principle;
2. Transparency regarding all aspects of radioactive waste management;
3. Sound decision-making based on scientific information, risk analysis and optimisation of resources;
4. Precautionary principle;
5. No import or export of radioactive waste;
6. Co-operative governance and efficient national co-ordination;
7. International cooperation;
8. Public Participation; and
9. Capacity building and education.

Nuclear spent fuel management has become a key activity within the nuclear strategies of each country (Palacio, 2017). Some countries HLW strategies and policies are driven by the availability of uranium resources in the country. For example, with an anticipated shortage of uranium supplies and limited uranium exploration activities, China said that it wanted to reprocess spent nuclear fuel from its commercial light water reactors (LWR), extract the resulting uranium and plutonium, and use them to fabricate nuclear fuel for use in fast breeder reactors (Zhou, 2011).

Table 3-54: Overview of spent nuclear fuel policies in 32 countries

Country	Spent fuel history	Current policy	Trends
Argentina	Experimental reprocessing facility operating in early 1970s	Interim storage, awaiting further decision	New fuel cycle initiatives in connection with launching of new nuclear policy in August 2006
Armenia	Transfer to Russia without waste return		
Belgium	Eurochemical international reprocessing facility (involving 12 OECD countries) in operation 1966–1974; export to France with return of vitrified high-level waste	Export to France with waste return/ direct disposal	Two alternatives acknowledged; research on geological disposal focused on clays at Mol
Brazil	Most fuel-cycle activities were developed, but not reprocessing	Interim storage, awaiting further decisions	Some interest in reprocessing
Bulgaria	Export to Soviet Union without waste return; some interruptions in 1990s	Export to Russia without waste return	New NPP with Russian reactors to be built
Canada	Pilot reprocessing activities in 1940s and 1950s (Gowing, 1974)	Direct disposal and retrievability	Search for repository site to start in 2009; interest in direct use of PWR spent fuel in CANDU (DUPIC)
Czech Republic	Export to Soviet Union without waste return	Open policy, NPP operators to decide	Site selection for geological waste repository expected in 2015
Finland	VVER SNF exported to Soviet Union until 1996; direct disposal of BWR SNF	Direct disposal of all fuel	Repository to be built at Olkiluoto
France	Reprocessing	Reprocessing	Losing important foreign reprocessing customers
Germany	Failed attempts to establish large-scale domestic reprocessing; massive exports to France and UK; SNF in GDR exported to Soviet Union without waste return (Tiggemann, 2004)	Direct disposal	Stagnation in SNF policymaking; new interim storage facilities under construction at each NPP in accordance with new legislation
Hungary	Export to Soviet Union without waste return	Direct disposal	
India	Military reprocessing since 1964; civil reprocessing since 1982 (Berkhout & Gadakar, 1997)	Reprocessing	Expansive reprocessing programme; diversifying from uranium- to thorium-cycle
Italy	NPPs decommissioned since 1987–1990; pilot reprocessing plant in operation until mid1990s; Magnox SNF exported to UK	Export of remaining fuel to France 2007–2015 with waste return	New NPPs planned
Japan	Pilot-scale reprocessing since 1977; export to France and UK while awaiting maturity of domestic reprocessing	Reprocessing	Large-scale reprocessing plant currently in test phase

Country	Spent fuel history	Current policy	Trends
Lithuania	Transfer to Russia without waste return	Direct disposal	New interim storage facility under construction
Mexico	No ambitious fuel cycle activities	Interim storage awaiting further decisions	
Netherlands	Export to France and UK	Export to France	For future reactors, a choice will be made by 2025 between export, direct disposal and 'partition and transmutation'
Pakistan	Reprocessing project on basis of French technology cancelled in 1978	Interim storage, awaiting further decisions	The question of future civil reprocessing remains open
Romania	First commercial reactor on-line in 1996 (CANDU type)	Direct disposal	Preliminary investigations regarding geological repository
Russia	Military reprocessing since 1948; reprocessing of VVER SNF since 1977; construction of larger reprocessing plant started in 1985 (Kuznetsov & Nazarov, 2006)	Reprocessing of VVER SNF; no reprocessing of RBMK SNF	Aggressive nuclear fuel policy, but in practice stagnation in reprocessing expansion
Slovakia	Export to Soviet Union without waste return	Direct disposal	Site selection for geological repository has commenced
Slovenia	Strategy for Long-Term Spent Fuel Management adopted in 1996	Direct disposal or, possibly, export	Interest in direct disposal abroad
South Africa	Ambitious fuel cycle policy, but no reprocessing facility built	Interim storage, awaiting further decisions	New nuclear energy policy envisages reprocessing as a strategic priority related to energy security
South Korea	Reprocessing ambitions halted in 1978 following US pressure (Kang and Feiveson, 2001)	Direct disposal and possibly DUPIC	Centralized interim storage planned for 2016; continued interest in reprocessing
Spain	Export to France and UK without waste return; open fuel cycle policy since 1983 (Berkhout & Walker, 1991)	Direct disposal	Decision on disposal to be made after 2010. Granite, clay and salt formations under consideration
Sweden	Domestic reprocessing given up at early stage, minor exports to France and UK 1977–1983	Direct disposal	Site selection for geological repository expected in 2009
Switzerland	Export to France and UK until 2006	No clear policy	Exports halted for 10 years from 2006
Taiwan	Reprocessing ambitions officially given up in 1976 following US pressure	Direct disposal	Geological repository planned for 2032; continued interest in both reprocessing and export
UK	Large-scale civil reprocessing since 1964	Reprocessing and/or direct disposal	Possibly moving to direct disposal; B205 Magnox reprocessing plant to be closed after Magnox reactors decommissioned around 2012

Source: Hogselius (2009)

Table 3-55: Overview matrix for management of used fuel and radioactive waste

	Long-term management policy	Funding of liabilities	Current practices / facilities	Planned facilities
Used fuel	Long-term storage with possible reprocessing or transmutation prior to disposal.	Long Term: Owners/ generators to contribute to National Radioactive Waste Management	Combination of wet and dry storage on site	Short Term: Additional dry storage facilities to be developed as needed. Long term:

	Long-term management policy	Funding of liabilities	Current practices / facilities	Planned facilities
	Disposal in geological repository.	Fund to be established Currently based on polluter pays principle owners/generators of used fuel are required to make financial provisioning for management of used fuel		Geological repository to be developed by National Radioactive Waste Disposal Institute (NRWDI)
Nuclear fuel cycle waste	Near surface disposal of Low and intermediate level radioactive waste (short lived) LILW-SL	Currently owners/generators - based on polluter pays principle Long Term: Owners/generators to contribute to National Radioactive Waste Management Fund to be established	Vaalputs National Radioactive Waste Disposal Facility (near surface disposal) for LILWSL Long term storage for other wastes	Possible medium depth disposal facility for Low and intermediate level radioactive waste (long lived) LILWLL or geological disposal based on investigations to be undertaken by NRWDI
Non-power waste	Near surface disposal of LILW-SL	Currently owners/generators - based on polluter pays principle Long Term: Owners/generators to contribute to National Radioactive Waste Management Fund to be established	Vaalputs (near surface disposal) Long term storage for other wastes	Possible medium depth disposal facility for LILWLL or geological disposal based on investigations to be undertaken by NRWDI
Decommissioning liabilities	Phased decommissioning with release or clearance from regulatory control. Immediate dismantling is the preferred option. Disposal of LILWSL in near surface repository. Disposal routes for other wastes to be established by NRWDI	Owners/ generators - based on polluter pays principle	Recycling and clearance of material meeting clearance requirements. Disposal of LILW-SL at Vaalputs Storage for other wastes	Disposal routes for other wastes to be established by NRWDI
	Return to manufacturer. Recycling and reuse where possible.	Contractual Agreements between owner and supplier. Where no	Storage in dedicated facilities at NECSA Pelindaba	Disposal routes to be established by NRWDI

	Long-term management policy	Funding of liabilities	Current practices / facilities	Planned facilities
	Disposal routes to be investigated by NRWDL.	agreement exists owners/ generators - based on polluter pays principle	site	
Mining & milling waste	Stabilise in place	Mine operator	Stabilise in place	

Source: NNR (2017)

3.3.8.1.1 Spent Fuel Storage R&D Political Considerations

Even though South Korea has a “wait and see policy” for SNF management, a couple of meaningful studies on technology development for a proliferation resistant SNF management such as DUPIC and ACP have been successfully carried out through a national mid- and long-term nuclear R&D project (Hwang, 2007). The concept of the ACP process was to change the spent fuel from the oxides form into metallic form so as to reduce the volume ($1/2 \sim 1/4$) and heat load ($1/4$) which will increase the capacity of a final repository (Kim, Chang & Ko, 2010). Hence, the ACP can be applied as a conditioning process for a long-term storage and eventual disposal of a PWR spent fuel (Kim et al., 2012).

3.3.8.1.2 Spent Fuel Storage Design and Engineering Political Considerations

Current SA waste management policies will inform spent nuclear fuel activities to be undertaken. Institutions or waste generators charged with NSF management can decide whether to insource or outsource the design engineering aspects. As an example, Eskom outsourced and financed the design of SF interim storage casks for the Koeberg used fuel. This is line with the SA radioactive waste management policy and strategy which advocates the “polluter pays principle”.

3.3.8.1.3 Spent Fuel Storage Manufacturing Political Considerations

Some countries have strategically created local manufacturing capabilities to supply SSCs for their SF storage facilities. The Spanish SOE Ensa is a good example of an entity that has developed SF fuel casks which give Spanish waste generators an option to either have the containers to be locally sourced or sourced from foreign entities. In addition, such structuring of the nuclear sector by the government enables the collaboration of Ensa with other foreign nuclear waste generators. Figure 3-58 shows the

new Ensa ENUN 24P Dual-Purpose Cask specifically designed for the transportation of high burnup spent fuel in the People's Republic of China (Palacioa, 2017). In SA, the Department of State Enterprises' Competitive Supplier Development is one such local government policy that promotes technology transfer from foreign technology suppliers to local suppliers. This programme leverages on the e.g. spending on mega waste management initiatives on foreign entities by the local SOE waste generators.

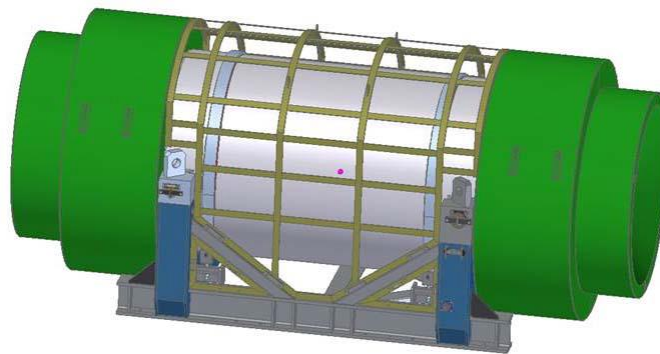


Figure 3-58: The new Ensa ENUN 24P Dual-Purpose Cask, shown on its transport configuration, specifically designed for the transportation of high burnup spent fuel in the People's Republic of China
(Source: Palacioa, (2017))

3.3.8.1.4 Spent Fuel Storage Construction Political Considerations

Installations of local SF storage facilities are also detected by the individual country waste management strategies. Financing for such installations are also provided by the waste generators. According to the Rio Declaration (1992), national authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, considering the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment. Since there is no clear national plan for spent nuclear fuel permanent disposal, the Korea Hydraulic Nuclear Power Company is planning to construct a spent fuel interim storage facility with 11,000 tHM capacity for PWR (Lee and Lee, 2007). In South Korea, the times of SNF pool saturation were estimated site by site and according to the recommendations of the

Public Engagement Commission on Spent Nuclear Fuel Management (PECOS), the installation of a pre-disposal storage facility, acting as an interim storage, would be available in 2031 (Park, 2017).

3.3.8.1.5 Spent Fuel Storage Operation and Maintenance Political Considerations

Countries with a direct disposal policy currently store their spent fuel in on-site or off-site interim storage facilities (Zhou, 2011). Whether it comes from a PWR or BWR, after used fuel is removed from a reactor core, it is moved directly into cooling ponds, where the used fuel loses a significant proportion of its heat load in that key three- to five-year cooling period (Rosner & Lordan, 2014). In some countries, they are gradually running out at-reactor (AR) SF storage space resulting in formulating of new storage strategies. As an example, the saturation of South Korea's AR spent fuel storage pools has necessitated additional spent fuel storage capacity. In Table 3-54, Hogselius (2009) indicated that the stance in South Korea was to have an SF interim storage by 2016.

3.3.8.1.6 Spent Fuel Storage Waste Management and Disposal Political Considerations

In SA, radioactive waste including used nuclear fuel shall be managed in terms of the radioactive waste management policy and strategy (DoE, 2008).

3.3.8.2 Spent Fuel Storage Economic Factors

Figure 3-59 below is an illustration that shows that spent fuel storage options considered for describing the Economic methodology comprise AR storage and AFR storage.

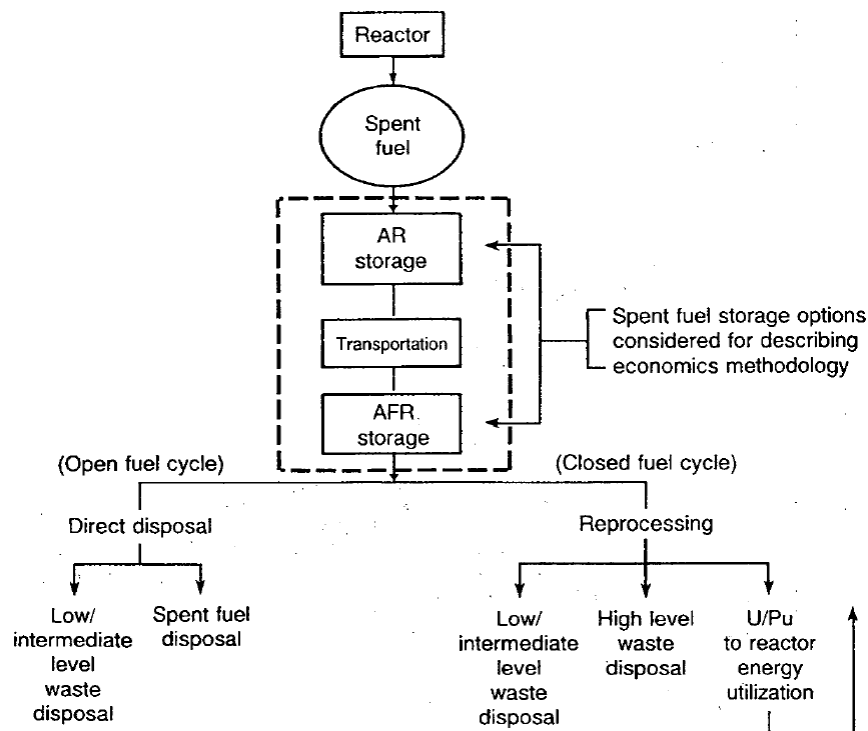


Figure 3-59: Stages of spent fuel management
 Source: IAEA (1994)

3.3.8.2.1 Spent Fuel Storage R&D Economic Considerations

According to the IAEA (1994), specific types of development costs include: initial feasibility studies to identify the storage options available; the conceptual design of the spent fuel storage facilities; and all other costs required to analyse or evaluate each storage option before commencing construction (including site characterization).

3.3.8.2.2 Spent Fuel Storage Design and Engineering Economic Considerations

According to IAEA (1994a), the following are some of considerations when designing SF storage facilities including the fuel handling and storage equipment:

- fuel type;
- the depth of the fuel storage pool; and
- the physical state of the cladding material at the start of the storage period.

3.3.8.2.3 Spent Fuel Storage Manufacturing Economic Considerations

The cost of storage facilities or their SSCs is a factor that can inform the interim strategy for managing SF. Such was case in South Korea. The entire decommissioning period of the Kori site would be approximately 26 years according to the decommissioning plan that was developed for this analysis and the cost assessment has shown that a spent fuel pool island (SFPI) can generate considerable savings as compared to dry storage options using concrete casks, metal casks, or dual-purpose cask systems (Songa, Kim & Kessel, 2018).

3.3.8.2.4 Spent Fuel Storage Construction Economic Considerations

As of January 2008, Korea has not selected a high-level waste storage site yet because of its tremendous cost that includes site construction, land purchase and compensation for local resident and various political issues.

3.3.8.2.5 Spent Fuel Storage Operation and Maintenance Economic Considerations

HLW comes from the nuclear power production, either as spent fuel (if it is declared waste) or as conditioned waste arising from the reprocessing of spent fuel, research facilities, disused sealed sources, and defence programmes (Rodriguez, 2014). In Finland, the share of waste management is roughly 10% of the production costs of nuclear electricity (Ryhanen, 2003).

3.3.8.2.6 Spent Fuel Storage Waste Management and Disposal Economic Considerations

It should be noted that the variability in the Economic of waste management is likely caused due the fact that most specific data concerning storage casks, transportation, security costs, and others are considered proprietary (Brinton & Kazimi, 2013).

3.3.8.3 Spent Fuel Storage Social Factors

About 25-30 t U of spent fuel are discharged annually from a 1000 MW(e) pressurized water reactor (PWR) after electricity sufficient to satisfy the needs of approximately 200 000 people have been generated (IAEA, 1994). As reactor operators have run out of space in their spent fuel pools, more

operators have turned to dry cask storage systems (Spent Nuclear Fuel, 2012). Kang (2011) notes that in South Korea public consultation along with input from independent experts and a joint fact-finding mission will be critical to the process for building dry-cask interim storage and a final disposal site.

The summer of 2012 was a significant period for Japan's nuclear and energy policy in that, in response to the Fukushima nuclear accident, the government decided to undertake, what it termed a "National Discussion" on energy policy (Springer, 2015). The Fukushima accident has had an impact on other countries' nuclear policies e.g. Germany that is contemplating nuclear phase out in the 2030s.

3.3.8.3.1 Spent Fuel Storage R&D Social Considerations

Transparency regarding the development and use of nuclear energy systems is critically important in order to develop and maintain the trust of stakeholders that nuclear energy organizations are behaving in an ethical and socially responsible manner (IAEA, 2008g). An expert group composed of members of South Korea's nuclear establishment was instructed to carry out a yearlong research project in 2010 as a basis for the public consensus process (Kang, 2011). Unfortunately, attempts to create additional storage sites have foundered, largely because of a failure to consult with communities that would be affected, and because of widespread belief that nuclear power plants and storage facilities in South Korea are not safe (Kang, Kim, & Lee, 2015).

3.3.8.3.2 Spent Fuel Storage Design & Engineering Social Considerations

Stakeholder attitudes towards SF storage facilities can be favourable if those responsible for designing such facilities thoroughly communicate what measures have been taken in making sure that the facilities will e.g. cost effective, secure, safe, proliferation-proof and not harmful to the environment. Accordingly, Andrianov et al. (2015) state that nuclear energy should provide benefits that outweigh the associated costs and risks, and be based on the open and transparent communication of all relevant information.

3.3.8.3.3 Spent Fuel Storage Manufacturing Social Considerations

Likewise, stakeholders can be assured by knowing that the e.g. SSCs of storage facilities have been manufactured by competent personnel and using well researched manufacturing processes within accredited facilities. The assurance to the stakeholders is made possible by the involvement of the regulator especially during the fabrication of SSCs that are critical to safety.

3.3.8.3.4 Spent Fuel Storage Construction Social Considerations

There are direct and indirect benefits during the construction and operation of SF storage facilities. Numbers range from a few dozens to some 200 additional jobs during the operational phase of a repository facility; and from a few 100 to some 2000 for the construction of such a facility (Bergmans, 2010.). Installation of SSCs for wet and dry SF storage facilities can be for Greenfield or Brownfield initiatives. For instance, there has been some needs to increase the capacity of existing wet storage facilities by installing additional for used fuel. Yet in certain situations, there has been a need to construct new wet or dry storage facilities. From a social perspective, stakeholders can participate on such installations through the environmental impact assessments.

3.3.8.3.5 Spent Fuel Storage Operation and Maintenance Social Considerations

The stakeholders are also interested in socioeconomic benefits that can be realised through utilisation and upkeep of the constructed of spent fuel storage facilities. The distribution of benefits and burdens between generations could be divided into three different categories: (1) future benefits versus future burdens (as in Dower's first interpretation of intergenerational equity), (2) current benefits versus current burdens, and (3) current benefits and burdens versus future benefits and burdens (Taebi & Kadak, 2010).

3.3.8.3.6 Spent Fuel Storage Waste Management and Disposal Social Considerations

Carter (1985) contended that the Panel on Social and Economic Aspects of Radioactive Waste created by the National Academy Panel of Sciences (NAS)'s aim of research should have been to explain why

community response to US DOE's repository siting activities has varied widely from place to place with most communities showing alarm and opposition, but some being surprisingly receptive. As for Sweden, the nuclear waste management attitude of the Swedish Nuclear Fuel and Waste Management Company (KBS) and National Board for Spent Nuclear Fuel (SKN) has been that they cannot just keep the public informed; they must also listen to what the public, which they regard as the ultimate judge, wants and accepts (Cook, Emel & Kaspersen, 1991).

3.3.8.4 Spent Fuel Storage Technological Factors

According to IAEA (1994), a spent fuel storage facility can be described by a combination of the following characteristics: heat transfer medium (i.e. wet or dry); location (i.e. at or away from the reactor); and size (i.e. the number of power stations that the facility can support). Table 3-56 below lists at reactor (AR) and away from reactor (AFR) as SNF storage technological capabilities that are used worldwide by NPP operators. Based on the country's waste management strategy, relevant know how has to be developed or acquired. The Indian nuclear waste management philosophy takes into consideration capabilities shown below in Figure 3-60 based on the diversity of its nuclear operations.

Some businesses have been built around capabilities in dealing with spent nuclear fuel storage. Holtec International is supplying engineering, site construction, security, fabrication, and pool-to-pad loading services for the Callaway installation, which is an underground storage facility that was developed after the 9/11 attacks (Reitenbach, 2015).

Table 3-56: Spent Nuclear Fuel Cycle Storage Capabilities

Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
Spent Fuel Storage	At Reactor (AR) Spent Fuel Storage	Facilities located in the reactor site, in which spent fuel is stored temporarily, usually in the reactor pool.
	Away from Reactor Wet Spent Fuel Storage	Facilities, located outside the reactor site, in which spent fuel is stored temporarily in pools.
	Away from Reactor (AFR) Dry spent Fuel Storage	Facilities, located outside the reactor site, in which spent fuel is temporarily stored in dry silos or containers.

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

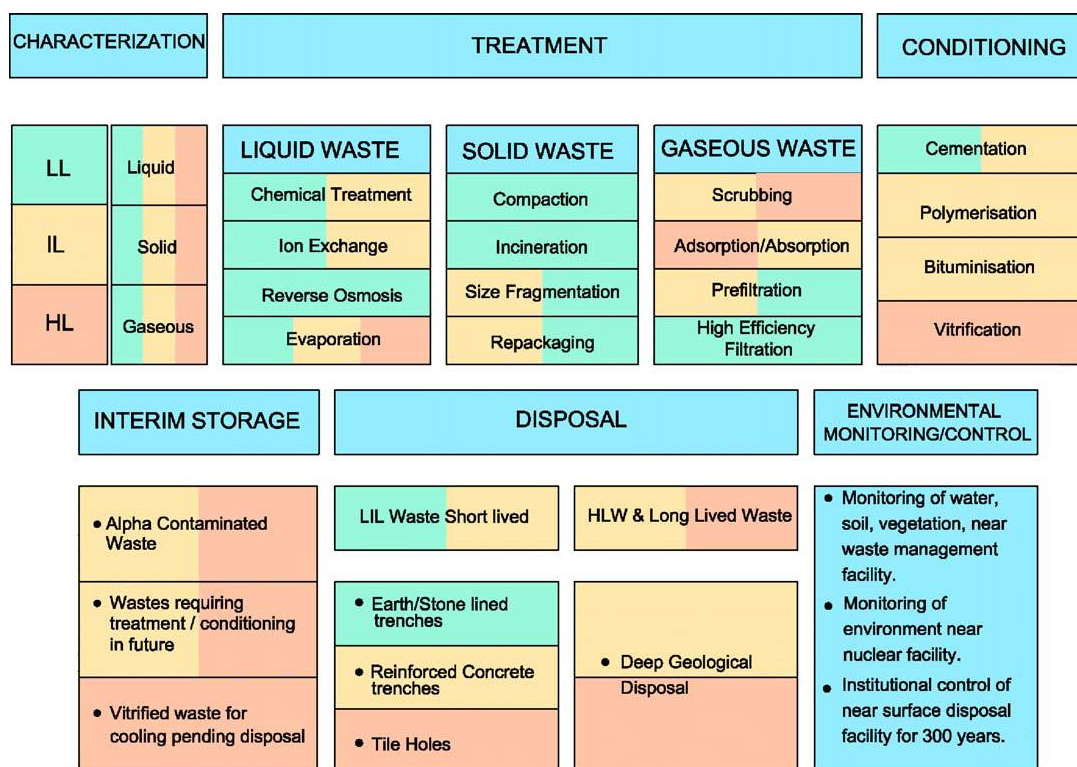


Figure 3-60: Management of radioactive waste

Source: Raj (2006)

3.3.8.4.1 Spent Fuel Storage R&D Technological Considerations

Development of dry storage technology was done for the following design concepts: metal cask; concrete cask or silo; vault; and dry well (IAEA, 1994a). Some advantages of dry storage over wet storage are that there is no generation of liquid waste, no need for a complex and expensive purification system, fewer corrosion concerns and dry storage is easier to transport if in the future the storage needs to be sent to another repository or to the final disposal (Ratiko et al., 2018). As for the SA, limited quantities of SAFARI spent fuel spent fuel based on the original US fuel supplies were sent back to the US whilst for the AEC produced MTR fuel it was decided from a technical and economic point of view to construct an away-from-reactor pipe storage facility on the Pelindaba site, called the Thabana Pipe Store.

3.3.8.4.2 Spent Fuel Storage Design and Engineering Technological Considerations

Most LWR fuel storage pools are of similar design, rectangular in horizontal cross-section and 12-13 metre-deep (IAEA- STI/DOC/010/361, 1994). Silva et al. (2008) contended that the design of such facilities must incorporate features that will be effective for their lifetime namely:

- a) maintenance of subcriticality;
- b) maintenance of fuel integrity;
- c) minimization of fuel cladding corrosion;
- d) removal of spent fuel decay heat;
- e) provision of radiation protection;
- f) maintenance of isolation of radioactive material;
- g) expansion of the facility capacity; and
- h) its eventual decommissioning.

According to Reitenbach (2015), cask designs vary by manufacturer, but some of the main variants involve purpose (some designs can be used both for transportation and storage), orientation (vertical or horizontal), materials (stainless steel is most common, though cast iron is also used), and siting (above ground on a cement pad or subsurface).

NSF cask design analysis and simulation are crucial in making sure that the storage will take into consideration the fuel assemblies conditions during storage. Accordingly, Ko et al. (2014) noted that in South Korea the following was undertaken for design of cask shielding:

- the evaluation simulated burnup up to 45,000 MWD/MTU and decay during ten years of cooling using the SAS2H/OGIGEN-S module of the SCALE5.1 system; and

- the results from the source term evaluation were used as input data for the final shielding evaluation utilizing the Monte Carlo N-Particle Transport Code MCNP Code, which yielded the effective dose rate

3.3.8.4.3 Spent Fuel Storage Manufacturing Technological Considerations

For Koeberg, Phase 1 of the Spent Fuel Storage initiative entails the procurement of fourteen HI-STAR 100 metal casks from Holtec (NNR Annual Report, 2016-2017). From a manufacturing perspective, the cylindrical canister that stores spent nuclear fuel is fabricated by welding together two rolled and axially welded cylindrical sections, so that there are four full-penetration welds of primary concern: the mid-circumferential weld, the bottom weld, and two axial welds (upper half and lower half), which are indicated in Figure 3-61 below. Similarly, a GAO (2014) report states that the dry storage systems typically consist of either a thick-walled, bolted steel vertical cask, or a welded steel canister inside a vertical or horizontal steel-reinforced concrete cask.

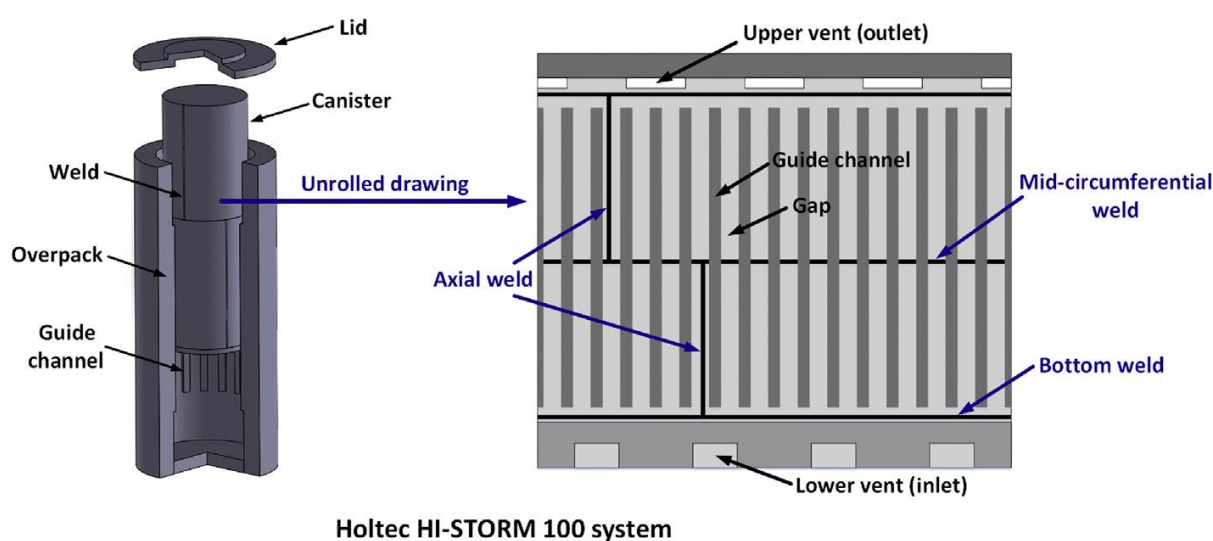


Figure 3-61: A 3-D cutaway view of vertical-axis HI-STORM 100 cask and an unwrapped overlay of the canister welds on the overpack inner liner

Source: Choi, Cho and Lissenden (2018)

3.3.8.4.4 Spent Fuel Storage Construction Technological Considerations

In the USA state of New Mexico, Holtec plans to build a \$280 million CISF to host 10,000 storage canisters, representing 120,000 MT of spent fuel, between the cities of Carlsbad and Hobbs (Nuclear Energy Insider, 2018).

3.3.8.4.5 Spent Fuel Storage Operation and Maintenance Technological Considerations

Extension of interim storage periods for spent fuel casks beyond the designed lifetime requires, in comparison to the components of an NPP, an increasing knowledge of material degradation with potential impact on cask integrity, e.g. leak tightness (Erhard et al., 2011). During long term interim storage, the main driving forces of aging effects are gamma radiation, neutron radiation, decay heat, outer corrosion effects (e.g. moisture and air pollution), relaxation, creeping, corrosion of bolted and sealed lid systems, basket and fuel rods (Wille et al., 2014). Figure 3-62 is an IAEA (1999) illustration of the process of aging management.

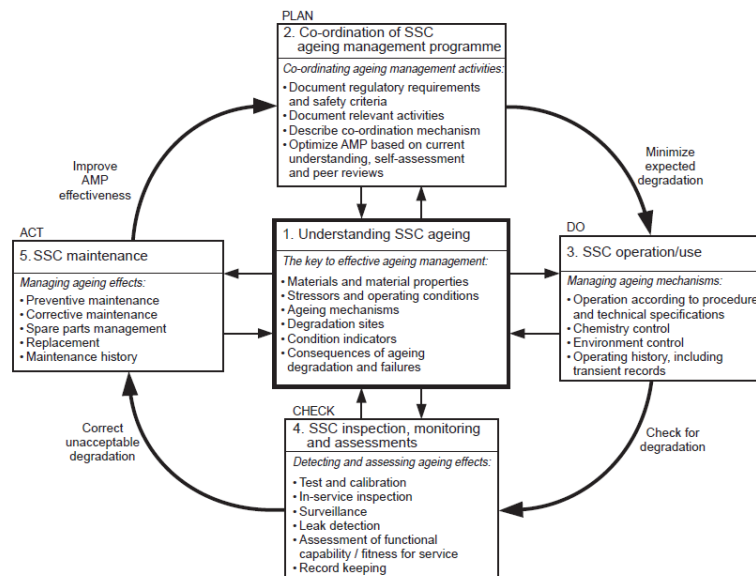


Figure 3-62: Process of aging management

Source: IAEA (1999)

3.3.8.4.6 Spent Fuel Storage Waste Management and Disposal Technological Considerations

The Koeberg NPS's original design was for it to store spent fuel on site for only 5 years and then send them to France for reprocessing (Eskom, n.d.). Recent designs of reactors have in fact now incorporated pools that can accommodate nuclear spent fuel for a lifetime of over periods of up to 40 years (IAEA, 1999b). In 1990, Eskom had to order and use four Castor X/28 F licensed for dual transport/storage casks for temporary storage of Koeberg spent nuclear fuel assemblies due to delays in the spent fuel pool re-racking initiative (Rokita, Hill & Clapisson, 2006). Jappie (2016) stated that Eskom currently has 112 spent fuel assemblies in dry storage inside four Castor X/28F casks that are stored inside the Cask Storage Building (CSB) on the Koeberg NPS site.

3.3.8.5 Spent Fuel Storage Environmental Factors

Dry storage of spent fuel in the United States has a good safety record and since storage began in 1985, no major safety incidents with radiation release have occurred (MacFarlane, 2001). Hence, efforts are needed to store more spent fuel in dry form, in structures called casks that are less susceptible to damage from industrial accidents, natural disasters, or even terrorist attacks (Alvarez, 2012). Spent nuclear fuel has been stored safely in pools or in dry systems in over 30 countries for a number of decades and because of these achievements, it is clear that spent fuel can be managed without any detriment to the public health and safety (IAEA, 2009). However, it is known that the two aforementioned storage methods are not permanent. Some countries are still examining the possibility of permanent storage at the repositories. The USA has been considering the Yucca Mountain as a possible site. The first construction licence for a deep geological disposal facility for spent nuclear fuel was granted for the Onkalo facility in Finland (IAEA, 2016d)

3.3.8.5.1 Spent Fuel Storage R&D Environmental Considerations

Research related to the safe operation, monitoring and analysis of spent fuel pool (SFP) behaviour includes probabilistic risk assessment, improved modelling of phenomena during abnormal and

accident conditions, non-destructive evaluation of SFP steel liners and concrete walls, and activities that support safe, integrated management of used fuel at nuclear plant sites (EPRI, 2014).

3.3.8.5.2 Spent Fuel Storage Design and Engineering Environmental Considerations

The selected worldwide alternative for the final disposal of HLW is the deep geological isolation in underground repositories comprising a multibarrier system made of engineered and natural barriers (Rodriguez, 2014). Specifically, designed casks that are multi-purpose or dual-purpose are required to transport spent fuel assemblies from e.g. interim wet or dry storage to the deep geological repositories. Ko et al. (2014) noted that in South Korea, for the purpose of interim storage and transportation, a dual-purpose metal cask that can load 21 spent fuel assemblies is being developed by Korea Radioactive Waste Management Corporation (KRMC) in Korea. Figure 3-63 shows a General Nuclear Systems, Inc. designed spent fuel transport cask. The main body of this particular CASTORH V/19 is cast iron as compared to other designs that have a rolled steel main body.

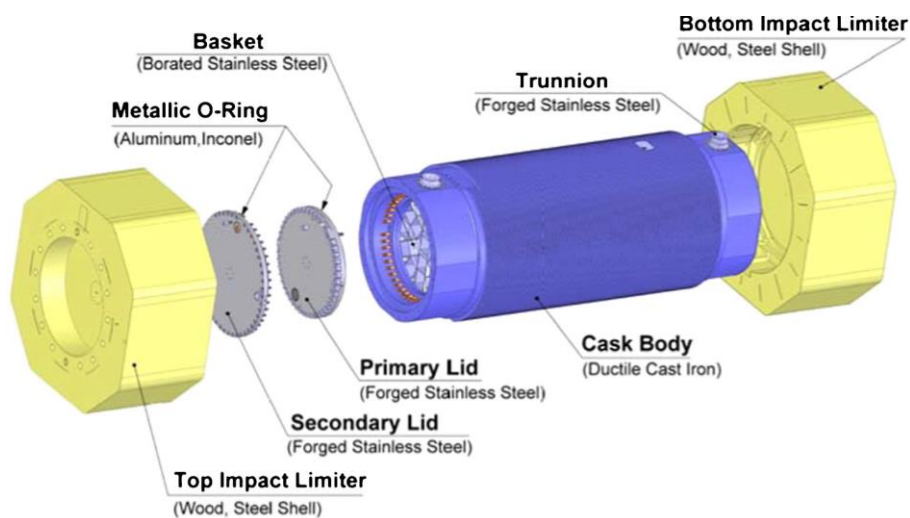


Figure 3-63: Main components of CASTORH V/19 spent fuel transport cask
Source: Droste et al. (2014)

When examining shielding design requirements for South Korea, Ko et al. (2014) contended that the design of the spent fuel storage facilities should consider many factors, such as the casks' arrangement, radiation workers' working condition (ex. installation, visual examination, radiation monitoring, and

maintenance, etc.), and operating procedures. Figure 3-64 below shows a shielding analysis model for single storage cask.

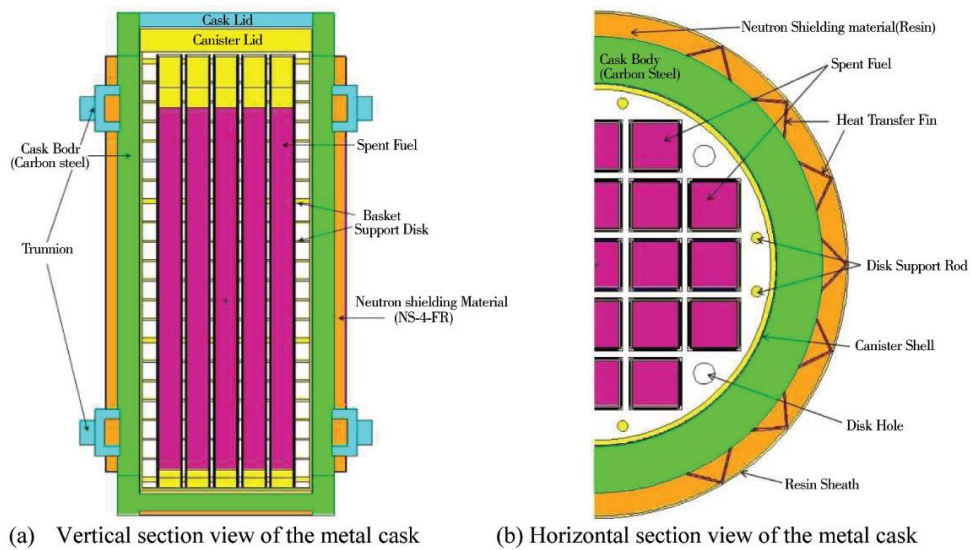


Figure 3-64: Shielding Analysis Model for Single Storage Cask

Source: Ko et al (2014)

Dry casks used for storage have to be designed taking into consideration environmental accidents or incidents. This being the case, dry casks have withstood earthquakes and floods, and are designed to withstand the heat of fires and the impact of airplanes; the 100-ton structures are hard to steal or damage, and require no cooling systems or power supplies (Rosner & Lordan, 2014).

3.3.8.5.3 Spent Fuel Storage Manufacturing Environmental Considerations

Figure 3-65 below is an illustration that lists areas of consideration during the safety assessment and manufacturing of dual-purpose casks (DPCs). The factors are still relevant for the development, design and usage of the DPCs.

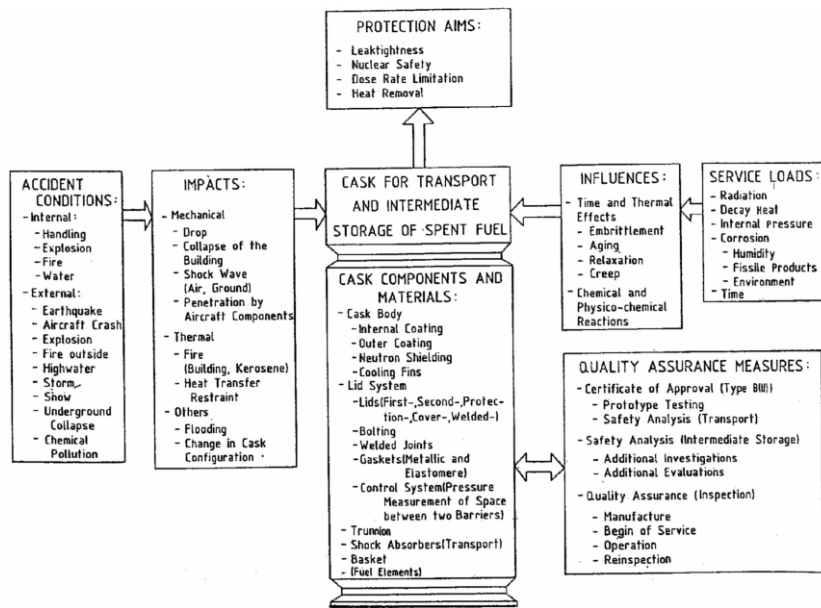


Figure 3-65: Dual-purpose cask safety assessment considerations
(Source: Droste et al. (2014))

3.3.8.5.4 Spent Fuel Storage Construction Environmental Considerations

In order to fulfil the requirements for the safety of fuel bundles, casks and storage facilities where casks are stored, deep understanding of different processes that take place in a cask and also its interaction with the environment is crucial (Poškas et al., 2017). For instance, in both wet and dry storage, the decay heat of spent fuel must be cooled to a safe temperature to prevent cracking of the spent fuel cladding from where hazardous radioactive nuclides could be released and harm humans and the environment (Ratiko et al., 2018).

3.3.8.5.5 Spent Fuel Storage Operation and Maintenance Environmental Considerations

Most commercial spent nuclear fuel is stored immersed in pools of water designed to cool and isolate it from the environment (Rusco, 2014). To ensure integrity of the fuel, the purity of the water in the spent fuel pool is controlled by filters and demineralizers, and the temperature of the water is maintained by use of coolers (Murray & Holbert, 2015). SF storage facilities that are in operation are not immune to accidents caused by natural disasters. Hence, the importance of taking into consideration of the severity and possible effect of natural disasters to the SF. The Fukushima disaster involved serious

accidents at four reactors and three storage facilities, a total of seven simultaneous severe accidents (Andrianov, 2015). In this regard, people are worried about nuclear safety and risk of environmental destruction, especially after the Fukushima accident in March 2011 (Lim, 2017). In this regard, the dry storage is said to be much safer than the wet storage. In addition, the casks used in dry storage systems are designed to resist floods, tornadoes, projectiles, fires and other temperature extremes, and other unusual scenarios (Alvarez, 2012). Overall, the storage facility contains all technical and security infrastructure for operation, casks with the radioactive contents under dry and inert conditions and a building containing the casks and all handling, maintenance and monitoring equipment (Wille et al., 2014).

3.3.8.5.6 Spent Fuel Storage Waste Management and Disposal Environmental Considerations

Most countries are still searching for sustainable ways of handling their back-end HLW. Sustainability could be seen as the process of preserving the status of nature and leaving it no worse than we found it: the value we relate to this notion is environmental friendliness (Taebi & Kadak, 2010). Hence it is crucial that that used fuel storage approaches which are chosen and employed should be those that will enhance safety and the preservation of the environment.

3.3.8.6 Spent Fuel Storage Legal Factors

In 2001, the Russian Parliament approved legislation to allow the importing of foreign SNF for storage and reprocessing in spite of negative public reactions, and it became the only country in the world that imports SNF (Lim, 2016). The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management was adopted on 5 September 1997 by a Diplomatic Conference convened by the International Atomic Energy Agency at its headquarters from 1 to 5 September 1997. Hence, the Republic of South Africa acceded to the Joint Convention on 15 November 2006, and its obligations under the convention entered into force on 13 February 2007 (NNR Fourth Report 2017). In the USA, NRC regulates the construction and operation of commercial nuclear power

plants and spent fuel repositories, as well as the storage and transportation of spent fuel (Spent Nuclear Fuel, 2012).

3.3.8.6.1 Spent Fuel Storage R&D Legal Considerations

Research and development assist in proving that storage methods developed can be licensed by individual regulators. R&D submissions to the regulators as part of obtaining authorization for the developed storage methods can therefore give assurance to the public that e.g. issues pertaining to safety and environment have been taken into consideration. Performance of existing wet and dry SF storage facilities' SSCs have to be monitored and investigated as part of maintaining the regulatory licence requirements. Figure 3-66 below is an illustration of the license renewal process based on the US NRC requirements. It is important to note that, the Fukushima disaster involved serious accidents at four reactors and three storage facilities, a total of seven simultaneous severe accidents (Andrianov et al., 2015). Hence, different countries embarked on the reviewing of their SF facilities using the Fukushima accident as the basis. In examining the Fukushima Dai-ichi accident for insights into reactors in the United States, the Task Force addressed protecting against accidents resulting from natural phenomena, mitigating the consequences of such accidents, and ensuring emergency preparedness (US NRC, 2011).

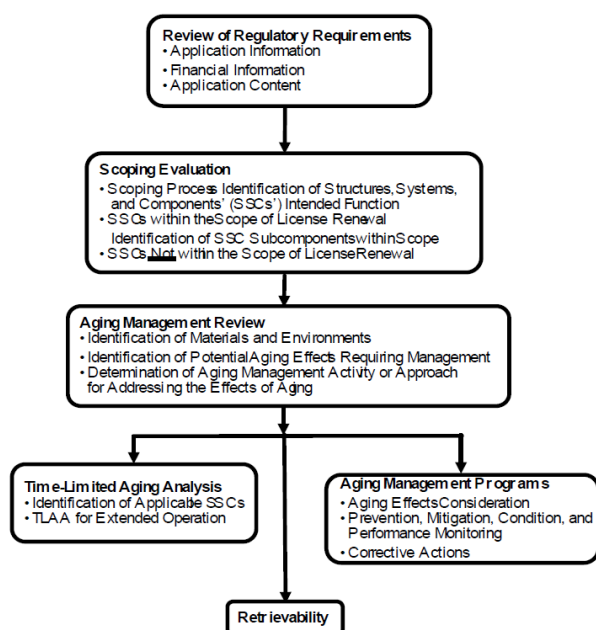


Figure 3-66: License Renewal Process
Source: Istar, Regan and Hornseth (2009)

3.3.8.6.2 Spent Fuel Storage Design and Engineering Legal Considerations

For Koeberg, the NNR (2016-2017) Annual Report stated that Eskom has recently submitted the safety justification for the use of the HI-STAR 100 metal casks. As shown in the fourth row of Table 3-57 below, the HI-STAR 100 is one of the cask designs that the US NRC approved for dry storage as of 2006.

Table 3-57: Dry spent fuel storage designs currently approved by US NRC

	Supplier	System Designator
1.	BNFL Fuel Solutions Corp.	VSC-24
2.	BNFL Fuel Solutions Corp.	Fuel Solutions
3.	General Nuclear Systems, Inc.	CASTOR V/21
4.	Holtec International	HI-STAR 100
5.	Holtec International	HI-STORM 100
6.	NAC International	NAC-UMS
7.	NAC International	NAC-MPC
8.	NAC International	NAC S/T
9.	Transnuclear, Inc.	NUHOMS-24P
10.	Transnuclear, Inc.	NUHOMS-52B
11.	Transnuclear, Inc.	NUHOMS-61BT
12.	Transnuclear, Inc.	NUHOMS-32PT
13.	Transnuclear, Inc.	NUHOMS-24PHB
14.	Transnuclear, Inc.	TN-24
15.	Transnuclear, Inc.	TN-68
16.	Transnuclear, Inc.	Advanced NUHOMS-24PT1

	Supplier	System Designator
17.	Transnuclear, Inc.	TN-32

Source: OECD-NEA (2006)

3.3.8.6.3 Spent Fuel Storage Manufacturing Legal Considerations

Nuclear regulators in countries that have wet and dry SF storage facilities have the responsibility to see to it that the SSCs manufacturing is undertaken in accordance with required regulatory codes and standards requirements. According to US NRC (2011), the primary responsibility for safety rests with licensees, and the NRC holds licensees accountable for meeting regulatory requirements. In the Koeberg situation, Eskom is the licensee that has to see to it that the wet and dry storage facilities SSCs meet NNR requirements. For instance, Holtec's supply of spent fuel HI-STAR 100 casks for Koeberg is in accordance to NNR requirements.

3.3.8.6.4 Spent Fuel Storage Construction Legal Considerations

Wet and dry SF facilities construction or installation of SSCs must comply with regulatory requirements. As stated earlier, both Greenfield and brownfield SF storage installations and their SSCs had to be evaluated and upgraded where it was deemed necessary i.e. using the Fukushima accident as the basis.

3.3.8.6.5 Spent Fuel Storage Operation and Maintenance Legal Considerations

Frazier and Bukharin (2009) contended that those who seek to design, construct, and operate future commercial nuclear facilities or transport special nuclear material would greatly benefit from an understanding of NRC licensing and oversight processes and procedures.

3.3.8.6.6 Spent Fuel Storage Waste Management and Disposal Legal Considerations

The National Radioactive Waste Management Policy and Strategy lays down options to be considered for managing used fuel and high-level waste in SA (DME, 2005). According to Bredell and Stott, (n.d.) the then regulatory authority Council for Nuclear Safety (CNS) that is now the NNR is responsible for

the licensing of all nuclear installations in SA including disposal of radioactive waste and the storage of spent fuel.

3.3.9 Spent Fuel Disposal

To ensure the effective management and control of radioactive waste, the government shall ensure that a national policy and a strategy for radioactive waste management be established (IAEA, 2012). Stamford and Azapagic (2011) contend that the end of the nuclear life cycle waste storage and disposal is arguably the most contentious issue for nuclear power. The international consensus is that geological disposal is the preferred solution for the ultimate disposal of higher activity radioactive waste (Gill, Livens, & Peakman, 2014). From a strategic point of view, Figure 3-67 below shows that waste disposal is an alternative to reprocessing. HLW from the reprocessing plants will need to be accommodated at the waste disposal sites or facilities as shown the illustration. Otherwise, the spent fuel disposal facilities entail spent fuel conditioning and spent fuel disposal activities as shown in Table 3-58.

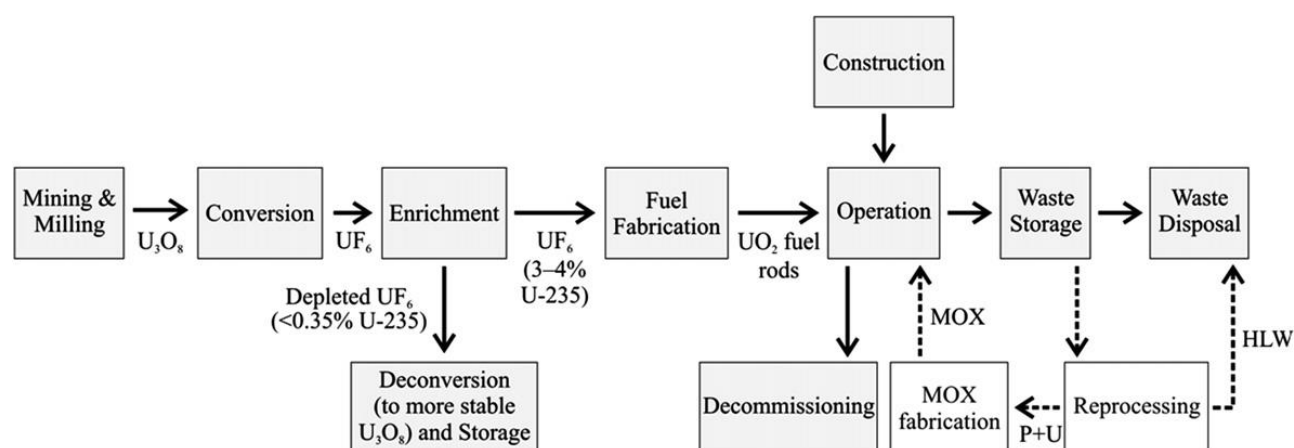


Figure 3-67: The life cycle of nuclear power (HLW: high-level waste; MOX: mixed oxide fuel).

Table 3-58: Spent fuel disposal facilities

Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
Spent Fuel Conditioning	Spent Fuel Conditioning	Facilities in which spent fuel is conditioned for a longer term interim storage or for disposal.
Spent Fuel Disposal	Spent Fuel Disposal	Facilities in which spent fuel is disposed permanently.

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

3.3.9.1 Spent Fuel Disposal Political Factors

At a time of intensifying debate over energy and environmental policies, the very high stakes in deciding what to do with spent nuclear fuel place in sharp reflection the value conflicts over decision-making structures that we confront in governing (Karlesky, 2012). To enable sustainable utilization of nuclear power and also to achieve a breakthrough for domestic deadlock situation, the Republic of Korea (ROK) changed its spent nuclear policy from the once-through usage and direct disposal to a total system approach that includes pyro-processing, sodium-cooled fast reactors, and a two-tier geological repository (Ahn, 2014). In Europe, both Finland and Sweden are moving towards geological disposal of SF using the KBS-3 concept that they have collaborated on (Bennett & Gens, 2008). Table 3-59 below shows progress so far in undertaking deep geological disposal options by different countries. Consequently, a new understanding of the public participation in the political decisions in nuclear issues after the Fukushima accident caused a restart of the process of finding and exploring a final repository site in Germany; this was from a technical point of view in works already done in the 1980s at the Gorleben site (Spykman, 2018). Rogers (2009) stated that for those countries that do follow a long-term highly radioactive waste disposal policy there generally are several common features to their disposal programmes namely:

13. First, governments have been slow to address the problem of the mounting inventories of highly radioactive waste generally due to the political costs of constructing a centralized disposal facility;
14. Second, the “polluter pays” principle is followed (i.e., those who generate the waste are responsible for paying the disposal costs) where special disposal funds financed by the nuclear utilities have been set up to pay for feasibility studies and operating costs;
15. Third, independent regulatory agencies have been established to be responsible for the final disposal of nuclear waste;
16. Fourth, the multi-barrier approach is being followed using both natural and man-made engineered barriers to contain the highly radioactive waste; and
17. Finally, a deep underground geologic repository is the preferred method for disposal.

Table 3-59: Commonly accepted disposal options

Option	Suitable waste types	Examples
Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of metres)	LLW and short-lived ILW	- Implemented for LLW in many countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK and USA. - Implemented in Finland and Sweden for LLW and short-lived ILW.
Deep geological disposal (at depths between 250m and 1000m for mined repositories, or 2000m to 5000m for boreholes)	Long-lived ILW and HLW (including used fuel)	- Most countries have investigated deep geological disposal and it is official policy in several countries. - Implemented in the USA for defence-related transuranic waste at WIPP. - Preferred sites selected in France, Sweden, Finland, and the USA. - Geological repository site selection process commenced in the UK and Canada.

Source: World Nuclear Association (2017)

3.3.9.1.1 Spent Fuel Disposal R&D Political Considerations

While the ultimate quantity of HLW that the USA must manage or dispose of is inextricably linked to the future of nuclear power, this future is more uncertain than in Sweden by comparison (Solomon, 2009). The U.S. Department of Energy has been studying a site at Yucca Mountain, Nevada, to determine if it is a suitable site for a geological repository for spent nuclear fuel and high-level radioactive waste (Saeb & Patchet, 2003). The 1982 Nuclear Waste Policy Act bound the federal government by law to take custody of all civilian waste from power companies for final disposal, under the assumption that the waste would be permanently stored in a deep geological repository at Nevada's Yucca Mountain and overseen by the Energy Department (Rosner & Lordan, 2014). However, in fiscal year (FY) 2009 the Obama Administration decided to terminate the Yucca Mountain Nuclear Waste Repository and explore nuclear waste disposal alternatives (OCRWM) Fiscal Year 2010). According to Gill, Livens and Peakman (2014), in democratic societies, proposals to develop major nuclear facilities are often controversial and hence difficult to implement, and the direction of whole programmes can change fundamentally over very short timescales in response to political changes (e.g. the German decision, post-Fukushima, to exit nuclear energy). Whilst the USA has been struggling to

reach political consensus on the Yucca Mountain Nuclear Waste Repository, other countries have been making progress in that regard. Bennett and Gens (2008) contended that in May 2001, the Finnish Parliament accepted a decision in principle, for deep geological disposal of SF in the bedrock at Olkiluoto, near the site of the existing nuclear power plant operated by Teollisuuden Voima Oy (TVO).

3.3.9.1.2 Spent Fuel Disposal Design and Engineering Political Considerations

Interim storage of spent fuel may be technically safe and cost-effective, yet political opposition may obstruct storage plans, ultimately causing nuclear reactors to shut down from lack of storage space (MacFarlane, 2001).

3.3.9.1.3 Spent Fuel Disposal Manufacturing Political Considerations

There is a need to develop sound national strategies to bridge the gap between the confidence that specialists have regarding the safety of the geologic disposal concept and the impression that the public and many national decision makers have that such disposal will result in unacceptable hazards and environmental risks to current and future generations (Semenov, 1992).

3.3.9.1.4 Spent Fuel Disposal Construction Political Considerations

A familiar argument against building new nuclear power plants in the U.S. is that there is no long-term solution to the used nuclear fuel storage problem (Hylko, 2008). For Finland disposal NSF at repository seems to be that long-term solution. As required by the Finnish Nuclear Energy Act that a policy decision (Decision-in Principle) needs to be applied for nuclear facilities prior to implementation, the Finnish Parliament ratified the Decision-in-Principle in 2001 for the construction of the final disposal facility of spent fuel to at the Olkiluoto site in Western Finland.

3.3.9.1.5 Spent Fuel Disposal Operation and Maintenance Political Considerations

The Swedish Nuclear Fuel and Waste Company (SKB) was formed by four nuclear power station utilities to assist in their adherence to Swedish law that requires a licensed operator of a nuclear facility to take primary responsibility for the safe handling and disposal of spent fuel and radioactive waste, as

well as for decommissioning and dismantling the facility (Skala, n.d.). In this regard, the said law drives the Swedish government policy on nuclear spent fuel management.

3.3.9.1.6 Spent Fuel Disposal Waste Management and Disposal Political Considerations

As for the Finnish policy, two utilities that operate nuclear power stations formed a company known as Poliva that has been given the responsibility to dispose of spent fuel at the ONKALA repository. The ONKALO repository in Olkiluoto on Finland's west coast will be at a depth of 400-450 metres with about 70 km of tunnels and shafts, will be receiving for disposal copper canisters filled with nuclear spent fuel for about 100 years before being sealed (IAEA Bulletin, 2017).

3.3.9.2 Spent Fuel Disposal Economic Factors

A \$222 billion industry has sprung up to decommission these behemoths (Griggs, 2018). A reflection of the intent to fix market failures in environmental regulation was the creation of the Polluter Pays Principle (PPP) that is a principle mandates that those who produce pollution have to bear the costs of managing it (Cordella, 2017).

3.3.9.2.1 Spent Fuel Disposal R&D Economic Considerations

The costs for developing the Swedish KBS3 repository technology and carrying out deposition can be estimated and covered by funds already paid in, and are still paid into the Nuclear Waste Fund (SKB, 2010). Otherwise, Figure 3-68 illustrates other possible arrangements for funding radioactive waste disposal R&D.

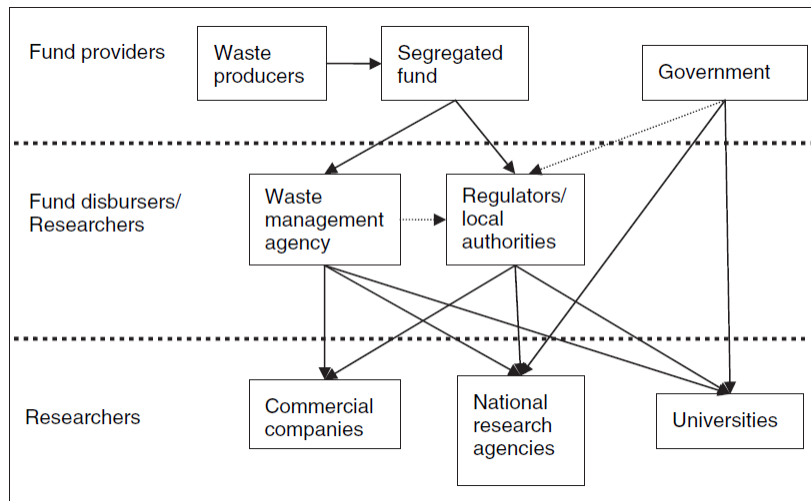


Figure 3-68: Example of funding arrangements for R&D on radioactive waste disposal – note that this is only one of many funding models.

Source: Hooper (2007)

3.3.9.2.2 Spent Fuel Disposal Design and Engineering Economic Considerations

One of the attributes of the KBS-3 design is to keep the radiation to personnel low during all handling steps and this disposal method is economic from a point of view that the canister is able to cater for unprocessed fuel assemblies (SKB, 2010).

3.3.9.2.3 Spent Fuel Disposal Manufacturing Economic Considerations

One of the advantages of the KBS repository is that it consists of a large number of identical modules of moderate dimensions that enables the fabrication the canister, the bentonite buffer and the handling equipment, as well as demonstration and verification of the handling of the waste in a repository prototype of moderate dimensions (SKB, 2010).

3.3.9.2.4 Spent Fuel Disposal Construction Economic Considerations

The IAEA Bulletin (1992) states that the highlighting of economic benefits derived from installation of a disposal facility is important when communicating with the public about disposal programmes. Likely, the Finland's ONKALA repository construction will take place at the Olkiluoto site that has a community that already appreciates economic benefits derived from installed nuclear facilities.

3.3.9.2.5 Spent Fuel Disposal Operation and Maintenance Economic Considerations

It will be possible to monitor the operation of the KBS3 disposal repository whilst at the same time, there are good prospects of preventing access by unauthorised persons and with comparable effort, future generations should be able to retrieve the spent fuel if they desire (SKB, 2010).

3.3.9.2.6 Spent Fuel Disposal Waste Management and Disposal Economic Considerations

In Finland, the share of waste management is roughly 10% of the production costs of nuclear electricity and since the beginning of power plant operation, funds for waste management were collected (Ryhanen, 2003).

3.3.9.3 Spent Fuel Disposal Social Factors

Transparency, procedural equity and public participation are regarded internationally as key elements of the safety management concerning all nuclear facilities (Di Nucci, Brunnengraber & Losada, 2017). In this regard, there must be recognition within the technical and scientific community that implementing any form of nuclear waste disposal is determined not only by technical or regulatory processes but also by broad public acceptance (Saeb & Patchet, 2003). In 1988, the Korean Atomic Energy Commission said that a repository not located on the site of a nuclear power plant was to be completed by the end of 1997, but the plan failed eventually, mainly because of opposition from communities near potential repository sites (Kang, Kim & Lee, 2015). Consequently, it is crucial for governments to correctly identify public perception, attitude, and preference towards spent nuclear fuel and its related facilities to establish public consensus and design a viable spent nuclear fuel management plan, that is, the construction and operation of new spent nuclear fuel facilities (Woo et al., 2017). Indeed, the earlier in the decision-making process that public and stakeholder engagement (PSE) occurs—for example, on the consideration of options and alternatives—the greater the chance of reaching a successful outcome that properly reflects the values and opinions of stakeholders (Kemp, Bennett & White, 2006).

3.3.9.3.1 Spent Fuel Disposal R&D Social Considerations

Bergmans et al. (2015) stated that particularly with regard to siting repository facilities, we have witnessed across the European Union (EU), a shift from a purely technical approach to one that includes stakeholders and the public in the decision-making process and aims to integrate, to a bigger or lesser extent, the technical with the social. Rosner and Goldberg (2013) contend that for those who favour an open cycle, Sweden and Finland serve as excellent models today for successfully navigating both technical issues and public opinion to dispose of their spent nuclear fuel in a permanent repository that does not allow retrieval of used fuel. Other countries have also been involved in public participation as they considered their disposal concepts. In Canada, the Atomic Energy of Canada Limited (AECL) has consulted government departments and agencies, scientists, engineers, sociologists, ethicists, and other members of the public members of Canadian society to help ensure that the disposal concept and the way in which it would be implemented are technically sound and represent a generally acceptable disposal strategy (Simmons & Baumgartner, 1994). Despite all the AECL efforts on the developing the disposal concept and stakeholder consultations, the Canadian government came up with new legislation that required AECL and the utilities to form an arm's length to deal with spent nuclear fuel. Ramana (2013) stated that in 2002, Ontario Power Generation, Hydro Quebec, New Brunswick Power Corporation, and AECL created the Nuclear Waste Management Organization (NWMO) in accordance with the 2002 Nuclear Fuel Waste Act (NFWA). Elaborating on the mandate Dowdeswell, (2003) noted that the NFWA was the government of Canada's response to the Seaborn Panel review of AECL's disposal concept for nuclear waste and at a minimum, it required NWMO to study the following options and make recommendations by November 2005.

- Deep geological disposal;
- Storage at the nuclear reactor sites; and
- Centralised storage either above or below ground.

The above NWMO selection challenge is a good example of where a strategic decision-making model can be used by a waste management organization to arrive to recommend a way forward. Organizations mandated with the responsibility of spent fuel management have to contend with stakeholders' concerns and perceptions during site selection. As an example, Table 3-60 below is a comparison of site selection processes and the role of public participation in Finland and Sweden.

Table 3-60: Comparison of site selection processes and the role of public participation

	Finland	Sweden
Beginning of the site selection process	Site selection process started in the 1980s.	Site selection process started in the 1970s.
Resistance to site selection	Local resistance by the mid-1980s.	Local opposition from the beginning.
Continuity/discontinuity of the site selection strategy	Continuity in site selection strategy.	Earlier site selection strategy discontinued in 1985.
Site selection strategy	DAD approach for site selection, but after new nuclear Energy Act [1987] with veto power to municipalities and EIA-law [1994] with public participation demand style moved towards MUM approach.	DAD approach for site selection in the beginning. Flexible, voluntarism-based siting strategy and MUM approach adopted in 1995. Municipalities interested in the siting investigations.
Participatory style	Public participation within EIA-process. Posiva's and municipality of Eurajoki's negotiations outside EIA result a benefits package.	Openness for participation initiatives coming outside of SKB. Nuclear communities' participation initiatives.
The time of site selection	In 1999, Posiva chose a site (Eurajoki) for both a repository and an encapsulation plant. DiP application for the government. Approval from the municipality council in 2000. Positive decision from the Government in 2000 and ratification by the Parliament in 2001.	In 2009, SKB chose sites for both the repository (Östhammar) and an encapsulation plant (Oskarshamn).
Handling of construction license application	Construction license application made on 28 December 2012 to the Government. A construction licence issued on 12 November 2015.	Construction license applications on 16 March 2011 to SSM and Land and Environment Court. Land and Environment Court's statement in February –June 2017. After that, Östhammar's and Oskarshamn's will make their decisions with veto power. A possibly referendum will be held in Östhammar in 2017 or 2018. In the end of the process there will be a Government decision on construction license.

Source: Litmanen et al. (2017)

3.3.9.3.2 Spent Fuel Disposal Design and Engineering Social Considerations

The engineering design effort put on the development of disposal facility SSCs is crucial in allaying fears by general public more so for communities in which disposal repositories will be located. Among the nuclear fuel management organisations (Finnish's Poliva, Sweden's SKB, Canadian's NWMO) are considering copper, the primary existing design consists of a two-part container, where an inner steel or cast-iron insert provides structural support and positions fuel, and an outer copper shell provides a corrosion barrier within the DGR (Keech et al., n.d.).

3.3.9.3.3 Spent Fuel Disposal Manufacturing Social Considerations

Various stakeholder perceptions on spent fuel disposal repositories are possible influenced by the availability and utilisation of proven manufacturing processes for spent fuel disposal repository SSCs. For the Canadian manufacture of disposal facility test prototypes and for fabrication development studies, and in the absence of codes specific to the fabrication and inspection of nuclear fuel waste disposal containers, currently recognized engineering codes (ASTM & ASME 111, V, VIII, IX) were used, both in direct application and as design guides for good engineering practice (Johnson et al., 1994).

3.3.9.3.4 Spent Fuel Disposal Construction Social Considerations

South Korean SF waste generators have been considering and undertaking stakeholder consultations about final disposal of its NPP used nuclear fuel. On July 16, 2015, the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS) recommended that the government should complete the construction of a permanent disposal facility by 2051 (Lim, 2016).

3.3.9.3.5 Spent Fuel Disposal Operation and Maintenance Social Considerations

According to Keech et al (n.d.), opposition to transportation of nuclear waste has been a key factor in anti-nuclear protests around the world, and these have had some impact both on the growth of nuclear power in general as well as on the siting of nuclear waste repositories.

3.3.9.3.6 Spent Fuel Disposal Waste Management and Disposal Social Considerations

In common with developments and trend in other countries, the UK has moved to a position where there is now widespread recognition that radioactive waste management requires not only sound technical assessment of risk, but also public participation, consultation and stakeholder dialogue on proposed solutions and the associated risks (Kemp, Bennett & White, 2006).

3.3.9.4 Spent Fuel Disposal Technological Factors

Nuclear waste management in Sweden corresponds with the pursuit of *Kärnbränslesäkerhet* (KBS), which literally translates as ‘nuclear fuel safety’ (Elam, & Sundqvist, 2011). Finland, Sweden and the UK have already indicated that they will adapt the KBS-3 concept (Figure 3-69 below) in managing their nuclear spent fuel (Bennett & Gens, 2008). According to Bråkenhielm (2013), the KBS-3 method entails the following:

- (1) The SNF is loaded into copper canisters with high resistance to corrosion in the repository environment. The approximately 5 m long canisters have an insert of nodular iron that increases their stability;
- (2) A buffer of bentonite clay (a naturally occurring material that swells in water) protects and shields the canister respectively against movements of rock and water. This limits the amount of corrosive substances in the groundwater that can reach the canister. The clay also absorbs radioactive substances that can be released if the canisters should be damaged;
- (3) The canisters with surrounding bentonite clay is placed at a depth of about 500 m in crystalline bedrock with long-term stable conditions; and
- (4) If any canister should be damaged, the nuclear fuel and the chemical properties of the radioactive materials, for example their low solubility in water, severely limit the transport of radionuclides from the repository to the ground surface.

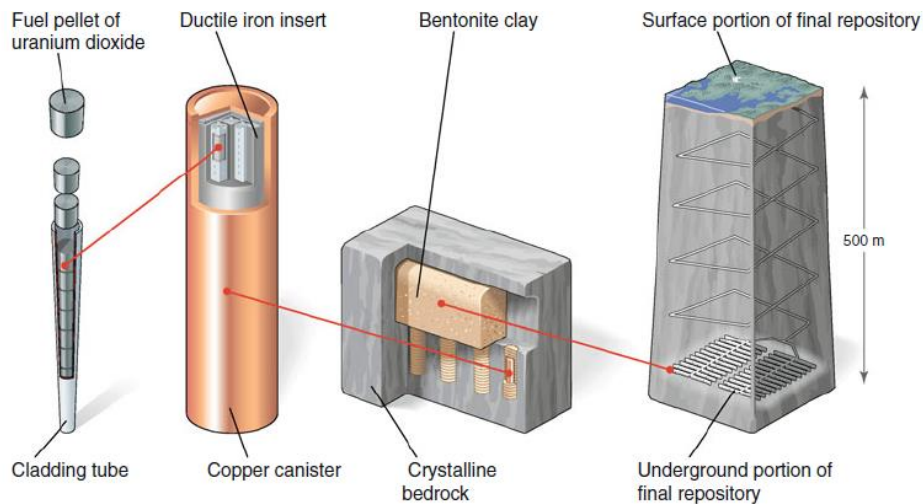


Figure 3-69: The KBS-3 concept for disposal of spent nuclear fuel
Source: Andersson et al. (2013)

3.3.9.4.1 Spent Fuel Disposal R&D Technological Considerations

It is important to note that research and development (R&D) is cross-cutting when undertaking the nuclear fuel cycle front-end and back-end programme. This means that R&D activities can be undertaken e.g. to develop design, manufacturing, construction, operation & maintenance and waste management technologies or knowledge. The cross-cutting nature of R&D is depicted below in Figure 3-70.

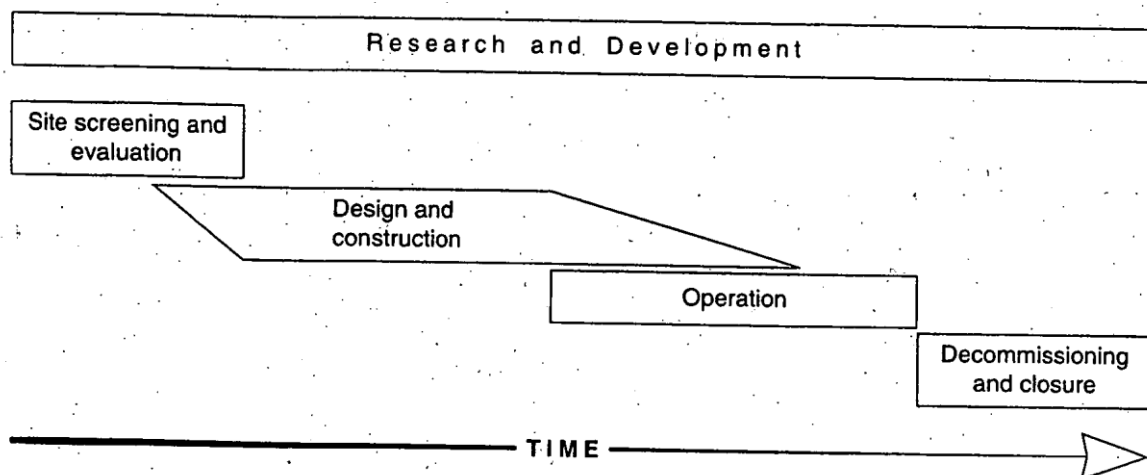


Figure 3-70: Stages in encapsulation and disposal
Source: OECD-NEA (1993)

The development of disposal spent fuel containers in the form of casks and canisters is crucial for the disposal concepts. In 1978, the company GNS started the approved application for the first CASTOR® cask (CASTOR® 1a) with a monolithic cask body made of ductile cast iron, closed with a double lid system with metallic gaskets (Wille et al., 2014). Figure 3-71 below is an illustration of the geoscientific disciplines forming the base for the SDM models included geology, thermal properties, rock mechanics, bedrock hydrogeology, bedrock hydro geochemistry, bedrock transport properties and surface ecology (Andersson et al., 2013).

The adoption of KBS-3 as the UK reference repository concept for high-level waste disposal as well as spent fuel disposal has reconnected the KBS project with nuclear reprocessing and a closed nuclear fuel cycle for the first time since the late 1970s (Elam & Sundqvist, 2009). In the KBS-3 concept (shown in, it is planned that after 30 to 40 years of interim storage, SF will be disposed of at a depth of about 500 m in crystalline bedrock, surrounded by a system of engineered barriers (Bennett & Gens, 2008). The French national radioactive waste management agency, Andra, is investigating reversible and irreversible radioactive waste storage/geological disposal in deep granite and clay formations (Bennett & Gens, 2008). Consequently, the European Union's Sustainable Nuclear Energy Technology Platform (2007) states that research and development activities related to residual high-level long-lived waste behaviour in geological disposal will be carried out within the framework of the proposed Geological Disposal Technology Platform currently being evaluated as part of the CARD project (Euratom Framework Programme) by the European waste agencies. Figure 3-72 below shows some of the European Commission R&D initiatives aimed at developing the closed fuel cycle as a solution to spent fuel disposal. In a timely fashion, with the international stagnation of developments in nuclear reprocessing, the back end of the nuclear fuel cycle was suddenly transformed into a new front for the Swedish nuclear industry (Elam & Sundqvist, 2009).

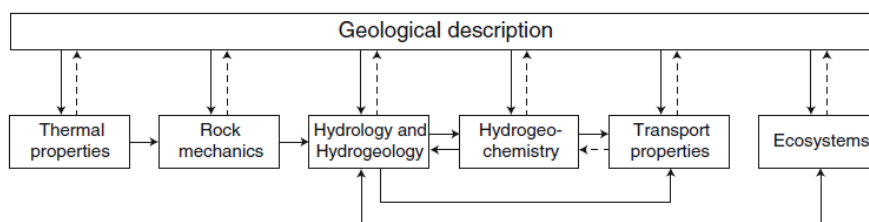


Figure 3-71: The different discipline descriptions in the site-descriptive modelling are interrelated by several feedback loops

Source: Andersson et al. (2013)

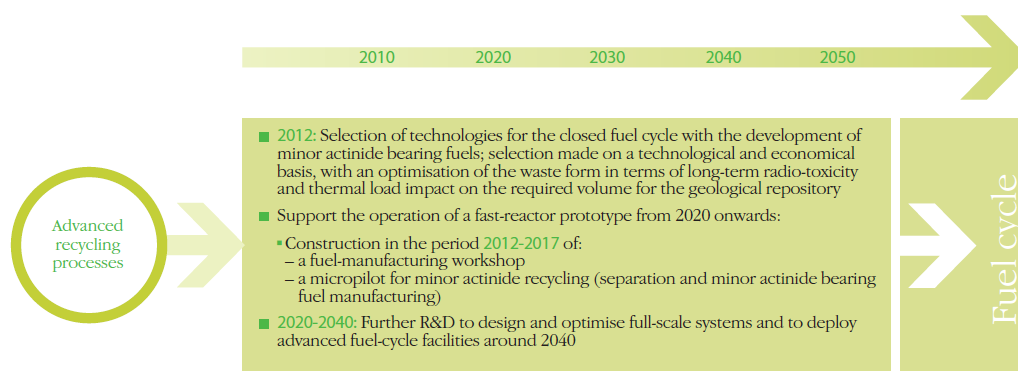


Figure 3-72: EU's Sustainable Nuclear Energy Technology Platform for closed fuel cycle

3.3.9.4.2 Spent Fuel Disposal Design and Engineering Technological Considerations

Based on the resulting site-descriptive models (SDM), repository engineering (design) will produce layouts of the underground facility (Strom et al, 2008). For the Yucca Mountain in the USA, among the more important considerations are the quantities and types of radioactive materials to be stored; geologic characteristics such as the rock strength and thermal behaviour of the designated site; and the projected impact on and functioning of the area's natural groundwater system (Rautman, Reid & Ryder, 1993).

Designers of SF disposal sites have to also contend with engineering of canisters which will contain the used fuel assemblies. According to Pusch and Weston (2015), the interest of nearly all countries that

consider HLW disposal in crystalline rock, exemplified by China, Korea, Czech Republic, Japan, Finland, Korea, Ukraine and India, is focused on the principal design proposed by the Swedish Nuclear Fuel and Waste Management Company (SKB) represented by its concept KBS-3V. Thus, current development in countries like Sweden and Finland, spent nuclear fuel will be placed into copper–iron canisters which will be disposed in the deep geological repository (Dušan & Matjaž, 2010). Hence, the designs for both Finland's and Sweden's repositories are based on a model called KBS-3, developed by SKB, a nuclear waste specialist firm set up by Sweden's nuclear utility firms (Mascarelli, 2013). KBS-3 encloses spent fuel rods in 5-metre-long copper capsules. In this regard, King et al. (2011) stated that a 1D reactive transport model has been developed to predict the evolution of the corrosion behaviour of copper canisters in a KBS-3 style repository. As for copper canister manufacturing development, several technical alternatives are tested in parallel, such as electron beam and friction-stir welding and ultrasonic, x-ray and eddy current inspection techniques. The plant's designer Posiva, a waste management specialist jointly owned by Finnish nuclear companies Fortum and TVO, says that it is now able to carry out detailed engineering work on the designs (The Chemical Engineer, 2015).

3.3.9.4.3 Spent Fuel Disposal Manufacturing Technological Considerations

The KBS-3 copper canisters require testing after they are fabricated so as make sure that they will perform in accordance with requirements. The technologies for both welding and testing are currently being developed and demonstrated in full-scale at the Canister Laboratory in the town of Oskarshamn (Grahn & Skogsberg, 2006)

3.3.9.4.4 Spent Fuel Disposal Construction Technological Considerations

SKB's concept implies that 20–25 m² tunnels are blasted at about 400 m depth a few tens of metres apart and that ~1.9 m diameter canister deposition holes are bored to about 8 m depth from the floor of them with a spacing of 6–8 m depending on the thermal properties of the rock (Pusch & Weston, 2015).

3.3.9.4.5 Spent Fuel Disposal Operation and Maintenance Technological Considerations

Deep geological disposal is planned to be operational in Finland by 2020, Sweden by 2023 and France by 2025, with Germany, the UK and Belgium possibly following by 2040 (Stanič, 2011). In SA the LLW and ILW is stored in Pelindaba or at Vaalputs. So far NECSA has had the responsibility to manage the two facilities. Table 3-61 below lists disposal facilities in different countries and entities that are responsible for operating and maintaining them. For instance, the facility in the United Kingdom is an operated consortium that includes foreign entities such as Areva.

Table 3-61: Examples of Disposal Facilities in Different Countries

Country	Disposal Facilities
UK	LLW Repository at Drigg in Cumbria operated by UK Nuclear Waste Management (a consortium led by Washington Group International with Studsvik UK, Serco, and Areva) on behalf of the Nuclear Decommissioning Authority.
Spain	El Cabril LLW and ILW disposal facility operated by ENRESA.
France	Centre de l'Aube and Morvilliers operated by ANDRA.
Sweden	SFR at Forsmark operated by SKB.
Finland	Olkiluoto and Loviisa, operated by TVO and Fortum.
Russia	Ozersk, Tomsk, Novouralsk, Sosnovy Bor, operated by NO RAO.
South Korea	Wolseong, operated by KORAD.
Japan	LLW Disposal Centre at Rokkasho-Mura operated by Japan Nuclear Fuel Limited.
USA	Five LLW disposal facilities: Texas Compact facility near the New Mexico border, operated by Waste Control Specialists; Barnwell, South Carolina; Clive, Utah; Oak Ridge, Tennessee – all operated by Energy Solutions; and Richland, Washington – operated by American Ecology Corporation.

Source: World Nuclear Association (2017)

3.3.9.4.6 Spent Fuel Disposal Waste Management and Disposal Technological Considerations

The extent of the radioactivity of the nuclear waste informs the type of technologies to be used for disposal. As mentioned earlier on, a number of countries such as Sweden and Finland are involved in different waste management programmes that include final disposal sites and NSF containers.

3.3.9.5 Spent Fuel Disposal Environmental Factors

The management and disposal of SNF is a very important issue in the current and future considerations of expansion of nuclear power and its environmental footprint (Vuji, Anti & Vukmirovi, 2012). A good part of environmental regulation i.e. both national and transnational is based on principles found in two international instruments namely; the 1972 Declaration of the United Nations Conference on the Human

Environment and the 1992 Rio Declaration on Environment and Development, both of which are built on the recognition of some general principles that must be observed by all States.

3.3.9.5.1 Spent Fuel Disposal R&D Environmental Considerations

As part of finding solutions for the final disposal of SF it is important to embark on R&D related initiatives aimed at determining or predicting the impact of the environmental phenomenon to the disposal facilities. Under the social consideration, it was mentioned that Posiva is the entity that was given the responsibility to establish the final depository for SF in Sweden. In order to obtain a decision-in-principle from the Council of State for establishing a final disposal facility Posiva was required by law (468/1994) to present an Environmental Impact Assessment (EIA) to the authorities as part of the application (Kojo, Kari & Litmanen, 2010). Equally important is the understanding of the impact of disposed SF to the environment. In recent years, the environmental issue has come to occupy a predominant place in energy policy and ISO 14000 series have prepared the standardization of environmental management system (EMS) including LCA for the environmental assessment of products or processes (Lee & Koh, 2002).

Earlier I also noted that Anderson et al. (2013) stated that a model known as the SDM could generate layouts for the Swedish spent fuel geological repository. These layouts in turn form the basis for a preliminary safety evaluation of the area and, eventually, a complete safety assessment (Strom et al, 2008). The national programmes of nuclear waste management have to identify and assess the anticipated degradation modes of the selected materials in the corresponding repository environment, which evolves in time (Rodríguez, 2014). Currently, requirements for final geological disposal are not well defined (IAEA, 2000a).

3.3.9.5.2 Spent Fuel Disposal Design and Engineering Environmental Considerations

The design of NSF geological disposal facilities has to take into consideration environmental phenomenon such as earthquakes and degradation of SSCs. Hence this is a paramount factor with the KBS-3 spent fuel repository in Sweden. According to the SKB Technical Report (2010), the safety and

radiation principles of most importance for the design of the KBS-3 repository are the multi barrier principle, the defence-in-depth principle and radiation protection principles to protect both human health and the environment and both current and future generations.

3.3.9.5.3 Spent Fuel Disposal Manufacturing Environmental Considerations

The Fukushima accident has had a major impact on the public perception of the safety of nuclear technology. The public opinion strongly believes that the accident had important consequences to population health and the environment (Poinssot et al., 2014)

3.3.9.5.4 Spent Fuel Disposal Construction Environmental Considerations

The disposal facilities that are constructed have to take into consideration the Fukushima debacle. Various repository SSCs have to meet the stringent standards to enable the human beings and environment protection.

3.3.9.5.5 Spent Fuel Disposal Operation and Maintenance Environmental Considerations

The operational safety of the repository facility refers to technical, organisational and administrative measures to prevent i) the canister from being damaged in such a way that the containment is breached and radioactive substances dispersed, or ii) the occurrence of radiation doses higher than those accepted for normal operation of the facility (SKB, 2010).

3.3.9.5.6 Spent Fuel Disposal Waste Management and Disposal Environmental Considerations

A Governmental review of nuclear policy has recommended that spent fuel from Koeberg should be stored at Vaalputs, but this will depend upon the policy followed after the reracking and deep spent fuel geological disposal evaluation (Moore & Hambleton-Jones, 1996).

3.3.9.6 Spent Fuel Disposal Legal Factors

The South African Vaalputs is at present licensed only for the disposal of low and intermediate radioactive level wastes and offers unique features as a potential interim spent fuel storage and final

disposal site, such as favourable geology (granite), low seismicity, low population density, remoteness from industrial centres and arid conditions (Bredell & Stott, 1997). The Radioactive Waste Management Policy and Strategy for the Republic of South Africa (2005) states that deep geological disposal is currently the most internationally pursued option and as such investigations to consider this as a South Africa option should commence as soon as possible. The OECD-NEA Report (2016) states that Posiva which is a company made of two Finnish nuclear utilities (Fortum Power and Heat (FPH) and Teollisuuden Voima (TVO)) is implementing a spent fuel disposal programme with the following main objectives, which are in line with Finnish Ministry of Employment and the Economy's decision:

Disposal site selection in 2000 (the Olkiluoto site was proposed by Posiva in the decision-in-principle application of 1999; the application was approved by the host municipality in Jan 2000, the decision was made the Government in Dec 2000 and ratified by the Parliament in May 2001)

18. Start of construction of an underground rock characterisation facility at Olkiluoto in 2004, the repository depth of 420 m was reached in 2010;
19. Construction licence application for the disposal facility in December 2012; and
20. Start of operation of the disposal facility around 2020.

Currently in Finland, the valid Regulatory Guides pertaining to nuclear waste management are Guides YVL 8.1–8.5 and according to the new drafts the Guides pertaining to the disposal of spent nuclear fuel will belong to the YVL-D series (Table 3-62 below) consisting of a total of five Guides (Posiva, 2013b).

Table 3-62: Guides pertaining to the disposal of spent nuclear

Radiation and Nuclear Safety Authority (STUK) Regulatory Guides YVL-D series	Regulatory Oversight Focus Area
D.1,	Deal with nuclear non-proliferation control
D.2	Deal with the transport of nuclear material and nuclear waste
D.3	Deal with the processing, storage and encapsulation of spent nuclear fuel
D.4	Deal with nuclear waste management and decommissioning activities
D.5	Deal with the disposal of nuclear waste

When it comes to the systems, structures and components important to safety, the manufacturing, installation and operating design shall be done in such a way that quality inspections and tests undertaken to verify their integrity are commensurate with the importance to safety of each item (Posiva, 2005).

3.3.9.6.1 Spent Fuel Disposal R&D Legal Considerations

According to SKB, the KBS-3 spent fuel disposal facility safety analysis offered scientific evidence that bedrock is of less importance for safety and therefore sites could be sought more freely (Elam, Soneryd & Sundqvist, 2010). The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently worked out a concept, KBS-3V (Figure 3-73 below), for disposal of highly radioactive waste in the form of spent reactor fuel and asked for the Government's approval and licensing (Pusch & Weston, 2015). An important part of SKB's licence application for the construction, possession and operation of the KBS-3 repository is the safety report (SKB, 2010).

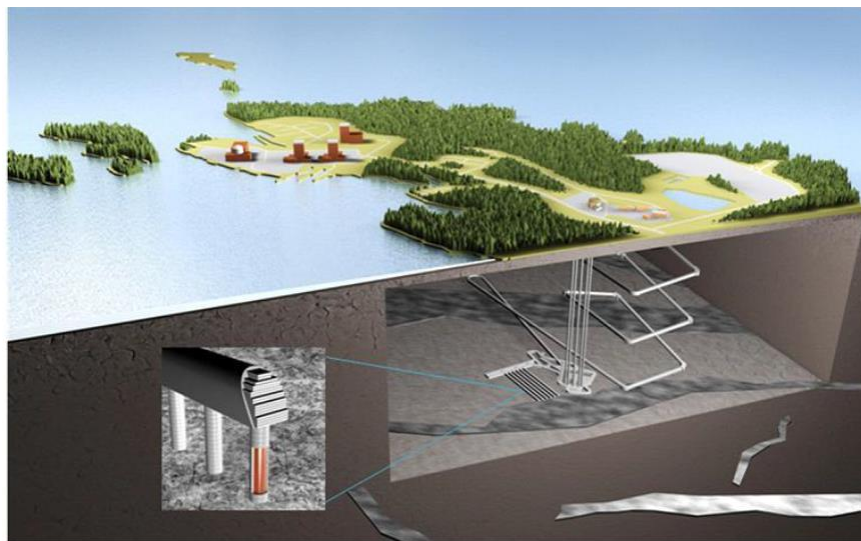


Figure 3-73: Concept image of the KBS-3V final disposal solution
Source: Posiva (2012)

3.3.9.6.2 Spent Fuel Disposal Design and Engineering Legal Considerations

STUK (2002) states that according to Section 4 of the Finnish Government Resolution, the disposal facility and its operation shall be designed so that:

- 1) as a consequence of undisturbed operation of the facility, discharges of radioactive sub-stances to the environment remain insignificantly low;
- 2) the annual effective dose to the most exposed members of the public as a consequence of anticipated operational transients remains below 0.1 mSv; and
- 3) the annual effective dose to the most exposed members of the public as a consequence of postulated accidents remains below 1 mSv.

3.3.9.6.3 Spent Fuel Disposal Manufacturing Legal Considerations

Disposal canisters consist of two main components: the outer shell, made of oxygen free copper and the insert, mainly made of nodular graphite cast iron (Posiva, 2013b). The quality assurance of the canister pre-fabrication process is undertaken according to the normal procedures adapted for nuclear power plant component manufacturing and Posiva and KBS are jointly developing qualifying procedures for canister manufacturing, welding and inspection (Posiva, 2003).

3.3.9.6.4 Spent Fuel Disposal Construction Legal Considerations

In Sweden, the Swedish Nuclear Fuel and Waste Management Company (SKB) has recently submitted a licence application for the construction of a spent fuel encapsulation plant, and SKB plans to submit a further license application in 2009 for the construction of a final repository for spent nuclear fuel (Bennett & Gens, 2008). The Chemical Engineer (2015) reported that Finnish regulators have given final approval to a plan to build a nuclear waste depository and processing plant beneath Olkiluoto Island.

3.3.9.6.5 Spent Fuel Disposal Operation and Maintenance Legal Considerations

Regulatory bodies in countries that have chosen the SF final disposal route will be challenged in operational approval or licences to the entities that will be operating and maintaining such facilities. All aspects of operation relevant to safety are considered, including surface and underground excavation,

construction and mining work, waste emplacement, and backfilling, sealing and closing operations (IAEA, 2011).

3.3.9.6.6 Spent Fuel Disposal Waste Management and Disposal Legal Considerations

South Africa has an AEC operated National Radioactive Waste Disposal facility called Vaalputs that is located some 600 km north of Cape Town and is at present licensed only for the disposal of low and intermediate radioactive level wastes (Bredell & Stott, 1997).

As the United States grapples with where and how to bury spent nuclear fuel and wastes, France recycles its used nuclear fuel and vitrifies radioactive wastes to stabilize them before burial (Valenti, 1995).

3.3.10 Spent Fuel Reprocessing and Recycling Factors

Reprocessing of spent fuel is a chemical process that separates spent fuel from remaining (unspent) low-enriched uranium, fission products produced in the fission process, and, importantly, a new material that has been produced in the fuel—plutonium-239, which is fissionable and so usable as fuel (Adamantiades & Kessides, 2009). For over 40 years, civil reprocessing of spent fuel utilizing the PUREX process on a commercial scale has occurred without incidents of diversion of special nuclear materials (IAEA, 2008h). The reprocessing industry began in the 1940s and 1950s when facilities were established to manufacture plutonium for weapons in the United States, Soviet Union, United Kingdom and France and then in the mid-1960s, attention shifted to civil reprocessing (Walker, 2006). The United States, the United Kingdom and Russia were the first countries to develop and exploit reprocessing technology in the nuclear weapons programmes and then later France, China and India embarked on the same (NWMO, 2003). According to the Radioactive Waste Management Policy and Strategy for the Republic of South Africa (2005), an investigation commissioned by the Department of Minerals and Energy has concluded that it would not be advisable to exclude the reprocessing, conditioning and recycling of used fuel. Reprocessing, which allows the uranium and plutonium contained in the spent fuel to be recovered for reuse, usually involves storage of the spent fuel for a period of time, typically 5-10 years, before reprocessing, followed by storage of the high-level radioactive waste for several

decades before disposal (IAEA, 1994). The French nuclear industry views uranium and plutonium as valuable fuels worth recycling because each metric ton of spent fuel contains the energy equivalent of 10,000 tons of oil (Valenti, 1995). The selection of a strategy for spent fuel management is a complex decision with many factors to be considered including politics, Economic, resource conservation, environmental protection, and public perception, the last of which has become a predominant factor in many Member States (IAEA, 2005). Before discussing reprocessing in detail, it is important to understand firstly the SNF, which is after all the raw material for reprocessing (Abdallah et al., 2015). The Table 3-63 below shows the composition of SNF and the issues associated with each constituent.

Table 3-63: Composition of SNF and the issues associated with each constituent

Constituent	Composition %	Issue	Disposition Path
Uranium (U)*	95-96	Energy resource	Separated uranium could be recycled as fuel in reactors
Plutonium (Pu)*	1	An energy resource, but also the major contributor to long-term radio-toxicity (and heat load) of the waste. Separated Pu constitutes a major proliferation concern	Separated Pu could be recycled in reactors as fuel. Proliferation concerns could be reduced by not separating pure Pu.
Minor Actinides (MAs) primarily Np, Am, and Cm	0.1	Important contributors to long-term radio-toxicity and heat source of the waste. Proliferation concerns exist concerning separated Np	MAAs can be burnt alone or in combination with Pu in fast reactors.
Stable or short-lived Fission Products (FPs)	3-4	Some FPs such as Cs and Sr are the primary contributors to the short-term radio-toxicity and heat source in the waste. Other FPs, e.g. noble metals, could be valuable	Storage of high-level waste (HLW) for a few hundred years or separation of Cs and Sr for separate disposal after a few hundred years of storage. Separated Cs has industrial applications
Long-lived fission products (LLFPs), Tc and I	0.1	Contributors to the long term radio-toxicity of the waste	No industrial process to limit the problem has been developed

Source: Abdallah et al. (2015)

*U and Pu are termed major actinides in the nuclear industry

At 40 000 MWdt⁻¹ burn-up, the used fuel assembly contains approximately 94.5% unused uranium, 1% plutonium, 0.2% minor actinides (neptunium, americium and curium), and 4.3% fission products by

weight (McFarlane & Todd, 2013). The selection of a strategy for spent fuel management is a complex decision with many factors to be considered including technical issues associated with the composition of the domestic reactor fleet, national legal and regulatory framework, political and public acceptance, Economic, and environmental protection (IAEA, 2008). Contributing to the IAEA proceedings Singer (1997) contends that “Higher uranium prices make nuclear power less attractive and favour reprocessing of nuclear materials over other disposal and storage options” (IAEA,1997). Table 3-64 below shows facilities and capability descriptions to be considered. The location of the reprocessing phase within the back end and with respect to the front end is illustrated below in Figure 3-74.

Table 3-64:Spent fuel reprocessing cycle stage facilities and their uses		
Nuclear Fuel Cycle Stage	NFCIS Facility Subtypes	Description
Spent Reprocessing Fuel and Recycling	Spent Fuel Reprocessing	Facilities in which spent fuel is reprocessed to retrieve nuclear material.
	Re-conversion to U_3O_8 (Rep. U)	Facilities in which Reprocessed uranium is converted to U_3O_8 .
	Co-conversion to MOX Powder	Facilities in which uranium and Plutonium is mixed in the form of MOX powder.
	Fuel fabrication (MOX Pellet-Pin)	Facilities in which MOX fuel pellets/pin are produced.
	Fuel fabrication (MOX Assembly)	Facilities in which MOX fuel assembly are produced.

Source: IAEA Nuclear Fuel Cycle Information System, 2009 Edition

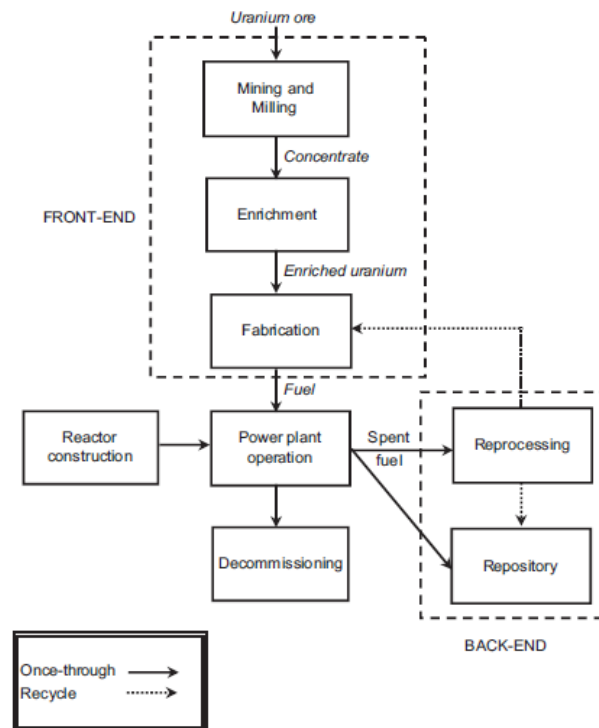


Figure 3-74: The nuclear fuel cycle
 Source: Norgate, Haque and Koltun (2014)

3.3.10.1 Spent Fuel Reprocessing and Recycling Political Factors

Political considerations include government policy and public support in particular, when the use of a reprocessing facility is under consideration (IAEA, 2017a). In several countries, there are governmental decisions pending on the desirability of pursuing either reprocessing or its alternatives, based on a number of considerations including the relationship of reprocessing to non-proliferation objectives and every country that chooses require the following:

1. Demonstration, on an industrial scale, of spent fuel reprocessing technology and waste management (some countries have already reached this stage);
2. Development and acceptance of methods for ultimate waste disposal;
3. Resolution of regulatory uncertainties;
4. Clarification of the respective roles and responsibilities of government and the private sector;
5. The assumption of increased responsibility for financing reprocessing plants by utilities; and

6. Provision of adequate information to the public.

France made the choice for a closed cycle very early on in the development of its nuclear programme and this strategic choice was driven with the aim of increasing the country's energy independence, while available domestic uranium resources were in limited amount (IAEA, 2005). According to the SA Nuclear Energy Policy (2008), Government, through NECSA, shall investigate the viability of building an indigenous reprocessing facility and in the short-term South Africa shall make use of existing commercial reprocessing facilities in other countries. While reprocessing of spent fuel was historically the favoured strategy for the back end of the fuel cycle, in the past few decades some countries have turned to other options (IAEA, 2005). Changing a fuel cycle from open to closed is a decision taken at the level of national governments and would take many years to implement (Rooney, Nuttall & Kazantzis, 2015). Some European countries pursue an active reprocessing policy (e.g. France, Great Britain) while others have opted for direct spent fuel disposal (e.g. Sweden and Finland) (Decamps & Dujacquier, 1997). However, it should be recognised that one person's waste may be another person's resource and this holds true, to a certain extent, for radioactive waste, although it is normally national policy that determines this point (McGinnes, 2007). Reprocessing-oriented fuel strategies have historically developed almost exclusively within the framework of strongly expansive nuclear policies (Hogselius, 2009).

3.3.10.1.1 Spent Fuel Reprocessing and Recycling R&D Political Considerations

Some countries already use reprocessing, and develop research to make it more secure and more competitive, while others prefer to adopt policies to prevent developments in this area due to the problem of nuclear proliferation (Silverio & de Queiroz Lamas, 2011). The U.S. and key international partners will accelerate the demonstration and deployment of new advanced recycling technologies such as UREX+ and pyro processing that recycle nuclear fuel in a manner that does not produce separated plutonium – a proliferation risk inherent in existing recycling technologies (DOE: GNEP, n.d.).

3.3.10.1.2 Spent Fuel Reprocessing and Recycling Design and Engineering Political Considerations

The aforementioned developments of new reprocessing technologies will require the USA government to acquire or develop the required UREX+ and pyro processing design-engineering expertise.

3.3.10.1.3 Spent Fuel Reprocessing and Recycling Manufacturing Political Considerations

The Purex process has been progressively and continuously improved, hence this improvement accounts for the successful commercialization of reprocessing in several countries (IAEA-TECDOC-1467, 2005). In retrospect, Feiveson et al., (2011) state that countries initially justified civilian reprocessing by the need for separated plutonium to provide start-up fuel for plutonium breeder reactors, but breeder reactors have not materialized. Listed in Table 3-65 below are examples of different countries' positions on NSF reprocessing. Bredell and Stott (1998) stated that no reprocessing facility exists in South Africa, and neither Eskom nor the AEC have plans to reprocess the spent fuel from Koeberg and SAFARI.

Table 3-65: Examples of various countries' reprocessing strategies

Country	Strategy
China, France, India, Japan, Russia and the United Kingdom	Reprocess spent fuel
Canada, Finland and Sweden	Keep the fuel for future reprocessing
United States	Has not completely defined its strategy.

Source: Leticia Borges Silverio, Wendell de Queiroz Lamas (2011)

3.3.10.1.4 Spent Fuel Reprocessing and Recycling Construction Political Considerations

As part of the ongoing Advanced Fuel Cycle Initiative (AFCI), the USA Department of Energy announced that it will initiate work toward conducting an engineering scale demonstration of the UREX+ separation process (operation planned for 2011) and developing an advanced fuel cycle facility

capable of laboratory development of advanced separation and fuel manufacturing technologies (CRS Report for Congress, 2008).

3.3.10.1.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Political Considerations

Government, through NECSA, shall investigate the viability of building an indigenous reprocessing facility and in the short-term South Africa shall make use of existing commercial reprocessing facilities in other countries (NEP, 2008).

3.3.10.1.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Political Considerations

According to the policy of Japan, spent fuel (SF) generated by nuclear power plants (NPPs) is designated as useful recyclable energy resource and shall be properly stored until reprocessing (Saegusa, Yagawa & Aritomi, 2008).

3.3.10.2 Spent Fuel Reprocessing and Recycling Economic Factors

Any State that does not produce an annual used fuel discharge sufficient to justify its own national reprocessing/recycling facility should be able to obtain adequate guarantees of supply through existing market players (WNA, 2011). Japan utilised reprocessing market players whilst it was still in the process of justifying the need to start the operation of its Rokkasho reprocessing plant. Its urge to get started with the operation was due to running out space for its used fuel and the cost of transporting and processing spent fuel in Europe. In the past during the 1970s, Japan's utilities made reprocessing contracts with BNFL in the United Kingdom and COGEMA in France that have resulted in the separation of a total of 41 tons of plutonium out of which only 2 tons have been returned to Japan (Katsuta & Suzuki, 2006). Decamps and Dujacquier (1997) noted that although reprocessing reduces the final volume of high-level waste by approximately half, some countries are currently reconsidering the direct disposal of spent fuel as a worthwhile alternative for a variety of reasons such as:

- 21.the reduced interest in recovering fissile materials, especially Pu;
- 22.Slow progress in the development of Fast Breeder Reactors; and
- 23.the high cost of reprocessing.

Some countries reprocess the spent fuel from their reactors to extract and reuse the uranium and plutonium and this substantially reduces the waste mass (most of that in the spent fuel is uranium) and can separate out the short-lived isotopes that are the primary heat source (Ahearne, 2011). With respect to India, Natarajan (2017) stated that it is prudent to recover the fissile material left in the spent fuel for reuse by reprocessing, as it reduces the requirement of fresh materials and it also reduces the volume of the radioactive waste to be disposed of for the same amount of power production. Figure 3-75 below shows trends in spent fuel management.

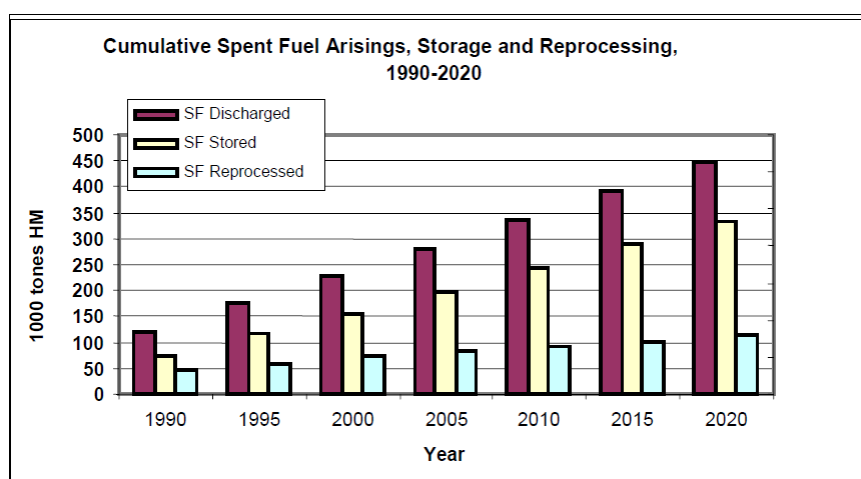


Figure 3-75: Trends in spent fuel management
Source: IAEA, (2008)

3.3.10.2.1 Spent Fuel Reprocessing and Recycling R&D Economic Considerations

Despite the anticipated nuclear renaissance, innovations such as closed NFC and plutonium breeder reactors that offer the possibility of large-scale and safe development of nuclear energy have not been commercially implemented (Andrianov, 2015). The early cycle costs not normally recovered in the price of a plant product sold consists of planning; research and development, pilot or prototype and

generic licensing costs (IAEA, 2008). In Finland, the nuclear power companies IVO and TVO manage the radioactive waste they produce; they are also responsible for the R&D programme needed for the safe and timely management of their waste; they have formed a joint body to coordinate their R&D work (Decamps & Dujacquier, 1997).

In situations where uranium is recovered from reprocessed spent fuel, it can be re-enriched for LEU fuel production (Bunn et al., 2003). The disadvantages of the recycling of spent nuclear fuel include the high costs, as well as the increase of low and intermediate level waste (LILW) generation (Choi, Hyo & Ko, 2016). An innovative development in recycling plutonium and uranium as MOX is Russia's REMIX fuel, not yet commercialised (WNA, 2017).

3.3.10.2.2 Spent Fuel Reprocessing and Recycling Design and Engineering Economic Considerations

The design-engineering and manufacturing costs for spent fuel reprocessing and recycling plant's SSCs are included in capitalised preconstruction costs presented in section 3.3.10.2.4 below as part of construction economic considerations.

3.3.10.2.3 Spent Fuel Reprocessing and Recycling Manufacturing Economic Considerations

According to Jackson (2007), commercial reprocessing costs at that time were approximately in the range of \$1,000 to \$2,000 CDN per kg of Heavy Metal (HM). Commercial reprocessing relies on a series of four main technological operations: fuel handling and shearing, fuel dissolution, materials separation and purification, and finally, waste treatment and conditioning (IAEA, 2005). According to McFarlane and Todd (2013), the following large-scale commercial reprocessing plants that are mostly similar in their designs and operating principles represent ninety percent of the reprocessing world market:

- the THORP plant in the United Kingdom, operated by Sellafield Ltd;
- the UP2 and UP3 plants in France, operated by AREVA; and

- the Rokkasho plant in Japan, operated by Japan Nuclear Fuel Limited (JNFL).

Otherwise, the WNA indicated that the commercial reprocessing capacity as of year 2017 was as shown in Table 3-66 below. France had the highest commercial capacity for LWR spent fuel.

Table 3-66: World commercial reprocessing capacity (LWR tonnes per year)

LWR fuel	France, Le Hague	1700
	UK, Sellafield (THORP)	600
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)	800*
	Total LWR (approx)	3500
Other nuclear fuels	UK, Sellafield (Magnox)	1500
	India (PHWR, 4 plants)	330
	Japan, Tokai MOX	40
	Total other (approx)	1870
Total civil capacity		5370

Source: WNA, 2017

*now expected to start operation in 2018

3.3.10.2.4 Spent Fuel Reprocessing and Recycling Construction Economic Considerations

Katsuta (2016) pointed out that in Japan the Rokkasho construction costs for the facility have nearly tripled, from the original estimate of \$7.6 billion to \$21 billion, mainly because of the increasing cost (\$260 million) of safety measures, according to Japan Nuclear Fuel Ltd. (JNFL). A reprocessing plant whose construction begins in the year T_0 , will come online 7 to 13 years later and have a plant life of 30–50 years (Recktenwald & Deinert, 2012). The IAEA (2008) states that capitalized costs are “up-front” costs that must be financed, and for which costs are recovered in the price charged for facility product over the amortization life of the project include:

- Total Directs = Capitalized Preconstruction (land, permits, licensing, etc.) + Capitalized Direct (structures, equipment, etc.);
- Basic Construction Cost = Total Directs + Capitalized Support Services (construction supervision, start-up costs, etc.);
- Total Overnight Cost = Basic Construction Cost + Capitalized Operations (staff recruitment and training, staff housing, etc.) + Capitalized Supplementary Costs (spare parts, taxes, etc.); and

- Capital Investment Cost = Total Overnight Cost + Capitalized Financial Costs (interest during construction; escalation, etc.)

3.3.10.2.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Economic Considerations

France also has capabilities in each area of the PWR and RR fuel cycle in particular, reprocessing capacity and technology is a major export earner (Kidd, 2009). Currently, uranium–aluminium SNF from research reactors is reprocessed at AREVA facilities on an industrial scale, and more than 23 t have already been reprocessed (IAEA, 2017a). The integrity and availability of nuclear fuel reprocessing plants for uninterrupted operation depends on the quality and performance of critical engineering components, vessels and piping (Raji & Mudali, 2006). Katsuta and Suzuki (2011) stated that despite the clear economic disadvantage, Japan’s Atomic Energy Commission has decided not to change its requirement that spent fuel be reprocessed and the Rokkasho reprocessing plant, therefore, started active testing on March 31, 2006. IAEA (2008) states that the annualized costs: recurring cash sums needed to sustain annual production include:

- Annualized Operations and Maintenance, such as salary costs (including benefits), operation chemicals, utilities, etc.; and
- Annualized Financial Costs, such as annual contributions to the Decontamination & Decommissioning Escrow Fund.

3.3.10.2.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Economic Considerations

The generation of radioactive waste in gaseous, aqueous, organic and solid forms by reprocessing plants is throughout the reprocessing flow sheet (McFarlane & Todd, 2013). Vitrification plants such as the one operated in Sheffield, UK are for managing the aforementioned waste on a commercial basis.

3.3.10.3 Spent Fuel Reprocessing and Recycling Social Factors

Gaining acceptance will be especially difficult unless the public can be shown the benefits of nuclear spent fuel reprocessing and the safety of the plant in a convincing and easily understandable way (IAEA, 2005).

3.3.10.3.1 Spent Fuel Reprocessing and Recycling R&D Social Considerations

Continuous efforts in R&D are resulting in new spent nuclear fuel (SNF) management technologies that might be the pathway towards helping the environment and the sustainability of nuclear energy and reprocessing and recycling of SNF could be one of the key points to improve the social acceptability of nuclear energy (Rodríguez-Penalonga & Soria, 2017). Because of nuclear proliferation concerns, the USA has been discouraging plutonium extraction but rather looking at advancing the uranium extraction as an alternative to former established spent fuel reprocessing method. Concerns about a “plutonium economy” led to the ban on spent fuel reprocessing and plutonium recycling by US Presidents Ford and Carter that was later lifted by President Reagan (Adamantiades & Kessides, 2009). In this regard, the US DOE advanced fuel cycle development programme proposes the uranium extraction (UREX) + process that is a concept with increased proliferation resistance since only uranium is recovered and recycled leaving plutonium with other transuranics for grouped fast reactor recycling (Glatz, 2012). When it comes to nuclear, many stakeholders keep on raising concerns on the management of nuclear waste. Hence the importance of R&D initiatives in bringing about SNF reprocessing and recycling technologies that will drastically reduce high-level nuclear waste. Stakeholders are interested in the reliability, safe and economic operation of the reprocessing plants. To ensure a reliable, safe and economic operation of reprocessing plants, the development of high corrosion resistant materials with high reliability is necessary since any failure of the component of reprocessing unit processes would lead to the leakage of radioactivity, and slowing down the production of useful fissile material required for sustained operation of power plants (Raj & Mudali, 2006).

3.3.10.3.2 Spent Fuel Reprocessing and Recycling Design and Engineering Social Considerations

The development of various advanced materials improves the reprocessing plant's performance by increasing safety margins and design flexibility. The design of reprocessing plant SSCs is important in terms of assuring the stakeholders that the reprocessing plant is perform in accordance to design requirements. Raj, Chellapandi and Mudali (2015) contend that factors that influence the service life of the structural components include: component design, selecting appropriate material, corrosion resistance, mechanical properties, fabrication, quality control, availability, cost, etc.

3.3.10.3.3 Spent Fuel Reprocessing and Recycling Manufacturing Social Considerations

Requirements of corrosion protection, decontaminability, and avoidance of radiation damage are the basis of selecting materials for fabricating reprocessing facilitates process equipment (Long, 1978). Katsuta (2016) stated that according to JNFL, the total length of the Rokkasho reprocessing plant piping is about 1,300 km (more than 800 miles) and piping that contains uranium and plutonium is about 60 km long, and the number of joints in this portion is about 26,000.

The first mixed-oxide (MOX) fuel elements manufacturing took place in the late 1950s and the process entails the blending of uranium (UO_2) and plutonium (PuO_2) powders to a plutonium enrichment that varies between 5 and 10%, followed by pressing and sintering at temperatures around 1700 °C.

3.3.10.3.4 Spent Fuel Reprocessing and Recycling Construction Social Considerations

As an example, the OECD-NEA (1977) states that the reprocessing industry has been unable to get large-scale units on-stream quickly to provide operating experience and technology demonstration because of the following reasons:

- regulatory uncertainties attributable in part to public acceptance; and
- the problem of the assumption of the financial burden has been a source of confusion and delay.

One of Japan's largest ever construction initiative, the Rokkasha, that is based on the French UP3 Cogema reprocessing plant design will be able to reprocess 800 tons of spent fuel from 10 Japanese

electric utilities responsible for construction, operation and decommissioning costs (Burnie & Smith, 2001). Takubo and von Hippel (2017) noted that the latest estimate of the total project cost for Japan's Rokkasho Reprocessing Plant, including construction, operation for 40 years, and decommissioning, is now 13.9 trillion yen (\$125 billion), with the construction cost alone reaching 2.95 trillion yen (\$27 billion), including 0.75 trillion yen for upgrades due to Fukushima accident. At the time of the undersea earthquake that caused the Fukushima disaster, Rokkasho use its emergency turbine generator for five days having lost its external power supply and a total of 600 litres (or more than 150 gallons) of water leaked from a pool used to store spent fuel rods (Katsuta, 2016).

3.3.10.3.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Social Considerations

There are times though that spent fuel reprocessing entities' operations have been off the mark in assuring stakeholders that they will remain ethical and remain resolute in adhering to safety requirements. A major public scandal occurred when it was revealed that the Cogema the French company managing the reprocessing plant at Cap La Hague, knew that about a third all shipping containers its subsidiary sent across Europe by rail were contaminated with "loose surface radioactivity" with some containers registering at levels as much as 3000 times the legal limit (Rothstein, 1998). UK has had its share of reprocessing plant shutdowns due to leaking process equipment. During an enforced shutdown, whether for scheduled maintenance or otherwise, as many maintenance jobs as possible are carried out among those which would likely become necessary during the subsequent operating period, even if their necessity may not be assured (Long, 1978). The thermal oxide reprocessing plant (Thorp) at Sellafield that takes on spent fuels from nuclear reactors for dissolving in nitric acids was due for restarting three years after a serious leak of radioactive liquor forced it to be shut down (Thorp three years on, 2008).

3.3.10.3.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Social Considerations

The compelling reason for adopting reprocessing over alternatives such as long-term storage or disposal of spent fuel is the conservation of energy resources, and although some analyses show that reprocessing also presents benefits from the Economic or waste management viewpoints its principal advantage lies in savings of both uranium and separative-work as the result of recycle (OECD-NEA, 1977). Even with the aforementioned benefits, there are still some concerns with the waste due to operating the reprocessing plants. Lidsky and Miller (2002) noted that despite the recent high capacity factors achieved by the French and British spent fuel reprocessing plants, the radioactive effluents emitted, the accumulating stocks of separated plutonium as well as high-level and transuranic wastes are a source of growing concern among the public, the media, environmental groups, and bureaucracies in many countries. Across the 80s, 90s and 2000s a number of encapsulation plants, engineered product stores, and effluent treatment facilities were built to support reprocessing operations, to treat effluents and hence reduce discharges to the environment to a tiny fraction of the 1970s levels, and store the resulting waste packages safely (Maxwell, 2017).

3.3.10.4 Spent Fuel Reprocessing and Recycling Technological Factors

There are two major nuclear fuel cycle technological options in the world: the once-through cycle (OTC) option and the closed fuel cycle (CFC) option which consists of the thermal reactor recycle (TRR) and the fast reactor recycle (FRR) (Zhou et al., 2014).

3.3.10.4.1 Spent Fuel Reprocessing and Recycling R&D Technological Considerations

In the 1970s, West Germany built an experimental civilian spent fuel reprocessing plant to recover plutonium from spent fuel and a small experimental breeder reactor, both located in Karlsruhe in the country's southwest region (Janberg & von Hippel, 2009). For spent fuel reprocessing plants, the technical feasibility evaluation includes construction conditions, transportation conditions, operation conditions and wastes management (Wang et al., 2013). Initially, material scientists need to become

aware of material demands concerning aspects of purity of raw material or manufacturing techniques within pre-processing, in order to address inter alia specific environmental impacts or market concentration (Helbig et al., 2017). In another line of research, new reactors are being developed in order to reduce the amount of waste in energy production and some will be designed to work in closed loop, recycling the materials generated (Silverio & de Queiroz Lamas, 2011).

According to Abdallah et al. (2012), UREX, NUEX and COEX are derivations of PUREX technologies, which each differ from its parent process in the sense that they do not produce pure plutonium streams, thereby representing an amelioration of the older process. Figure 3-76 below is a suggested material and product life cycle approach by Helbig et al. (2017), that illustrates that the four-level architecture represents basic research (blue), technical development of a material for a prototypical application (orange), application (grey) and the re-phase (green), displayed from bottom to top. Each level includes the value chain of a material or product life cycle, their concomitant risks and suitable risk mitigation strategies.

As for South Korea, the construction of the Advanced spent fuel Conditioning Process Facility (ACPF) is the first step to demonstrate feasibility of the pyro process (Lee, 2008). Russia is one of the countries involved in SF reprocessing. According to Hore-Lacy (2012), the Russian pyroprocessing will consist of three main stages:

- 1) Dissolving of used nuclear fuel in molten salts;
- 2) Precipitation of plutonium dioxide, or electrolytic deposition of uranium and plutonium dioxides, from the melt; and
- 3) Processing of the material deposited on the cathode or precipitated at the bottom of the melt for granulated fuel production. This recovers the cathode deposits, without changing their chemical composition or redistributing the plutonium.

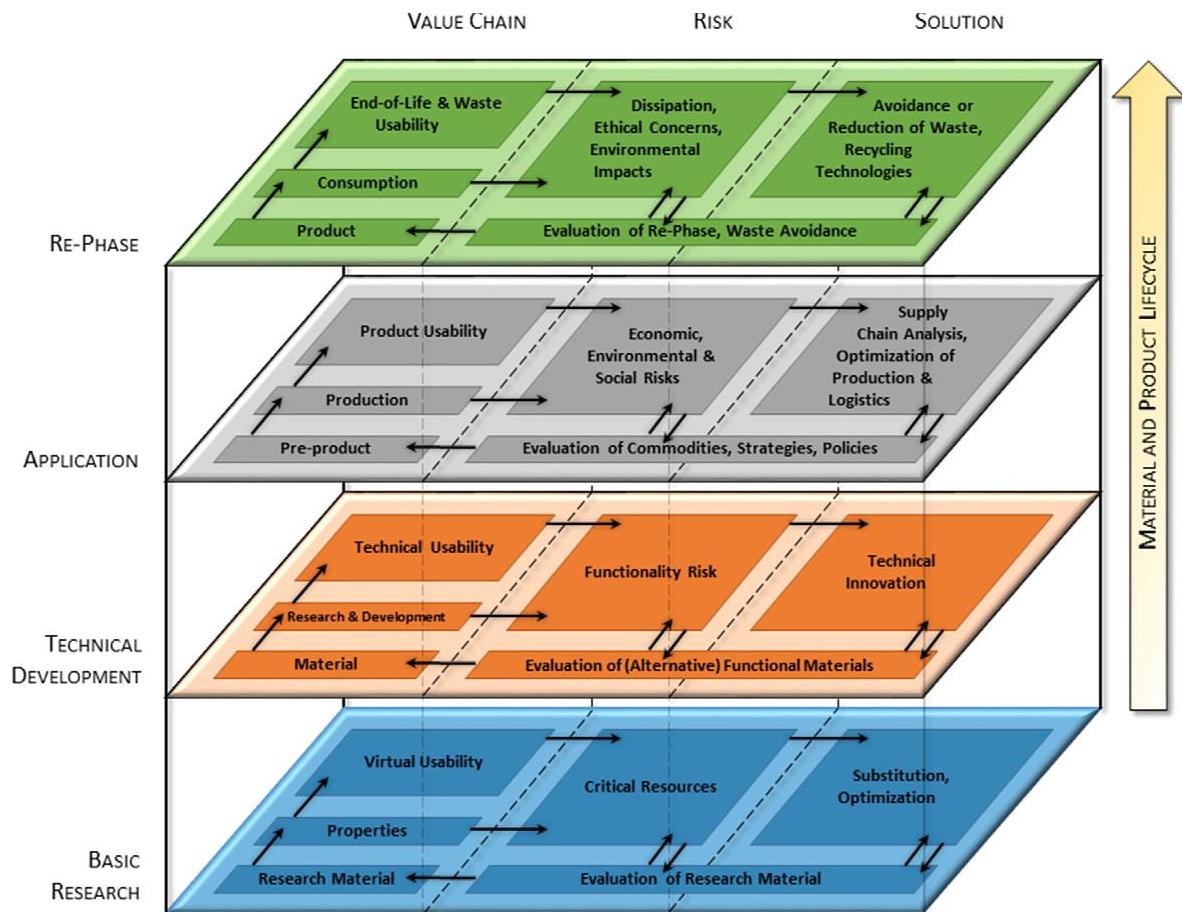


Figure 3-76: Intersectional, multidisciplinary aspects of material and product lifecycles.
Source Helbig et al. (2017)

3.3.10.4.2 Spent Fuel Reprocessing and Recycling Design and Engineering Technological Considerations

According to the IAEA (2008), the design of advanced reprocessing methods must deal in a comprehensive manner with (1) safety, (2) the control and minimization of plant effluents, (3) minimization of the waste generation, (4) the production of stable and durable waste forms, and (5) economic competitiveness.

3.3.10.4.3 Spent Fuel Reprocessing and Recycling Manufacturing Technological Considerations

Spent nuclear fuel (SNF), previously dissolved in a nitric acid solution, is extracted by TriButyl Phosphate (TBP) in the PUREX (Plutonium Uranium Extraction) process (Bascone, Angeli & Fraga,

2018). Fedorov et al. (2015) contend that to date, more than 30 years of experience has been gained in the Russian Federation in commercial use of reprocessed uranium for the fabrication of nuclear fuel based on Russian specifications (VVER-440 spent nuclear fuel (SNF) is used to fabricate fuel for RBMK reactors).

3.3.10.4.4 Spent Fuel Reprocessing and Recycling Construction Technological Considerations

Figure 3-77 below shows typical process capabilities to be found in a PUREX type NSF reprocessing plant.

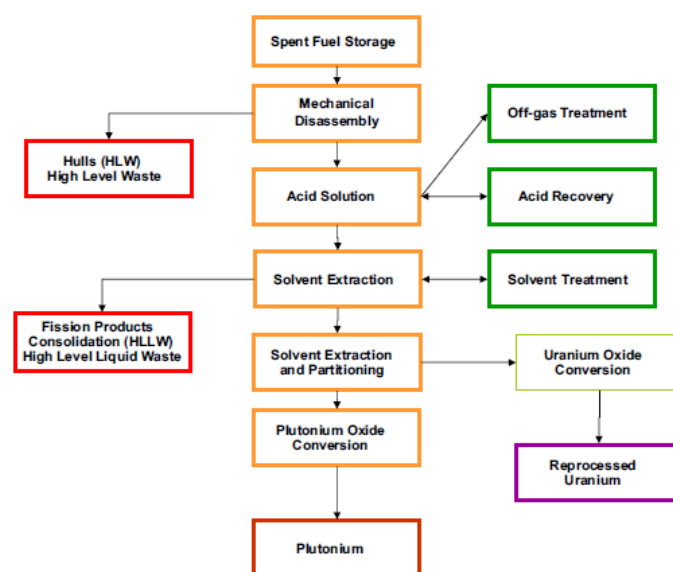


Figure 3-77: Scheme of PUREX reprocessing process

Source: Silverio and de Queiroz Lamas, 2011

3.3.10.4.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Technological Considerations

Besides safeguards and maintenance technologies, technology and experience feedbacks such as components of corrosion resistant material, radioactive chemical analysis, plant control system, aqueous

solution chemistry and physics, quality assurance system are important to realize a reliable, effective, and economical advanced reprocessing plant (Yamamura et al., 2008).

3.3.10.4.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Technological Considerations

For the long-term management of SNF, two major options have been adopted commercially to date:

- Direct disposal, where the fuel is used once and is then regarded as waste to be disposed of; and
- Partial recycling, where the spent fuel is reprocessed to recover unused uranium and plutonium for recycling in light water reactors, in the form of reprocessed uranium oxide (REPUOX) and mixed-oxide (MOX) fuel, respectively (OECD-NEA, 2013).

Figure 3-78 below shows the 97% reusable material amount available in the spent fuel.

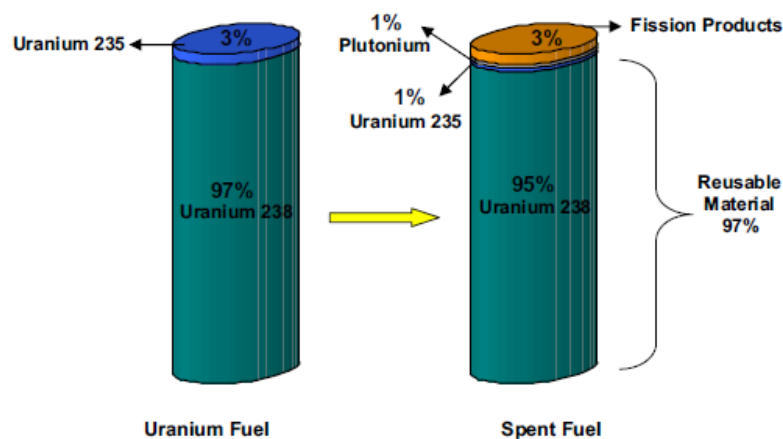


Figure 3-78: Nuclear fuel composition
Source: Silverio and de Queiroz Lamas (2011)

3.3.10.5 Spent Fuel Reprocessing and Recycling Environmental Factors

The assumption that reprocessing for open fuel cycle (OFC) and closed fuel cycle (CFC) will result in more short-term radiological risks, both to the environment and to the public health and safety, is illustrated below in Figure 3-79.

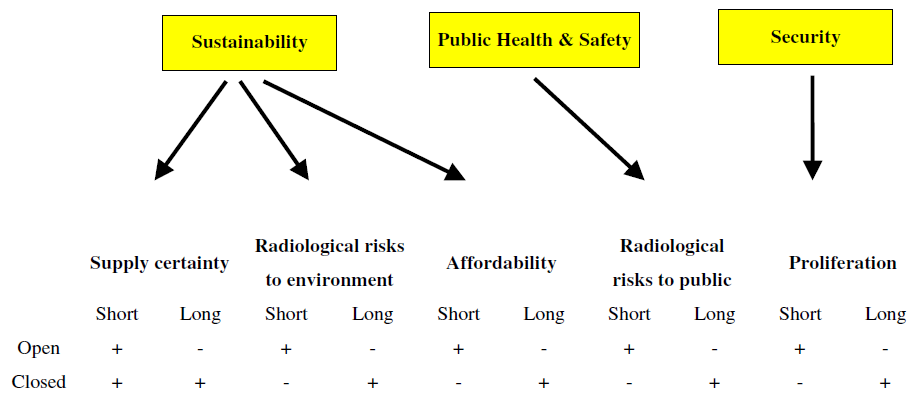


Figure 3-79: Ethical values (first row) and their specification (second row) related to the OFC and CFC.
A plus sign represents an improvement of the ethical value and has a positive connotation,
a minus sign is a drawback of the value
Source: Taebi and Kloosterman (2008).

3.3.10.5.1 Spent Fuel Reprocessing and Recycling R&D Environmental Considerations

The safety reliability evaluation mainly includes external natural accidents and external human accidents (Wang et al., 2013). Studies show that the key risk posed by spent nuclear fuel involves a release of radiation that could harm human health or the environment (Spent Nuclear Fuel, 2012).

For South Korea, the preliminary analysis of the proliferation resistance of the nuclear fuel cycle options indicates that pyro processing is a most attractive option for Korea of its spent fuel and resource management (Kim, Chang & Ko, 2010). Pure plutonium cannot be separated from the spent fuel via the pyro processing and this difference makes pyro processing significantly more proliferation resistant (Kim et al., 2012). This is in line with the aim that Safety and Security should be coordinated from the conceptual stages of development, through infrastructure building, sitting, design, and operation and decommissioning (Zakariya & Kahn, 2015). Equally important is the development of RR spent fuel services that can address the needs of RR operators in countries that have strategies for exporting their RR spent fuel. To provide research reactor operators safe and sustainable solutions for SNF

management, AREVA is conducting R&D on SNF reprocessing at its facilities and steady R&D efforts, including new types of fuel, such as uranium–silicon and uranium–molybdenum (IAEA, 2017a).

3.3.10.5.2 Spent Fuel Reprocessing and Recycling Design and Engineering Environmental Considerations

Safeguards-by-Design (SBD) is a new approach to the design and construction of nuclear facilities in which nuclear safeguards provisions and features are designed into the facility from the very beginning of the design process (INL, 2010). Hence, new recycling technologies are being designed with a degree of added resistance to proliferation by incorporating inherent features that make it more difficult to separate pure plutonium.

3.3.10.5.3 Spent Fuel Reprocessing and Recycling Manufacturing Environmental Considerations

Original equipment manufacturers have to supply various special equipment required prevent environmental pollution by e.g. toxic emissions and effluents from reprocessing facilities. Resnikoff (1975) stated that over one billion curies a year must be kept from the environment, and a large part of the reprocessing charge pays for containment-shielding, filters, scrubbers, evaporators, demisters (for removal of moisture vapour), and silver zeolite beds (which absorb iodine).

3.3.10.5.4 Spent Fuel Reprocessing and Recycling Construction Environmental Considerations

For some structures, systems and components important to safety, where verification of compliance may not be possible after construction and installation is complete, testing should take place during construction and installation (IAEA, 2017).

3.3.10.5.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Environmental Considerations

It is important to manage waste emanating from the reprocessing of nuclear spent in order to prevent polluting the environment. The IAEA (1996) states that classification of radiological waste from reprocessing operations is in the following five categories:

- High level liquid waste;
- Intermediate level liquid waste;
- Low level liquid waste;
- Gaseous waste; and
- Solid waste.

3.3.10.5.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Environmental Considerations

Nowadays, the main objective of reprocessing is to use uranium more efficiently and to reduce the waste volume and its toxicity considerably (Taebi & Kloosterman, 2008). Existing and planned reprocessing facilities are based on a technology that achieves a high level of purity in recovered uranium and plutonium products and ensures that only a small fraction of the uranium and plutonium appears in wastes and the bulk of this is concentrated in a solid form (NEA-OECD, 1994). Whereas, in normal operation, reprocessing facilities generate significant volumes of gaseous and liquid effluents with a variety of radioactive and chemical constituents (IAEA, 2017).

3.3.10.6 Spent Fuel Reprocessing and Recycling Legal Factors

The removal of some volatile radionuclides generated during used nuclear fuel (UNF) reprocessing in the US is nearly certain to be necessary for the licensing of a future reprocessing plant in the US and to meet regulatory emission limits (Soelberg et al., 2013). Katsuta and Suzuki (2011) stated that under Japan's nuclear regulatory requirements, utilities must submit evidence that their spent fuel will be

reprocessed before they load the fuel and they also commit to their local communities to ship spent fuel from the reactor site to reprocessing plants "soon" (without any time period being specified, however).

3.3.10.6.1 Spent Fuel Reprocessing and Recycling R&D Legal Considerations

The United States Department of Energy (US DOE) is conducting R&D activities within the Used Fuel Disposition Campaign (UFDC) to support storage, transportation, and disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles (Nutt et al., 2013). This being the case the USA is advancing toward the siting and licensing of a larger interim storage facility to be available by 2025 that will have sufficient capacity to provide flexibility in the waste management system and allows for acceptance of enough used nuclear fuel to reduce expected government liabilities (DOE, 2013). In SA, Eskom's Koeberg Nuclear Power Plant and NECSA's SAFARI-1 are licensed to store their SNF on site respectively at the Interim Dry Fuel Storage Facility and Thabana which are both. SA is also in the process of examining other options such as final disposal at Vaalputs and possible reprocessing and recycling.

3.3.10.6.2 Spent Fuel Reprocessing and Recycling Design and Engineering Legal Considerations

The most relevant lessons learned from the Rokkasho Reprocessing Plant, and all previous efforts by the IAEA to deploy international safeguards, is that the involvement and dialog between all interested parties must start from the earliest stages of a facility's design (Ehinger & Johnson, 2010).

3.3.10.6.3 Spent Fuel Reprocessing and Recycling Manufacturing Legal Considerations

All nations that have signed the Non-Proliferation Treaty (NPT) have the right to pursue enrichment and reprocessing for peaceful purposes in conformity with Articles I and II of the Treaty (IAEA, 2008).

3.3.10.6.4 Spent Fuel Reprocessing and Recycling Construction Legal Considerations

To address the problems of the effective prevention of misuse of nuclear technologies and materials, waste management, and resource utilization, it is essential to formulate a comprehensive package of technical, political, and institutional measures, accompanied by furthering the educational and ethical

levels of staff involved in nuclear activities (Andrianov, 2015). Accordingly, May (2017) states that if nuclear power is to make its full contribution to low-carbon electricity, it will require a globally agreed cooperative safety culture to go along with it.

3.3.10.6.5 Spent Fuel Reprocessing and Recycling Operation and Maintenance Legal Considerations

The operation and maintenance of reprocessing and recycling plants operate are in accordance with the required nuclear safety legislation and safeguard. According to Bokov et al. (2018), among all types of nuclear facilities the most complicated for oversight over nuclear material control and accountancy is a spent fuel recycling plant.

3.3.10.6.6 Spent Fuel Reprocessing and Recycling Waste Management and Disposal Legal Considerations

When the SF reprocessing plants are licensed, the management of HLW emanating from the plant is taken into consideration. Remaining materials (i.e. fission products and transuranic elements other than plutonium) are usually treated as high-level nuclear waste (Hogselius, 2009). In the UK, highly radioactive (HA) liquor from the reprocessing of spent nuclear fuel is converted into a borosilicate glass at the Sellafield Waste (Harrison, 2014). Figure 3-80 is an illustration of a reprocessing plant HLW vitrification process on the Sellafield, UK site.

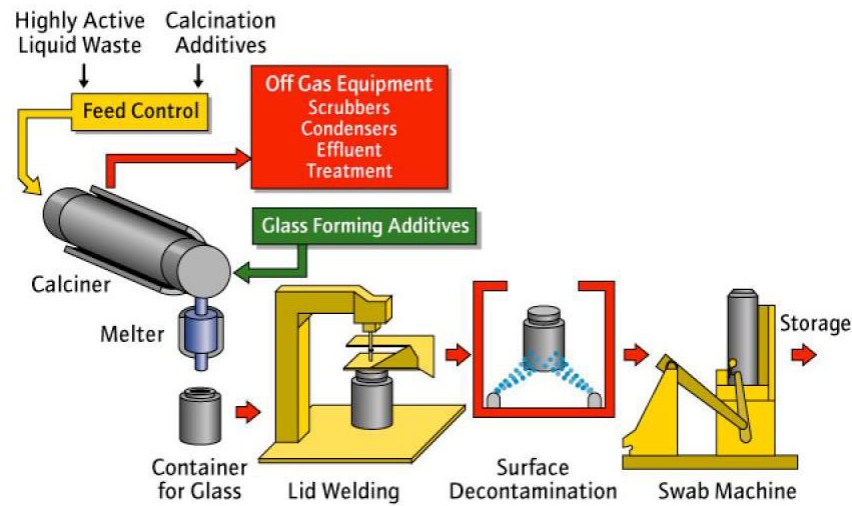


Figure 3-80: Schematic of the HLW vitrification process on the Sellafield site
Source: Harrison (2014)

3.4 Summary

With a forward-looking research study design presented in this chapter, the main thrust of developing the model and using it to identify, collect, validate and document nuclear sector secondary data in the repository with the intention to use it to generate primary data for strategic decision-making purposes was achieved. Developing a model is one aspect and demonstrating its use is another. The two aspects are key elements of this research study objectives. Fundamentally, the first achievement at this stage of the study was the demonstration of the synchronisation of the AHP, SWOT, PESTEL, LCA and linking this combination to NPP and NFC related installations. As part of responding to the set aims it is important to note that the reasoning behind hybridisation of the popular decision-making techniques was to e.g., harness the qualitative and quantitative attributes of the four individual decision-making methods. This resulted into two hierarchal conceptual models that were presented at an international nuclear conference in Moscow. With respect to the Moscow presentation, the main outcome was the need to validate the model.

The combining of the two conceptual models into one final one was accomplished in this chapter but at the same refined but the case study activities in following chapter since the whole development process is iterative and integrative. As part of meeting the study objectives, another major milestone in this part of the research was the deriving from the model, the nuclear sector data (factor) collection and archiving (documenting) instrument. An important element of this instrument was the validation of data classification from a SWOT and PESTEL categories perspective whilst documenting in the repository (Section 3.3). The data classification or categorization validation was achieved through the utilization of Harvard Business Review (HBR) SWOT Analysis Guideline and the UNICEF SWOT/ PESTEL Guideline. For instance, UNICEF Guideline gives examples factors or issues that can interpreted as being classified as political, economic, social, technological, environmental and legal.

The AHP used in the case study in the following Chapter 4 already has an embedded validation feature brought about by the involvement of knowledgeable participants together with the measuring of the pairwise comparison judgements. The survey results are used to calculate consistency ratios (CRs) hence the authentication of the judgements.

In essence, the collected internal and external secondary data through literature review i.e., centred around the ten SA historical, present and envisioned nuclear installations and documented in the repository (Section 3.3) is as a result of i.e. to certain extent, comparing the local industry programmes against international ones. A common factor for successful nuclear programmes in countries such as Japan, S. Korea and China has been bold government decisions coupled with identifying established technology partners such as the USA, Russia and France. Yet nuclear programme success in countries e.g., UK, USA, Germany, S. Korea, Russia and Japan has been driven in the main by government sponsored R&D and availability of local and international markets. The common feature in all these

countries with successful nuclear sectors was their ability to strike a balance between nuclear and non-hydro renewable energies in the face of civil society opposition and energy bipartisan political affairs.

As part of developing and testing the model, in the next chapter, the factor extraction (retrieving) and case study instrument also derived from the model, is utilised for qualitatively and quantitatively appraising the possibility of resuming and implementing the SA PBMR R&D activities. This is enabled by the AHP that has both qualitative and quantitative analysis attributes. These AHP qualities are complemented by the qualitative attributes of the other decision making methods which are part of the model as will be demonstrated by using the case study's secondary data extraction and listing template that also enabled validation of factor adequacy, appropriateness and comprehensiveness.

4 Case Study: Prioritising the external factors that have a potential to impede the resumption and implementation of the SA PBMR R&D activities

4.1 Introduction

This SA PBMR case study is a continuation and final stage of the conceptual model development and utilization. It is aimed at meeting the set research objective aspects of retrieving (extracting) and operationalising the documented internal and external factors (secondary data) in the repository (Section 3.1.1 to Section 3.3.10). Thus, the data extraction, narrowing down and qualitatively and quantitatively analysing secondary data from the repository for strategic decision-making purposes was enabled by the internal and external factors extraction and case studies instrument shown with its activities or steps as Figure 4-1 below. This identifying and prioritising of threats factors (basis for strategic decision) that can inhibit the successful resumption and implementation of SA PBMR R&D related activities mostly utilised the documented secondary data or factors within the SMR category (Section 3.3.2) of the repository (Section 3.3.1 to 3.3.10). In this regard, the rest of the case study entails the following:

- The description of the data or factor extraction and listing template is undertaken in Section 4.2 (shown as Table 4-1). The novel template more than any other instrument in this research study demonstrates the benefits derived from synchronisation and concurrent utilisation of conceptual model's four decision-making methods e.g., the initialisation of the narrowing down process and validating the documented and extracted data with its feedback or revalidation effect at the stage when model development documents are reviewed by the nuclear sector knowledgeable experts (activity 52 of Figure 4-1 below);
- The reasoning behind the identification of the need of the case study on which the survey questionnaire question (QQ) is based is articulated in Section 4.3;
- Section 4.4 is about the upfront formulation of the QQ using the Saaty's 9 point scale;

- The populating of the extraction and listing template (Table 4-1) with this case study threats factors is presented in Section 4.5. as a prelude to the demonstration of narrowing down, further validation and operationalization of the collected data documented from Section 3.3.1 to Section 3.3.10;
- Section 4.6 is about the selection of the case study participants (nuclear sector expert team) using a criteria informed by convenience and purposive sampling that are both non-random;
- The merits e.g., of enabling content validation through the in advance distribution of research study documents and instruments to the Expert Team (ET) are articulated in Section 4.7.
- The ET reviewing and endorsement of distributed documents is discussed in Section 4.8.
- The AHP decomposition showing the case study goal, decision criteria and sub criteria is presented in Section 4.9;
- The development of the survey questionnaire matrixes is discussed in Section 4.10;
- The utilization of questionnaires for pairwise comparisons and the results are presented in Section 4.11;
- AHP Expert Choice software computations of sub factor and factor weights and consistency/inconsistency ratios are discussed in Section 4.12; and
- Summary of the computed weights and consistency ratios in Section 4.13.

4.2 Factors Extraction and Case Studies Instrument and Factors Listing Template

Figure 4-1 below shows the factors extraction and case study instrument that operationalises the collected and documented secondary data. The extraction component of the instrument is from step 1 to step 48, which mainly mirrors the repository structure (Section 3.3.2) that was followed to document the SMR or SA PBMR related factors. It is important to note that other relevant data or factors could have been retrieved from other repository sections other than the SMR section if it was deemed necessary by the investigating team. For instance, most of the SA PBMR nuclear fuel were documented within the Fresh uranium fuel fabrication repository's sub-section 3.3.7.5.4. There is therefore a relationship between the way the identified factors are documented in the repository and the method they are extracted for the purposes of initiating the AHP processes (from 49 to step 59.

Step 1 in the extraction and SA PBMR case study design illustration (Figure 4-1 below) is about the development of the extracted internal and external factors listing template shown as Table 4-1 below. The following are the purposes of this novel template:

1. Counting from left to right, the first column groups the life cycle phases shown in the fourth column in accordance with the indicated PESTEL groupings;
2. Second column is used for quantifying of the identified factors per PESTEL category which allows the investigator and survey participants to check or analyse the sufficiency of the documented factors i.e., per PESTEL category and be Life Cycle demarcations;
3. The third column from the right enables the participants to establish the total factors count per each PESTEL category and across life cycle phases. As an example, Table 4-3's third column from the right i.e., below indicates that for political, economic, social, technological, environmental and legal there were respectively a total of two, nine, six, eight, five and six threats factors across life cycle phases retrieved from the repository. Based on this assessment the investigation team might deem political threat factors as inadequate thereby making a call that additional political threats data or factors be identified e.g., in other repository sections, journal articles etc. Other than the factor gap analysis, another plus of this factors quantification is that it can enable a decision to be taken to e.g., for an investigation to be focused only on one specific threats PESTEL category;
4. Column number four makes it possible to account for the total factors per each life cycle phase;
5. Column number five is meant for narrowing down the extracted factor phrase or sentence to a factor that it can be operationalised or measured using the AHP technique;
6. The sixth column is for coding thereby allowing the investigating team to have an option of either differentiate factors with the codes or column five factors wording. Otherwise, the code TPR&D1 appearing in Table 4-3's sixth column from the right and fifth row is explained as: the letter "T" stands for Threats factor, "R&D" means it's a research and development related factor, and the number "1" means it is the first political threats factor on the template list. The utilisation of the codes instead of narrowed down factors becomes necessary in situations in which the relative

comparison is among factors from across the SWOT (strengths, weaknesses, opportunities and threats) categories. Central to Template Analysis is the development of a coding template, which summarises themes identified by the researcher(s) as important in a data set, and organises them in a meaningful and useful manner (Brooks & King, 2014).

7. Column number 7 is for indicating the sources of the identified and listed factors. For whatever reason the investigating team members may e.g. question the use of old sources since the year of the literature will be indicated;
8. Enables the investigator and nuclear industry expert teams to validate and verify the adequacy, relevance and comprehensiveness of the repository documented and template listed internal or external factors;
9. Enables the investigator and expert teams to validate and verify the credibility of the formulated questionnaire question (QQ) to address the identified need of the case study.
10. Further demonstrates the integrative or hybrid nature of the SA sector strategic decision-making model since the template gives an application snapshot of the various model components i.e., individual decision-making techniques of the model;
11. It enables the researcher or investigator to simultaneously use the model's decision-making techniques to summarise the repository (Section 3.3) strategic internal (strength and weaknesses) and external (threats and opportunities) factors from a PESTEL categories (first column from the right) and nuclear facilities life cycle (second column from the right) perspectives.
12. The third column is meant for further summarising or narrowing down of the factors so that they can be user friendly for the AHP decomposition structure presented in Table 4-3 and Figure 4-2 below;
13. Enables further validation e.g., using the Harvard Business Review (HBR) SWOT Analysis Guide and UNICEF SWOT/ PESTEL Guideline verifying whether the strategic factors were documented in their rightful repository categories; and
14. It enables a broader life cycle assessment that is not only from an environmental perspective but

also from other viewpoints namely economic, social, technological and legal viewpoints.

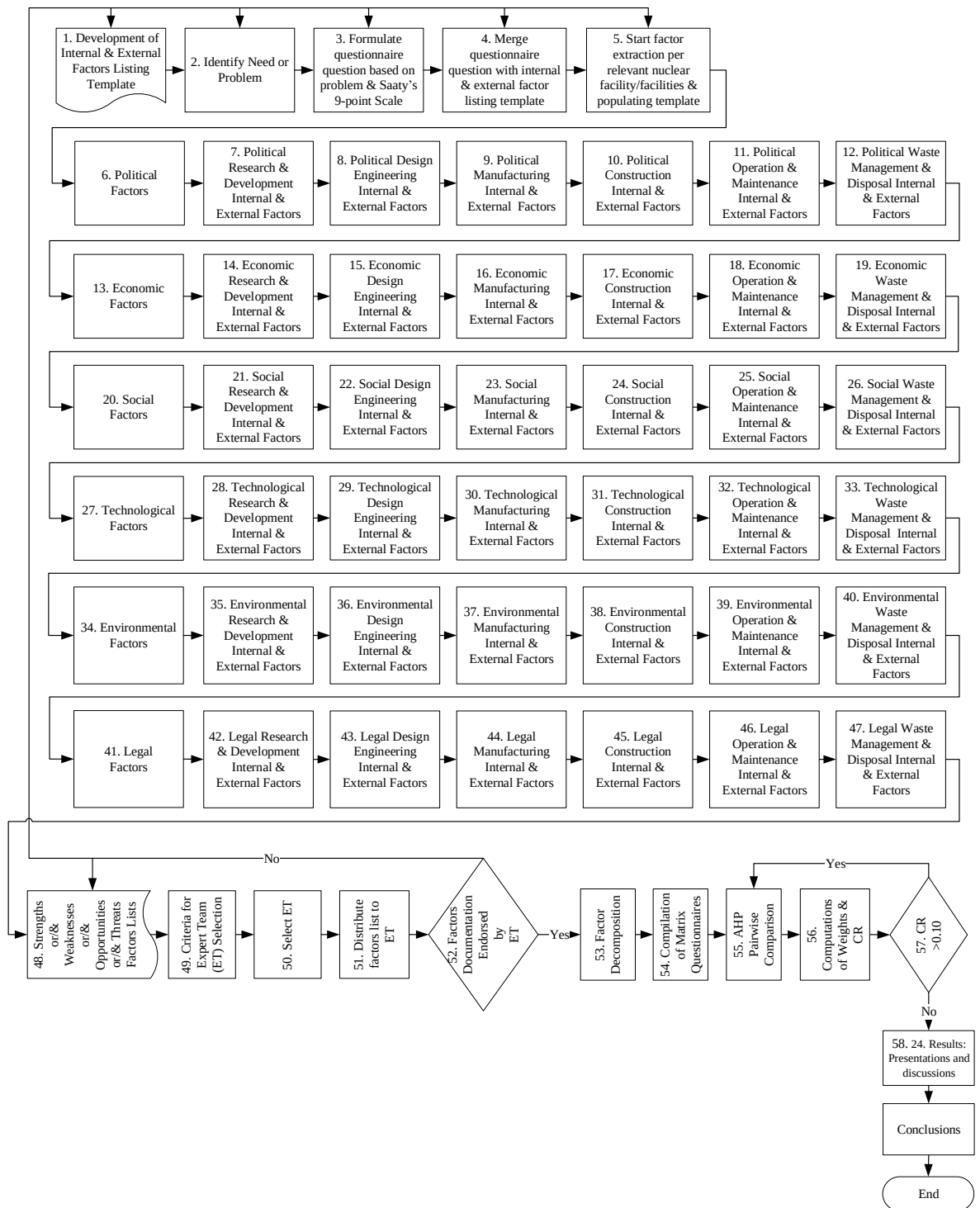


Figure 4-1: Internal and External Factors Extraction and Case Studies Instrument

Table 4-1: Internal and External Factors Extraction and Listing Template

Questionnaire Questions						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Political			R&D			
	1.	1.	1.			
	2.	2.	2.			
			Engineering Design			
	3.	3.	1.			
	4.	4.	2.			
			Manufacturing			
	5.	5.	1.			
	6.	6.	2.			
			Operation and Maintenance			
	7.	7.	1.			
	8.	8.	2.			
			Waste Management and Disposal			
	9.	9.	1.			
	10.	10.	2.			
Economic			R&D			
	11.	1.	1.			
	12.	2.	2.			
			Engineering Design			
	13.	3.	1.			
	14.	4.	2.			
			Manufacturing			
	15.	5.	1.			
	16.	6.	2.			
			Operation and Maintenance			
	17.	7.	1.			
	18.	8.	2.			
			Waste Management and Disposal			
	19.	9.	1.			
	20.	10.	2.			
Social			R&D			
	21.	1.	1.			
	22.	2.	2.			
			Engineering Design			
	23.	3.	1.			
	24.	4.	2.			
			Manufacturing			
	25.	5.	1.			
	26.	6.	2.			
			Operation and Maintenance			
	27.	7.	1.			
	28.	8.	2.			
			Waste Management and Disposal			
	29.	9.	1.			
	30.	10.	2.			
Technological			R&D			
	31.	1.	1.			
	32.	2.	2.			

Questionnaire Questions						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	33.		Engineering Design			
	34.	3.	1.			
	35.	4.	2.			
			Manufacturing			
	36.	5.	1.			
	37.	6.	2.			
			Operation and Maintenance			
	38.	7.	1.			
	39.	8.	2.			
			Waste Management and Disposal			
	40.	9.	1.			
	41.	10.	2.			
Environmental			R&D			
	42.	1.	1.			
	43.	2.	2.			
			Engineering Design			
	44.	3.	1.			
	45.	4.	2.			
			Manufacturing			
	46.	5.	1.			
	47.	6.	2.			
			Operation and Maintenance			
	48.	7.	1.			
	49.	8.	2.			
			Waste Management and Disposal			
	50.	9.	1.			
	51.	10.	2.			
Legal			R&D			
	52.	1.	1.			
	53.	2.	2.			
			Engineering Design			
	54.	3.	1.			
	55.	4.	2.			
			Manufacturing			
	56.	5.	1.			
	57.	6.	2.			
			Operation and Maintenance			
	58.	7.	1.			
	59.	8.	2.			
			Waste Management and Disposal			
	60.	9.	1.			
	61.	10.	2.			
			Total Number of Factors			

4.3 Identifying the Need

The aim of this case study is twofold. Firstly, there was a need for the additional validation of the developed model. Secondly, the case study provided an opportunity to demonstrate the retrieving and operationalisation of the collected SMR related data whilst addressing the identified need of prioritising critical threats factors with a potential to impede the successful resumption and implementation of SA PBMR R&D related activities. The two aims resulted in the populating of the template with threats factors as shown in Table 4-3 below. Similarly, Sub-appendices B1, B2 and B3 are respectively opportunities, weaknesses and strengths factors which were extracted merely to demonstrate that it is possible to appraise the PBMR R&D activities from the other SWOT categories perspectives. This extraction also enabled content validation in terms of e.g., in terms adequacy and accuracy of categorization of the data collected. For this case study, only the threats factors were utilised leaving the opportunities, weaknesses and strengths factors for possible future investigations.

4.4 Formulating Questionnaire Question

It is important for the investigator and participants to constantly validate that the data being retrieved from the repository is appropriate in terms of addressing the objectives of the case studies which are based on identified or anticipated industry or organization challenges. Validating the appropriateness of the factors (data) to address the challenge being responded to through the case study is enhanced by keeping the questionnaire question (QQ) in the mind of the investigator and other participants e.g., as in this case the pairwise comparison Expert Team. In this regard, the Saaty's 9-point scale of comparison shown below as Table 4-2 is used for formulating the QQ in advance (refer to step 3 of Figure 4-1) for its inclusion when the template populating process is initiated. The inclusion of the QQ in the template as shown in the first column of Table 4-3 below enhances the focusing on extracting each specific factor in accordance with the case study objective, in this instance being the identifying and prioritising threats factors that can inhibit the successful resumption and implementation of SA PBMR R&D related activities. Specifically, the case study approach is informed by the AHP component

of the strategic decision-making model. It is also crucial that the extracted threat factors data is configured for use with the AHP technique steps (49 to 59).

Table 4-2: Saaty's 9-point scale of comparison

Intensity of importance	Degree of preference	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one factor over another	Experience and judgement slightly favour one activity over another
5	Strong or essential importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another, i.e. of the highest possible order of affirmation
2,4,6,8	Values for inverse comparison	When compromise is needed

Source: Saaty (1988)

4.5 Internal and external factor extraction and listing

Table 4-3 below is a factor extraction and listing template. It was populated with threats factors in preparation for distribution to the Expert Team that participated in the narrowing down of the factors. In the main, the factors were extracted from the SMR section of the repository (Section 3.3.2). For demonstration purposes, the retrieving instrument (Figure 4-1) and the listing template (Table 4-1) that are above, were used to also extract other SA PBMR related factors namely; opportunities, weaknesses and strengths respectively presented in Sub-appendices B1, B2 and B.3. Consequently, in response to prevailing or anticipated circumstances or needs of strategic importance, a similar factor retrieving and populating of the template can be undertaken based on one or a combination of the other nine facilities (pressurised water reactors, research reactor, uranium production, conversion, enrichment, uranium fuel fabrication, spent fuel storage and spent fuel disposal). Such an endeavour will further demonstrate the generic attribute of the proposed conceptual model.

Table 4-3: Populated Extracted Internal and External Factors Listing Template

Threats Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor R&D activities? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Political			R&D			
	1.	1.	1. Renewable technologies such as solar or wind, have benefited from generous policies (i.e. feed-in tariffs) that helped their deployment	Feed-in tariffs benefiting renewables	TPR&D1	Magwood and Paillere, (2018)
			Operation and Maintenance			
	2.	2.	1. The Republic of Korea is the latest OECD country to debate actively a policy of a nuclear phase-out following decisions to do so undertaken earlier by Germany, Switzerland and Belgium.	Nuclear Phase Out Policy	TPO&M2	Budnitz, Rogner, and Shihab-Eldin, (2018)
			Disposal and Waste Management			
Economic			R&D			
	3.	1.	1. Unavailability of government funding for PBMR programme	Government funding	TER&D3	The South African News Agency (2010); Mckune (2010)
	4.	2.	2. Current SMR capital and operational expenses have a wide range of uncertainty.	Uncertainty on Capex & Opex	TER&D4	(Vegel and Quinn, 2017)
	5.	3.	3. Economic of SMRs needs more analysis in order to show possible advantages over large LWRs	Inadequate analysis of SMR advantages over large LWRs	TER&D5	Vujic et al. (2012)
	6.	4.	4. A few SMR designs have reached the commercialisation phase, whereas the rest are at conceptual phase (especially Generation IV designs), substantial research and development efforts are required.	Few SMR at commercialization phase	TER&D6	Rowinski, White and Zhao (2015)

	7.	5.	5. In contrast to many of the organisations pursuing the development of Generation IV systems, SMR technologies are receiving very substantial resources and investment from large industrial companies a factor that improves the prospects for commercialisation in the near future	Gen IV resources & investments constrained unlike other SMRs	TER&D7	Magwood and Paillere, (2018).
	8.	6.	6. It seems likely the credit crunch did no more than hasten the end of the programme and poor management allowed the programme to continue long after it should have been abandoned.	Financial crisis of 2007–2008	TER&D8	Thomas (2011)
	9.	7.	7. The most significant component of operation and maintenance (O&M) cost in the SMRs is the direct and indirect cost of personnel; it is therefore essential for the operators of SMRs to improve the efficiency and effectiveness of their organizational structures and staffing in order to maintain the economic viability of their plants	Direct and indirect O& M costs are significant	TER&D9	IAEA, 2001a; Wood, Upadhyaya and Floyd (2017).
	10.	8.	8. There is a need to address the cost of reactor decommissioning and spent nuclear fuel management.	Reactor decommissioning SNF management	TER&D10	Vujic et al. (2012)
	11.	9.	9. AVR decommissioning was found to be extremely complicated and costly and is not expected to be completed before 2080.	Costly AVR decommissioning	TER&D11	Thomas (2011)
Social			R&D			
	12.	1.	1. Public acceptance of new concepts is a challenge due to perceived risk factors for nuclear power plants negatively impact SMRs deployment	Public acceptance of new concepts is a challenge	TSR&D12	Vujic et al. (2012)
			Operation and Maintenance			

	13.	2.	1. One of the compelling socio-political issues is public opposition and anti-nuclear politics, especially on the rise whenever there is a nuclear accident causing an incremental increase in the negative reaction among the public.	Public Opposition	TSO&M13	Budnitz, Rogner, and Shihab-Eldin (2018)
			Waste Management and Disposal			
	14.	3.	1. Spent nuclear fuel from small reactors could be located in remote areas, which will make its transport more difficult.	Spent fuel transportation challenges	TSWM&D14	Vujic et al. (2012)
	15.	4.	2. Spent fuel will be spread across many more sites while currently it is congregated at a limited number of locations	Spent fuel spread across many sites	TSWM&D15	Vujic et al. (2012)
	16.	5.	3. Nuclear power produces radioactive wastes and there are public concerns about safety	Public concerns on radioactive waste	TSWM&D16	Kupitz (1995).
	17.	6.	4. Nuclear risks and liabilities are hindering deployment;	Concerns on nuclear risks & liabilities	TSWM&D17	Knol et al. (2016)
Technological			R&D			
	18.	1.	1. Challenges on testing and validation of technological innovations in components, systems and engineering	Challenges on testing & validation of components	TTR&D18	Vujic et al. (2012)
			Engineering Design			
	19.	2.	1. There are fears of first-of-a-kind reactor designs	F-O-A-K reactor design fears	TTED19	Vujic et al. (2012)
	20.	3.	2. Challenges in testing and fabrication of fuel	Testing and fabrication of fuel challenges	TTED20	Vujic et al. (2012)
			Operation and Maintenance			
	21.	4.	1. Although many of the SMR designs use large-sized reactors as their basis there concerns pertaining to safety of operation,	Safety of technology	TTO&M21	Nian (2017)
	22.	5.	2. Although many of the SMR designs use large-sized reactors as their basis there concerns pertaining to emergency planning	Concerns on Emergency planning	TTO&M22	Nian (2017)

	23.	6.	3. Although many of the SMR designs use large-sized reactors as their basis there concerns pertaining to staffing and security requirements	Staffing and security requirements	TTO&M23	Nian (2017)
	24.	7.	4. During its 12-year operation since 1960s, the first 20 MW HTGR was the UK's Dragon that faced a number of problems, especially with its heat exchangers a reactor component that allows the heat produced by the fission reactions inside the nuclear core to be transferred out of the reactor without any escape of radioactive materials	Challenges with UK's Dragon HTGR during its operation	TTO&M24	Ramana (2016).
	25.	8.	5. Two hundred seventy nine events were catalogued for the USA's Fort Saint Vrain Gas Cooled Reactor operational experience i.e., into seven general categories: (1) water incursion events, or failures of moisture detection systems; (2) air or other unwanted gas incursion events and failures of gas detection systems; (3) fuel failures or anomalies; (4) failures or cracks in graphite, pipes, and other reactor structural components; (5) failures of nuclear instrumentation systems; (6) human factors and operator performance issues; and (7) other events or conditions that may be relevant to current GCR designs	Challenges with the USA's St Vrain	TTO&M25	Copinger, Moses and Cupidon (2004)
Environmental			R&D			
	26.	1.	1. The possibility of radioactive contamination of product water, however, is a very important issue to be considered for nuclear desalination plants.	Radioactive contamination	TENR&D26	Misra (2007)
	27.	2.	2. The environmental competitiveness of SMRs study's analysis that The GHG emissions of the AP1000 are 9% less	Concerns on Life Cycle GHG emissions	TENR&D27	Carless, Griffin, and Fischbeck (2016)

			than the W-SMR, but when the nuclear fuel cycle is not part of the analysis the GHG emissions for the W-SMR and the AP1000 are effectively the same given the inherent uncertainties in the analysis.			
			Operation and Maintenance			
	28.	3.	1. Energy generation by burning fossil fuels raises a number of concerns regarding atmospheric emissions and waste production. Combustion by-products include sulphur dioxide, nitrogen oxides and carbon dioxide, which bring about the threat of global climate change and acid rain.	Global climate change	TENO&M28	Kupitz (1995)
	29.	4.	2. Renewable sources also induce environmental impacts, including noise, land requirement and irreversible changes to land uses, perturbation of ecosystems and various emissions associated with raw material processing in the energy chain.	Renewable energy induced impacts	TENO&M29	Kupitz (1995)
	30.	5.	3. Nuclear power produces radioactive wastes and, in several countries, the public raises concern about safety.		TENO&M30	Kupitz (1995)
Legal			R&D			
	31.	1.	1. The NRC, though highly esteemed as a safety regulator of standard light water reactors, has little experience licensing new and unusual designs	Inexperience with unusual designs	TLR&D31	Eaves (2017)
	32.	2.	2. For SMR the key challenge is the development of new 'tailored' standards and codes enabling the issuance of prescriptive based license process	Development of new tailored standards	TLR&D32	Sainati, Locatelli and Brookes (2015)
	33.	3.	3. A consistent and up-to-date regulatory framework is lacking	Lack SMR dedicated regulatory framework	TLR&D33	Knol et al., 2016; Nian, (2017)

	34.	4.	4. Even if the SMR use the large reactors as their reference, there are licensing and certification concerns	Licensing & Certification concerns	TLR&D34	Nian (2017)
	35.	5.	5. The process to adapt the current regulations and guidelines for SMR is in the planning and defining phase and due to the unique design features, the applicable codes and standards will need to be updated and expanded	Regulations and guidelines for SMR is in the planning and defining phase	TLR&D35	Hidayatullah, Susyadi and Subki (2015).
			Engineering Design			
	36.	6.	Obtaining design certification and licensing may take longer than expected	Design certification	TLED36	Vujic et al. (2012)
Total Factors Across PESTEL	36					

4.6 Expert Group/Team Selection

The AHP requires a group of experts to undertake the pairwise comparison of identified factors as a prelude to the quantification of intangible and tangible factors. The qualitative and quantitative attributes of AHP on which the extraction and case study instrument is based relies on (non-random) non-probability sampling when it comes to the selection of participants.

Convenience sampling was used in choosing the informants listed in Table 4-4 below because there were easily available to participate in the pairwise comparison i.e., among the twenty who were initially consulted (Cohen, Manion & Morrison, 2011). At the same time, the selection criteria met the requirements of purposive sampling since the interviewees were also deliberately chosen on their ability provide the richest information by virtue of being knowledgeable on the phenomenon and also that they could articulate and reflect whilst motivated to communicate at length and in depth with the researcher (Moser & Korstjens, 2017).

As per convenience and purposive sampling techniques requirements, the following criteria was applied in the selection of the seven individuals or decision-makers (DM) herein referred to as the Expert Team as shown in Table 4-4 below:

- At least 10 years of work experience in the nuclear sector;
- Ability to discuss and inform decision making in the nuclear sector from a political, economic, social, technological, environmental and legal perspective;
- Experience or familiarity with SA PBMR and international SMR developments;
- Understanding and appreciation of the PBMR or HTGR technology and its value chain; and
- Employees of or past experience with state owned entities since they will have a better understanding of government legislation and policies.

Table 4-4: Pairwise Comparison SA PBMR Expert Team

1	Former Nuclear Industry Association South African Chief Executive Officer
2	Present Nuclear Industry Association of South Africa Managing Director
3	Present Executive Manager for Engineering at the South African Nuclear Energy Corporation previously involved in the PBMR design
4	Former PBMR Project Manager
5	Former PBMR Design Engineer and ASME III Professional Engineer
6	Former PBMR Chief Technology Officer and presently a Professor at University of Pretoria still involved in the SMR developments
7	Facilitator who was previously involved in the PBMR Supplier development and localization studies; He also an Expert in AHP Expert Choice Software

4.7 Distribution of documents to the Expert Team for validation

Conceptual models, developed extraction and case study instruments, questionnaires and the populated template were distributed to the Expert Team for review and validation as indicated in Step 51 of the extraction and case study instrument (Figure 4-1). One of the aims of distributing the documents was to introduce the whole research study to the Expert Team and to make sure that they align their roles to the main objectives of the research e.g., undertaking threat factors pairwise comparisons.

4.8 Expert Team Reviews and Endorses the Distributed Documents

As indicated in activity or step 1 of Figure 4-1 (extracting and case study instrument), it was crucial for the informants to be made aware that the credibility of the data was dependent on the legitimacy and relevancy of the following preceding study steps or document contents:

1. Developing of internal and external factors listing template;
2. Identifying need or problem;
3. Formulating questionnaire question based on the problem or need and Saaty's 9-point Scale;
4. To keep on making sure that factors were relevant in terms of responding to research and case study objectives;
5. Starting factor extraction per relevant nuclear facility/facilities and populating the template; and
6. Extracting internal and external factors and explaining how and why they were initially gathered and documented in the proposed repository structure.

Table 4-5 below shows a total of twenty-one threats factors that were endorsed by the ET for pairwise comparisons i.e., after reviewing the ones that were listed in the template (Table 4-3). As shown in the below Table's first row, the Expert Team made some additions to the list of factors namely; sanctions, trade wars, political will, political stability and political system under the Political category of PESTEL.

Table 4-5: Potentially Impeding factors final list endorsed by the Expert Team

Threats Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor R&D activities? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)				
PESTEL		Factor	Initial Code Number	Source
Political	1	Sanctions	None	Expert Team (2019)
	2	Tariff	TPR&D1	Magwood and Paillere (2018)
	3	Trade War	None	Expert Team (2019)
	4	Political will	None	Expert Team (2019)
	5	Political stability	None	Expert Team (2019)
	6	Political system	None	Expert Team (2019)
Economic	7	Private Funding	None	Expert Team (2019);
	8	Government Funding	TER&D3	Ramana, Hopkins and Glaser (2013)
	9	Operation and Maintenance Costs	TER&D9	IAEA, 2001a; Wood, Upadhyaya and Floyd (2017).
	10	Decommissioning costs	TER&D10 and TER&D11	Vujic et al. (2012); Thomas (2011)
Social	11	Public acceptance	TSR&D12	Vujic et al. (2012)
	12	Skills development	None	Expert Team (2019)
	13	Public Concerns about Waste management	TSWM&M15	Kupitz (1995);
Technological	14	Testing and Validation	TTR&D18	Vujic et al. (2012)
	15	Safety Technology of SMRs/HTGRs		Nian (2017)
	16	FOAK	TTED19	Vujic et al. (2012); Gao, (2015)

Threats Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor R&D activities? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)				
PESTEL		Factor	Initial Code Number	Source
Environmental	17	Accidents (e.g. Fukushima)	None	Expert Team
	18	Nuclear Waste Disposal	TTO&M21	Kupitz (1995)
	19	Radioactive Water Contamination	TENR&D32	Misra (2007)
Legal	20	Tailored Standards	TLR&D32	Sainati, Locatelli and Brookes (2015)
	21	Unusual Designs	TLR&D31	Eaves (2017)

4.9 Decomposition of SA PBMR R&D Factors

Figure 4-2 below is an AHP required stage (activity 53) of decomposition of the potentially impeding external threat factors (shown above in Table 4-5). The decomposition enabled the compilation of matrix questionnaires to incorporate the QQ and threat factors. Prioritisation of external factors with a potential to impede the successful resumption and implementation of the SA PBMR R&D activities was the case study goal as indicated in the hierarchical structure (Figure 4-2 below).

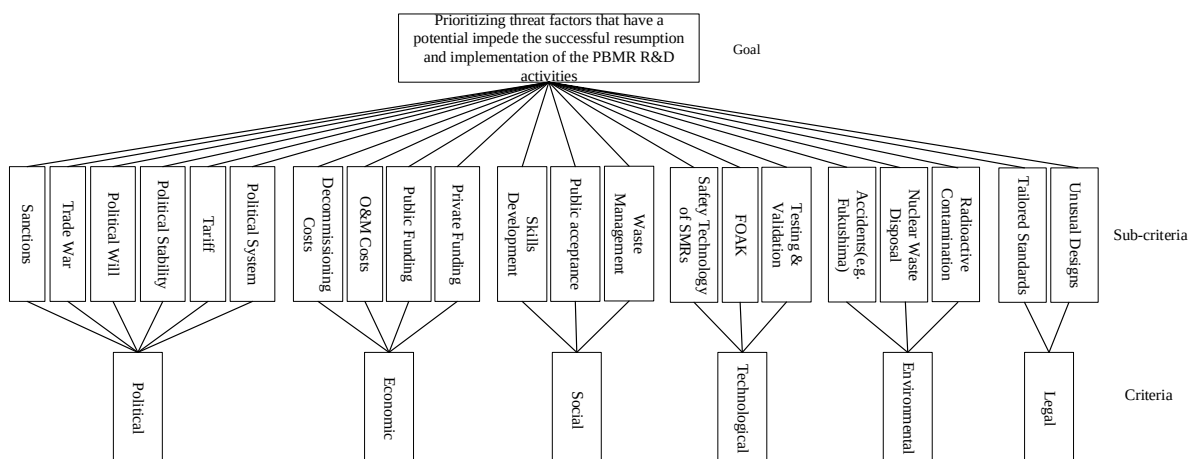


Figure 4-2: Potentially Impeding factors AHP hierarchical structure

4.10 Matrix Questionnaires Development

The survey matrix questionnaires that are presented as Sub-appendices C1, C2, C3, C4, C5 and C6 are based on the Saaty's 9-point scale and the number of threats factors in each PESTEL grouping. As indicated in Figure 4-1 above, the QQ was developed at activity 3 to include on the yet to be populated extraction and listing template. At this stage, the QQ was also included in survey matrix questionnaires. Earlier it was stated that the reasoning of including the QQ in the aforementioned template was to make sure that the study participants continuously validate the relevancy of the listed strategic threats factors to be used as criteria and sub criteria of addressing the stated PBMR case study goal (see Figure 4-2 above).

4.11 Using questionnaires for primary data collection

Populated political, economic, social, technological, environmental and legal questionnaire forms with pairwise comparison results are respectively shown below in this section as Table 4-6, Table 4-7, Table 4-8,

Table 4-9, Table 4-10 and Table 4-11. The surveying or pairwise comparison by the ET took place on the 24 May 2019 at NECSA's Pelindaba's Visitors Centre. The participants attendance register is shown in Sub-appendix A2.

Table 4-6: Political Sub-factors Pairwise Comparison Questionnaire Matrix

<i>Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?</i> <i>Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
	Sanctions	Tariff	Trade War	Political will	Political stability	Political system
Sanctions	1	7	3	3	7	1/5
Tariff	1/7	1	1/7	1/5	1/7	1/7
Trade War	1/3	1/3	1	1/3	1/3	1/7

Political will	1/3	5	3	1	1/3	1/3
Political stability	1/7	7	3	3	1	1/3
Political system	5	5	7	3	3	1

Table 4-7: Economic Sub-factors Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Private Funding	Government Funding	Costs(O&M)	Decommissioning costs
Private Funding	1	5	1	7
Government Funding	1/5	1	5	7
Operation and Maintenance Costs	1/7	1/5	1	5
Decommissioning costs	1/7	1/7	1/5	1

Table 4-8: Social Sub-factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Public acceptance	Skills development	Waste management	
Public acceptance	1	9	1	
Skills development	1/9	1	1	
Waste management	1	1	1	

Table 4-9: Technological Sub-factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble

<i>Bed Modular Reactor research and development activities?</i>			
<i>Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>			
	Testing and Validation	Safety Technology of SMRs	FOAK
Testing and Validation	1	0,2	1
Safety Technology of SMRs	5	1	5
FOAK	1	1/5	1

Table 4-10: Environmental Sub-factors Pairwise Comparison Questionnaire

<i>Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important than other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?</i>			
<i>Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>			
	Fukushima	Nuclear Waste Disposal	Radioactive Contamination
Fukushima	1	7	5
Nuclear Waste Disposal	1/7	1	1/3
Radioactive Contamination	1/5	3	1

Table 4-11: Legal Sub-factors Pairwise Comparison Questionnaire

<i>Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important than other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?</i>		
<i>Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>		
	Tailored Standards	Unusual designs
Tailored Standards	1	3
Unusual designs	1/3	1

4.12 Results: Presentations and discussions

Step 57 of the extraction and case study instrument indicates that the ET pairwise judgements are deemed consistent if the consistency ratios (CRs) are below 0.10. In this regard, AHP Expert Choice (EC) software was used to calculate the threat factors priority weights and their consistency ratios (CRs). EC is a computerised decision support system designed by Dr. Ernest H. Forman for professional decision-makers who use the AHP that was developed at the Wharton School of Business by Thomas L. Saaty (Saaty, 1988). Using the pairwise survey results as input, EC software was used to compute threats factors priority weights and consistency ratios (CR) presented in the following sections 4.12.1, 4.12.2, 0, 4.12.4, 4.12.5, 4.12.6, 4.12.7 and Table 4-19. In the same sections, the EC software graphs (Figure 4-3, Figure 4-4, Figure 4-5, Figure 4-6, Figure 4-7, Figure 4-8 and Figure 4-9) also show the computed threat factors weights. In general, a response with a CR value of 10% or less is considered to ensure consistency, and a response with a CR value of 20% or less is occasionally included in the analysis (Lee, Son, Park, 2020). In all the weights and CRs in this case study, the ET made a decision not to redo pairwise comparisons because most CRs were less than 0.10 or close to this value. This redoing of the pairwise comparison is an ET decision option indicated as Step 21 in the research study design (flowchart) i.e. (Figure 3-1) and Step 57 of the extraction and case study instrument (Figure 4-1).

4.12.1 Political threats sub-factors comparison priority weights and consistency ratio

Figure 4-3 and Table 4-12 below show in increasing order that political system (0.39), sanctions (0.24) and political stability (0.16), are the sub-factors within the political external category that have the highest potential to impede the PBMR R&D activities. The tariff (0.03) and trade war (0.07) were deemed to have the least potential to impede. It is important to note that some political system decisions in a country can lead to political instability or even sanctions that will can result in closing possible opportunities to collaborate with nuclear countries that possess the required nuclear technologies. Nian (2020) stated that based on East Asian experience in developing nuclear competence, participation with international cooperation in the research and development of Generation IV and nuclear fusion reactor systems could demonstrate strategic entry points for countries with a long-term plan to derive indigenous nuclear reactor technologies. On Japan and S Korea, Valentine and Sovacool (2020) identified six factors having clear influence on supporting nuclear power development (1) strong state

involvement in guiding economic development; (2) centralization of national energy policymaking and planning; (3) campaigns to link technological progress with national revitalization; (4) influence of technocratic ideology on policy decisions; (5) subordination of challenges to political authority, and (6) low levels of civic activism.

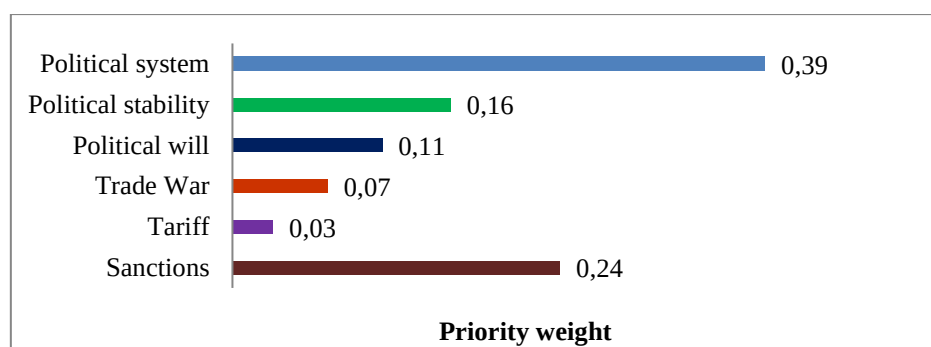


Figure 4-3: Political threats factors priority weights

Table 4-12: Political Sub-criteria Weights and Consistency Ratio/Inconsistency Ratio

Criterion	Local weight
Sanctions	0.24
Tariff	0.03
Trade War	0.07
Political will	0.11
Political stability	0.16
Political system	0.39
Inconsistency ratio = 0.104	

4.12.2 Economic threats sub-factors comparison priority weights and consistency ratio

As shown below in Figure 4-4 and Table 4-13, in decreasing order the local weights for economic threats sub-factors were private funding (0.54), government funding (0.31), operation and maintenance costs (0.10) and decommissioning costs (0.05). It is important to note that the SA government and other SA nuclear sector stakeholders stated from the onset underpinned the continuity of PBMR R&D being dependent on the availability of both public and private funding. In this regard, the local weights

obtained are in line with SA government stance on how the PBMR funding sources were to be structured. Towards the closure of the PBMR programme, the government had gone ahead and committed its funding portion. Unfortunately, this commitment was not matched by the private sector. When it comes to private funding, the SA government stated in 2010 that the PBMR company had not been able to secure an anchor customer or another investment partner and that further investment in the programme could well be in excess of an additional R30 billion.

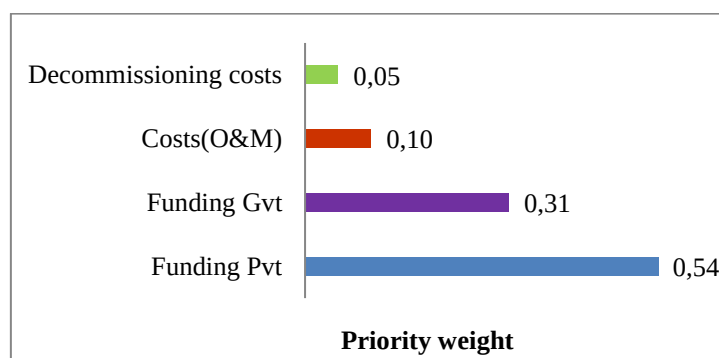


Figure 4-4: Economic threats factors priority weights

Table 4-13: Economic Sub-factors Weights and Consistency Ratio/Inconsistency Ratio

Criterion	Local weight
Funding (Private)	0.54
Funding (Government)	0.31
Costs(O&M)	0.1
Decommissioning costs	0.05
Inconsistency ratio = 0.086	

4.12.3 Social threats sub-factors comparison priority weights and consistency ratio

Figure 4-5 and Table 4-14 below show that public acceptance has the highest priority weight followed by waste management and CR of 0.028 which far less than 0.10. This is in line with the possibility that lack of public acceptance or support of the implementation of nuclear programmes can negatively affect political parties or governing political parties' willingness to support or fund such initiatives.

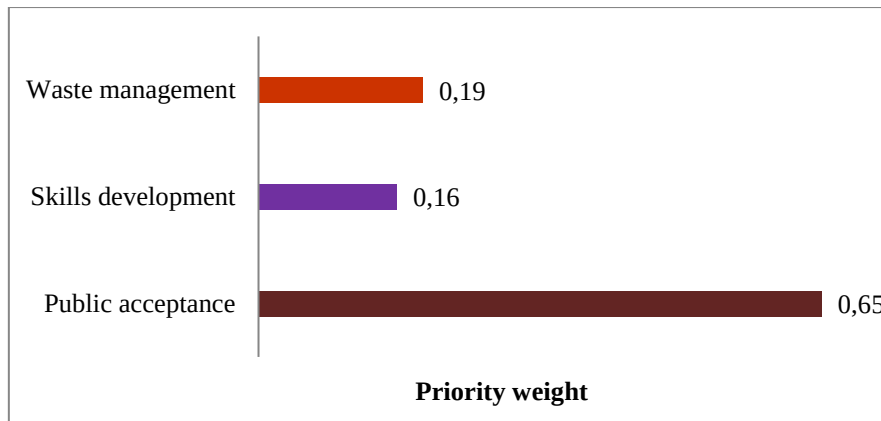


Figure 4-5: Social threats factors priority weights

Table 4-14: Social Sub-criteria Weights and Consistency Ratio/Inconsistency Ratio

Criterion	Local weight
Public acceptance	0.65
Skills development	0.16
Waste management	0.19
Inconsistency ratio = 0.028	

4.12.4 Technological threats sub-factors comparison priority weights and consistency ratio

As shown below Table 4-15 and Figure 4-6 below safety of SMRs were found to have the highest potential (0.71) to impede the PBMR R&D activities. The inconsistency of the judgement by the Expert Team is 0.00 that was below the AHP requirement that it should be less than 0.10. Strong safety concerns on nuclear technologies are usually premised on past (Chernobyl, Three Mile Island) and recent (Fukushima) nuclear disasters.

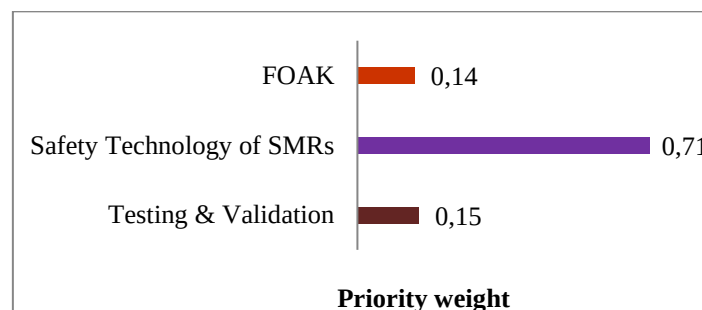


Figure 4-6: Technological threats factors priority weights

Table 4-15: Technological Sub-factors Weights and Consistency Ratio/Inconsistency Ratio

Criterion	Local weight
Testing & Validation	0.15
Safety Technology of SMRs	0.71
FOAK	0.14
Inconsistency ratio = 0.00	

4.12.5 Environmental threats sub-factors comparison priority weights and consistency ratio

The high 0.73 weighting for the Fukushima accident factor shown in Figure 4-7 and Table 4-16 below evidences the negative impact it has on the SMR or SA PBMR despite the fact that these technologies are premised on eliminating such disasters. The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (2020) concluded that the accident was clearly “manmade” since it was as a result of collusion between the government, the regulators and TEPCO, and the lack of governance by said parties who effectively betrayed the nation’s right to be safe from nuclear accidents. Such accidents feed into the safety sentiments and public acceptance of the SMR programmes hence their high weights as well. Those opposed to nuclear have often mobilised against nuclear by focusing on the aforementioned challenges or disasters.

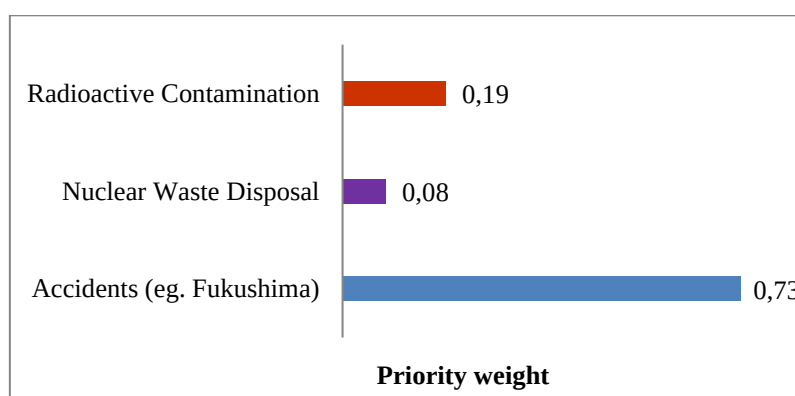
**Figure 4-7: Environmental threats factors priority weights**

Table 4-16: Environmental Sub-factors Weights and Consistency Ratio

Criterion	Local weight
Accidents (e.g. Fukushima)	0.73
Nuclear Waste Disposal	0.08
Radioactive Contamination	0.19
Inconsistency ratio = 0.063	

4.12.6 Legal threats sub-factors comparison priority weights and consistency ratio

There are challenges of licensing of SMRs worldwide because most of the technologies are first of a kind (FOAK) hence the “Absence of HTGR tailored standards” factor got the highest ranking. Most of the existing standards are tailored to the existing large NPP technologies that are already in construction and operation for many years. The PBMR had its own licensing challenges but the SA National Nuclear Regulator gained some experience that became invaluable for future nuclear new builds. The high weighting of 0.73 earmarked to Fukushima accident factor evidences the belief that past nuclear industry experiences have an impact on SMR or PBMR programme. This feeds into the Safety sentiments and public acceptance of the SMR programme hence their high weights as well. Those opposed to nuclear have often mobilised against nuclear by focusing on the aforementioned challenges.

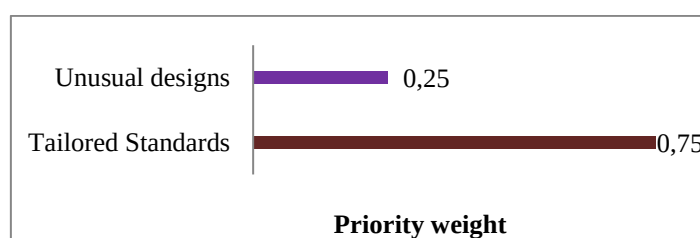
**Figure 4-8: Legal threats factors priority weights**

Table 4-17: Threat legal research and development factors' potential

Criterion	Local weight
Tailored Standards	0.75
Unusual designs	0.25
Inconsistency ratio = 0.00	

4.12.7 PESTEL threats factors comparison priority weights and consistency ratio

This was a computation of enabling relative comparison of weights at PESTEL groupings or global level. Figure 4-9 and Table 4-18 below show in decreasing order the PESTEL categories strategic threats factors with the highest potential to hinder the resumption and implementation of the PBMR R&D activities are namely political (0.34), economic (0.24) and social (0.23). Technological (0.07), environmental (0.07) and legal (0.05) strategic factors have the lowest hindrance potential weights. The ET judgement CR was 0.11 which is very close to the AHP required 0.10. These results are in line with sentiments expressed by the SA nuclear sector stakeholders that a major factor that contributed to the discontinuing of the PBMR initiative was the “waning of government willingness to support the programme towards 2010”. These stakeholder views coincided with transitional period from one SA government administration to another that wanted to reconsider the implementing the nuclear new builds against other possibilities. It is worth noting that the ET thoughts of judgement were in line with findings expressed by other researchers who noted that “governmental policies favourable to foreign investment are well-suited for future SMR deployment.” But then again, perceptions of SA government unwillingness to support the continuation of the programme were also driven by the fact that right after the PBMR programme was stopped a similar fate befell two SA PWR nuclear build programmes respectively in 2012 and 2018.

At PESTEL category level, the economic threat factors got the second highest ranking. It is important to state that towards the shelving of the PBMR, it became apparent to every stakeholder that economic and financial support by the government and private sector and securing future customers were among the key factors for the PBMR continuity, hence these factors still resonated with the survey team. These factors remain relevant for the future for the SA PBMR or any PWR programme. The GTM (2020) noted that the USA NuScale SMR was progressing towards its 2030 completion target because of (1) the Department of Energy's \$1.36 billion funding and 10-year cost-share pledge to Utah Associated Municipal Power Systems (UAMPS) as the first customer and off taker for the 213 MW of the 720 MW Carbon Free Power Project (CFPP) produced under a combined construction and operating license process.

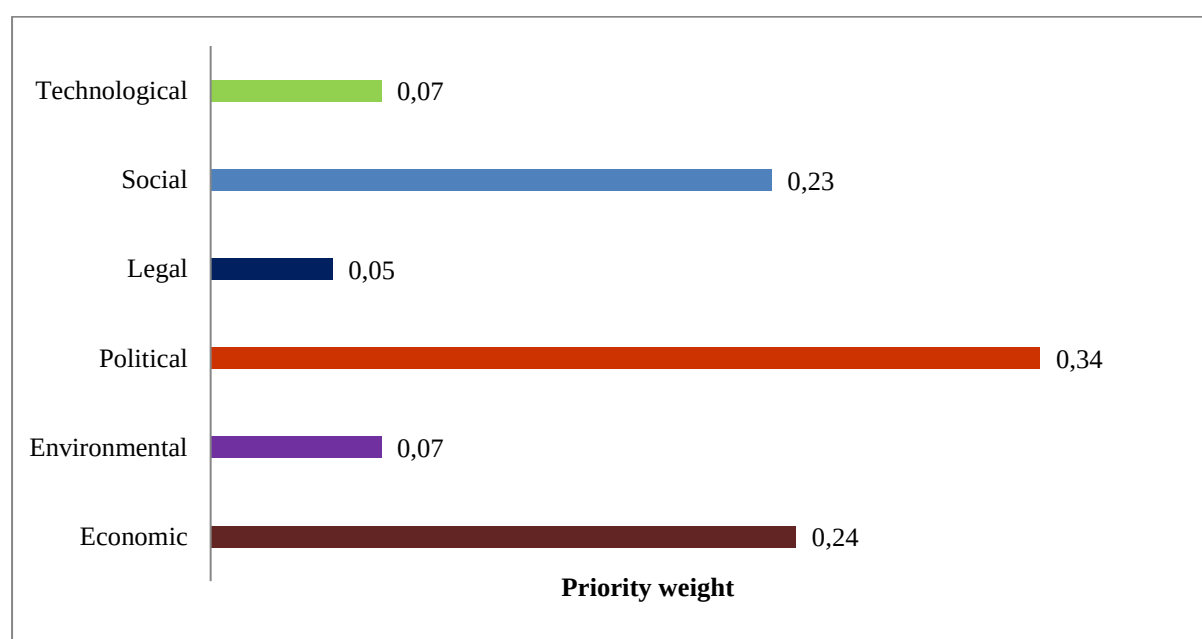


Figure 4-9: PESTEL threats factors priority global weights

Table 4-18: PESTEL Factors Global Weights and Consistency Ratio/Inconsistency Ratio

Criterion	Local weight
Economic	0.24
Environmental	0.07
Political	0.34

Criterion	Local weight
Legal	0.05
Social	0.23
Technological	0.07
Inconsistency ratio = 0.11	

4.13 Summary

As per set research study objectives, this case study demonstrated the retrieving, further validation, and operationalisation of the secondary data documented in the repository for the purposes of strategic decision-making. All the aforementioned activities supported the main or ultimate objective of developing a strategic decision-making model for the SA nuclear sector. Table 4-19 below is a snapshot of the qualitative and quantitative analysis of SA PBMR R&D threat factors rankings and ET judgement consistency results. The results culminated from the aims of the case study that were to rank or prioritise threat factors in terms of their potential to inhibit the successful resumption and implementation of the SA PBMR R&D activities.

The second column from the right shows that the political category had the highest ranking (0.34) followed by economic (0.24) and social (0. 23) groupings. Technological and environmental and legal categories had the lowest rankings which are respectively 0.07, 0.07 and 0.05. The judgement CR value of 0.11 that is close to the required 0.10 was obtained for these category level comparisons. The requirement of repeating the pairwise comparison when the CR is above 0.10 as stipulated by step 57 of the Figure 4-1 was deemed unnecessary by ET because the value of 0.11 was close and the fact that some related AHP nuclear investigations used 0.20 instead of 0.10.

The weights priority rankings among the threat factors in each category are presented in the fourth column from the right. For instance, political system had the highest ranking of 0.39 among the political

category. All the sub-factors or local weight judgement CR calculation results (0.014, 0.086, 0.028, 0.00 and 0.06) met the requirement that they should be less than 0.10.

Relative weights among the individual threat factors are listed below in the fifth column. In descending order, the highest ranked individual threat factors results were for public acceptance (0.18), private funding (0.14) and political system (0.13). All the other individual threat factor rankings were below 0.09. The calculated global weights CR value of 0.097. This can be said to be at par with the required guide of 0.10.

Table 4-19: Summary of all factor rankings and Consistency Ratios

PESTEL threats categories	Relative threat priority weights at category level	Strategic Sub-factors	Relative priority weights of threat sub-factors within individual categories	Relative priority weights of all threats sub-factors
Political	0.34	Sanctions	0.24	0.08
		Tariff	0.03	0.01
		Trade War	0.07	0.02
		Political will	0.11	0.03
		Political stability	0.16	0.04
		Political system	0.39	0.13
		Political factors (in)consistency ratio	0.104	
Economic	0.24	Private Funding	0.54	0.14
		Government Funding	0.31	0.07
		Operation and Maintenance Costs	0.1	0.02
		Decommissioning costs	0.05	0.01
		Economic factors inconsistency ratio	0.086	
Social	0.23	Public acceptance	0.65	0.18
		Skills development	0.16	0.04
		Public Concerns on Waste management	0.19	0.04
		Social factors inconsistency ratio	0.028	
Technological	0.07	Testing and Validation	0.15	0.01

PESTEL threats categories	Relative threat priority weights at category level	Strategic Sub-factors	Relative priority weights of threat sub-factors within individual categories	Relative priority weights of all threats sub-factors
		Safety Technology of SMRs/HTGRs	0.71	0.05
		FOAK	0.14	0.01
		Technological factors inconsistency ratio	0.00	
Environmental	0.07	Accidents (e.g. Fukushima)	0.73	0.04
		Nuclear Waste Disposal	0.08	0.01
		Radioactive Water Contamination	0.19	0.01
		Environmental factors inconsistency ratio	0.063	
Legal	0.05	Tailored Standards	0.75	0.03
		Unusual designs	0.25	0.01
Criterion Ranking Inconsistency ratio	0.11	Legal factors inconsistency ratio	0.00	Overall ranking inconsistency ratio=0.097

The overall research study conclusions, interpretations of results, recommendations, policy implications, limitations and possible future research studies emanating from this research study are presented in the next chapter.

5 Research Study Conclusions

5.1 Introduction

This research study accomplished the main objective of developing the SA nuclear sector strategic decision-making model as a response to the problem of the sector's lack of expansion. The lack of growth since the dawn of democracy in 1994 was evidenced by the sector's failure to implement its PWR and PBMR based nuclear new build programmes. As part of developing the novel conceptual model, an iterative and integrative research study design provided the methodology for this empirical investigation that partly entailed the collection, validation and documentation of nuclear sector related secondary data. Through this research study, it was established that it is feasible for the SA Nuclear Sector or any other organization for that matter to efficiently and effectively anticipate or respond to challenges by continuously in structured manner collect, archive and operationalise secondary data as part of its strategic decision-making process. The novel conceptual generic hybrid strategic decision-making model hinged on the synchronisation of the following (1) present, past and envisioned or anticipated nuclear sector facilities (2) the combined qualitative attributes of SWOT, PESTEL and LCA techniques and (3) the qualitative, quantitative and integrating qualities of the AHP.

Through the initial literature review, it was found out that SA nuclear sector's lack of growth was being worsened by both local and international trends. The examples of these trends are NPP construction cost overruns specifically in the USA and Europe, the drop in variable renewables installation costs, competitive gas prices and the phasing out of NPP plants use in Germany and other countries because of the Fukushima debacle. It was also observed that nuclear opponents locally and abroad tend to influence energy policies by e.g., highlighting construction problems in the USA that resulted in Westinghouse filing for bankruptcy and Areva's NPP section being taken over by EDF because of unsustainable losses. Specifically, in SA, anti-nuclear groups have been buoyed by their successful use of court interdicts to stop the nuclear new build programme. Just like in other democracies, the energy

debate in SA now embedded in the bipartisan or functional politics thereby creating a major stakeholder consensus huddle. All these challenges have contributed in one way or another towards the stagnation that has befallen the SA nuclear sector. Of all the challenges, the most devastating ones were the successive failures to implement the PWR and PBMR based nuclear new build programmes.

Based on the aforementioned challenges, a novel hierarchal hybrid generic strategic decision-making model that synchronised existing popular strategic decision-making techniques (SWOT, PESTEL, AHP and LCA) and the ten historical, present and potential future SA nuclear sector nuclear installations or facilities (pressurised water reactor, small modular reactor, research reactor, uranium production, conversion, enrichment, fuel fabrication, reprocessing and recycling, spent fuel storage, spent fuel disposal) was developed. This hybridisation was aimed at harnessing the qualitative and quantitative qualities of techniques, which were chosen because of their frequency or popularity in being used for strategic decision-making. For example, it was established that the AHP is one of the IAEA recognised multi-criteria techniques that it recommends for decision-making. Fundamentally the synchronization of techniques and superimposing them to the nuclear infrastructure was aligned to the specific objective of demonstrating how and why a developed SA nuclear sector strategic decision-making model should be a combination of existing popular decision-making techniques and SA's historical, present and possible future nuclear facilities.

The second specific objective was to demonstrate how the proposed model can be used to continuously, identify, collect, validate, archive, retrieve and operationalise SA nuclear sector factors for strategic decision-making purposes. The accomplishment of this objective was enabled by two instruments which were derived from the hybrid conceptual model. The continuous identification aspect of the objective is meant to emphasise the crucial importance that the collection of such secondary data should not stop because challenges and needs do not take a break. This being the case, the needs can be forecast

well ahead of time, hence the initial strategic response should be identifying, collecting and documenting relevant data with timeous operationalisation in mind. These objective aspects (identify, collect, validate, archive) were demonstrated through the design and utilisation of the data identifying, collecting and archiving instrument together with the secondary data repository for the ten SA nuclear infrastructure installations. The retrieving and operationalisation of the secondary data or factors for decision-making purposes was successfully demonstrated by using the retrieving or extraction and case study instrument. Categorization validation of the secondary data that went into the repository was made possible by using the UNICEF SWOT and PESTEL Guideline and the Harvard Business Review SWOT and PESTEL Guideline. Whereas the data retrieving and listing template which is part of the extraction and case study instrument afforded the validation of the comprehensiveness, appropriateness and adequacy of the secondary data to be operationalised. The AHP was used to quantify the factors for prioritisation purposes and to measure the consistency of the survey team's pairwise comparison judgements.

5.2 Main findings

As part of developing the model, this research study demonstrated how case studies can be used for strategic decision-making. This being the case a PBMR case study was used to identify and prioritise threat factors that can impede the successful resumption of its R&D activities. The threat factors that were found to have the highest potential to impede the resumption and implementation of the PBMR R&D activities were public acceptance, private funding and the political system. The validity of the relative weights were confirmed by AHP pairwise comparison weight judgements consistency ratios (CRs) which were < 10% although it was also established that < 20% was used as a guide in some nuclear related case studies. For instance, it was stated in an AHP study that examined S. Korea's nuclear R&D priorities based on private sector's domestic demand that "in general, a response with a CR value of 10% or less is considered to ensure consistency, and a response with a CR value of 20% or less is

occasionally included in the analysis. The validity of categorising the threats factors and the minimising of the participants' biasness was accomplished through the utilization of the SWOT and PESTEL guidelines from reputable organizations such as Harvard and UNICEF. These two guidelines have examples of categorisation of factors when using SWOT and PESTEL. For the case study, the holistic identification and structuring of the threats factors was enhanced by PESTEL and LCA respectively elaborate categories and phases. The SWOT method enabled the required narrowing down of data i.e., towards operationalisation. Yet the AHP afforded and enhanced the qualitative attributes of the aforementioned techniques at the same time enabling the quantitative, forward looking, iterative and integrative aspects of the novel model. For instance, the repository structuring was driven or informed by the anticipation that the operationalisation was going to be based on the AHP steps. Hence the enabling of the forward-looking qualities. This was the case also for the opportunities, strengths and weaknesses factors that were not operationalised in this study because the threats factors were sufficient for developing and demonstrating the how the model can be used. The implications of having demonstrated the secondary data validation and operationalisation augurs well for the proposed conceptual model to be used in nuclear or energy sector situations in which having a consensus within a stipulated time frame as way forward is of crucial importance. The generic attribute of the model was demonstrated through the archiving of ten different nuclear facilities.

The credibility identifying other similar studies had the same findings or conclusions of the research's PBMR case study. The highest priority weight given to public acceptance is in line with NEA (2020) study that established that the first-of-a-kind (FOAK) Generation III programmes, particularly in OECD member countries, have been affected by construction delays and cost escalations resulting in eroded stakeholder and public confidence in the ability of the nuclear industry to implement new nuclear builds. Likewise, the IAEA (2020b) stated that while SMRs appear to be a promising complement to conventional NPPs in the energy transition, one factor affecting the uptake of all nuclear energy

technologies is the level of public and political acceptance. This OECD finding is indicative of how cost escalations during construction impact public confidence on nuclear new build. This notion is also confirmed by Escobar and Leveque (2015) who stated that public opinion is not the only barrier that nuclear power faces today: a less addressed but also an important issue is whether new nuclear power plants can be built at a reasonable cost.

For PBMR case study, the threat factor “private funding” had the second highest impeding ranking. This is not surprising because it was widely reported that “the PBMR Company failed to meet conditions whereby the R6 billion was approved by SA parliament on two conditions which were (1) by February 2010, the PBMR needed to attract additional private investment other than the US energy corporation Westinghouse (which held only 4% of its shares), the Industrial Development Corporation (IDC), Eskom and government; and (2) the PBMR needed to find an international customer to which they would provide plants once the technology was proven”.

For the same PBMR case study, the third highest impeding factor was political system. More than likely, this is due to the fact that the SA nuclear sector perceives the local political system to be polarised to such an extent that local political rivals seem to lack consensus in implementing nuclear new build programmes. This is not surprising considering the fact that the energy debate in democracies globally e.g. in the USA and Germany tends to be bipartisan. In addition, civil society groups with interests in energy projects are operating at a global stage making it possible for them to influence energy projects decisions globally.

The strategic factors which were deemed to have the least potential to impede were within the technological, environmental and legal categories. This least impeding potential ranking of the SA

PBMR case study legal or regulatory factors is not in line with e.g. the OECD (2013) study that established that the principal challenge for the SMRs is licensing (a sub factor under the legal category), because of innovative and passive design features, difficulties of modifying the existing regulatory and legal frameworks. Within the three environmental local weights evaluated, the “impact due to the Fukushima calamity” sub factor had the highest impeding ranking yet it was one of the sub factors that had the lowest ranking relative to a total of twenty-one factors considered. Such a low level ranking was surprising considering some studies by other investigators. For instance, Joebel et al (2015) noted that the impact of the Fukushima disaster on environmental concerns, well-being, risk aversion, and political preferences especially in Germany resulted in nuclear power plant closures. This indifference on the part of this study participants is more than likely due to the strong belief within the local and international nuclear sectors that HTGR are designed to be much safer than the Generation II technologies which are presently in operation.

It was established that the model’s novel factor extraction and listing template was not only a tool for narrowing down data retrieved from the repository. It also demonstrated profound abilities to give a feedback to the research participants on the following:

- The degree or measure of literature review and data collection or factor identification from different model demarcated areas and sources; and
- More than any other instrument derived from the model i.e., in this study, the template demonstrated the reasoning behind synchronizing of chosen frequently used decision-making techniques since it e.g. enabled the quantifying of factors which were identified in each demarcated area. For instance, the template was able to reflect which PESTEL category or LCA phase had the investigator been able to identify factors and how many. This accounting of collected factors gives an option to decision-makers to decide whether to focus undertaking a survey based on factors within a PESTEL category or a LCA phase i.e., if there is a compelling reason. That compelling

reason is dictated by the need at hand. The second option afforded by the template to the investigation is whether to have the survey focus on factors appearing across PESTEL (political, economic, social, technological, environmental, legal) categories or across the LCA phases (R&D, engineering design, manufacturing, operation and maintenance, waste management). Thirdly, the investigating team can opt to utilise factors in the life cycle phases demarcated within any of the six PESTEL categories. It is also important to note that the participating experts can be the source of some factors as it happened in this research case study. Thus the analysis flexibility afforded by the novel synchronisation and concurrent use of the nuclear facilities, LCA, PESTEL, AHP, SWOT when wanting to narrow down to specific issues of the nuclear sector infrastructure programme for strategic decision making purposes.

Through this research study, it was demonstrated that the developed novel model has some robustness to be used by the local industry stakeholders to proactively respond to immediate and future needs. The model brings to bear the importance and value derived from combining popular decision-making techniques namely AHP, SWOT, PESTEL and Life Cycle Assessment. The other area of special emphasis emanating from the developed model is the importance of continuously, holistically identifying local and international factors data and structuring it in such way that it can be efficiently and effectively retrieved for decision-making. This attribute of the proposed model augurs well not only for the turnaround time of responses but also enhances the quality of responses since it was noted in this research that there is a possibility that some of the failures in the nuclear sector could have been due to lack of an agreed upon decision-making tools.

5.3 Contribution to body of knowledge

This investigation managed to demonstrate how the synchronization of decision-making techniques can further enhance the group decision-making and arriving at a consensus within industry sectors that have been declared to be strategic. This supports the notions advanced by other researchers who combined

AHP and other techniques such as PESTEL and SWOT. The expert group that participated in this study also assisted in the demonstration how decision makers can arrive at a consensus at critical moments of strategic programmes. This is in line with Tam and Tummala (2000) who noted that the AHP can be very useful in involving several decision-makers with different conflicting objectives to arrive at a consensus decision. This study went further by showing how the combined methods can also be in sync or superimposed to the historical, present and future nuclear infrastructure of a given organization or country. Fundamentally, there was a contribution to the awareness of integrative qualities of the AHP multi-criteria decision approach.

For the pilot case study, the conveniently and purposively chosen Expert Team participated in the prioritising the SA PBMR programme related threats factors. In this regard, the main focus was conducting a qualitative and quantitative analysis of SA PBMR external threats factors leaving the other listed factors namely; opportunities, strengths and weaknesses for possible future studies. The prioritisation of threat factors as this research's case study, advances the notion expressed by other researchers who are "recommending an approach in which the external factors are first examined and then proceeding to the internal ones so as to enable stronger focus on results, and identification critical threats (i.e. those that are compounded by corresponding weaknesses) and which opportunities are 'promising opportunities' (i.e. those that are matched by corresponding strengths)". In this study, the aforementioned recommended approach of identifying the threat factors first was taken further by quantifying their potential to impede. The other SWOT factors were identified using the same recommended order but operationalisation of factors is part of recommended future studies.

This research contributes to the identification and management of tangible and intangible factors that have a potential to impede or enhance the success of programmes within complex industry sectors such as that of nuclear. An established trend is to appraise non-nuclear and nuclear programmes from a

financial perspective using e.g. NPV and IRR. This proposed hybrid model enables non-nuclear and nuclear industry sector stakeholders such as executives, practitioners and policymakers to be also knowledgeable with examining programmes from broader non-financial perspectives. This is line with researchers who contend that the nature of an investment in energy production requires enlarging the range of parameters influencing strategic decisions, moving from technical, economic and financial, to social, environmental and political.

From time to time, professionals, executives, policymakers come across nuclear sector related literature that resonates with challenges they are encountering. The proposed conceptual model contributes on how such valuable data can be continuously documented and operationalised for the purposes of enhancing decision-making at critical moments e.g.; when state-owned entities' executives are called upon to comment or make an input on the implementation of strategic programmes. The novel systematic approach demonstrated by using the suggested conceptual model's e.g., structured repository instrument and data retrieving and case study instrument augurs well for shortening the time it takes to contribute towards a decision and ultimately to make a strategic-decision.

This study has contributed significantly in demonstrating the benefits derived from using integrated hybrid methods in strategic decision-making by taking advantage of existing and extensively used qualitative and quantitative decision techniques. Specifically, the use of qualitative analysis techniques namely PESTEL, SWOT, and LCA together with AHP, which is both quantitative and qualitative. The importance and benefits of using quantitative and multi-criteria techniques in the complex nuclear environment are advanced since the AHP is given a more holistic approach by e.g. PESTEL factor groupings.

The utilization of guidelines from reputable organizations such as the UNEP and Harvard University's Harvard Business Review for validating collected data was highlighted in this study. Content validation of collected data or factors was also enhanced by the utilization of the novel extraction and listing template which was used to highlight repository areas in which factors were not identified or more or less than other areas.

The consideration of strategic factors from ten different nuclear facilities life cycle stages perspective in this research advances the possibility of expanding and improving on the LCA three-dimension view point to be in line with those of the five-dimension PESTEL approach. This supports the UNEP/SATEC (2011) endeavour that noted that while using (environmental) LCA to measure the environmental dimension of sustainability is widespread, similar approaches for the economic (LCC) and the social (S-LCA) dimensions of sustainability have still limited application worldwide. The proposed model caters for these two approaches since those LCA derived techniques indicated as having limited usages are accommodated by PESTEL's economic and social considerations, which is demonstrated in the model's data collection structure and factor extraction template. This research novel use of LCA advances the notion that within the decision-making context, each organization has to solve and decide on each case depending on e.g. the size and culture of the organization, its products, the strategy, the internal systems, tools and procedures and the external drivers since there is no single solution as to how LCA can best be applied. In addition, it was established that the main drivers for the scientific developments towards Life Cycle Sustainability Assessment (LCSA) are the paradigm shift from environmental protection towards sustainability and the current developments with regard to evaluation methods and tools for environmental and sustainability performance.

5.4 Policy Implications

During the compilation of the SA Integrated Resource Plan (IRP) there are usually arguments pertaining to which electricity generating technology can have the best benefits. For instance, there are questions

on which technology is most suitable in terms of addressing factors such as employment, localization, contribution to security of energy supply, addressing climate change etc. Using this model, studies can be undertaken to establish which programme approach is the most suitable from a political, economic, social, technological, environmental and legal perspective.

Considering the socio-economic challenges faced by SA that have been worsened by covid-19 pandemic, it is important that policymakers foster harmony between nuclear sector and VRE sectors by using the proposed model as a standard approach of appraising benefits derived from the energy mix. It is envisioned that the developed SA strategic decision-making model can be used to highlight the merits of having an integrated VRE and NPP energy system as contemplated in the IRP; i.e., for the purposes of decarbonisation. In SA, the various energy generating technologies seem to be pitted against each other. This hostility impedes opportunities and benefits which can be realised when various energy technologies complement each other. According to the IAEA (2020), nuclear energy and renewables such as wind and solar power should not be seen as being competitors but rather as all being essential for achieving the low carbon future that world leaders have agreed to strive for. Sustainable development will require sustained R&D support backed by a long-term vision that may require changes to current policies (OECD-NEA, 2000).

The approach taken in the utilization of the model's data or factor gathering instrument hinges on contrasting South African nuclear programme undertakings against those of other countries that have nuclear programmes. This therefore creates an opportunity to benchmark SA nuclear sector policies against those of other countries with similar programmes. In SA the creation of growth, job creation, and industrial development promoting strategies such as the National Development Plan (NDP) is the latest in a line of such policies dating back to the Reconstruction and Development Programme in 1994 indicating the state's commitment to economic progress and executing this obligation that has been

severely tested by the locus of authority, cohesion among and capacity of state institutions (Naidoo & Maré, 2015). Through this investigation, it was established that parallel to the planning of implementing the nuclear new build other countries nuclear bodies such as UK's Nuclear Industry Council have come up with a Nuclear Deal Sector Deal that highlights areas of cooperation between government and the private sector aimed at addressing possible nuclear programme impediments. The Nuclear Industry Association of South Africa (NIASA) needs to consider coming up with a similar proposal based on the 2500 MW nuclear new build, which was reported to be due for the 11 November 2020 Section 34 determination approval by the National Energy Regulator of South Africa (NERSA). This determination will enable the private sector bidding process. Nuclear new build threats identified in this research can be considered for management by nuclear interest groups such the Nuclear Industry Association of South Africa.

Coincidentally, the SA PBMR research case study which was crucial in the development of the proposed model was conducted at a time when there is growing interest and opposition on the utilization existing and possible future large NPPs and SMRs in SA and abroad. In this regard, it will be important for nuclear sector decision makers to see to it that the following SA government policies (IRP and Nuclear Energy Policy) driven initiatives prioritise the in advance management of public acceptance, private funding and the political system threats factors. For instance, putting some effort in generating information on funding methods and the socio-economic benefits well ahead of time can have an effect of allaying concerns of political and non-hydro renewables sceptics.

5.5 Recommendations for possible future studies

Various options of responding to spent nuclear fuel challenges such as reprocessing, storage, deep geological disposal were noted during the collection, and archiving of nuclear sector related secondary data in this investigation's repository. It was found out that Japan was embarking on installing a nuclear spent fuel reprocessing plant that was equivalent to the one in France. At the same time, it was

established that even if comparing programmes in order to identify best practices and generate ideas for improvement on envisaged approach to tackle the decommissioning challenges (and due to the nuclear decommissioning programmes' uniqueness), until now, benchmarking has been only partially used. SA is set to have its Interim Spent Fuel Storage Facility and examining various options. This provides an opportunity not only to advance the benchmarking as a practise but to use the SA strategic decision-making model to benchmark what is being proposed for SA and how it's being realised in other countries that are responding same challenge of spent nuclear fuel. Fundamentally, the utilization of the model's instruments demonstrated how secondary data for comparing potential nuclear programme partners can be collected and operationalised so as to have consensus on e.g., which nation and why it should be part of SA's country to country long-term agreement.

In this research study, during the development, utilization of the model to collect, document and operationalise the nuclear sector secondary data, there were constraints encountered. For instance, there were ten facilities under which the literature reviews were conducted using the model instruments for purposes of identifying internal and external factors. However, the secondary data which was operationalised was in the main from SMR repository section and few factors retrieved from other repository's nuclear facilities categories. The operationalisation of the collected data under the other nine nuclear installations was hampered by the unavailability of survey informants to attend additional one-day survey workshops. This could have further demonstrated not only the generic qualities of the model but also specifically the robustness of its individual instruments e.g., the ability of extraction and listing template to validate the credibility of the secondary data per nuclear facility. This therefore opens an avenue for further studies.

A factor listing template analysis for narrowing down SMR (specifically PBMR) strategic factors in this research was initiated for the four categories namely threats, opportunities, strengths and

weaknesses. However, the threats factors were the only ones used for the SA PBMR case study. The operationalization of the other three factor categories was again not feasible because of the availability of the expert team considering the fact that the pairwise comparison workshop took a day. This being the case, it is recommended that future investigations of the SA PBMR R&D should include the appraisal of opportunities, strengths and weaknesses factors.

Demonstrating the full potential of the novel template requires additional time which was not afforded in this research. For instance, employing the template quantified factors across PESTEL groupings, quantified factors in each PESTEL grouping and quantified factors within life cycle phase needs to be exploited further e.g., during validating the adequacy and comprehensiveness of the collected factors per nuclear facility categories.

The generic attributes of the model were demonstrated through the gathering of internal and external factors of ten different types of nuclear facilities. This augurs well for utilising the same framework for undertaking similar qualitative and quantitative analysis of other technologies e.g. variable renewable energy (VRE) technologies. The reasoning behind conducting similar evaluations on VRE is that it is equally important for the nuclear sector to be equally conversant of energy technologies that are perceived to be either in competition or complementary to itself. Obviously, the main thrust of identifying VRE strategic factors will be to identify opportunities for cogeneration. Such integrated energy systems are conceived as a nuclear power reactor coupled with renewable energy generation and industrial processes that may simultaneously tackle the concerns regarding grid flexibility, climate change, energy security, optimal return on invested capital, and settling public concerns (Suman, 2018). Correspondingly, the IAEA (2018) contends that further research and development, the introduction of appropriate policies and market incentives are important next steps for fostering cogeneration for seawater desalination, hydrogen production, district heating, cooling and other industrial applications.

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Appendix A: International Workshop and SA Expert Team Workshop

A.1 Moscow International Workshop on Capacity Building

**PhD Thesis Title: Development of a strategic decision making model for the South African nuclear sector
Presented at: International Workshop “Capacity Building for Nuclear Industry: International Cooperation in Nuclear Education (23 July 2018. Moscow branch of Rosatom Technology Academy, 2nd Kazachy per. 11. Moscow, Russian Federation**

**Name: Jabulani Mangena
Executive Manager: South African Nuclear Energy Corporation
Education Institution: North West University, South Africa
Faculty: School of Mechanical and Nuclear Engineering
Study Towards: PhD in Development and Management Engineering**

A.2 Expert Team Pairwise Comparison Pelindaba Workshop Attendance Register

Development of the SA Nuclear Industry Strategic Decision-making Model: Model Validation Case Study Factors Pairwise Comparison Session Attendance Register

Venue: South African Nuclear Energy Corporation (Necsa) Visitors Centre Date: 24/05/2019

Time: 10:00 am to 14:30

	Name	Company	Position	Phone Number	email
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Appendix B: Extracted PBMR Opportunities, Weaknesses and Strengths Factors

B1: Possible SMR PBMR Related Case Study Identified Opportunities Factors

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Political			R&D			
	1.	1.	1. Since the 1950s, the HTR development program has been part of the national energy research program	National energy research program	OPR&D1	Allelein and Verfondern (2018)
	2.	2.	2. In Germany, the Federal Government and the State Government of Northrhine Westphalia (location of the nuclear research centre Jülich (KFA), today: research centre Jülich (FZJ)) provided political support that eventually resulted in the construction and operation of the AVR test reactor and the demonstration plant THTR-300	Political support	OPR&D2	Allelein and Verfondern (2018)
	3.	3.	3. Government commitments and support both at national and international level in the establishment of technical partnerships between the industry, business, R&D organizations and universities can enhance international collaboration and increase the pace of work on SMRs	Government support & commitment on partnerships	OPR&D3	Hidayatullah, Susyadi and Subki (2015)
	4.	4.	4. The US DOE has selected Very High Temperature Gas Cooled Reactor System (VHTR) for the Next Generation Nuclear Power (NGNP) Project, a project to demonstrate emissions-free nuclear-	US DOE Selection of VHTR	OPR&D4	INEEL (2003)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			assisted electricity and hydrogen production by 2015.			
	5.	5.	5. Argentina, Canada, China, France, India, Italy, Japan, the Republic of Korea, Pakistan, the Russian Federation and the United States of America are countries with active programmes on SMR design development and deployment (IAEA, 2013a).	World Wide SMR Development Programmes	OPR&D5	IAEA (2013a).
Economic			R&D			
	6.	1.	1. Formation of international and national research centres, experimental centres and scientific user facilities to increase effectiveness of education and training needed for the development and deployment of SMRs are means and mechanisms for enhancing international collaboration could increase the pace of work on SMRs	Formation of international SMR R&D centres	OER&D2	Hidayatullah, Susyadi and Subki (2015)
	7.	2.	2. Whereas Russia and China have large government investments in a few advanced nuclear technologies, the United States has a robust and thriving private sector for advanced nuclear development, drawing on both decades of public research and development and a high-tech investment ecosystem.	Public-Private Investment	OER&D3	Lovering and De Kirb (2019)
	8.	3.	3. SMRs are cost competitive with large reactors when the power required is 1-3	Economies of scale by the	OER&D4	Magwood IV and Paillere (2018)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			GW _e , since there is compensation of economies of scale by the “economy of multiples”	“economy of multiples		
	9.	4.	4. SMR are ideal for financial capabilities which preclude raising the huge capitals required by LRs	Competitive capital investment	OER&D5	Carelli et al (2010)
	10.	5.	5. Attractive to investors because of reduced risk in construction	Reduced construction risks	OER&D6	IFNEC-NEA (2016); Vujic, Anti and Vukmirovi (2012).
	11.	6.	6. SMRs concepts are being pursued for use in electricity and cogeneration (combined heat and power) markets	Cogeneration	OER&D7	Shropshire (2011; Carelli et al. (2010)
	12.	7.	7. Large market forms opportunity for low CO ₂ emission HTR technology	Large HTR marketCO ₂	OER&D8	Knol et al. (2016)
	13.	8.	8. Offering possibilities for synergetic energy systems that combine nuclear and alternate energy sources	Ability to combine with alternative energy	OER&D9	IAEA (2014a)
	14.	9.	9. To assure that the Agency's efforts are desirable and useful to Member States, the Agency's efforts in development of water-cooled, liquid metal-cooled and gas-cooled reactors are guided by three International Working Groups, which are committees of leaders of the national programmes in each technology area.	HTGR IAEA Working Groups	OER&D10	Kupitz (2019)
			Engineering Design			
	15.	10.	1. Formation and encouragement of international design consortiums like IRIS can foster collaborative efforts for development of SMRs and enhance	International Design Consortiums	OEED11	Hidayatullah, Susyadi and Subki (2015)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			international collaboration and increase the pace of work on SMRs;			
	16.	11.	2. In the United States, for example, the Department of Energy has offered up to \$452 million to support engineering, design certification, and licensing of two SMR designs	Government funding in developing technology	OEED12	Ramana, Hopkins and Glaser (2013)
		12.	Manufacturing			
	17.	13.	1. Shorter, more efficient supply chain. SMRs are a fraction of the size of Generation II and III+ plants. Typically, Generation II and III+ plant components are large leaving only a few vendors with the resources available to manufacture these components. SMRs will utilize smaller components meaning additional vendors can be included in the supply chain;	Shorter more efficient supply chain	OEM13	Carless, Griffin and Fischbeck (2016)
	18.	14.	2. Europe benefits from an excellent manufacturing industry capable of supporting HTR R&D&D, although it would require upgrading existing manufacturing lines and competences	Local manufacturing support during R&D	OEM14	Bredimas, Kugeler and Fütterer (2014)
	19.	15.	3. Economy of scale is compensated by offering the economy of mass production of multiple prefabricated modules,	Mass production	OEM15	Söderholm et al. (2014); Hidayatullah, Susyadi and Subki, (2015)
	20.	16.	4. Prefabricated modules assembled on site	Prefabrication	OEM16	Locatelli, Bingham and Mancini (2014)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	21.	17.	5. Built in factory setting because of because of their small size and modularity	Built in factory setting	OEM17	WNA (2015a)
		18.	Construction			
	22.	19.	1. Most nuclear plants take 5-7 years to begin operations and providing a return on investment whilst SMRs are expected to be able to be fully installed (12 x 50 MWe modules) within 40 months	40 months modules installation	OEC18	IFNEC-NEA (2016).
	23.	20.	2. SMRs, due to their inherently modular approach, are easier to build and, because of their smaller size, the FOAK impact on cost escalation has a limited effect	Limited FOAK Impact on Cost	OEC19	Locatelli, Bingham and Mancini (2014)
	24.	21.	3. Ramp-up (serial) construction to enable self-financing	Serial Construction	OEC20	Söderholm et al. (2014)
	25.	22.	4. The business case for SMR projects may be much more attractive to investors because of reduced risk in construction (short construction time)	Reduced Construction Risk	OEC21	IFNEC-NEA (2016); Söderholm et al. (2014)
	26.	23.	5. Modular concept that reduces the amount of work on-site, makes it simpler and faster to construct	Reduced site work due factory modules	OEC22	Vujic, Anti and Vukmirovi (2012)
	27.	24.	6. Expanded potential siting options since more sites are suitable for SMRs	Expanded siting options	OEC23	Vujic, Anti and Vukmirovi (2012)
	28.	25.	7. Smaller nuclear island and footprint of the whole nuclear power plant	Small nuclear island & footprint	OEC24	Vujic, Anti and Vukmirovi (2012)
	29.	26.	8. SMR are ideal for remote areas requiring smaller, localised power centres, to avoid long and expensive transmission lines;	Transmission installation costs reduction	OEC25	Carelli et al (2010)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	30.	27.	9. SMR are ideal for a geography and demography featuring mid-size urban and power needing areas fairly scattered, rather than concentrated in a few “metropolitan areas	Mid-size scattered urban areas power	OEC26	Carelli et al (2010)
	31.	28.	10. Improved construction efficiency through modularity. Building on site is typical of the Generation II NPPs. Generation III+ plants such as the Westinghouse AP1000 have introduced modularity into the design; resulting in several structural and mechanical components being built in a factory and shipped to site where it is assembled.	Construction efficiency due to modularity	OEC27	Carless, Griffin and Fischbeck (2016)
			Operation and Maintenance			
	32.	29.	1. Less operation and maintenance cost		OEO&M28	Hidayatullah, Susyadi and Subki (2015).
	33.	30.	2. SMR are ideal for the need for cogeneration (i.e. desalination, district heating, industrial steam) although in principle cogeneration is independent on the size of the NPP, in practice economic considerations have driven the large reactors to be essentially pure electricity producers.	Cogeneration	OEO&M29	Carelli et al. (2010)
	34.	31.	3. Their small size and passive safety features lend them to countries with smaller grids and less experience of nuclear power	Less nuclear experience	OEO&M30	WNA (2015a)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	35.	32.	4. SMR are ideal for electrical grids with limited capacity, where power variations in excess of 10% of the total grid capacity can endanger grid operation and stability	For grids with limited capacity	OEO&M31	Carelli et al (2010); WNA (2015a)
	36.	33.	5. SMR are ideal for remote areas requiring smaller, localised power centres, to avoid long and expensive transmission lines	Remote areas avoiding expensive transmissions	OEO&M32	Carelli et al (2010)
	37.	34.	6. The business case for SMR projects may be much more attractive to investors because of reduced risk in operation	Reduced operation risk	OEO&M33	IFNEC-NEA (2016)
	38.	35.	7. Meeting the need for flexible power generation for wider range of users and applications	Wider range of users	OEO&M34	IAEA (2014a)
	39.	36.	8. Suitability for non-electric applications	Non-electric applications	OEO&M35	IAEA (2014a)
	40.	37.	9. options for remote regions without established electricity grid infrastructures	For remote areas without established grid	OEO&M36	IAEA (2014a)
	41.	38.	10. offering possibilities for synergetic energy systems that combine nuclear and alternate energy sources	Enables synergetic systems	OEO&M37	IAEA (2014a)
	42.	39.	11. HTR heat provision is flexible (large range of pressures and temperatures);	Flexible heat provision	OEO&M38	Knol et al. (2016)
	43.	40.	12. HTR fits very well in small grids. Many heat intensive industrial complexes are located in such areas;	Appropriate for small grids	OEO&M39	Knol et al. (2016)
	44.	41.	13. Power generating systems for areas difficult to access or without infrastructure for transportation of fuel	For difficult areas to access	OEO&M40	Vujic, Anti andVukmirovi (2012)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	45.	42.	14. Long-life cycle and reduced need for refuelling (perhaps every 10-15 years)	Reduced need for refuelling	OEO&M41	Vujic, Anti and Vukmirovi (2012)
	46.	43.	15. Low operation and maintenance costs	Reduced operational costs	OEO&M42	Vujic, Anti and Vukmirovi (2012)
	47.	44.	16. Longer refuelling cycles. Typically, Generation II NPPs need refuelling every 12-18 months, whereas the expectation is to refuel SMRs every 24 months as a minimum.	Longer refuelling cycles	OEO&M43	Carless, Griffin and Fischbeck (2016)
	48.	45.	17. There are some SMR designs that will not need refuelling during their lifetime. Within this design after the fuel is depleted, the core is removed for decommissioning;	No need for refuelling during their lifetime	OEO&M44	Carless, Griffin and Fischbeck (2016)
	49.	46.	18. Increased thermal efficiency. Generation II and III+ NPPs typically have a thermal efficiency of 30%-33%. While this is also true for most SMR designs, a thermal efficiency of around 48% is what the General Electric's Energy Multiplier Module (EM2) Gen-IV SMR aims to achieve. This higher efficiency increases the amount of energy you receive per unit of fuel;	Increased thermal efficiency	OEO&M45	Carless, Griffin and Fischbeck (2016)
	50.	47.	19. Lower operation and maintenance cost. The simpler design of SMRs will employ fewer materials as well as have a majority if not all of their components fabricated in a factory. The benefits of having a simpler	Lower operation and maintenance cost	OEO&M46	Carless, Griffin and Fischbeck (2016)

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1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			design will allow for fewer pumps, valves, and components. This will increase the quality and therefore reduce the amount of maintenance required during the lifetime of the plant			
Social			R&D			
	51.	1.	1. Development of open public forums, access to information in understandable formats, participation of universities in preparing and distributing educational materials, and other measures will be needed to support widespread public confidence in the improved safety and performance characteristics of HTGR technology.	Open public forums	OSR&D1	Hannink, Kuhr, Morris (2008)
	52.	2.	2. In order to restore both society's sense of security and its trust in nuclear technology, nuclear industry organizations and their personnel need to work with a deeper understanding of public opinion, based on "co-evolution" with society.	Understanding of public opinion	OSR&D2	Yamano, Shioda and Sawada (2008)
	53.	3.	3. Nuclear safety concepts are difficult to explain to the public at large;	Challenges to explain to the public	OSR&D3	Knol et al. (2016)
	54.	4.	4. The business case for SMR projects may be much more attractive to investors because of reduced risk in societal aspects	Reduced Societal Risks	OSR&D4	IFNEC-NEA (2016)
	55.	5.	5. SMRs are relatively new entrants in the energy markets and promoting SMRs could improve the positioning and	Employment opportunities	OSR&D5	Iyer et al. (2014).

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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			competitiveness of domestic industries in the global value chain and possibly create employment opportunities			
			Engineering Design			
	56.	6.	1. There is a large European knowledge and experience base	Engineering knowledge & experience base	OSR&D6	Knol et al. (2016)
	57.	7.	2. Given the inertia of perceptions of nuclear power, going beyond awareness raising to engaging the public in the design process of nuclear power plants has a potential to offer a more transparent, participatory approach to improve the governance of energy supply options.	Engaging public in the design process	OSR&D7	Goodfellow, Williams and Azapagic (2011)
			Manufacturing			
	58.	8.	1. The general expectation is that the first movers will have a considerable advantage in capturing the global SMR market and this would help create domestic jobs in the manufacture of these technologies	Grabbing of global market by first movers	OSM8	Ramana, Hopkins and Glaser (2013).
	59.		Construction			
	60.	9.	1. During the construction phase, there are three different impacts on employment: (1) Direct: People employed in the manufacturing of components and modules, on-site construction and operation of NPP. (2) Indirect: Jobs created in the extended nuclear supply chain: suppliers of equipment	Direct, Indirect and Induced Employment	OSC9	Locatelli and Mancini (2011)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			manufacturers, suppliers of machineries and building materials, agencies for inspection and safety controls. (3) Induced: Jobs created in non-nuclear industries due to the new jobs added in the previous categories.			
	61.		Operation and Maintenance			
	62.	10.	1. Access to affordable energy enables efficient economic and social development, prosperity, health, education, and security of a people	Enhancing social development	OSO&M11	Vujic, Anti and Vukmirovi (2012)
	63.	11.	2. In South Korea, the SMART Power Company is marketing a 100MW SMR that can also produce some 10 million gallons of potable water every day.	Water desalination	OSO&M12	Lovering and De Kirby (2019)
Technological			R&D			
	64.	1.	1. If the demonstration project is successful, HTR-PMs may expect commercial deployment by 2030 in China followed by export to the global market	HTR-PM Deployment	OTR&D1	Nian (2018)
	65.	2.	2. Collaboration of technology holders and users through collaborative projects and studies on SMRs by sharing experiences in R&D can enhance international collaboration and increase the pace of work on SMRs	Collaboration of technology holders	OTR&D71	Hidayatullah, Susyadi and Subki (2015)
	66.	3.	3. A single reactor that can be grouped with others to form a large nuclear plant	Reactor grouped with others	OTR&D72	Locatelli, Bingham and Mancini (2014)
	67.	4.	4. Provision of heat for use for seawater desalination plant, Gasoline production	Provision of process heat	OTR&D73	Locatelli et al. (2017)

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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			plant, Oil sand extraction facility Algae-Biofuel production plant, District heating, Diesel-like fuel production from waste plastic pyrolysis, Waste wood palletisation plant and Hydrogen production from water splitting plant			
		5.	Engineering Design			
	68.	6.	1. An overall plant design comprising multiple small reactor units on a single site, deployed in sequence	Designed to enable multiple units on the same site	OTED74	Söderholm et al. (2014)
	69.	7.	2. Modular technology design	Design for modularity	OTED75	WNA (2015a)
	70.	8.	3. The common design goal of SMR fuel and core is higher burnup and longer lifecycles	Design for higher burnup and longer lifecycles	OTED76	Liu and Fan (2014)
	71.	9.	4. A longer refuelling interval will decrease proliferation risks and lower chances of radiation escaping containment	Longer refuelling interval	OTED77	Liu and Fan (2014)
	72.	10.	5. A higher burnup value which leads to a more fully utilization of uranium resources;	Higher burnup	OTED78	Liu and Fan (2014)
	73.	11.	6.			
	74.	12.	7. SMRs differentiate from Generation II and III+ nuclear plants by designing for simpler decommissioning.	Design for simpler decommissioning	OTED80	Carless, Griffin and Fischbeck (2016)
	75.	13.	8. SMRs differentiate from Generation II and III+ nuclear plants by designing for increased thermal efficiency;	Design for increased thermal efficiency	OTED81	Carless, Griffin and Fischbeck (2016)

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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	76.	14.	9. SMRs differentiate from Generation II and III+ nuclear plants by designing for improved construction efficiency through modularity	Design for improved construction efficiency through modularity;	OTED82	Carless, Griffin and Fischbeck (2016)
	77.	15.	10. SMRs differentiate from Generation II and III+ nuclear plants by designing for longer refuelling cycles;	Design for longer refuelling cycles	OTED83	Carless, Griffin and Fischbeck (2016)
	78.	16.	11. SMRs differentiate from Generation II and III+ nuclear plants by designing for shorter, more efficient supply chain;	Design for shorter, more efficient supply chain	OTED84	Carless, Griffin and Fischbeck (2016)
	79.	17.	12. SMRs differentiate from Generation II and III+ nuclear plants by designing for lower operation and maintenance costs;	Design for lower operation and maintenance costs	OTED85	Carless, Griffin and Fischbeck (2016)
	80.	18.	13. SMRs differentiate from Generation II and III+ nuclear plants by designing for reduction in construction time and mass production	Design for reduction in construction time and mass production	OTED86	Carless, Griffin and Fischbeck (2016)
	81.	19.	14. Small power and compact architecture and usually (at least for NSSS and associated safety systems) employment of passive concepts. Therefore, there is less reliance on active safety systems and additional pumps, as well as AC power for accident mitigation;	Design for passive safety	OTED87	WNA (2015a)
	82.	20.	15. The compact architecture enables modularity of fabrication (in factory),	Design for modularity	OTED88	WNA (2015a)

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1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			which can also facilitate implementation of higher quality standards;			
	83.	21.	16. Lower power leading to reduction of the source term as well as smaller radioactive inventory in a reactor (smaller reactors);	Design for lower power & smaller radioactivity inventory	OTED89	WNA (2015a)
	84.	22.	17. Potential for sub-grade (underground or underwater) location of the reactor unit providing more protection from natural (e.g. seismic or tsunami according to the location) or man-made (e.g. aircraft impact) hazards;	Improved seismic or tsunami safety	OTED90	WNA (2015a; Vujic, Bergmann, Skoda and Miletic (2012)
	85.	23.	18. The modular design and small size lend itself to having multiple units on the same site	Modular design	OTED91	WNA (2015a)
	86.	24.	19. Lower requirement for access to cooling water – therefore suitable for remote regions and for specific applications such as mining, desalination	Designed to have lower requirement to cooling water	OTED92	WNA (2015a)
	87.	25.	20. Ability to remove reactor module or in-situ decommissioning at the end of the lifetime.	Designed for in-situ decommissioning at end of lifetime	OTED93	WNA (2015a)
	88.	26.	Manufacturing			
	89.	27.	1. The German High Temperature Reactor fuel development program successfully developed, licensed and manufactured one million spherical fuel elements with high-enriched (Th,U)O ₂ BISO coated particles	Fuel Manufacturing		Allelein and Verfondern (2018)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			that were used to power the AVR and THTR.			
	90.	28.	2. Large components or modules are standard and factory manufactured (modular manufacturing and construction)	modular manufacturing	OTM85	Söderholm et al. (2014; WNA (2015a)
	91.	29.	Construction			
	92.	30.	1. Large components or modules are standard and factory manufactured for module installation	Modular construction	OTC85	Söderholm et al. (2014)
	93.	31.	Operation and Maintenance			
	94.	32.	1. After a successful operation for 21 years, the Germany experimental HTGR AVR plant stopped its operation in 1988.	Successful operation of the German AVR	OTO&M98	
	95.	33.	2. A complete steam supply system module already loaded with fuel	System module already fuelled	OTO&M99	Söderholm et al. (2014)
	96.	34.	3. The low power density and large heat capacity of the graphitic core, the absence of coolant phase changes, and the prompt negative temperature coefficient represent inherent safety advantages.	Inherent safety	OTO&M100	Verfondern, Nabielek and Kendall (2007)
Environmental			R&D			
	97.	1.	1. Low carbon is one of drivers of SMRs	Low carbon emissions	OENR&D1	Shropshire (2011)
	98.	2.	2. If the objectives of advanced nuclear power development programmes are met, nuclear power could provide a long term, safe and economical energy supply and thus make an even larger contribution to sustainable development, which is defined as development, which "meets the needs	Sustainable	OENR&D2	Kupitz (1995)

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1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			of the present without compromising the ability of future generations to meet their own needs".			
			Manufacturing			
	99.	3.	1. Other than district heating, the production related areas in which SMR will find use are (1) District heating; (2) Seawater desalination; (3) Pulp & paper manufacture; (4) Methanol production; (5) Heavy oil desulfurization; (6) Petroleum refining; (7) Methane reforming hydrogen production; (8) Thermochemical hydrogen production; (9) Coal gasification and (10) Blast furnace steel making.	Provision of heating & for production	OEM109	IAEA (2016b),
			Operation and Maintenance			
	100.	4.	1. The volumes of waste from nuclear energy generation systems, including the entire fuel cycle, are relatively small, about 1000 times lower than the volumes of waste produced by fossil fuel chains and are therefore much easier to manage safely and to isolate from the biosphere.	Nuclear waste 1000 times lower		Kupitz (1995)
Legal			R&D			
	101.	1.	1. The mega-utility Exelon has invested in a project of the South African state utility Eskom to develop and commercialize the PBMR, and is now engaged in detailed discussions with the U.S. Nuclear Regulatory Commission (NRC), in	Foreign licensing by foreign anchor partner		Lyman (2001)

Opportunities Analytic Hierarchy Process Question: Which past and prevailing international nuclear industry below factor is more important and to what measure over other below factors in terms of enhancing the successful resumption and implementation of the South African pebble bed modular reactor development project? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			anticipation of submitting a license application for construction of ten 110 MWe PBMR modules in December 2002			
	102.	2.	2. In 2005, the US passed the Energy Policy Act of 2005 mandating the construction and operation of a high-temperature gas reactor (HTGR) by 2021.	Legislation supporting HTGR project	OLR&D115	Kadak (2016)
	103.	3.	3. Development of passive safety	R&D on passive safety	OLR&D116	Vujic, Anti and Vukmirovi (2012)
	104.	4.	4. A longer refuelling interval will decrease proliferation risks and lower chances of radiation escaping containment	Longer refuelling interval	OLR&D117	Liu and Fan (2014)
	105.	5.	5. Proliferation resistance	Proliferation resistance	OLR&D118	Vujic, Anti and Vukmirovi (2012)
	106.	6.	6. The business case for SMR projects may be much more attractive to investors because of reduced risk in regulatory, safety, operation, and societal	Reduced risk in regulatory requirements	OLR&D119	IFNEC-NEA (2016)
	107.	7.	7. One of the most important aspects of the SMRs assessment pertaining to licensing and regulatory issues is reactor safety (including seismic safety)	Reactor safety	OLR&D120	Vujic, Bergmann, Skoda and Miletic, (2012)
	108.	8.	8. One of the most important aspects of the SMRs assessment pertaining to licensing and regulatory issues is radiation protection	Radiation protection	OLR&D121	Vujic, Bergmann, Skoda and Miletic, (2012)
	109.	9.	9. One of the most important aspects of the SMRs assessment pertaining to licensing and regulatory issues is power plant security	Power plant security	OLR&D122	Vujic, Bergmann, Skoda and Miletic, (2012)

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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			Engineering Design			
	110.	10.	1. Enhancing safety performance through inherent and passive safety features	Designing for inherent & passive safety	OLED123	IAEA (2014a)
			Construction			
	111.	11.	1. The NNR in its Annual Report of 2001 to 2002 noted that it received nuclear installation license application from South African electricity utility, lodged in terms of NNR Act, Act No 47 of 1999 for the prospective sitting, construction, operation, decontamination and decommissioning of a demonstration unit 110 MW electricity generating power station making use of PBMR design	SA ability to license PBMR activities	OLC126	NNR Annual Report of 2001 to 2002

B.2 Possible SMR PBMR Related Weaknesses Case Study Identified Factors

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Political			R&D			

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Economic			R&D			
		1.	1. PBMR Company failed to meet conditions whereby the R6bn was approved by parliament on two conditions: (1) by February 2010, the PBMR needed to attract additional private investment other than the US energy corporation Westinghouse (which holds only 4% of its shares), the Industrial Development Corporation (IDC), Eskom and government; and (2) the PBMR needed to find an international customer to which they would provide plants once the technology was proven	Failure to attract private investment	WER&D1	McKune (2010)
		2.	2. In February 2010, Finance Minister Pravin Gordhan announced that the South African government would stop funding the development of a demonstration power plant for the Pebble Bed Modular Reactor (Pty) Ltd (PBMR).	Withdrawn government funding	WER&D2	McKune (2010)
		3.	3. The increased flexibility that utilities need to compete in a deregulated market limits their timelines for decision-making, and may well be incompatible with the caution and rigor that advanced nuclear reactor development requires.	Incompatibility to deregulated market limits	WER&D3	Lyman (2001)
		4.	4. The Minister of the Department of Public Enterprises stated in 2010 that government, after careful deliberation, analysis and review, and mindful of the fiscal constraints in these hard-economic times, has had to decide to no longer invest in this project	Government stoppage of funding the project	WER&D4	Thomas (2010)

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	1.	5.	5. In 2002 a US energy Company Exelon which was one of the PBMR project initial investors withdrew their contributions because of a strategic shift rooted in change of company leadership a shift from being a technology developer to an electricity supplier	Investment withdrawal	WER&D5	Mckune (2010)
	2.	6.	6. The most recent attempt to commercialize an HTGR design, the Pebble Bed Modular Reactor (PBMR), was abandoned in 2010 after 12 years of effort and the expenditure of a large amount of South African public money.	Failed Commercialize after 12-year effort	WER&D6	Thomas (2010)
	3.	7.	7. Thomas (2010) questioned whether it was appropriate for such a risky project to be funded by public money, especially in a country like South Africa with so many demands for public money many of which were high return and low risk.	Using public money to fund risky projects	WER&D7	Thomas (2010)
	4.	8.	8. Eskom forecast that by 2004, PBMRs would be available to order commercially and that it would export more than 1000 units over the following two decades.	Missed targets	WER&D8	Thomas (2010)
	5.	9.	9. Eskom switched their support for nuclear reactors from the PBMR to 'conventional' nuclear power plants such as the Areva EPR or the Westinghouse AP1000,	Lost anchor partner	WER&D9	Thomas (2010)
	6.	10.	10. Poor management allowed the project to continue long after it should have been abandoned.	Poor project management	WER&D10	Thomas (2010).
	7.	11.	11. Well before 2008, costs and time- scales were escalating at an alarming rate,	Cost & time overruns	WER&D11	Thomas (2010).

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
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PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	8.	12.	12. Well before 2008, there was no interest from any customers and international investors showed no interest in providing new funds.	Unavailability of customers & investors	WER&D12	Thomas (2010).
	9.	13.	13. Had the resources poured into the PBMR gone into lower risk, more prosaic options such as energy efficiency, renewable and gas-fired generation, it is hard to imagine supplies would not have been cheaper, more reliable and 'greener'.	Competition against alternative technologies	WER&D13	Thomas (2011)
Social	10.		R&D			
	11.	1.	1. Compounding the difficulty are the nagging questions that continue to inhibit public acceptance of nuclear power: severe accident risk	severe accident risk		Lyman (2001)
	12.	2.	2. Compounding the difficulty are the nagging questions that continue to inhibit public acceptance of non-proliferation	non-proliferation		Lyman (2001)
	13.	3.	3. Compounding the difficulty are the nagging questions that continue to inhibit public acceptance of vulnerability to sabotage	vulnerability to sabotage		Lyman (2001)
	14.	4.	4. The nuclear industry has a long history of proposing new nuclear plant designs that sound great in theory but disappoint in practice, and the PBMR may be no exception.	plant designs that sound great in theory but disappoint in practice		Lyman (2001)
Technological			R&D			
	15.	1.	1. A design for the demonstration plant had still not been submitted to the South African safety regulator to start to carry out a detailed assessment of the design despite the fact that	Design licensing delays		Thomas (2011)

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			PBMR Ltd. had been saying since 2002 that the design was only about 6 months away from being submitted.			
	16.	2.	2. In 2009, when PBMR Ltd. announced that they were making radical revisions to the design, the helium gas turbine was abandoned in favour of a conventional steam cycle in which the helium coolant produces steam in a heat exchanger, which then powers a normal steam turbine.	Indecision whether gas turbine or conventional steam cycle		Thomas (2011)
	17.	3.	3. By moving away from the Modul-200, which had been produced by designers with a large amount of experience of the PBMR concept, it is possible that significant new problems were created.	Possibility of new design problems		Thomas (2011)
	18.	4.	4. Real technical issues, for example, the problem of high temperatures in the fuel, which the US Nuclear Regulatory Commission uncovered very quickly when it began to review the design, were swept under the carpet.	High temperatures in the fuel		Thomas (2011)
			Engineering Design			
	19.	5.	1. Only a handful of high-temperature gas-cooled reactors (HTGRs) have operated in the past, had mixed results and none of these reactors had employed the unique power conversion system proposed for the PBMR, in which the reactor coolant is used as the working fluid of a gas turbine to directly generate electricity	Fears of F-O-A-K		Lyman (2001)
Environmental			R&D			
Legal			R&D			

Weaknesses Analytic Hierarchy Process Question: Which past and prevailing below factor within South Africa is more important and to what measure over below other factors in terms of impeding the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) development programme? Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	20.	1.	1. Projects like German AVR and THTR, require extensive international cooperation and a sharing of efforts with other interested countries, respective contracts were established, such as the “Umbrella Agreement on Cooperation in the Field of Gas-cooled Reactors” between the Federal Government and the United States Research and Development Administration (ERDA) signed in 1977 and later joined by France and Switzerland, which worked successfully over many years	International Cooperation agreement	OLR&D1	Allelein and Verfondern (2018)
	21.	2.	2. A more robust system of scrutiny of public expenditure, through Parliamentary Committees and national public expenditure audit bodies should have been able to expose the problems of the project much sooner.	Lack of robust oversight	OLR&D2	Thomas (2011)
	22.	3.	3. Although the general outlines of the PBMR are known, the design that Exelon planned to submit to the NRC had not been finalized, so the following description is subject to change	NRC submission challenges	OLR&D3	Lyman (2001)
	23.	4.	4. Among the largest sources of uncertainty for the PBMR are the potential for and consequences of a graphite fire.	Possibility of graphite fire	OLR&D4	Lyman (2001)

B.3 Possible SMR PBMR Related Case Study Identified Strengths Factors

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
Political			R&D	Factor Summary	Factor Code	
	1.	1.	1. Necsa also hosts the development laboratories for the PBMR fuel and the PBMR Helium Test Facility (HTF).	Endorsement of utilisation of existing through government policy	SPR&D1	South African Department of Minerals & Nuclear Energy Policy (2008)
	2.	2.	2. In April 2000, the SA national electricity utility, Eskom, obtained Cabinet approval to carry out a feasibility study for constructing the prototype of a new design of the pebble bed modular reactor	Government approval for feasibility study	SPR&D2	Auf der Heyde and Thomas (2002).
	3.	3.	3. South Africa has a declared intention to pursue a Pressurised Water Reactor (PWR) Programme and a nationally developed Pebble Bed Modular Reactor Programme subject to the success of the first demonstration unit	SA Nuclear Energy Policy Endorsement	SPR&D3	SA DME Nuclear Energy Policy (2008)
	4.	4.	4. PBMR's continuous and successful involvement in the United States Department of Energy's Next Generation Nuclear Plant (NGNP) programme	Involvement in the US NGNP	SPR&D4	Annual Report Presentation to the Portfolio Committee on Public Enterprises (2010)
	5.	5.	5. The PBMR Company was developing a fuel manufacturing	PBMR fuel development capabilities	SPR&D5	SA Nuclear Energy Policy DME (2008)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			plant and a demonstration high temperature gas cooled reactor, which is a low power output reactor designed toward meeting Generation IV requirements, applicable to both electricity generation and process heat applications			
	6.	6.	6. The South African government designated PBMR a National Strategic Project whereby it appointed a cabinet level committee on February 2004 and was to make an official announcement of full launch on September 2004	Declaration of national strategic project status	SPR&D6	Matzner (2004)
	7.	7.	7. The PBMR said to be a strategic national project due to its significance to South Africa and its potential in international markets, as a prospective provider of safe, clean energy.	As above	SPR&D7	PBMR Website (2017)
	8.	8.	8. Availability of PBMR fuel development facilities at NECSA		SPR&D8	SA Nuclear Energy Policy (2008)
	9.	9.	In April 2000, the South African Cabinet approved the carrying out of a feasibility study by the South African State electric utility, Eskom, for the construction of a prototype of a new design of	Government approval of feasibility study	SPR&D9	Auf der Heyde and Thomas (2002)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			nuclear power plant, the pebble bed modular reactor (PBMR).			
Economic			R&D			
	10.	1.	1. The higher temperature alone could allow the reactor to achieve a conversion efficiency of 39% and use of the coolant in a direct gas turbine cycle (known as the Brayton cycle) was meant to further increase the efficiency to about 43%	Increased efficiency		Lyman (2001)
	11.	2.	2. The decision to base a cost evaluation on a preliminary design rather than deriving it from costing models was due to that cost references are firstly, not direct cycle specific and secondly, there were deviations from German design basis.	Ability to undertake cost evaluation using preliminary design	SER&D15	Fox and Mulder, (1995)
	12.	3.	3. About R9, 2 billion has was spent on the Pebble Bed Modular Reactor project, with 80% of the money provided by the government.	Availability of government funding	SER&D16	Mail & Guardian (2010)
	13.	4.	4. In 1999, a separate entity known as PBMR (Pty) Ltd was established initially to develop the design and to establish	Establishment of the PBMR Company	SER&D17	Nicholls (2002)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			beyond doubt the technical and commercial feasibility of the project.			
	14.	5.	5. Stimulation of economic development since PBMR was to contribute to this through the range of new activities that were to be developed and to support the further development, construction and commercialisation of the technology	Economic Development	SER&D18	PBMR Website (2017)
	15.	6.	6. 6 South African universities and Necsa participated in various research activities to further the technologies required to keep PBMR at the forefront of nuclear reactor development in future	Involvement of Local Universities	SER&D19	PBMR (2010)
	16.	7.	7. A total of R8.8 billion was spent on the PBMR as of December 31 December 2010	Public and private funding	SER&D20	McKune (2010)
			Construction			
	17.	8.	1. The SA PBMR was seen as a logical solution of building lower capital cost intensive power plants, with 18 to 24 months' construction	Lower capital costs	SEC23	Koster, Matzner, Nicholls (2003)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	18.	9.	2. For the planned demonstration module that was be erected at Koeberg, several modules could be placed on the same site and use a common service building, but would not share other facilities. and is suitable for remote locations	PBMR plant was meant to be idea for remote locations	SEC24	Koster, Matzner, Nicholls (2003)
	19.	10.	3. For the planned demonstration module that was be erected at Koeberg, several modules could be placed on the same site and use a common service building, but would not share other facilities making it to be suitable for countries with an underdeveloped electricity generation system	PBMR plant option ideal for underdeveloped electricity generation system	SEC25	Koster, Matzner, Nicholls (2003)
	20.	11.	4. A solution competitive in countries with a well-developed electricity infrastructure or where gas prices are low the PBMR company offered a second option which it was being developing in parallel which was to have a multi module power plant within a common building and sharing some facilities.	PBMR plant option ideal for countries with a well-developed electricity infrastructure or where gas prices are low	SEC26	
			Operation and Maintenance			

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	21.	12.	1. Because the PBMR is loaded with fuel while operating, shutdowns would be required only for maintenance purposes and would take place every six years.	Reduced refuelling frequencies		Lyman (2001)
	22.	13.	2. SA utility identified the PBMR in 1993 as an option for increasing its electricity generation capacity	Chosen as Eskom's option	SEO & M27	
	23.	14.	3. PBMR suitability for remote areas eliminating the considerable costs associated with transmission	Suitability for remote areas	SEO&M28	Fox and Mulder (1995)
	24.	15.	4. Electricity produced by the PBMR plants shall be competitive with present major electricity generating systems when calculated for the lifetime of all plants and assuming conservative discount rates as well as escalation costs for the various fuels	Competitive electricity produced	SEO&M29	Koster, Matzner, Nichols (2003)
Social			R&D			
	25.		1. It was reported that through the PBMR project resulted in 31 post graduate diplomas in nuclear technology to date with 13 currently enrolled, the 33 M-level degrees in nuclear	Nuclear Human Capital	SSR&D1	Mulder (2010)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			engineering with 73 currently enrolled, and a number of PhDs delivered as part of the human capital development program in the Post Graduate School of Nuclear Science and Engineering at NWU			
	26.		2. The politically sensitive nature of nuclear projects from a public acceptance point of view is well acknowledged	Sensitive nature of nuclear projects	SSR&D2	Fox and Mulder (1995)
	27.		3. According to Tom Ferreira of PBMR Ltd., there were about 2000 support staff and engineers in various countries were working on the PBMR project, with about 700 at PBMR's headquarters in Centurion at the capital city Pretoria	Skills Development & Job Creation	SSR&D3	Langston (2008).
	28.		4. It was postulated that public support of the SA PBMR project could be found in the potential exploitation of the existing skills base	Utilization of the existing skills base	SSR&D4	Fox and Mulder (2019)
	29.		5. For the SA PBMR project public support, it was stated that it was important to recognize the export development potential	Potential of exports	SSR&D5	Fox and Mulder (2019)
	30.		6. For the SA PBMR project public support, it was stated that it was	Desalination potential benefits	SSR&D6	Fox and Mulder (2019)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			important to recognize desalination potential benefits			
	31.		7. For the SA PBMR project public support, it was stated that it was important to recognize the minimal environmental impact	Minimal environmental impact	SSR&D7	Fox and Mulder (2019)
	32.		8. Management of energy-related environmental and health impacts based on e.g., that the impact of nuclear power on the environment is significantly lower than coal	Management of energy related health impacts	SSR&D8	(PBMR Website)
	33.		9. Securing of energy supply through diversity since PBMR was to provide a "home-grown", emission-free alternative to coal for South Africa.	Security of supply	SSR&D3	(PBMR Website)
	34.		Manufacturing			
	35.		1. For the SA PBMR project public support, it was stated that it was important to note of potential of high local content benefits	High local content	SSM11	Fox and Mulder (2019)
Technological			R&D			
	36.		1. In June 1999, Eskom concluded an agreement with HTR GmbH for non-exclusive rights to the technology.	Technology transfer agreement	STR&D1	Thomas (2011)
	37.		2. Stated that Eskom through its research, test and development group is exploring the	Eskom willingness to relaunch	STR&D46	Fipaza et al. 2017)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			collaboration with academic and research institutions for the relaunching of the development of AHTR based on the PBMR programme that has been in a state of “care and maintenance” since 2010.			
	38.		3. As a three-shaft closed Brayton cycle has never been built before, a micro model of such a system that mimics the PBMR design and control and operating with nitrogen, was recently commissioned at the University of Potchefstroom in South Africa.	Local University support with the PBMR design	STR&D47	Koster, Matzner, Nichols (2003)
			Engineering Design			
	39.		1. The basis of the PBMR design of the reactor was on internationally proven, available technology.	Using internationally proven, available technology as design basis	STED48	Fox and Mulder, (1995)
	40.		2. As part of the PBMR plant core design validation and verification programme, a series of reactor physics experiments were performed in the ASTRA critical facility at the Kurchatov Institute in Moscow, and excellent agreement between experiment and calculation was established.	International support during designing	STED48	Koster, Matzner, Nichols (2003)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			Manufacturing			
	41.		1. SA demonstrated its ability to manufacture PBMR fuel	Ability to manufacture PBMR fuel	STM50	
	42.		2. Site welding of the PBMR plant components is undesirable and should be limited to those components that just cannot be transported in one piece	Modularity	STM51	Koster, Matzner, Nichols (2003)
Environmental	43.		R&D			
	44.		1. Because the PBMR is continuously refuelled, the excess reactivity can be kept low.	Excess reactivity can be kept low		Lyman (2001)
	45.		2. Mounting public awareness of the fact that the environmental impact of power sources derived from coal energy, is not negligible, contributes towards greater acceptance of nuclear as energy source.	Public awareness on coal energy emissions effects	SER&D55	Fox and Mulder, (1995)
			Engineering Design			
	46.		1. Fission products contained within the PBMR fuel TRISO particles cannot escape to the atmosphere and endanger the public as long as the fuel temperature remains below about 1600° C	No event that may need evacuation of residents near the reactor	SEED56	Koster, Matzner, Nichols (2003)
			Operation and Maintenance			

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
	47.		Reduction of GHG when operating the PBMR plants	Reduction of GHG emissions	SEO&M58	
Legal			R&D			
	48.		There was insufficient technical justification of the proposed relaxation of some NRC requirements	Insufficient justification for relaxing regulatory requirements		Lyman (2001)
	49.		PBMR designers claimed that in the event of a total loss of primary coolant and no operator intervention, the core heats up rate would be slow and the maximum fuel temperature would not exceed 1600°C.	Maximum temperature not exceeding 1600 ⁰ C		Lyman (2001)
	50.		The design has a more negative fuel temperature coefficient than LWRs, as the Doppler feedback is greater for the less-thermal neutron spectrum associated with a graphite moderator. * These features reduce the risk of reactivity accidents for most scenarios (but increases the risk for accidents involving core overcooling).	Reduce the risk of reactivity accidents		Lyman (2001)
	51.		Advocates of the helium-cooled, graphite-moderated PBMR argue that it is significantly safer than LWRs and should be exempted from a number of regulatory requirements that apply to the current generation of nuclear plants	Safer than LWRs and should be exempted from a number of regulatory requirements		Lyman (2001)
	52.		A major component of the PBMR safety basis is a low power density (an order of magnitude below that of an LWR) and large thermal capacity (as a result of the large mass of graphite in the core), together	Low power density		Lyman (2001)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			with the high-temperature resistance of the fuel			
	53.		PBMR advocates were so confident in the safety of the reactor (some even call it "meltdown-proof") that they have proposed a drastic weakening of a number of safety requirements that apply to the current generation of U.S. nuclear plants.	Meltdown proof leading to proposing relaxation of NRC requirements		Lyman (2001)
	54.		PBMR engineers involved in the development of SMRs ASME codes and standards	Development of codes & standards	SLR&D60	
			Engineering Design			
	55.		The then SA CNS that later became NNR proposed PBMR design reference to be the German "HTR Module" design, which was reviewed by German Regulatory Authorities and declared "licensable".	Availability of a design reference plant	SLED62	Mysen, Clapisson and Metcalf (2000)
	56.		The PBMR has inherently safe characteristics as a result of the design, materials used, fuel and physics involved	Inherently safe characteristics	SLED62	PBMR Website (2017)
	57.		The Chernobyl type of accident cannot happen with the PBMR technology because the peak temperature that can be reached in the core of the reactor 1000 degrees Celsius is well below the temperature that cause damage to the fuel	Fuel Safety	SLED64	PBMR Website (2017)
			Operation and Maintenance			
	58.		The danger to the public during operation was to be eliminated by controlling the heat	Public Safety Enhanced	SLO&M67	Koster, Matzner, Nichols (2003)

Strengths Analytic Hierarchy Process Question: Which past and prevailing below internal strengths factor within South Africa is more important in enhancing the and to what measure over other factors in terms of the successful resumption and implementation of the SA Pebble Bed Modular Reactor (PBMR) R&D activities? <i>(1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>						
1	2	3	4	5	6	7
PESTEL Categories	Factors Count Across PESTEL Categories	Factors Count per each PESTEL category	Nuclear Facility Life Cycle/Value Chain Capabilities and Factors Count per Phase	Factor Summary	Code Number	References
			production in the fuel by limiting decay heat levels and excessive reactivity excursions thereby the PBMR fuel reaming below about 1600° C			

Appendix C: PBMR R&D Case Study Pairwise Comparison Matrix Questionnaires

C.1 Political Sub-Factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Sanctions	Tariff	Trade War	Political will	Political stability	Political system
Sanctions						
Tariff						
Trade War						
Political will						
Political stability						
Political system						

C.2 Economic Sub-Factors Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Private Funding	Government Funding	Costs(O&M)	Decommissioning costs
Private Funding				
Government Funding				
Operation & Maintenance Costs				
Decommissioning costs				

C.3 Social Sub-Factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Public acceptance	Skills development	Waste management
Public acceptance			
Skills development			
Waste management			

C.4 Technological Sub-Factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Testing and Validation	Safety Technology of SMRs	FOAK
Testing & Validation			

Safety Technology of SMRs			
FOAK			

C.5 Environmental Sub-Factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble Bed Modular Reactor research and development activities?

Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)

	Fukushima	Nuclear Waste Disposal	Radioactive Contamination
Fukushima			
Nuclear Waste Disposal			
Radioactive Contamination			

C.6 Environmental Sub-Factors Pairwise Comparison Questionnaire

Using Saaty's nine-point importance rating scale below, which international (external to South Africa or external to SA implementing organization) nuclear industry factor is more important to other factors and to what measure in terms of impeding the successful resumption and implementation of the South African Pebble

<i>Bed Modular Reactor research and development activities?</i>			
<i>Equal Importance (1) Moderate Importance (3) Strong Importance (5) Very strong Importance (7) Extreme Importance (9)</i>			
	Tailored Standards	Exorbitant Costs	Unusual designs
Tailored Standards			
Exorbitant Costs			
Unusual designs			

Appendix D: Unicef SWOT Guideline

The list of opportunities, threats, strengths and weaknesses factors shown below are meant to be used as a guide in terms of making sure that the factors are placed at their rightful categories when populating the extraction and listing template as shown as Table 4-3 (listed Threats factors), Appendices B1 (listed Opportunities factors), B2 (listed Weaknesses factors) and B3 (listed Strengths factors).

Opportunities
Opportunities are external factors: They are found in the operational context within which the project, initiative or decision will be implemented.
1. Events or trends that offer opportunities: Political (government policies, favourable changes in power/influence of relevant actors, political agendas), economic (rising prosperity, new economic opportunities or other favourable economic change), social (behaviour patterns, demographic change), technological (innovations, changes in technology use), environmental (favourable climate/weather), legal (upcoming legislation or treaties/international agreements).
2. Relationships or partnerships that can be applied or drawn upon.
3. Other actors that will likely play a role in the initiative/project under consideration; if they could support you, they represent potential opportunities.
4. New information that has become available.
5. Practices adopted by other organizations/actors in addressing similar challenges, which suggest opportunities.
6. Potential funding sources.
7. Possible efficiency gains from re-allocation of resources.
8. Other initiatives, actions, projects or products that relate to the project/initiative under consideration.
9. Include under opportunities the advantages, benefits or probable results that are offered by the project/initiative that is being considered in the SWOT.
Threats
Just like opportunities, threats are external factors in the operating context for the project, initiative or decision.
1. Events or trends that could threaten the project/initiative or that put progress at risk: Political, economic, social, technological, environmental, legal.
2. Risks and disadvantages that would be incurred by a given initiative/action under consideration: risks to staff and/or partners, to populations, reputational risk, financial risk, political risk, costs, additional responsibilities, etc. A complete risk analysis cannot usually be completed in a SWOT, but basic risks can be identified, or risks identified in a separate pre-existing risk analysis can be mentioned. Alternatively, a more complete risk analysis could be called for at a later stage.
3. Time, including disappearing opportunities, deadlines, unrealistic timelines.
4. Other actors (harmful competition, contrary interests).
5. Opportunities that would be foregone if a given initiative/action is undertaken.
6. Other obstacles.
Strengths
Strengths are internal to the organization. Strengths include any kinds of capabilities or resources that the organization (and potentially any partners involved, and any stakeholders who are active participants in a development effort) can bring to bear, in order to achieve the desired result of the project, initiative, proposal, etc.
1. Political: power, influence, connectedness, image and reputation.
2. Access (to governments, partners, populations, etc.), reach, awareness.
3. Presence on the ground.
4. Economic / financial resources.
5. Capital assets, infrastructure, equipment.
6. Cost/competitiveness advantages.
7. Skills, experience, knowledge (including academic or theoretical, and also know-how, i.e. practical or applied knowledge).
8. Qualifications, accreditation.
9. Data, especially if it is unique or hard-to-replicate.

10. Allies, contacts.
11. Dedication, leadership and drive.
12. Cultural strengths.
13. Geographical advantages (presence; other)
14. Comparative advantages (with regard to other actors in the same context) in systems, processes, operational efficiency, flexibility, quality standards, other areas.
15. Things your team/organization/partnership does well.
16. Other noteworthy capabilities (technical, scientific, management, leadership, other) which the organization can apply.

Source: [https://www.unicef.org/knowledge-exchange/files/SWOT and PESTEL_production.p](https://www.unicef.org/knowledge-exchange/files/SWOT_and_PESTEL_production.p)